DATA EVALUATION AND APPLICATION

Geