Chapter 6

Analytical Techniques

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CHAPTER OVERVIEW

Operators and regulatory authorities use a wide range of techniques to interpret and analyze data when predicting the impacts of mining and reclamation and designing reclamation, and the ultimate success of reclamation may depend on the validity of those techniques. Some **analytical techniques in use, however, may not consistently produce realistic predictions or valid interpretations with available data, or must rely heavily on assumptions to compensate for data inadequacies.**

Predicting the Impacts of Mining and Reclamation

A reasonable assessment of the impacts of mining and reclamation on surface and ground-*wafer hydrology,* over the life-of-mine area, can be made at most Western surface coal mines. Data will become more abundant and more reliable within each permit area due to monitoring as mine development progresses. In areas farther from the center of current operations, the knowledge of the physical system is less certain, and predictions of hydrologic impacts are less reliable. Regulatory authorities require worst-case analyses to compensate for this built-in error. So, as uncertainty about the system increases, assumptions made for input to the various analytical techniques become more conservative. Although this strategy avoids errors from underestimating potential impacts, it may entail other consequences from overstatements of impacts, including increased reclamation costs.

The development and use of quantitative methods for predicting impacts to groundwater quantity during mining—pit inflows and associated drawdowns—have tended to lag behind other quantitative developments in groundwater science. The effects of this are evident in the wide range of analytical techniques used in the mine permit applications reviewed for this assessment, which varied from simple linear extrapolations based on historical trends, to relatively simple analytical models, to sophisticated numerical computer models. A continuing problem in most mine permit applications is the lack of justification for selecting a particular analytical technique and description of the assumptions inherent in the analysis.

After mining, it is necessary to predict the nature and sources of spoils recharge, including postmining spoils aquifer characteristics; the time required for spoils resaturation and reestablishment of hydraulic equilibrium; and postmining spoils water quality. The nature and sources of recharge to the spoils are difficult to quantify without monitoring data. Most mines must use a water budget approach for calculating soil moisture storage and infiltration in order to estimate recharge from surface sources, and groundwater modeling techniques to predict postmining spoils aquifer flow characteristics.

Estimates of the time required for spoils resaturation and reestablishment of hydraulic equilibrium in the Western mining regions range from as few as 10 to as many as 2,900 years. While this introduces uncertainty about the long-term success of hydrologic restoration in some areas, that uncertainty was recognized during the formulation of the Surface Mining Control and Reclamation Act (SMCRA) and not considered so great that mining should be foreclosed in such areas. Continued analysis of field data on spoils recharge would reduce the level of uncertainty.

The validity of predictions of groundwater quality impacts-primarily levels of total dissolved solids (TDS)-is **critical because, given the time required for spoils to become fully saturated and groundwater flow patterns to be reestablished, there may be no way to verify the predictions by comparison with actual results. Analysis and prediction of postmining groundwater quality impacts are very difficult,** however, because the magnitude of such impacts is highly variable, the processes governing water quality changes are poorly understood, and the processes controlling recharge rates are unknown. **As a result, there is little agreement as to the best technique for producing consistent, valid predictions. Monitoring programs can be used to verify assumptions made about the trends of spoils-water quality over time, but will not necessarily provide information on the final postmining groundwater quality.**

Impacts on surface water quantity and quality are more readily observable than for groundwater, and the analytical techniques used to predict these impacts are more often based on actual conditions than on assumptions. The greatest potential impact to surface water quality from mining and reclamation is an increase in total suspended solids (TSS). When site-specific data are not available (the usual case for ephemeral streams), a well-accepted method is available to estimate the amount of sediment that will erode from the mine site and be subject to transport downstream during a precipitation event. Surface water quantity impacts are estimated primarily to support surface water engineering design, and valid statistical techniques are available for computing runoff volumes and peak flows. Deterministic models also are available, but their results are only as valid as the assumptions used about the hydrologic regime of the site.

The uncertainties in cumulative hydrologic impacts assessments (CHIAS) are greater than in determinations of the probable hydrologic consequences (PHC) of mining because of the absence of data from areas in which there is no active mining, and because of the lack of coordination and standardization in data collection (see ch. **5). The uncertainty could be minimized if regulatory authorities used monitoring and repermitting data to recalibrate the models used in CHIAS and to assess the validity and sensitivity of the various input assumptions.** periodic sensitivity analyses of the variables would provide valuable information about data inadequacies and could be used to focus data collection.

***Wildlife* are mobile, unpredictable, and adaptable, all of which make their responses to environmental change difficult to predict. It** also is extremely difficult to identify and isolate those unpredictable responses or adaptations that are attributable to mining and reclamation from those caused by any of the other environmental factors present. **As a result, quantitative techniques for predicting the impacts of surface coal mining and reclamation activities on wildlife populations have not been found to be effective and are attempted infrequently.** Instead, these assessments generally are made by intuitive professional judgment based on a knowledge of the operational aspects of the mine and of the ecological resources of the mine site and surrounding area.

Statistical analyses of the effectiveness of wildlife mitigation measures are possible but very costly. Where such analyses have been undertaken, their results generally are consistent with these intuitive professional judgments, indicating that a subjective approach to wildlife impact assessment based on measures of habitat quality from key ecological parameters, probably is the most satisfactory method of predicting impacts on wildlife resources.

***Revegetation* analyses focus on predicting the success of revegetation. While OTA found little emphasis on the development or use of analytical techniques for predicting long-term revegetation success, the lack of quantitative models does not appear to diminish the potential for accurate predictions.** The most common, and probably most valid technique for predicting revegetation success is to consider results of the most recent technology at other mining operations in the region with similar soil, overburden, and climatic characteristics.

However, there are few vehicles for disseminating the results of different revegetation techniques. Indeed, some companies may be reluctant to share such information for competitive reasons. Moreover, some techniques may show initial promise, but poor long-term results, or vice versa. With a qualitative comparative analysis for revegetation planning, the former may be adopted, and the latter rejected, prematurely.

Analytical Techniques Used in the Design of Reclamation

Accurate characterization of the overburden and delineation of potentially deleterious overburden material, design of an optimum soil-salvage plan, design of well-stabilized stream channels, and design of efficient sedimentation control measures are important factors in the ultimate success of reclamation.

Overburden **forms the basic material for the reclamation process, and the chemical and physical character of the overburden are key factors in determining impacts on postmining spoils hydraulics and water quality, as well as revegetation success.** However, overburden is not easily observed premining, the geology of the overburden in many of the mining regions of the West is highly variable, and the science of overburden characterization is neither old nor well-established. As a result, **analysis of the physical and chemical properties of overburden is difficult.** Thousands of overburden data points will be generated at the average Western surface mine and there are no well-established procedures for interpreting these data to determine the chemical suitability of overburden materials. Operators and regulatory authorities generally agree on the methods for characterizing overburden and for handling potentially deleterious materials on a case-by-case basis. The primary risk of not identifying such materials before backfilling is that problems may not become evident until after bond release, yet may require costly reconstruction.

The *redressed soil serves* as a chemical and physical buffer between the disturbed mine spoils and surface water, vegetation, and wildlife resources, and also is a critical element for successful reclamation. Soils are relatively easy to observe and the science of soil characterization is well established. A low sampling density can result in significant errors in estimating the volume of salvageable soil material, however.

Valid approaches to design of an erosionally stable surface ***drainage system*** **are available,** ranging from direct field measurement of channel cross-sections and profiles that duplicate the undisturbed channel, to computer-assisted, detailed hydraulic analyses. **In the case study mines reviewed for this assessment, however, the amount of detail in such designs ranged from virtually none to very elaborate geomorphic and hydraulic studies, although an encouraging trend toward a comprehensive, multidisciplinary approach to design of surface drainage systems was observed.** Greater attention to drainage system design in permitting could reduce the potential for costly repairs of erosion damage during reclamation.

Techniques for the design of *hydrologic and sediment control facilities* have changed very little since SMCRA, although there has been an increasing use of computers, and a gradual standardization of runoff- and sediment-estimating techniques. The techniques in use accommodate the lack of site-specific data for sediment erosion and transport rates by providing relative estimates for comparison of alternative designs. Use of a computer allows rapid, accurate analysis so that larger areas can be simulated in greater detail and over shorter time steps than with hand calculations. **Monitoring data could be used to calibrate the models used, but OTA found little indication that this is occurring.**

Restoration of *alluvial valley floors* (AVFS) combines some of the more rigorous design aspects of surface and groundwater restoration. SMCRA only allows mining in AVF areas that are not significant to agriculture. There is little experience with mining in these areas under the SMCRA design and performance standards, although several plans for AVF restoration have been approved by the regulatory authorities. Premining analysis of the essential hydrologic functions of AVFS and postmining evaluation of AVF reclamation are based on accepted engineering and hydrogeologic principles, and operators and regulatory authorities view the probable success of reclaiming AVFS with confidence. As with hydrologic restoration in non-AVF areas, however, if AVF areas are mined it may be decades or centuries after mining and reclamation before the success of their hydrologic reclamation can be assessed completely.

USES OF AND REQUIREMENTS FOR ANALYTICAL TECHNIQUES

The term "analytical techniques," as used in this report, refers to all methods used to interpret and analyze baseline and monitoring data in order to make them useful in reclamation planning, permitting, and evaluation. **The use of analytical techniques for data interpretation is an integral part of the process of planning and evaluating reclamation, and the applicability and accuracy of the techniques used will, to some extent, determine the validity of that planning and evaluation, and therefore the ultimate success of reclamation.** The analytical techniques used in the permit applications reviewed for this assessment ranged from qualitative techniques in which the conclusions are dependent on professional judgment, to objective, quantitative modeling that requires sophisticated computer software to analyze the data plus technical competence to interpret the computer analysis. Some analytical techniques in use, however, may not consistently produce realistic predictions or valid interpretations with available data.

In this chapter, analytical techniques are divided into two broad groups: those used to predict the impacts of mining, and those used to plan and design reclamation. Techniques used to evaluate the success of reclamation are discussed in chapter 7. To the extent possible, individual analytical techniques are described and their applications, merits, and limitations discussed. Examples of their use, taken from case studies of Western mines (see vol. 2), are illustrated in boxes.

SMCRA'S requirement for a detailed reclamation plan that demonstrates an operation's ability to meet the performance standards implicitly requires the development and use of analytical techniques for designing and reviewing reclamation practices.[1] SMCRA includes few explicit requirements for the development and use of such techniques,[2] however, beyond the PHC determination and the CHIA (see ch. 4).

There are, however, informal requirements in the State regulatory programs. For example, the Wyoming Department of Environmental Quality (DEQ) expects data in permit applications to be interpreted to some degree and would likely reject an application that included raw data or conclusions not supported by data analysis. At a recently permitted mine in Wyoming, the techniques used to analyze premining data and to estimate impacts to the surface and groundwater systems were chosen to meet guidelines prepared by DEQ.[3] On the other hand, at least one permit application in New Mexico contained raw, uninterpreted data. d

[1]The **distinction is made between laboratory techniques used to derive data from samples** of soil, water, vegetation, etc., and analytical techniques used to interpret those data. The former often are required explicitly in State regulations or guidelines and are required to be performed in a prescribed manner (see ch. 5).

[2]The recent challenges to the Federal regulations implementing SMCRA (see ch. 4, box 4-C) will affect the applicability of various analytical techniques for predicting both the impacts of mining and the success of reclamation, including the techniques used for PHC determinations and CHIAs, as well as those used to predict mine-induced changes in streamflow sediment load and to design sediment controls.

[3]See case study mine N in reference 30.

[4]See case study mine L in reference 27.

ANALYTICAL TECHNIQES USED TO PREDICT THE IMPACTS OF MINING

Introduction

Predictions of the impacts of mining on the various components of the ecosystem support the demonstration, in the permit application package, that the performance standards will be met, and enable the regulatory authority to make the finding of reclaimability required by SMCRA before a permit can be issued. The resulting reclamation practices in turn affect both the profitability of the mining operation and the ultimate success of the reclamation. It is therefore in the best interests of all parties that the most reliable and efficient methods be used to predict the impacts of mining.

The ease and accuracy of predictions of the environmental impacts of mining varies widely among disciplines. For example, extracting coal by surface mining methods obviously will destroy the premine vegetation resource temporarily. It is less obvious whether overburden strata will have detrimental effects on the postmining vegetation. The less obvious the impact of mining on the environment, the greater the need for careful interpretation and analysis of sufficient data to predict the potential extent of adverse impacts in order to design reclamation properly.

Impacts to the quality and quantity of the surface and groundwater resources, and to the quality and quantity of the soil resource and the material within the postmining root zone are two major areas of concern because because they are critical to the postmining ecology, yet they embody a high degree of uncertainty. Impacts to vegetation, and to a limited extent wildlife, are determined indirectly from the predicted characterization of the postmining soil and water resource.

Although in this chapter the discussions of analytical techniques are categorized by discipline (i.e., groundwater hydraulics, overburden chemistry), it is important to keep in mind the concept that reclamation planning involves predicting the impacts of mining on a complex, integrated ecological system. Overburden stratigraphy and geochemistry determine groundwater hydraulics and water quality; soil volume and quality contribute to vegetative productivity. None of the components of the system is independent or isolated. As reclamation planning becomes more interdisciplinary, so do the more advanced analytical techniques, which are beginning to utilize the full range of modern computing technologies to simulate reclamation problems.

Predicting Groundwater Impacts[5]

Surface coal mining can affect groundwater resources in two ways. During mining, the pit acts like a large well, creating a low-pressure zone ("cone of depression") that draws water from the surrounding aquifers. This can cause local springs to fail, or wells located close to the disturbed area to be dewatered to the extent that they are no longer usable (fig. 6-l A, B). After mining, the shallow aquifers in the mine area are replaced with spoils materials that may have hydrologic characteristics substantially different from premining conditions (fig. 6-1 C).

Impacts to groundwater quality during mining are minimal. Because the groundwater flow is in the direction of the pit, there is little opportunity for any contaminants introduced by mining to affect offsite areas. **The greatest potential for groundwater quality impacts arises after mining, when groundwater saturates the spoils and returns to a steady-state flow pattern.** This section describes the analytical techniques used by mine operators and regulatory authorities to predict the magnitude of the impacts to the groundwater system during mining (which, it must be remembered, can last 40 or more years), and the methodologies used to predict or design postmining aquifer characteristics.

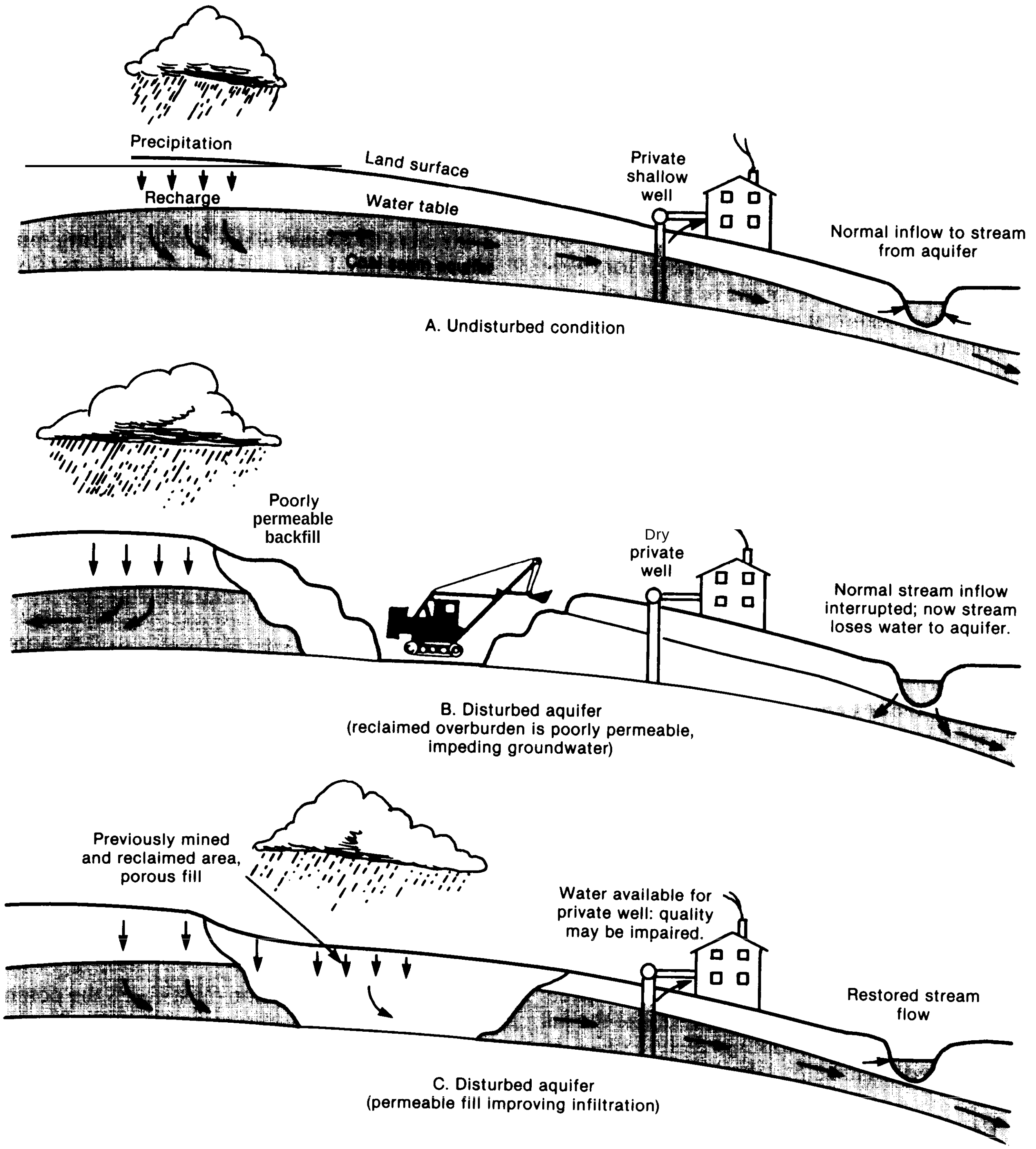
These impacts, as well as those to surface water quantity and quality, are predicted in the PHC determination. The geographic extent of this impact analysis is not defined in SMCRA, and the size of the area covered by a PHC determination varies from permit to permit. In areas of concentrated mining activity, the PHC determination may encompass one or more adjacent mines. At a mine in Montana, for example, the Department of State Lands required the PHC to include hydrologic impacts associated with another company's proposed surface coal mine operation immediately adjacent to the applicant's mine area.b

The PHC determination must assess the potential for: 1) groundwater contamination; **2)** contamination, diminution, or disruption of surface or groundwater supplies already in use; and 3) impacts to the surface water hydrologic balance. Some permit applications reviewed for this assessment used the 5-year term-of-permit area and others the life-of-mine area, depending on the regulatory authorities' needs for CHIAs (see ch. 4, box 4-C).

'Unless otherwise noted, material in this section is adapted from reference *30.*

⁶See case study mine E in reference 30.

Figure 6-l.— Possible Impacts of Mining Aquifers



SOURCE: F.E. Roybal, et al., Hydrology of Area 60, Northern Great Plains and Rocky Mountain Coal Provinces, New Mexico, Colorado, Utah and Arizona; USGS Water-Resources Investigations, OFR S3-203, p. 7,

Groundwater Impacts During Mining

To predict the impacts on groundwater resources during mining, it is important to define the aquifers in a mine area, determine the premine level of the water table, and determine to what extent the proposed pit will intersect the water table and disrupt the aquifer(s). The areal extent of impacts on groundwater levels depends largely on the geologic and hydrologic setting of the mine and the duration of mine dewatering. Aquifer boundaries generally coincide with geologic-unit boundaries, and the geology of the overburden and coal must be characterized in order to assess the potential impacts of mining. Once drawdowns and affected areas are defined, their impact must be determined by examining existing groundwater uses within the cones of depression.

In the coal regions of North Dakota, Montana and eastern Wyoming, for example, the sandstone, siltstone, and shale strata are complex and can change abruptly. The numerous aquifers in these strata tend to be small and to have limited communication with each other. As a result, water-level changes resulting from mining usually are relatively localized in the overburden. In these areas, however, the coal itself is a regional aquifer.

In the coal mining regions of northwestern Colorado, and western and southern Wyoming, geologic units are more continuous, aquifers may or may not be confined, and the potential for mining to cause changes in water levels over a large area is greater. In New Mexico, for the most part, the water levels are quite deep and below the level of mining except for very local perched water tables.

Prediction of pit inflows and associated drawdowns requires determination of the hydraulic properties of affected aquifers and knowledge of the mining methods and the mining schedule. Aquifer hydraulic characteristics that must be described include transmissivity, saturated thickness, storage coefficients, locations of hydrologic barriers or boundaries, and areal extent of aquifers. Long-duration pump tests are conducted to define aquifer hydraulic parameters. The pump tests must be analyzed with full consideration of boundary conditions determined from geologic maps and cross-sections in order to provide valid results. Selection of the technique for such analysis depends on many factors, including site-specific hydrogeologic conditions, pit configuration, and the experience and capability of the investigator. The available techniques are summarized in table 6-1 and described below; additional details may be found in the technical report on hydrology in volume 2.

For existing mines, where substantial amounts of data are available, pit inflows and drawdowns often are predicted from historical data on adjacent and hydrogeologically similar areas. This method is illustrated in boxes 6-A and 6-B for mines in North Dakota and Montana, which both used simple linear extensions of historical trends but with different amounts of data and demonstrations of premining conditions. In cases like the North Dakota example, where sufficient data on inflows and drawdowns are available and they demonstrate that the impacts of mining are minimal, the estimates should be valid provided that no changes are made in mining rates or methods and no unforeseen boundary effects are encountered. Thus, there would be no reason to conduct a more sophisticated analysis than the one used in that example.

When historical data are not available for estimating the impacts of mining, mathematical modeling must be used. The first step in developing a mathematical model is to translate the physics of the hydrologic process into mathematical terms. This requires an understanding of the process of groundwater flow and its relationship to the various hydraulic parameters. Certain simplifying assumptions about the hydrologic system, as well as assumptions about initial and boundary conditions, have to be made. Partial differential equations can then be derived that describe the physical process and form the basis of the mathematical model (13).

The mathematical model can be solved in one of two ways, thus dividing the models into two groups: **analytical models** use some additional assumptions for the groundwater flow equation, such as radial flow and infinite aquifer extent, and can be solved by hand calculation or using pro-

Table 6-1.—Summary of Analytical Methods Typically Used for Computation of Pit-Water Inflows and Resultant Drawdowns

Method	Data requirements	Advantages	Disadvantages
Extrapolation of existing data.	Historic records of pit inflows and resulting drawdowns.	Easiest method to use. Proven for given site conditions.	Not applicable for new mine. Not applicable to changing aquifer conditions or mining methods or schedules.
Simple application of Darcy's Law.	Potentiometric surface gradient, aquifer transmissivity.	Simple to use.	Limited predictive tool because either gradient or flow must be assumed. Basic assumptions of aquifer homogeneity and parallelism between base of aquifer and water table seldom met. Hydrologic barriers and boundaries difficult to address.
Theis nonequilibrium radial-flow equations.	Potentiometric heads, aquifer transmissivity and storage coefficient.	Simple to use. Better simulation in most cases than simple Darcy. Can simulate barriers and boundaries with image wells.	Limited predictive tool because drawdown or pit inflow must be assumed. Basic assumptions of aquifer homogeneity, instantaneous release of water with change in head, and infinite aquifer extent seldom met. Radial flow may not occur. Difficult to simulate movement of pit and reduction of aquifer transmissivity in time.
One-dimensional flow equation for fully penetrating excavation.	Potentiometric heads, aquifer transmissivity, location(s) of aquifer recharge sources.	Simple to use. Good simulation in certain cases.	Assumption that source of recharge and mine pit are infinite in length and parallel not met. Assumption that recharge equals pit inflow not always met. Requires assumption of drawdown or flow.
Combined radial and linear storage-release equations.	Potentiometric heads, aquifer transmissivity and storage coefficient.	Simple to use. Better simulation of actual pit configuration than previous methods.	Same basic assumptions as Theis equation. Does not consider downgradient flow of water—only storage release.
Finite-difference digital computer model (FDM).	Potentiometric heads, boundary conditions, aquifer transmissivity and storage coefficient, recharge; all must be input for respective nodes.	More accurate than previous methods. Better simulation of moving pit than previous methods. Facilitates accommodation of changes once data input is complete. Capable of handling larger problems, such as cumulative impacts of several mines, than previous methods.	More difficult to use than previous methods. Requires access to computer. Requires substantial calibration and verification. Difficult to check results without independent model study. Need to estimate recharge.
Finite-element digital computer model (FEM).	Same as FDM.	More flexible data input than FDM. More precise results than FDM. Handles irregularly shaped areas and complex boundary conditions better than FDM.	More difficult to use than FDM. Requires substantial calibration and verification. Difficult to check results without independent model study.

SOURCE: Western Water Consultants, "Hydrologic Evaluation and Reclamation Technologies for Western Surface Coal Mining," contractor report to OTA, August 1985.

[Page Omitted]

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grammable calculators or personal computers; and **numerical models,** in which the partial differential equations are approximated numerically by computer, and the continuous variables are replaced with discrete variables that are defined at points (grid nodes) in the area being modeled to generate a system of algebraic equations that are solved by matrix mathematics.

Analytical Models.–The available analytical models include the Darcy Equation, Theis Non-Equilibrium Equations, and various one-dimensional flow equations (see table 6-1).[7] All these methods use data readily available from standard aquifer tests, geologic investigations, and mine-plan maps and figures. **Any of these analytical flow models can be used to provide reasonably accurate predictions of pit inflows and drawdowns, provided that the investigator performing the calculations does so in full recognition of the assumptions on which the equations are based, the applicability of the individual methods to the site-specific hydrogeologic conditions, and the mining methods and schedules (see box 6-C).** The most common mistake made in this type of analysis is the use of an equation that is familiar or convenient but is not valid for the conditions that have been or that will be encountered. For example, two of the assumptions on which the Darcy Equation is based are invalid for most surface mining situations, and this equation can provide unreliable estimates of pit inflow if not used properly.

In addition, these analytical flow modeling techniques cannot account for the wide variations in aquifer hydraulic characteristics and boundary conditions normally encountered at mine sites. The simpler analytical techniques are, however, widely known to both industry and regulatory personnel, do not involve the use of proprietary analytical methods, and can be duplicated easily, all of which facilitate regulatory review and permit approval.

In employing any of these analytical flow modeling techniques to predict pit inflows or drawdowns over the life of a mine, the number of calculations required can become large. Many

[7]Detailed descriptions of these analytical flow models may be found in reference 30 in vol. 2 of this report.

Box 6-C [illegible]

[illegible] Powder River [illegible] estimated life [illegible] using predicted [illegible] program [illegible] model the [illegible] inflows were [illegible] at a con- [illegible] and draw- [illegible] pit loca- [illegible] A [illegible] the pump- [illegible] pit [illegible] by as- [illegible] as a [illegible] the theo- [illegible] presuma- [illegible] discussion in the permit application as to how well the under- [illegible] isotropy [illegible] well di- [illegible] storage were [illegible] this method [illegible] method [illegible] the change [illegible] the aqui- [illegible] surface be- [illegible] Moreover, this [illegible] is carefully [illegible] simulation [illegible] by syn- [illegible] unless the [illegible] are cho- [illegible] does not [illegible] or on [illegible] of wells [illegible] methodology [illegible] how- [illegible] and the [illegible]

investigators solve the equations using programmable calculators or personal computers, which improve both computational accuracy and speed, and a large amount of software has been developed to facilitate the analysis. Due to the enormous number of calculations required to calculate inflow and drawdown for each configuration of **a** moving pit (theoretically, there are infinite configurations), the investigator generally will select a limited number of pit configurations and perform a few "worst-case" predictions. Although this usually results in the overstatement of predicted drawdowns, worst-case studies are required by regulatory authorities to compensate for the built-in errors in the analysis methods.

A common means of overcoming the limitations of analytical flow models is to use a combination of mathematical prediction and direct observation via monitoring wells. This was the approach at one mine in Montana, which has been in operation since 1972.[8] The Darcy equation was used in conjunction with a flow net to estimate pit inflows and interactions between aquifers, and groundwater system monitoring was used to show development of the cone of depression. This combination of methodologies generally is not practicable at a new mine where sufficient monitoring data have not been amassed.

Numerical Flow Models.–Numerical flow models are used for systems that are more complex in terms of spatial variability or boundary conditions; because of the extensive computations required, they are only practical when solved by computer (1 3). These models can be used to predict the response of groundwater systems to mining as a function of aquifer parameters (transmissivity and storage coefficient), hydrologic and geologic boundary conditions, and the positioning of the pit within the system being modeled. The goal is to predict the value of an unknown variable (e.g., potentiometric head or discharge rate) at one or more specific locations, by solving a system of algebraic equations for each discrete time-step or region within the system.

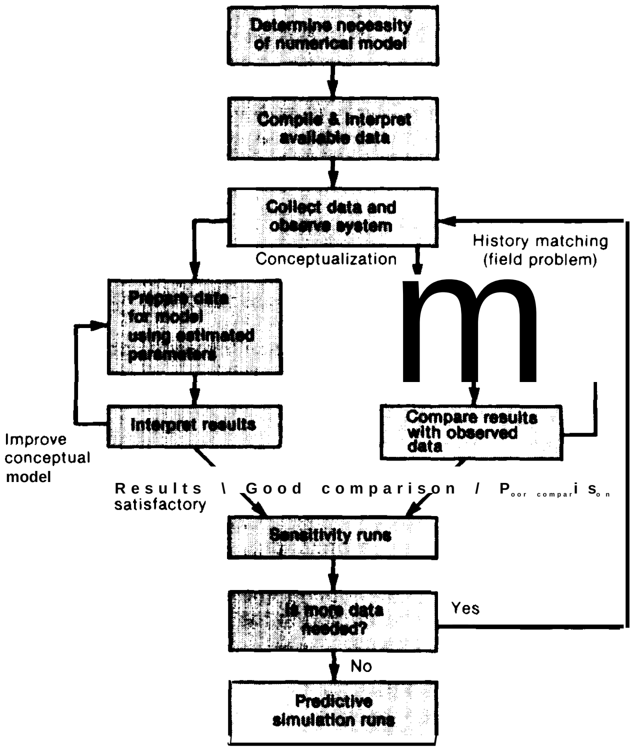
Numerical flow models are gaining in use among large operators, even though they are time-consuming to set up initially and can be more difficult for the regulatory authority to review even with proper documentation. The primary value of numerical models is as a qualitative guide to the behavior of an aquifer under various simulated stresses; more often, however, **they are used as predictive tools.**

[8]See case study mine D in reference 30.

Numerical models are more flexible than analytical models. Thus they can better represent the physical and temporal variations in a system. Moreover, the same model can be used to analyze a variety of problems. Numerical models also are not limited by some of the restrictive assumptions necessary for analytical models, and they can perform more sophisticated sensitivity analyses. These models, and the concepts on which they are based, are well accepted by hydrologists. However, the accuracy of the predictive results of numerical computer models is variable and depends on model limitations, accuracy of calibration, reliability of input data, and individual aquifer characteristics (9).

The application of a numerical groundwater model involves four primary activities: 1) data collection, 2) data preparation for input to the model, 3) trial-and-error calibration, and 4) simulation (see fig. 6-2) (6). Numerical models can be run with any amount of available data, but the quantity and quality of input data will determine

Figure 6=2.—Flow Diagram of Model Use



SOURCE: C.R. Faust and J.W. Mercer, "Ground-water Modeling: An Overview," *Ground Water*, vol. 18, No. 2, 1980, pp. 108-115.

the validity of the results ("garbage in, garbage out"). Special attention must be given to the collection, preparation, calibration, and verification of data input to the model. As shown in table 6-2, the two numerical models currently in use require extensive input data and substantial calibration and verification, and their results are difficult to check.

Numerical models also require an understanding of the behavior of the hydrologic system. Flow of groundwater and declines in water level can be described and analyzed mathematically, provided adequate hydrologic and geologic information is available (see table 6-2) (1 3). Thus, the model is not simply a predictive tool, but also an aid in conceptualizing aquifer behavior.

A numerical model is useful only if it is documented (i.e., there is a model description, a listing of its code, and a user's manual), is available at no cost in the public domain (this includes models developed by Federal and State agencies, or by universities under Federal grants), and has been applied once or more in the field. Out of 138 flow models examined in one survey, *39* were fully documented, 57 were available to the public, and 106 had been applied in the field; only 20 met all three criteria and were considered useful (l).

There are two mathematical flow modeling techniques in general use: finite-difference models (FDMs), and finite-element models (FEMs). The important components and steps of model development for the two alternative methods and their application are shown in figures 6-3 and 6-4; detailed descriptions may be found in volume 2. Although selection of the modeling technique should be made to correspond with the physical system being modeled (a tenet which holds for all analytical techniques), it is more commonly made to fit the user's experience or computer system (8).

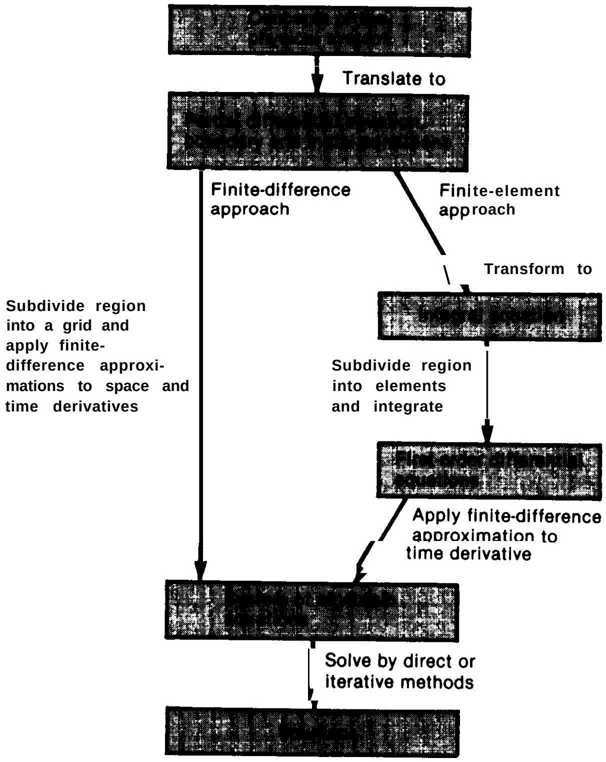
Table 6-2.—Possible Data Requirements for Groundwater Flow and Solute Transport Models

Requirements for grvundwater flow models:
- **hydrologic information on areal extent, boundaries, and boundary conditions of ail aquifers;**
- **locations of major surface-water bodies;**
- **water table, bedrock elevation, and saturated thickness information;**
- **confining layer information;**
- **transmissivity information for the study area, derived from pump tests or maps;**
- **permeability information on the relations of saturated thickness to transmissivity;**
- **the extent of aquifer and stream hydraulic connection;**
- **type and extent of recharge areas;**
- **groundwater pumping information;**
- **streamflow information; and**
- **precipitation information.**

Requirements for solute transport models (in addition to above data):
- estimates of hydrodynamic dispersion;
- effective porosity information;
- natural water quality information for the aquifer;
- hydraulic head distribution in the aquifer;
- water quality distribution in the aquifer;
- stream water quality;
- understanding of chemical reactions going on in the groundwater system; and
- **sources and concentrations of pollutant.**

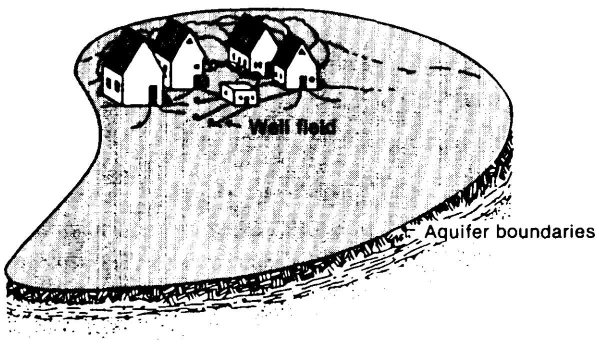
SOURCE: K. Kirk and G. McIntosh, Ground *Water Modeling by Use of OSM Modified* ***Prickett Lonnquist Ground Water Model,*** **U.S. Department of the Interior, Office of Surface Mining, training seminar, 1984.**

Figure 6-3.–Generaiized Model Development by Finite. Difference and Finite= Element Methods

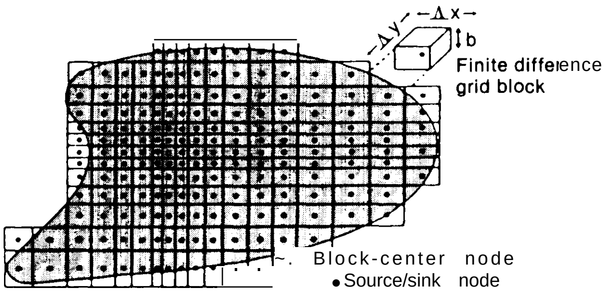


SOURCE: C.R. Faust and J.W. Mercer, "Ground-water Modeling: Numerical Models," ***Ground Water,*** **vol. 18, No. 4, 1980, pp. 395-409.**

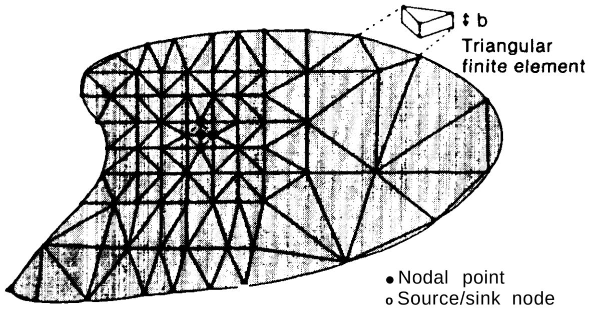
Figure 6-4.-Appiication of Mathematical Flow Modeling Techniques



Map view of aquifer showing well field and boundaries.



Finite-difference grid for aquifer study, where Ax, is the spacing in the x-direction, Δy is the spacing in the y-direction and b is the aquifer thickness.



Finite-element configuration for aquifer study where b is the aquifer thickness.

SOURCE: C.R. Faust and J.W. Mercer, “Ground-water Modeling: Mathematical Models,” *Ground Water,* vol. 18, No. 2, 1980, pp. 212-227,

At present, two finite-difference models are used frequently in Western surface coal mining. The Prickett-Lonnquist model, developed by the Illinois State Water Survey (box 6-D), has **been** used by mine operators and the Office of Surface Mining (OSM) to determine both site-specific and cumulative groundwater drawdown impacts for permit applications and CHIAS (see below) (1 3,19). The model is available in the public domain for mainframe computers and can be purchased for a modest sum for use on mini- and microcomputers. The U.S. Geological Survey (USGS) uses another model developed by Trescott and others in 1976 (box 6-E).

Although the FDM currently is more widely used, there is a consensus among computer modelers that the newer FEM is a superior analytical technique and eventually will be the predominant type of model used for the analysis of groundwater flow (30). Overall, the FEM is more flexible than the FDM because it has a more advanced mathematical basis and can provide higher levels of accuracy, but data input and programming are more difficult. Using the FDM, data input and customized changes to the program are accomplished more easily, but the relatively low accuracy of predictive results is unacceptable for some applications. However, when the typical low precision and sparse quantity of available data for large areas are considered, the distinction between the accuracy of the two methods is probably insignificant.

Digital computer models are not an appropriate analytical technique in every instance. For example, the USGS was unable to produce a verifiable, calibrated groundwater flow model of the Powder River basin coal mining region, covering some 4,500 square miles and 21 mines in northeastern Wyoming. This model was requested, and partially funded, by the Wyoming regulatory authority as part of their obligation to perform a CHIA for this area. Due to time and budget constraints, USGS simplified the groundwater system, assuming it consisted of only three separate, unrelated aquifers: overburden, coal, and underburden. Because of the considerable discharge or recharge from the vast bodies of burned-out coal (“scoria”) in the area, and the significant interaction between aquifers, the simplifying assumption of separate and unrelated aquifers produced unreliable results. While part of the reason for lack of success may have been the inadequate time and money, the unsuccessful study caused USGS to question whether such a large area could be modeled (28).

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Box 6-E.—Use of the Trescott Model[1]

USGS used the Trescott model to simulate the effects of mine spoils on postmining groundwater flow of the Anderson-Dietz coal aquifer in the West Decker area of Montana. First, the area was divided into rectangular grids, and the grids aligned with the major and minor axes of hydraulic conductivity (coincident with cleats in the coal). Boundaries simulated fault zones, the Tongue River, the Tongue River Reservoir, head-dependent variable-flow boundaries, or constant-flow boundaries (see fig. 6-5). Water-level measurements were available for 92 wells, of which 68 were completed in coal, and the rest in scoria, interburden, overburden, and replaced spoils. Results of 16 aquifer pumping tests conducted in coal aquifers and six conducted in spoils also were available.

Premining steady-state calibration of the model was performed until it accurately simulated measured head distribution. Sensitivity analyses determined that the model is most sensitive to changes in hydraulic conductivity and least sensitive to changes in recharge, probably because of the localized extent of the recharge area. The sensitivity analyses also were used to determine future data needs: measurements of coal-aquifer hydraulic conductivity and the anisotropy ratio and of spoil-aquifer hydraulic conductivity.

With this model, USGS predicted that, at postmining equilibrium, water levels west of the West Decker Mine probably would increase almost 12 feet over premining levels, although the increases would diminish within several miles of the mine. These postmining increases were ascribed to the damming effect of the less permeable spoil on regional aquifer flow. The model also predicted that water would take about 13 years to flow from the spoils to the Tongue River Reservoir. Using the results of the flow model together with estimates of groundwater quality effects of mining, however, USGS predicted that the increase in dissolved-solids contribution to the reservoir due to mining would be less than 1 percent.

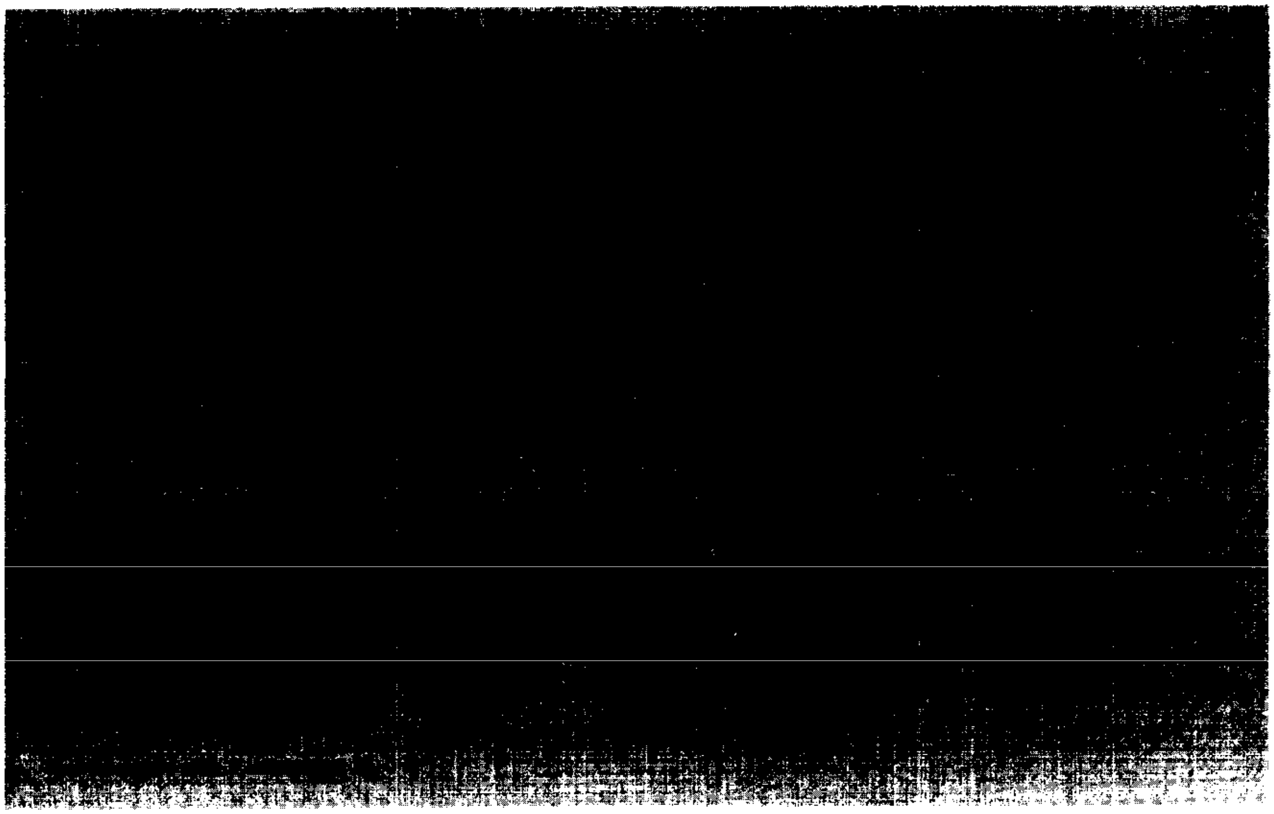
[1]Adapted from reference 4.

If onsite data are available, recharge is determined relatively easily. For example, the Montana Department of State Lands studied spoils recharge at the West Decker and Rosebud Mines based on data from the mine permit applications plus data collected by the Montana Bureau of Mines and Geology. Representative monitoring wells in the coal and spoils aquifers for each mine were selected, and hydrography utilizing all available water level data were plotted and analyzed to correlate water level changes with seasonal fluctuations and mining operations. From these data, it was determined that spoils recharge at the West Decker Mine comes mainly from adjacent, unmined coal beds that occasionally break the bed surface beneath the Tongue River Reservoir. Secondary sources are the underlying, unmined coal beds. Surface infiltration is considered insignificant due to the thickness and fine-grained texture of the spoils. At the Rosebud Mine, recharge is predominantly from adjacent unmined coals, but in localized areas, surface recharge is enhanced by thin spoils, coarse-textured spoils, and surface water bodies (30).

Without field data, groundwater recharge is difficult to quantify because it is a function of the spatial and temporal distribution of precipitation, topography-runoff relationships, and the unsaturated and saturated hydraulic properties of a spatially heterogeneous geologic environment. Where onsite data are not available, a water budget approach can be used to calculate recharge from *surface* infiltration. Box 6-F illustrates the use of this approach to predict spoils recharge for the purpose of permitting subgrade disposal of utility wastes in mine spoils (see also ch. 3, box 3-J).

Most mines have devised monitoring programs that may help quantify recharge to the spoils (see ch. 5). At a mine in Montana, where well data from resaturated spoils are available, the reestablishment of groundwater flow was predicted by comparing the hydraulic conductivity values from tests of spoils wells with those from tests conducted with wells in bedrock aquifers.[9] From the comparison, the operator was able to demon-

[9]See case study mine F in reference 30.



strate that the spoils were approximately as transmissive as the coal aquifers they replaced, and that the reclaimed mine area would not cause obstruction of regional groundwater flow.

Some research is being conducted to validate methods for identifying specific sources of recharge. One study at the Center Mine in North Dakota was successful in isolating the various sources of spoils recharge by analysis of stable isotopes of oxygen and hydrogen in the water (1 1). However, this is not a technique that can be applied readily to other mining situations, because the isotope data indicated that the source of the water in the lower spoils at this mine was vertical infiltration from nonevaporative sites, predominantly during the period of spring snowmelt. Lateral inflow from adjacent mine pits or unmined areas is much more common.

Spoils **Resaturation.–Spoils hydraulic characteristics, primarily permeability and porosity, determine the capacity** of the spoils materials to store and transmit water. Unfortunately, **few field data on spoils hydraulics are available due to the youth of the Western surface mining industry (see** ch. 5). Therefore, permeability and porosity must be estimated analytically to predict the ability to restore premining storage and transmissivity.

Spoils aquifer characteristics are primarily a function of overburden lithology, especially the sand content of the rock, and mining method. Very fine-grained materials tend to have the highest porosity, but their permeability is very low due to the small particle size and the lack of interconnections between pores. The presence of a rubble zone at the base of the spoils also can increase hydraulic conductivity. When overburden aquifers occur chiefly as small, discontinuous sand lenses within a large matrix of clays and shales, the postmining spoils probably will have low permeability. The equipment selected and the mining configuration determine the degrees of swell, mixing, and compaction of the spoils that will occur (see ch. 3). The increase in volume due to swell factor increases porosity, which in turn increases permeability if the pores are sufficiently large and interconnected.

Where pump tests have been conducted in resaturated postmining spoils, hydraulic conductivities and storage coefficients of the spoils can be measured directly. Otherwise, the time required for recharge is predicted with estimates of spoils hydraulics and groundwater modeling studies. Due to the low permeability of spoils material throughout the Eastern Powder River basin, operators there have estimated that it could take from 70 to 2,900 years, depending on the recharge rate, for replaced spoils aquifers to reach a steady-state condition in which groundwater flow patterns are reestablished (34).

Postmining Spoils-Aquifer Water Quality.– One of the potential impacts after surface coal mining is a change in the quality of groundwater because the backfilling of overburden material results in the exposure of fresh mineral surfaces and provides an opportunity for chemical reactions. In the Western United States, the primary groundwater contamination problem resulting from these reactions is the elevation of total dissolved solids **(TDS) levels** in spoils groundwaters –primarily dissolved sodium, calcium, magnesium, and sulfate. It has not yet been determined whether acidity will be a problem for revegetation in postmining spoils (see ch. 8).

The magnitude of postmining groundwater quality impacts is highly variable, depending on the quality of groundwater entering the spoils, the amount of recharge from precipitation that has reached the water table, and the type, distribution, and leachability of spoils materials through which groundwater or precipitation percolates. The length of time required for spoils to become fully resaturated and groundwater flow patterns to be reestablished also will affect the timing and magnitude of impacts, but also will mean that there may be no way to verify the predictions by comparison with actual results. As a result, the validity of the predictions takes on a greater importance. Unfortunately, there is little agreement as to the best method for producing consistent, valid predictions. Furthermore, generalizations are not readily made from one mine to another, because geochemistry is highly site-specific.

Two general approaches are used today to predict spoils water quality. One involves measuring water-soluble constituents in the spoils and relating those values to observed spoils water quality at the mine site. The second is based on deterministic modeling of the chemical processes responsible for the evolution of spoils water quality, which is the basis for calculating the ultimate water quality.

The measurement and extrapolation method assumes that spoils water quality is largely a function of readily soluble constituents in the spoils that may be leached easily by groundwater. Batch-leach tests, saturated-paste extract analyses, or column-leach tests are the methods used most frequently in the West.[10] All three require sampling and chemical analysis of overburden and interburden materials from the mine area. Tests comparing the data from these methods indicate that their results are very similar. Column-leach tests are the most expensive, however (see box 6-G),

Predictions based on batch leaching of overburden samples can be made in the absence of any field data from resaturated spoils. However, the samples of water and overburden selected for the test may not be entirely representative of postmining spoils conditions—at best a few pounds of material are being tested to make predictions about hundreds of millions of tons of spoils—and the mixing ratios and contact times used for the test may not represent actual conditions. The samples of overburden selected for the test usually represent a worst case of material potentially detrimental to water quality; then, for comparison, the test also is run on samples of “suitable” or average overburden material. Therefore, the predictions of postmine spoils water quality from this test will be conservative. Batch-leach tests were used by the USGS to simulate changes in groundwater quality that may occur as a result of mining operations in the West Decker area in Montana (4).

Saturated-paste extract tests are especially useful where spoils water data are available because a statistical correlation can be derived between

[10]See reference 30 for a detailed description of these techniques and their application.

the predicted water quality and actual analyses of spoils water. For this reason, this method was used in a 1982 study of cumulative impacts for mines in the Tongue River basin of Montana and Wyoming, which estimated that dissolved solids contents in postmining groundwater would increase between 63 and 300 percent. Sodium, sulfate, and bicarbonate concentrations were predicted to increase the most (25).

Typically, when any of these three methods is used to predict postmining spoils water quality, spoils recharge subsequently is monitored, and the spoils water quality sampled as resaturation occurs. Such monitoring programs should contribute information to allow the verification of assumptions made about the trend of spoils water quality over time (and the time frame in which recharge will occur). Monitoring will not always provide direct information on postmining groundwater quality, however, because it cannot be assumed that the monitoring will be continued for the centuries predicted to be required for groundwater systems to establish a postmining equilibrium.

Predictive modeling methods are under development that could estimate changes in groundwater quality based on statistical analyses of geochemical trends. The USGS currently is working with three process-oriented deterministic models of the chemical processes occurring in and downslope from the spoils, of recharge to the spoils, and of water movement through the spoils (28). The three models are: WATEQF, BALANCE, and PHREEQE.[11] Data from coal mines in Wyoming are being used to test the modeling concepts, and one of the large mining companies currently is using these models to try to understand the geochemical reactions that are resulting in undesirable spoils-water chemical characteristics at a mine in the Powder River basin of Wyoming. It must be kept in mind, however, that as with the groundwater models discussed previously, the results of these predictive water quality models will only be as good as the input data and assumptions.

Researchers at the North Dakota Geological Survey are using computer methods to develop a comprehensive hydrogeochemical approach to the prediction of spoils water quality, because they believe that the saturated-paste extract method estimates only the short-term spoils water quality, and ignores the long-term salt generation capacity. The researchers concluded that, in order to assess the chemical conditions on a long-term basis, it will be necessary to develop analytical techniques to determine calcite content at very low levels of concentration, abundance of potentially oxidizable pyrite, and actual ion-exchange characteristics under field conditions (15). The work probably is only applicable within the Fort Union mining region (see box 6-H).

Predicting the Impacts of Powerplant Waste Disposal.– At some **mines** in the West, ash and sludge from mine-mouth powerplants are disposed of in the mine backfill. The analytical tech-

[11] See vol. 2 for detailed descriptions of these models.

Box 6-H.—Deterministic Model Development in North Dakota[1]

The term "engineered cast overburden" (ECO) was coined ●ki$Wth'-i3akota to refer to an approach to reconstruction of the entire landscape rather thanjust its soil. This approach to post-mining groundwater chemistry requires a thorough understanding of several geochemical and mining processes as well as the development of analytical techniques mapping, geologic mapping, development of a three dimensional framework, geohydrological studies, and geochemical studies are conducted to define the properties materials. An understanding of form and internal structure of material deposited by various types of mining equipment and techniques also is necessary to determine which equipment and procedures produce desired physical and chemical characteristics at appropriate locations within the cast overburden.

The analysis assumes that a model that adequately represents observed water chemistry in the premining overburden will be reliable for predicting postmining. The model must account for several variables, including the predominant ions in the groundwater, the pH of the water, variations in the concentration of TDS of the groundwater, and partial pressure of carbon dioxide in the water. It also must account for water chemistry changes that occur as water infiltrates and migrates through the underlying unsaturated zone into the groundwater zone.

ECO studies resulted in the development of a hydrogeochemical model that accounts for the observed chemical characteristics of subsurface water in disturbed and undisturbed settings. Critical hydrogeochemical processes were determined to be sulfide oxidation, gypsum precipitation and dissolution, carbonate mineral dissolution, and cation exchange. Major species of concern are sodium and sulfate. Sulfides are the major source of sulfate. The solubility of sulfate in groundwater was determined to be largely controlled by the sodium/calcium ratio. Wetting and drying in the near-surface landscape was found to be a key factor in hydrogeochemical evolution. The worst impacts on postmining groundwater quality were predicted to result from placement of unoxidized sodic and sulfide-rich sediments near the surface and above the water table where surface infiltration could contact them en route to the groundwater table. Placement of these below the postmining water table can result in short-term degradation of groundwater, but the long term will prevent oxidation of the sodic and sulfide-rich sediments and water quality will improve after initial flushing of soluble salts. This modeling technique allowed the investigators to predict both short- and long-term effects of mining on the groundwater quality, and if the modeling and input assumptions are correct, the predictions should be valid (input assumptions can be tested as monitoring data are collected and used to verify the model).

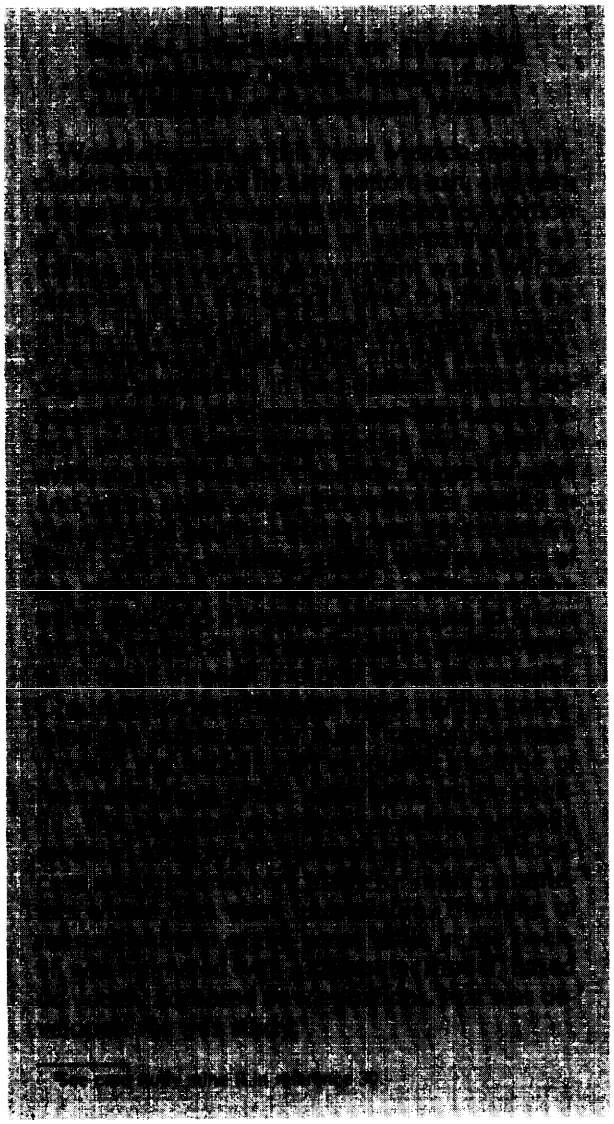
[1]See reference 30 at pp. 414-417, and sources cited therein.

niques used to evaluate potential impacts to groundwater quality at these sites utilize the various methods described above. The techniques used at one New Mexico case study mine are described in box 6-1 (see also box 6-F, and ch. 3, box 3-J).

Predicting Surface Water Impacts[12]

Surface mining can affect surface water in several ways. During mining, streamflows can be reduced by the local lowering of the water table in the vicinity of the mine or by disruption of the aquifer (see fig. 6-1 B). Natural flow also can be augmented by mine-discharge water, but usually the discharge is not significant in relation to the mean annual runoff volume of streams in the Western United States. More important in the West is the impact of mining-related augmented or diminished flows on surface water quality. In addition, both suspended and dissolved solid levels are often elevated, reflecting the higher rates of erosion and the higher availability of soluble cations often associated with any large earth-moving operation. After mining, as the hydrologic equilibrium is reestablished, few residual impacts on surface water quantity or quality are likely, although not enough time has elapsed at most Western mines to verify this assumption with monitoring data.

[12]Unless otherwise noted, material in this section is adapted from reference 30.



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Surface water impacts are readily observable, and analytical techniques for predicting these impacts are less hypothetical than those used for groundwater analysis. **As** with any analytical technique, however, the quality of the input data will determine the validity of the analytical results. **As** discussed in chapter 5, there are few reliable data on streamflow quality and quantity for ephemeral streams in the coal mining areas of the Western States. Because most of the surface water affected by Western mining activities is in ephemeral drainages, this lack of data is a constraint on the use of analytical techniques to design reclamation measures for the surface water resource.

Surface Water Quantity Impacts

Peak flows and low flows of streams are important characteristics in describing the hydrology of the general mine area, and thus in predicting the impacts of mining and designing reclamation (see below). Streamflow is derived from two components: base flow and direct runoff. Base flow is supplied by groundwater aquifers, while runoff is supplied by precipitation, snowmelt, and, in the case of surface mining, by mine discharges. Peak flows generally coincide with periods of peak runoff. Low flows coincide with periods of little or no runoff, when perennial streamflow is maintained by groundwater inflows.

The primary potential effect of mining on water levels in streams is a reduction in base flow in response to drawdowns in the water table caused by the cone of depression created around the mine pit. Because most of the streams directly affected by mining are ephemeral and thus have no base flow component, they are not affected by mining-related drawdowns, and individual mines have relatively little impact on the quantity of surface water supplies. Intermittent streams (which have seasonal flows) may be impacted to the extent of their base-flow component.

During seasons of high runoff or when groundwater intercepted by the pit exceeds onsite needs, water also will be discharged from a mine into area streams. The discharge may be temporary, intermittent, or continuous, and usually will be small in relation to the mean annual runoff volume of the receiving streams except when saturated scoria is intercepted. Short-duration, high-volume discharges are difficult to predict during mine planning, but in a water-short area no adverse impacts result provided the water quality of the discharge is within the range of the water quality of the receiving stream.

When mine discharges can be predicted, estimation of the resulting impacts on water quantity generally involves comparing the estimated rate of flow of the discharge to the range of natural flows typical for the receiving stream. If these are relatively equal, the discharge will not exceed the hydraulic capacity of the stream, and thus will not cause erosion downstream from the discharge point. This analysis can be done either using actual gage data, or with statistical or deterministic models.

The Log-Pearson Type III distribution method uses gage data to estimate the frequency (2 to 100 years) at which designated peak flows will be exceeded. Data collected over at least a 20-year period are required for meaningful results using this method. Although these data are available at some locations for all major perennial streams that may be affected by Western surface coal mining, they are rarely available for intermittent and ephemeral streams, unless mining has been conducted in the area for a long period of time.

Statistical Models.–USGS hydrologists, in the course of studying the hydrology of various drainage basins in the West, have developed multiple-regression equations for estimating flood peaks at ungaged stream sites. In general, the equations are a means of extrapolating, over a large area, correlations derived from data collected at a limited number of sites. Individual sets of equations are specific to a particular hydrologic region, and to drainage basins of a certain size. Application of statistical models generally requires only the use of a topographic map to determine drainage area, basin slope, maximum basin relief, and main-channel slope.

Deterministic Models.–Most rainfall-runoff models used by mine operators are based on the Soil Conservation Service (SCS) method of estimating direct runoff from storm rainfall, which in turn is based on the widely accepted unit-hydrograph theory (14). Input data on the vegetation and watershed characteristics of the drainage area, and on channel slope, relief, and soils are readily obtained from topographic maps, soils maps, and field observation. Data on precipitation frequency-duration relationships are available from published U.S. Weather Bureau and National Oceanic and Atmospheric Administration (NOAA) reports.

This method is calculation-intensive, and not easily used without a computer. Moreover, estimation of runoff volumes and peak discharge by these various deterministic methods can be considered more of an art than a science. Even using the same method, it is probable that two independent investigators will achieve different results because the assumptions that must be made about the hydrologic regime of the site will influence the input parameters and therefore the resu lts.

Surface Water Quality Impacts

Both direct runoff and groundwater discharges to surface streams can have high TDS and/or TSS levels, depending on the medium the discharge is flowing over or through and the rate of flow, among other variables. Elevated TDS concentrations usually result from groundwater discharges, but normally are not included as limiting parameters in discharge permits because of the difficulty of controlling them. Increases in TSS levels are more likely to result from runoff and subsequent erosion, and are controlled with sediment control structures (see below). Peak flows typically coincide with low TSS levels due to dilution, while low flows coincide with high TSS. Low-flow values usually are used to quantify the worst-case stream water quality degradation that may occur in perennial streams.

In the absence of site-specific data (the usual case), the amount of sediment that will erode from a watershed and be subject to transport downstream during a precipitation event generally is estimated using the Universal Soil Loss Equation (USLE), developed and calibrated by the Agricultural Research Service. With limited data, the strength of USLE lies in its ability to provide relative estimates for comparison of alternative projects, rather than absolute determinations.

Prediction of Cumulative Hydrologic Impacts

CHIAS of all ongoing and anticipated mining in a permit area are mandated in section 507 of SMCRA. CHIAS are conducted by the regulatory authority based on the PHC determinations submitted in permit applications and other data available from Federal and State agencies. A CHIA must be for the proposed life of a mine, including the time needed to achieve permanent steady-state after mining. It is intended primarily to demonstrate that the proposed mining activity, when added to all other mining activity in the region, will not materially damage the hydrologic system outside the mine permit area.

Depending on the availability of data and the impacts of concern, a CHIA may emphasize either the full range of potential hydrologic impacts or only specific sets of impacts. For example, while each operator in the powder River basin of Wyoming is required to submit a comprehensive PHC determination to address all components of surface and groundwater hydrology, the CHIAS that have been conducted in this region were concerned primarily with cumulative impacts to groundwater flow, cumulative drawdowns from mine dewatering (see box 6-D), and the cumulative impacts of sedimentation control (see ch. 8).

The interpretation and implementation of the Federal law as it pertains to PHCS and CHIAS is the subject of considerable controversy. As discussed in chapter 4, recent Federal court decisions remanded to the Department of the Interior regulations on whether a PHC determination should cover the 5-year permit area or the life-of-mine area. The court also found DOI'S definition of "anticipated mining" for CHIAS to be inconsistent with SMCRA.

A reasonable cumulative assessment of impacts to the various components of the hydrologic system over the life-of-mine area can be made at most Western surface coal mines using some combination of the available analytical **techniques already described for surface and groundwater systems.** As discussed above, however, none of these techniques is a perfect indicator of hydrologic impacts.

The principal limiting factor to the predictive capability of all of the techniques is the availability of reliable data. In the case of certain techniques, the lack of site-specific data can be accommodated (e.g., techniques that predict hydrologic responses based on assumptions derived from widespread but relatively sparse data, such as the flow-estimating techniques based on statistical models). In other instances, the data required to perform one analysis of impacts over the life of the mine must be obtained using many other techniques, sometimes at prohibitive expense. For some analytical techniques, however, the data often are not obtainable for term-of-permit assessments, much less for a life-of-mine assessment (e. g., spoils water quality determinations in areas where recharge is predicted to take centuries).

The built-in errors associated with inadequate data or with the need to make assumptions are accommodated through regulatory requirements for worst-case analyses. So, as uncertainty about the system increases, assumptions made for input to the various analytical techniques become more conservative. Although this strategy avoids errors from underestimating the potential hydrologic impacts, it may entail other consequences resulting from overstatements of those impacts, including increased reclamation costs.

Another important limiting factor is the incomplete knowledge of some of the geochemical processes occurring in the postmining spoil, which makes it difficult to express these processes mathematically. This problem is exemplified by the current controversy over the correct methodology for predicting the potential for acid-formation in Western mine spoils (see ch. 8).

One possible approach to the problem of conducting CHIAS is to use repermitting data–the data submitted by active mines every 5 years to support applications for permit renewal—to recalibrate the models used for the CHIAS and to assess the validity and sensitivity of the various input assumptions. Periodic sensitivity analyses of the variables wou Id provide valuable information about data inadequacies and could be used to focus industry and Federal and State agency data collection efforts (see ch. 5).

PHCS and CHIAS can be accomplished with or without a computer, but the use of computer modeling appears to be a more efficient way of assessing the complex hydrologic problems that must be addressed in a cumulative analysis. Examples of both methods of analysis are discussed in box 6-J. More detailed information about specific data requirements and the analytical techniques used in these examples can be found in volume 2.

Predicting Impacts to Wildlife[13]

Quantitative techniques for predicting the impacts of surface coal mining on wildlife *populations* have not been found to be effective and are used infrequently. One constraint on such techniques is data inadequacy (see ch. 5). Moreover, while the basic responses of wildlife to environmental factors are often easy to analyze and predict intuitively, it is difficult to quantify this sort of analysis. It is even more difficult to segregate sources of influence on the populations or variation in the environment to determine which factors have caused what percentage of the observed effect. **Consequently, wildlife impact assessments generally are made by intuitive professional judgment, based on a knowledge of the mining operation and the ecology of the affected area.**

Although numerous baseline and monitoring data are collected on wildlife populations to determine patterns of wildlife use of the mine site and adjacent areas, these data generally are perceived as unreliable and typically are not analyzed statistically (see ch. 5). Instead, the data are reviewed by industry and agency biologists who look for trends from which they can interpret habitat affinity and predict the impacts of habitat disruption. These qualitative or intuitive impact assessments involve comparing available data with the characterization and analysis (often quantitative) of wildlife habitats. Such indirect

[13]Unless otherwise noted, material in this section is adapted from reference 2.

Box 6-J.-A CHIA of the Yampa River Basin*

The coal mining areas of the Yampa River basin in northwestern Colorado contain several important perennial streams, and the water quality of those streams is subject to degradation as the overburden and coal aquifers that contribute to base flows are replaced with mine spoils. Eventually, these mine spoils will leach water with elevated TDS relative to the undisturbed aquifers. A 1982 CHIA of this region did not use computer modeling methods, and so was only able to estimate mining-related changesin TDS concentrations for two cases, as opposed to the infinite number of cases that can be computer simulated. The two cases chosen were the historic low flow [representing the worst case) and the mean flow. Other limitations of the method were the difficutty in using available data because of nonstandard collection methodologies and reporting procedures, and the lack of flexibility and complexity in the mathematical basis of the model. In 1983, a computer model for a portion of this same basin was developed by USGS for use by the Colorado Mined Land Reclamation Division (MLRD) in evaluating potential cumulative surface water impacts of proposed mines. The model is based on a more complex algorithm that enhances its flexibility with respect to simulating various mining scenarios. As with most computer techniques, the limiting factor is availability of reliable input data. Analytical results are only as valid as the various methods for estimating, interpolating, and extrapolating input data where measured data are lacking.

[1]Adapted from reference 30.

assessments of impacts to habitat quality may be more meaningful in terms of predicting the ultimate impacts of mining to wildlife (box 6-K; see also ch. 3, box 3-G).

OSM recently funded a study to evaluate quantitatively the effectiveness of mitigation measures practiced at coal mining operations in the Western States (20). This study, using multiple linear regression analyses, assessed the relationship between various wildlife populations (mammals and birds, both large and small) and the biological and

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sis. This is true even in the field of wildlife biology, where valid data are not easily obtained. At one mine, Los Alamos National Laboratory was contracted to perform computer-analyses of wildlife data.[14] The extent of the computer assistance was to expedite the plotting of big game movement information on maps, which usually is done by hand. Another computer application attempted to choose an appropriate population estimation model for the small mammals and then estimate population sizes. This attempt was unsuccessful due to insufficient data, and exemplifies the inherent problems involved with accurate prediction of many wildlife populations.

Another use of computers to evaluate wildlife data is the U.S. Fish and Wildlife Service's Habitat Evaluation Procedures (HEP) program. HEP was developed to provide a standardized approach to evaluating wildlife impacts based on changes in habitat quality values. Habitat quality for selected species is evaluated with an index value obtained for individual species from habitat suitability models (over 80 published) employing measurable key habitat variables. Index values are multiplied by area of available habitat to obtain Habitat Units for individual species. Index and habitat unit values derived for land prior to and after disturbance are used to provide a quantitative measure of the impact to wildlife habitat. The more that is known about habitat requirements of the various indicator species, the more accurate is the rating scale developed to measure habitat quality.

As with any impact prediction methodology, HEP's ability to provide accurate projections of the magnitude of future impacts can be no better than the user's ability to predict habitat conditions subsequent to disturbance. However, HEP does provide a quantitative mechanism for performing projections of the severity of impacts resulting from habitat disturbance. HEP has been used extensively for water development projects where the extent of temporal and spatial habitat loss can be documented. As yet, however, only a few attempts have been made to use HEP for projecting wildlife impacts related to Western surface coal mining disturbances.

[14] See case study mine G in reference 2.

Predicting Revegetation Success[15]

The impact of surface mining on plant life is immediate and predictable: with few exceptions, once the soil is removed from a mine site the original vegetation has been destroyed. Therefore the primary emphasis is on devising methods to predict the long-term impacts, or revegetation success. The success of a given revegetation technology or method is assessed qualitatively based on a comparison of data from different reclaimed areas.

This qualitative method for predicting revegetation success at a particular location considers the results of the most recent revegetation methods at other mining operations in the region which have similar soil, overburden and climatic characteristics. In the comparison, it is assumed that given similar environmental factors, the results of particular reclamation technologies also will be similar. This case-by-case approach is essentially the technique used by State regulatory personnel when making their technical evaluation and analysis of permit applications. It also is the basic technique available to agencies such as the Bureau of Land Management (BLM) for impact prediction in environmental impact statements. Although this type of analysis does not lend itself to a rigorous mathematical treatment, the lack of a quantitative model for predicting reclaimability does not appear to diminish the potential for accurate prediction.

One quantitative model for predicting revegetation success was developed in the study region. It used data collected in 1976 and 1977 on sites revegetated under pre-SMCRA requirements as well as from unmined areas (18). This model assumed three factors to be driving (independent) variables: annual precipitation, growing season length, and the age of revegetation. The dependent variables were cover and production. Woody plant density and lifeform or species diversity were not addressed. Because the baseline data were collected from areas revegetated pre-SMCRA with what is now considered somewhat primitive technology, they form a poor basis for predicting success with current technology. The authors of the model acknowledge that the baseline data are weak in many respects, and that variations in cultural treatments and the young age of most of the revegetation samples confound potential conclusions from the data. Without further development of the model and improved data inputs, it is doubtful it could be useful in current revegetation analyses.

[15] Unless otherwise noted, material in this section is adapted from reference 28.

ANALYTICAL TECHNIQUES USED IN THE DESIGN OF RECLAMATION

Because techniques for predicting the various impacts of mining are imperfect, and because in many instances reclamation results cannot be observed directly (e.g., groundwater aquifer restoration where recharge is measured in centuries), the analytical techniques used to design reclamation are critical to reclamation success. The reliability of these techniques is especially important when the evaluation of reclamation success is based on design, rather than performance, standards, given the uncertainty about who is responsible for design failure. The most important design elements for the ultimate success of the reclamation plan are: 1) accurate characterization of the overburden and delineation of overburden material potentially detrimental to groundwater quality or revegetation, **2)** optimization of soil salvage, 3) well-stabilized stream channels, and 4) efficient sedimentation control. This section discusses the analytical techniques used to design these components of the reclamation plan, plus the design and reclamation of alluvial valley floors.

Overburden Characterization and Reclamation Planning

After the coal has been extracted, the overburden and interburden form the basic material for reclamation, and the chemical and physical character of these materials are major factors in determining the impacts of mining on postmining spoils hydraulics and water quality (16). In actuality, the geology of the overburden in many of the mining regions of the West is so complex that it is usually not practical (and often infeasible) to define the overburden in great detail. As a result, gross characterization of the overburden is the basis for the design of the earth-moving portion of the reclamation plan of many surface coal mines in the West (see ch. s).

The objectives of methods used in characterizing the overburden are to determine its physical and chemical character in order to evaluate reclaimability; to estimate the volume and location of different types of overburden material; and to design a backfill plan that achieves chemical and physical stability and approximate original contour. Table 6-3 shows the current criteria for overburden unsuitability for three of the five States (Colorado and New Mexico have no formal unsuitability criteria for overburden). These criteria are referred to as "suspect levels." If prescribed laboratory techniques show overburden components to be above these suspect levels, the components may be considered unsuitable if

Table 6-3.–Overburden Unsuitability Criteria by State

Parameter	Montana (DSL 1983)	New Mexico (MMD 1984)	Wyoming (DEQ 1984)
PH acid	<5.5	<b. U	< 5.0
pH alkaline.	>8.5	>9.0	>9.0
EC (mmhos/cm)	>4.0-8.0	>16.0	>12.0
Texture.	excessively clayey, silty or sandy	none given	none given
Sat % .,	< 250/o > 85%	none given	none given
SAR	none given	>12.0 >15.0 >20.0 depending on texture	>12.0 >15.0 depending on texture
ESP .,	>15.0 >18.0 depending on texture	none given	none given
B	>5.0 ppm	>5.0 ppm	>5.0 ppm
Se	>0.1 ppm	>0.5 ppm	none given
ABP	none given	O tons $CaCO_3$ equivalent/ 1,000 tons	< –5 tons $CaCO_3$ equivalent/ 1,000 tons
Mo . . . . . ., .,	>0.5-1.0 ppm	none given	none given
Organic carbon	none given	none given	> 10'%0

SOURCE: James P. Walsh & Associates, "Soil and Overburden Management in Western Surface Coal Mine Reclamation," contractor report to OTA, August 1985.

replaced in reconstructed root zones or where they might contaminate surface water or groundwater supplies.

Unsuitable overburden can be categorized in one of two ways, depending on the mode of occurrence:

- Type 1: Mappable strata (e.g., carbonaceous shales, pyritic sands) that occur over more than 25 percent of the mine site, are predictable in occurrence, and generally are regarded as uniformly deleterious to root growth and/or groundwater; or
- Type 2: Unmappable pods of unsuitable material, usually exhibiting elevated levels of trace metals (e.g., arsenic, boron) that are not readily predictable in occurrence. While they may occur only in one particular strata or lithotype, the occurrence is not uniform or the associated rock units are not mappable with the density of drill holes which can be reasonably required (17).

While there are no standardized methods for the interpretation of overburden data, there are several methods that seem to be commonly used to characterize the geochemistry of the overburden and define volumes of potentially deleterious material. These techniques usually are repeated and refined as additional data are collected in potentially unsuitable areas. The methods described below are illustrative of the varying degrees of qualitative versus quantitative analysis possible, and are not intended to be a comprehensive listing of methodologies.

One approach is the use of classical statistical analysis to determine a thickness-weighted mean, standard deviation, and range for each parameter in the overburden database. However, a statistical analysis may not be valid for some parameters (e.g., pH, which is a logarithmic function). Moreover, this approach does not include the correlation of geochemical values (laboratory data) to individual rock strata in the overburden, nor does it provide a way of determining either the total volume of potentially deleterious material or the position of that material within the overburden. Rather, this technique assumes that perfect mixing of the overburden is achieved with whatever mining and backfilling techniques are proposed. Therefore, the technique seems to be valid only for the broad characterization of overburden over the mine-site. Under certain conditions, such as when all of the overburden is considered suitable or unsuitable, this level of analysis is adequate.

Other methods of characterizing overburden must be employed in the more common situation of overburden that is only partially unsuitable. With such overburden, it becomes important to determine both the volume and location of the unsuitable material (given the modes of occurrence listed above). The same classical statistical analysis can be used if the overburden data are segregated into data sets representing individual mining benches. The underlying assumption for this technique is that, during mining, perfect mixing of the overburden will occur *within each bench. In* general, this approach is valid for demonstrating that an individual bench is either entirely suitable or unsuitable. This approach also can be used reliably if the unsuitability is specific to either the vegetation or the groundwater resource, and it can be demonstrated in the mining plan that the unsuitable bench will be placed in the backfill such that it will not be in contact with the resource to which it is deleterious.

It is unusual, however, for all of the material in a bench to be of uniform suitability, Many regulatory authorities have adopted a working assumption that if the unsuitable overburden comprises less than a certain percentage of the total overburden by mining bench[16] it will be mixed adequately with suitable spoil material and no vegetation or groundwater problems will arise in the backfill. Based on field studies and empirical observations, the cut-off has been set at 15 percent unsuitable material for dragline operations and 20 percent for truck and shovel mines (5). Several operators of large truck and shovel mines in the Powder River basin of Wyoming are presently conducting mixing studies to refine these estimated mixing ratios.

If the unsuitable strata are mappable (type 1), this bench method of overburden characterization is adequate if it can be demonstrated that the unsuitable material constitutes less than the cut-off percentage. Ideally, this demonstration can be made (either manually or by computer) by correlating the unit in question from all available geologic information, mapping the extent and thickness of the unit, and then comparing this elevation and thickness projection to the elevation and thickness of the proposed mining benches. Using the correlations, one can determine the location and extent of areas where the unsuitable stratum represents a greater percentage of the bench than is permissible, In practice, however, more subjective and cost-effective techniques relying on professional expertise often are employed.

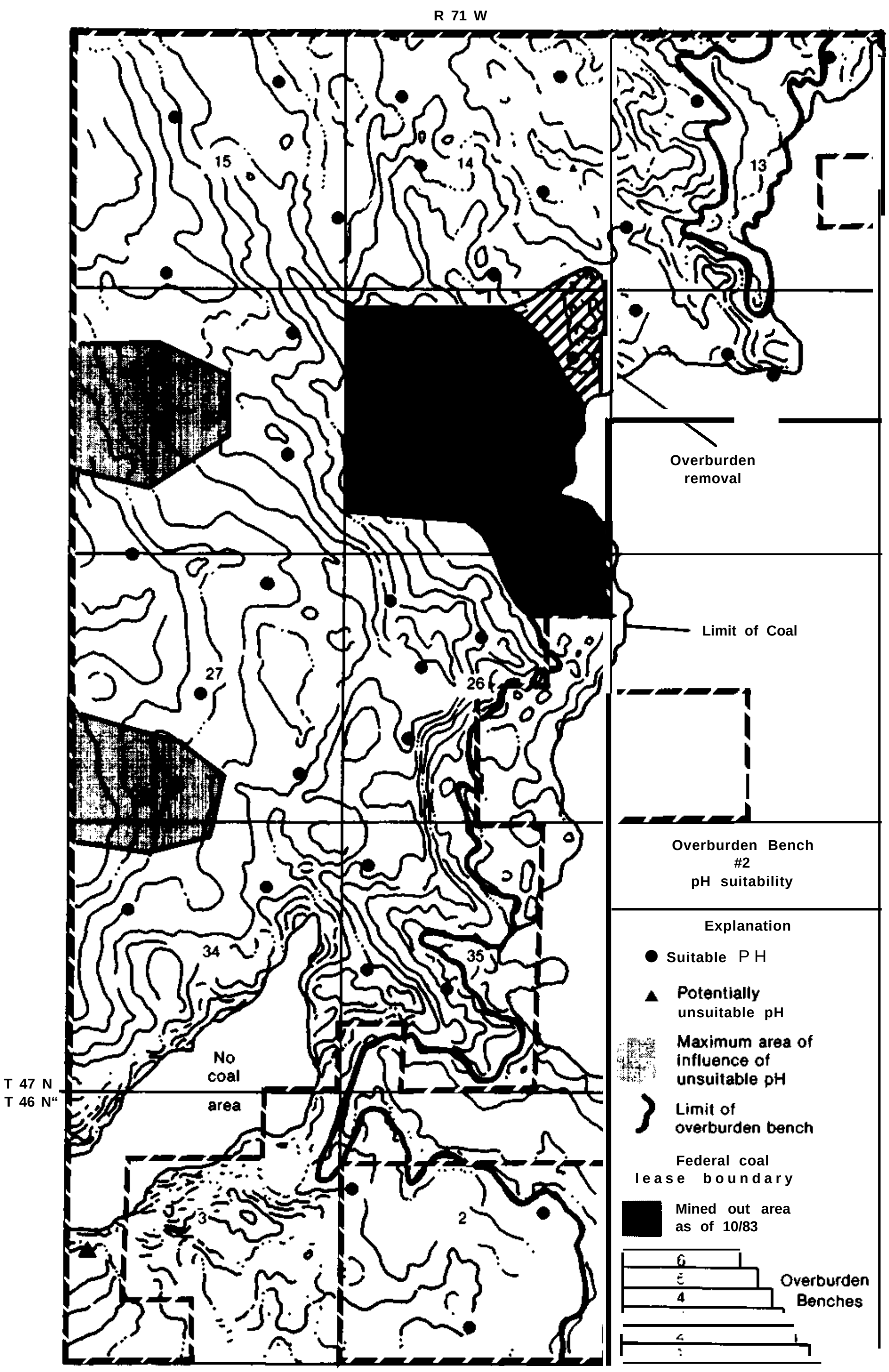
If, on the other hand, the unsuitability is unmappable (type 2), and a correlation between the occurrence of the unsuitability and a geologic feature cannot be found, the bench method must be modified further. This technique incorporates the proposed mining-bench configuration but more or less ignores the stratigraphy of the overburden. Data from each drill hole are grouped by mining bench, and the percent unsuitable material, weighted by sample thickness, is determined within each data group. Finally, the area of influence of each drill hole is determined, usually by the conservative polygon method of interpolation.[17] Maps are generated to portray graphically the limits of potential unsuitability for the mine permit application (see fig. 6-5). Generally, the analysis is performed manually because it is as accurate as and less time-consuming than using a computer.

This last method of overburden characterization is becoming common in Wyoming, where most of the mines are large and where the State regulations and guidelines, by virtue of their level of detail, promote conformity among the permit applicants by emphasizing design standards. In other States, methods for characterizing the overburden generally are more empirical or intuitive. in Colorado, for instance, the regulatory authority regularly receives and reviews uninterpreted

[16] One bench is assumed for a dragline operation, while the number of benches in a truck and shovel operation will vary with the thickness of the overburden.

[17] A method by which the area of influence of each drill hole is defined by connecting a series of lines drawn around that hole bisecting the distance between that hole and the next adjacent hole so that the resultant area is polygonal in planview.

Figure 6-5.–Overburden Bench Suitability



SOURCE:

laboratory data (3). To the extent anomalous data are found, the operator is asked to provide additional data or analysis to further define the unsuitability.

Once the nature and extent of the overburden unsuitability is defined, the operator and the regulatory authority can agree on the best method of mitigation. In most cases, the operator must selectively place unsuitable materials **4** to 8 feet below the ground surface, and away from reconstructed stream channels. Special handling of unsuitable material may also be required to keep the material out of the root zone or groundwater recharge zones (see ch, 3, boxes 3-C, 3-H, and 3-J). For unsuitable material exhibiting parameters that are not mobile under reducing conditions, there is some debate about whether the material should be placed above or below the postmining water table to prevent the entry of undesirable elements into the groundwater system. The practicability and/or cost-effectiveness of selective placement generally are a function of the type of mining equipment used (see ch. 3).

Soil Characterization and Reclamation Planning[18]

The redressed soil serves as a chemical and physical buffer between the backfilled mine spoil and surface water, vegetation, and wildlife resources, and therefore is a critical element in successful reclamation. In designing soils reclamation, the objective is to determine which materials will be salvaged for use as topdressing over the postmining recontoured spoil surface. The three steps involved in planning soil reclamation are: 1) determining the premining physical and chemical character of the soil (see ch. s); 2) estimating the total volume, the "suitable" volume, and the final redressed thickness of the salvageable soil resource; and 3) designing a redressing plan to ensure chemical and physical stability of the postmining soil. Each State has soils unsuitability criteria (see table 6-4). Differences among the State criteria reflect differences in reclamation objectives or emphasis, as well as in professional judgment and interpretation among the technical staff.

[18] Unless otherwise noted, the material in this section is adapted from reference 27.

Determination of salvageable soil is usually accomplished by direct comparison of physical and chemical parameters of individual map units with State unsuitability criteria. For example, salvage depths are determined by comparing soil analytical data to limiting chemical and physical criteria, and assigned to each unit based on this comparison. The area of each soil map unit is measured directly from the soils map, and the composition of the map units determined from the soil inventory, Available soil salvage volume is then calculated as the product of: 1) the area of the map unit; 2) the percent of each component comprising that map unit; and 3) the salvage depth, summed over all the components and all map units (see table 6-5). Salvageable soil volume estimates are then divided by the area to be reclaimed to get the average thickness of soil redressing.

This method, although easily accomplished, may not maximize salvage volumes. One reason is that the limiting criterion often is linked with an observable trait that can be described to the equipment operator (e. g., color). At the Navajo mine in northwestern New Mexico, for instance, an intensive soil analysis and mapping program conducted in 1973 resulted in topdressing material being mapped initially as 12 distinct groups of soils based on standard agronomic diagnostic criteria. Then soil color and texture (measured by feel) were shown to correlate highly with salinity, infiltration, and permeability, and the soils classification system was simplified to identify only those specific diagnostic properties that were directly related to what was known to be the most growth-limiting factor: effective moisture. By 1978, through continued analysis and observation of vegetative response, the original 12 groups of soils had been reduced to 3 (1 2).

A more quantitative methodology that weights limiting parameters may allow greater recovery of marginal soils in situations where soil volume is deficient, or maximization of soil quality where quantities are adequate (see box 6-L). This system is complicated and requires technical judgment for implementation. Moreover, unless the selection criteria and the weighting factors for the limiting parameters are well documented, use of the system may be subject to criticism during permitting.

Table 6.4.—Topsoil Unsuitability Criteria by State

Parameter	Montana (DSL 1983) (lift 2 only)	New Mexico (MMD 1984)	North Dakota (PSC, 1983) (lift 2 only)	Wyoming (DEQ 1984)
pH acid	<5.5	<6.0	none given	<5.0
pH alkaline	>8.5	>9.0	none given	>9.0
EC (mmhos/cm)	>4.0-8.0	>16.0	>4.0	>12.0
Texture	excessively clayey, silty or sandy	none given	none given	none given
$CaCO_3$%	none given	none given	none given	none given
Sat%	< 250/o > 850/o	none given	none given	none given
SAR	>11.0 >14.0 depending on texture	12.0 >15.0 >20.0 depending on texture	>10.0	15.0 >12.0 depending on texture
ESP	>15.0 >18.0 depending on texture	none given	none given	none given
B	>5.0 ppm	>5.0 ppm	none given	>5.0 ppm
Se	>0.1 ppm	>0.5ppm	none given	>0.1 ppm
Coarse fragments (% volume)	>35%	none given	none given	>350/0

SOURCE: James P. Walsh & Associates, "Soil and Overburden Management in Western Surface Coal Mine Reclamation," contractor report to OTA, August 1985,

As a further check on the reliability of the annual salvage volume estimates, some operators conduct an annual accounting of soil volumes. The volume of soils in stockpiles, the volume salvaged during the year and where it went (i. e., new stockpile, existing pile, or redressing), volumes redressed on reclaimed land and where it came from, and the volume remaining to be salvaged and the remaining area to be redressed, are calculated. This is referred to as the "soil budget," and provides a constant check on the reliability of presalvage estimates. Each year stripping depths are reevaluated and the salvage plan fine-tuned based on new data from ongoing salvage operations and on the results of monitoring the soil budget.

Salvage volumes usually can be estimated with sufficient accuracy for mine planning using the initial baseline data. However, due to the necessarily low density of sample sites in a baseline survey, it is possible to have a significant error. At one Montana mine, for example, the baseline soil survey delineated a foot of suitable topsoil in one area of approximately 1,000 acres (a small percentage of the total mine acreage). Subsequently the soil in this area was found to be suitable to only 4 inches due to a limiting chemical factor, representing a 67-percent reduction over the initial estimate.[19]

For actual salvage or annual volume calculations, more intensive soil-surveying methods are needed. For 5-year planning, the density of transects and sample points is increased to achieve better than 90-percent confidence in the predicted salvage volumes for that specific area. Annual planning is based on analysis of daily sampling and staking data to achieve better than 95-percent confidence in the volume estimates in order to maximize the efficiency of the soil stockpiling and replacement program and to avoid an unforeseen shortage and consequent expensive special handling. In fact, it is becoming increasingly common for a soil scientist to accompany equipment operators to ensure full recovery of the redressable soil material. Another approach is to leave soil pillars at roughly 200-foot intervals for inspection by agency and qualified mine personnel as a further check on the completeness of the salvage program.

There is a trend among larger mine operators to digitize soil inventory data and use computer

[19]See case study mine D in reference 27.

Table 6-5.—Topsoil Volume Summary

Mapping unit symbol and name	Composition of mining area acres		Composi ion of mapping unit in % (should include 'nclusions)	Depth of topsoil (inches)	Total volume of topsoil (A-ft)	Average salvage volume of topsoil (A-ft)	Salvage dep h of topsoil (inches)	Limi ations[a]
1A Haverson loam	25.6	4.0	00	60+	28.0	50.7	28.0	SAR 5 at 28 in.
2B Bidman loam	76.8	12.0	90	50	345.0	345.0	50.0	
(Briggsdale sandy loam)			10	29	18.6	18.6	29.0	
44C Tassel-Shingle	44.8	7.0						
Rock outcrop			50	8	33.6	33.6	18.0	
complex								
Tassel								
Shingle			25	8	7.5	7.5	8.0	
Rock outcrop			25	0	0.0	0.0	0.0	
5A Stoneham loam	96.0	15.0	90	60	432.0	432.0	60.0	
(Cushman			10	24	19.2	19.2	24.0	
78 Briggsdale	140.8	22.0	95	29	323.2	323.2	29.0	
sandy loam			5	12	7.0	7.0	12.0	
(Shingle)								
9A Ft. Collins-Ulm	70.4	11.0						
Association ...			50	60	176.0	176.0	60.0	
Ft. Collins Ulm			45	60	158.4	58.4	60.0	
(Shingle)			5	12	3.5	3.5	12.0	
6B Thedalund	108.8	[illegible]	100	24	217.6	2 7.6	24.0	
7B Cushman	76.8	[illegible]	00	24	53.6	153.6	24.0	
Total	640.0	[illegible]			2023.3	1951.9		

ndicates inclusion

Average depth of replacement $\frac{1951.9 \text{ A-ft}}{640 \text{ A}} = 3.0$

[a]Where topsoil salvage depth is different from the depth of topsoil, the limiting factor should be defined.

SOURCE: James P. Walsh & Associates, "Soil and Overburden Management in Western Surface Coal Mine Reclamation," contractor report to OTA, August 1985.

[page omitted]

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The scanned version of the page was almost entirely black and not usable.

software to analyze the data and to update the estimates of available soil volumes on a daily or weekly basis. This level of sophistication is especially useful at mines with daily staking and sampling programs, where otherwise there would be some question about whether or not the data were being fully utilized.

The principal model for predicting the success of soil reclamation is an informal analysis of spoil quality and soil thickness. Research in the five States on production, cover, rooting depth, and plant quality as a function of soil thickness over spoil with various characteristics has been used to develop guidelines for factors that affect optimum soil thickness for revegetation. These factors are: vegetation type, soil and spoil quality, landscape position, and average annual precipitation. Table 6-6 summarizes some of the published research on soil thickness requirements, and illustrates the concept that soil depth must increase as spoil quality decreases. To evaluate proposed soil reconstruction plans, regulatory authorities use a qualitative analysis that compares predicted spoil characteristics, redressed soil quality, and average precipitation. The informal model illustrated in figure 6-7 was developed for evaluating reclamation plans in the high-desert Southwest. This model is useful because it allows formulation of site-specific recommendations for soil reconstruction, rather than blanket requirements for soil thickness.

Designing Hydrologic Reclamation[20]

In designing hydrologic and sediment control structures and restored surface drainage systems, it is necessary first to estimate the peak and low flows. As discussed previously, this can be accomplished with statistical methods if sufficient historical data are available; otherwise statistical or deterministic models are used. The USGS multiple regression equations (Log-Pearson Type III distribution method) are especially useful in predicting peak flood flows for sizing culverts and ditches at coal mines, and have officially been approved for this use by at least one State regulatory authority (Wyoming).

[20] Unless otherwise noted, material in this section is adapted from reference 30.

The numerous permit applications reviewed for this study revealed that many operators are using computers to calculate rainfall-runoff for use in the design of hydraulic structures. Programs in common use are: TR-20 (21), TRIHYDRO (30), and SEDIMOT II (32). Input and output from the TRIHYDRO model are illustrated in figure 6-8. The TR-20 model was used at one case study mine in North Dakota to quantify the loss of water storage and the resulting increase in area streamflow for wetlands that would not be restored after mining.[21] The program SEDIMOT II can be used to predict the runoff and sediment response of a watershed to a particular rainfall event. It is similar to the first two models, and is thus useful in the design of sediment control structures.

Where in-house computer capability is not available, deterministic modeling can be applied indirectly through the use of technical reports based on models, These reports enable users to obtain approximate runoff for a precipitation event using a family of curves developed for steep or mild slopes within a hydrologic region. One such report is used extensively by operators in Colorado to design sedimentation ponds and size culverts and ditches (22,23).

Deterministic rainfall-runoff models have several advantages over other methods of estimating peak flows and runoff volumes in the design of hydrologic control structures. They can be used to compare runoff from a given precipitation event for conditions before, during, and after mining. Also, because they utilize precipitation as a direct input they fulfill the common regulatory requirement for the determination of a runoff hydrography for a designated precipitation event (e.g., the 10-year, 24-hour storm used for the design of sedimentation ponds). Finally, rainfall-runoff models can be used to compute a complete runoff hydrography rather than merely a peak discharge and total runoff volume.

As noted previously, however, the results of deterministic models can be unreliable. Additionally, there appears to be no general consensus among regulatory personnel on a preferred method, and selection of a particular method depends on the capabilities or preferences of the individ-

[21] See case study mine C in reference 30.

Table 6-6.—Summary of Some Topsoil Depth Research

Overburden quality	Topsoil quality	Land use or vegetation	Region	Optimal depth	Comments
No adverse properties, similar to soil	Nonsaline, nonsodic, loamy	Cool season grasses	Eastern Powder River Basin	No soil required	It appears that in some areas of the Northern Great Plains spoil is equal to soil in its ability to support plant product ion
—	—	Wheat	Colstrip MT	Greater than 4 in.	4 to 8 in. adequate
Slightly saline	—	Wheat grain	ND	6 in.	No higher yields on thicker topsoils
Good	—	Row crops	—	6 in. minimum	May not be significant in later years
Slightly sodic	—	Annual crops	ND	12 in.	—
Poor SAR =20-30	Loamy 1:1 clays	—	Northern Great Plains	12 in.	May be adequate if the mine soils physical characteristic prevent upward salt migration
Orphan mine overburden	—	—	Southern WY	12-18 in.	"Satisfactory" cover not obtained unless 12 to 18 in.
NW Colorado overburden	—	Wheat; intermediate wheatgrass	—	18 in. (or more)	Yields increased from O to 18 in. optimum may have been greater
Slightly saline	Nonsaline, nonsodic, loamy	Cool season grasses	WY, MT, ND	20 in. optimal	Native plants require slightly more; optimal depth increases in wet years
Sodic	—	Wheat grain	ND	20-28 in.	Yields did not increase when thickness exceeded 20 to 28 in.
Medium EC <6 SAR <12	Good topsoil	—	ND	24-30 in.	Landscape position as important as depth; 12 in. topsoil over 12 to 18 in. subsoil
Slightly saline	—	Wheat, straw, corn	ND	25 in. or more	Increased with each application of soil thickness
Sodic SAR =25 dispersed	Good topsoil slightly saline sodic subsoil	Crested wheat and native grass; alfalfa spring wheat	Central ND	28-36 in. optimal	Best results when topsoil was over subsoil; 8 in. topsoil over <8 in. subsoil
—	—	Native grass	WY	28-42 in.	Low precipitation regimes; 4 to 6 in. topsoil over 24 to 36 in. subsoil
—	—	—	—	Greater than 30-40 in.	Maximum production with thin soil layer
Sodic SAR 28 clayey	Nonsaline, nonsodic, loamy	Cool season grasses	MT and ND	32 in.	Annual and species variations can range from 28 to 37 in.
Coarse EC <6, SAR <12	Good topsoil	—	ND	36-42 in.	12 in. topsoil over 24 to 30 in. subsoil
SAR 12-20	Good topsoil	—	ND	36-48 in.	12 in. topsoil over 24 to 36 in. subsoil
—	—	Deep rooted crops	WY	40-46 in.	Higher precipitation regimes; 4 to 6 in. topsoil over 36 in. subsoil
SAR >20	Good topsoil	—	ND	48-60 in.	12 in. topsoil over 36 to 48 in. subsoil
Strongly acid ph=4.O	Nonsaline, nonsodic, loamy	Cool season grasses	WY, ND, MT	More than 60 in.	Maximum yields occur at depths greater than 60 in.

SOURCE: James P. Walsh & Associates, 'Soil and Overburden Management in Western Surface Coal Mine Reclamation, " contractor report to OTA, August 1985.

Figure 6-7.—Minesoil Construction in the High Desert Ecosystem in the Southwestern United States Where Limited Soil and Regolith Are Available for Salvage

January 1984

	Good topeoil	Marginal topsoil	Coarae-textured unsuitable topsoil	Fin-textured[a] unsuitable topsoil
Good overburden				
Marginal overburden				
Coarse-textured unsuitable overburden				
Coarse-textured unsuitable overburden with major mitigation				
Fine-textured unsuitable overburden[(a)]				

[a]If the saturation percentage is above *85* percent, the problems and attenuate risks will be even more severe

SOURCE" James P. Walsh & Associates. "Soil and Overburden Management in Western Surface Coal Mine Reclamation, " contractor report to OTA, August 1985.

ual performing the calculations. Conflicts do arise between the regulatory authority and the operator over the validity of the estimate, on which much of the surface water engineering design is based. To avoid these conflicts and the potential for expensive redesign, and to avoid the property damage and loss of life that could result from failure of a structure due to underdesign, most operators are intentionally conservative in their calculations.

Design of Hydrologic and Sedimentation Control Structures

Techniques for the design of hydrologic control structures and sediment control facilities have changed very little since promulgation of final rules and regulations under SMCRA. There is an increasing use of computers in design, and there has been a gradual standardization of runoff and sediment estimating techniques toward the SCS triangular hydrography technique and the Universal Soil Loss Equation (USLE), respectively.[22]

Whether designing sediment ponds, or planning alternative sediment control measures, it is necessary to estimate the amount of sediment that will erode from a watershed and be subject to transport downstream during a precipitation event. Most operators use some form of the SCS triangular hydrography technique to compute the 10-year 24-hour runoff volume, and some estimate of gross erosion, together with an appropriate sediment delivery ratio, to estimate sediment accumulation. In the absence of site-specific data (the usual case), the most widely accepted method for estimating gross erosion is the USLE. With limited available data for input, the strength of the method lies in its ability to provide rela-

[22]Examples of application of the SCS triangular hydrography and of the USLE can be found in case studies E, Q, S, and T in reference 30.

Figure 6-8.—Example of Input and Output for TRIHYDRO Rainfall-Runoff Model

SAMPLE INPUT SESSION:

ENTER TITLE FOR THIS STUDY
Sample Watershed, 1O-YR 24-HR storm
Drainage area in square miles. . . . . ? 0.68
Watercourse length in miles . . . . ? 2.00
Elevation difference in feet . . . . ? 195,0
Curve number (CN) . . . . ? 75
Minimum infiltration rate (in/hr). . . . . ? 0.24
Adjusted precipitation (inches) . . . . ? 2.99

ARE ALL VALUES OK? (Type N or carriage return)

INPUT OPTIONS

NOW YOU MUST SELECT A DESIGN PRECIPITATION DISTRIBUTION. YOU MAY SELECT EITHER A DEFAULT DISTRIBUTION OR INPUT YOUR OWN.

DEFAULT DISTRIBUTION SELECTIONS:

-1,-1 . . . . .USBR 6-HR General storm, Zone C, Extended to 10 hrs-use for PHP
-2,-2 . . . . .USBR 1-HR Thunderstorm, Zone III
-3,-3 . . . . USBR 24-HR General Storm, Zone C
-4,-4 . . . . USBR 24-HR General storm, Zone B
-5,-5 . . . . USBR 1-HR Thunderstorm, Zone II
-6,-6 . . . . .SCS TYPE II 24-HR General storm
-7,-7 . . . . USBR 6-HR General storm, Zone B
-8,-8 . . . . USBR 6-HR General storm, Zone C
-9,-9 . . . . SCS TYPE II 6-HR General storm
-10, -10.... . . SCS TYPE I 24-HR General storm
-11, -11..., . .SCS TYPE I 6-HR General storm

Enter one of the above default distributions or type in a new distribution. To type in a new distribution give the time in hours and the percent of the precipitation that has fallen by that time. Each pair of data (i.e., each time increment and percent value) is followed by a carriage return, Both the time increments and the percentage values must be in ascending order or an error will result. Percent values are given as whole numbers (i.e., 10.4 = 10.4 percent). Terminate with 0,0 (carriage return)
-3,-3

SAMPLE SUMMARY OUTPUT

SAMPLE WATERSHED, 1O-YR 24-HR STORM

BASIN CHARACTERISTICS:
Drainage area (sq.mi.) . . . . = 0.680
Stream length (mi) . . . . = 2.000
Elevation difference (ft) . . . . = 195.00
Runoff curve number (CN) . . . . = 75,00
Minimum infiltration loss (in/hr) . . . . = 0.240

PRECIPITATION FOR SPECIFIED STORM:
Adjusted precipitation for selected storm. . . = 2.99

UNIT HYDROGRAPHY PARAMETERS
Unadjusted time of concentration (hr) . . . . . . = 0.76
Adjusted time of concentration (hr) . . . . = 0.91
Duration of excess rainfall, D (hr). . . . . = 0.12
Time to peak (hr) . . . . = 0.61
Base time (hr). . . . . = 1.62
QPEAK (peak flow in CFS for unit hydrography) . . . . = 541.6

RESULTANT HYDROGRAPHY VALUES
Peak discharge (CFS) . . . . = 78.79
Runoff volume (acre-feet) . . . . = 7.36
Time to peak discharge (hr) . . . . = 10.41

USED: 24-HOUR GENERAL STORM, ZONE C

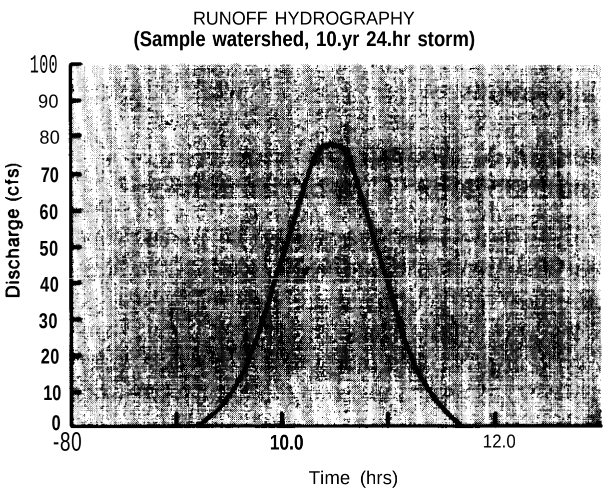
DESCRIPTION OF INPUT DATA VALUES

DRAINAGE AREA IN SQUARE MI LES—Planimetered from the largest topographic map available.
STREAM LENGTH IN MILES—Length of longest watercourse from the point of interest to the watershed divide, measured from the best topographic map available.
ELEVATION DIFFERENCE IN FEET—Determined by subtracting the elevation at the point of interest from the elevation at the watershed divide where the stream length was determined, elevations taken from the best topographic map available.
CURVE NUMBER (CN)–Dimensionless index developed by the SCS to represent the combined hydrologic effect of soil, land use, agricultural land treatment class, hydrologic condition, and antecedent soil moisture. Taken from Hydrology, section 4, National Engineering Handbook, Soil Conservation Service (1972).
MINIMUM INFILTRATION RATE (in/hr)-Minimum infiltration rate for the soils in the drainage area. Estimated using Design of Small Dams, United States Bureau of Reclamation (1977).
ADJUSTED PRECIPITATION (inches)—The rainfall amount associated with desired recurrence interval. Estimated using NOAA Atlas 2, Precipitation-Frequency Atlas of the Western States.
DESIGN PRECIPITATION DISTRIBUTION—Within-storm distribution of rainfall selected from 1 of the 11 distributions provided in the program or entered by the user.

OUTPUT OPTIONS

1. Summary Output (always provided)
2. Summary of Intermediate Calculations (optional)
3. Data Describing Individual Triangular Hydrography for the Runoff Period Only (optional)
4. Tabulation of the Resultant Runoff Hydrography (optional)

HYDROGRAPHY EXAMPLE
(Plotted using the runoff hydrography table output from TRIHYDRO)



SOURCE: Reference 29.

Box 6-M.—Use of the SEDIMOT II Model[1]

A mine operator in Wyoming developed a design method using an industry-standard computer simulation model (SEDIMOT II) to design and substantiate both conventional and alternative sediment control practices in support of a permit application. SEDIMOT II simulates runoff from an area as well as the effectiveness of a variety of sediment control techniques, allowing the various techniques to be tested, without actual implementation, and the best sediment control technique can be chosen on a site-by-site basis. By using this design method, it is not necessary to have an actual runoff event in order to determine problem areas. The goal of this computer-assisted design procedure was to obtain computed water quality (suspended-sediment concentration), via alternate sediment control techniques, within the limits of the selected design standard (30,000 mg/l). Successive computer iterations were conducted and additional sediment controls added as necessary until the design TSS concentration is achieved (see also ch. 8, box 8-B).

[1]See case study mine I in reference 30.

tive rather than absolute estimates for comparison of alternative projects.

Design of sediment control structures requires calculation of the runoff response of the watershed to a specified precipitation event using one of the flood-estimating techniques discussed previously, and of the sediment yield, normaily using the USLE. A computer program, SEDIMOT II, has been developed specifically for this purpose (see box 6-M); it allows rapid, accurate analysis in simulating larger areas in greater detail and over shorter time steps than is possible with hand calculations **(32).** In the example in box 6-M, an extensive monitoring program was instituted to determine the effectiveness of the various control techniques (see also ch. 8, box 8-B). The additional monitoring data also could be used to calibrate the model, since an initial data insufficiency did not allow calibration of the model to each of the separate drainages evaluated.

Design of Restored Surface Drainage Systems

individual site characteristics will determine whether restoration of stream channels is a simple matter of reestablishing premining channel slopes, cross-sections and bed form, or whether a complete analysis of the pre- and postmining drainage basins must be undeflaken to reconstruct an entire drainage system on the reclaimed surface (see ch. 3). Several approaches have been developed toward restoration of the surface drainage system. Selection of the approach depends on the experience and preference of the operator (or permit applicant), the desires of the regulatory personnel reviewing the application, and the site characteristics" In the permit applications examined for this assessment, OTA found that the amount of detail in the designs of reclaimed surface water drainage systems ranged from almost none to very elaborate designs based on geomorphic and hydraulic studies (see box 6-N).

Box 6-N.—Surface Drainage System Design[1]

At a mine in North Dakota, a surface drainage system was to be restored in an area of relatively steep slopes. A quantitative analysis of the premining drainage basin included a topographic map on which basins and channels were located, and a determination of the various geomorphic parameters of the premining drainage basin. However, the operator apparently made little use of these data in designing the postmining drainage system. The permit application did not discuss the analytical techniques used to design the restored system. The application did include a postmining topographic map indicating the location of postmining channels, along with a comparison between longitudinal profiles of the restored channels and premining profiles. In the comparison, the postmining channels had steeper, more variable slopes and a lack of upward concavity compared to the premining channels. There were no postmining drainage basin characteristics, no design flood flows, and no hydraulic designs of channels and flood plains in the permit application.

[1]See case study mine A in reference 30.

In the simplest case, where mining only removes a portion of a channel, the reclaimed segment design is made by direct field measurement of channel cross sections and profiles, and then duplication of the undisturbed channel cross section, longitudinal profile, and sinuosity. If the channel is alluvial, data are required on bed-material size and gradation to assure maintainance of adequate sediment transport rates and channel stability.

The advent of computers, especially personal computers, and readily available software for applications such as rainfall-runoff computations and water surface profile calculations, have added to the operator's abilities to prepare and analyze site-specific channel properties. This increases the assurance that well-designed, restored drainage systems will be erosionally stable. Design is aided by the use of computerized water-surface profile analysis programs (e.g., HEC-2, developed by the U.S. Army Corps of Engineers). Predicted velocities from successive postmining channel designs are compared to those found under undisturbed conditions until a channel geometry is found that meets all of the design goals. Data requirements for this type of hydraulic analysis are not extensive, and include only the data from the field survey of the channel and those data necessary to compute or select design-discharge levels and cross-sections and profiles.

Mines that cover large areas or contain relatively small watersheds often must reconstruct entire drainage basins. Where the overburden to coal ratio is very large or very small, the postmining drainage basin characteristics may differ substantially from the premining characteristics, further complicating the design problem (see ch. 3). Many operators base their reclamation plan in part on a quantitative geomorphologic analysis of the premining drainage system, and attempt to apply relationships determined from this analysis to the design of the restored system. Hydrologists and engineers work together to create a new "steady state" by manipulating the surface, slope, and channel configuration so that the newly formed system will be approximately in equilibrium with respect to erosion and sediment transportation processes. The most important design parameters are channel longitudinal profiles, drainage density, and channel and floodplain cross-sectional geometry.

Review of mine plans has revealed an encouraging trend toward a comprehensive, multidisciplinary approach to the design of restored surface drainage systems, Operators are combining the concepts of quantitative geomorphology with rainfall-runoff hydrology and detailed hydraulic analyses to develop plans for the restoration of erosionally stable channels and watersheds. The importance of this aspect of reclamation is becoming increasingly apparent as reclamation proceeds and problems in channel stability are beginning to appear at some mines. Considering that the performance bond evaluation period is relatively short in comparison to the frequency of design flow events for restored surface drainages, it would be difficult to judge the success of surface drainage restoration within the bond release period. Evaluation of drainage restoration will have to be based to a large extent on the design in the reclamation plan, which underscores the importance of the correct application of the analytical techniques that produce that design.

Design and Reclamation of Alluvial Valley Floors[23]

in general, the analytical procedures for AVFS are similar to those used in non-AVF areas, but are applied more intensively. In AVF areas, monitoring and data collection are more concentrated spatially and temporally, and the results are reviewed more rigorously by regulatory authorities due to statutory protections for AVFS. Hydrologic studies of AVF areas are unique in that, by law, they are required to analyze the relationships between hydrologic conditions in surface and groundwaters and in land use, soil characteristics and vegetative productivity. In addition, most mine permit applications provide a thorough assessment of the geomorphic and erosional characteristics of the valley floor, if it is to be physically disturbed. To assess the special relationships in AVF areas, most permit applications attempt to quantify the variables of the hydrologic budget of the valley floor.

[23]Unless otherwise indicated, the material in this section is adapted from reference 30.

Analytical techniques used to predict the impacts of mining on AVFS and to demonstrate that the essential hydrologic functions will be restored are similar to those previously described for surface and groundwater investigations. Special functions of AVFS that must be determined premining include the interchange of water between the surface stream and the alluvial aquifer and between the alluvial aquifer and bedrock aquifers; the depth to the alluvial water table and the soil texture above the water table; and water quality in the stream and alluvium. In planning for the restoration of AVFS, attention is focused on channel and floodplain geometry and erosional stability, and alluvial aquifer depth, thickness, and water-storing and transmitting capabilities (transmissivity and storage coefficient).

At a mine in Wyoming, potential alluvial drawdowns were predicted using a well-field simulation model.[24] Use of this model required assumptions of the alleviated valley width, aquifer-specific yield, and dewatered aquifer length. The volume of water extracted in the dewatered alluvium was compared to flood flows in the intermittent channel. This evaluation indicated that "any moderate-sized flood event would totally recharge the dewatered material." The postmining monitoring program includes detailed plans to support this contention.

The criteria for premining evaluation of the essential hydrologic functions of AVFS are generally standardized among the regulatory agencies of the Western States. These same criteria are also applied, postmining, in evaluating the success of AVF reclamation (see ch. 7). The criteria are based on accepted engineering and hydrogeologic principles, and the probable success of reclaiming AVFS generally is viewed with confidence. As with hydrologic restoration in non-AVF areas, however, in some instances it may be many years or decades until reclamation success in AVF areas can be finally assessed.

[24] See case study mine J in reference 30.

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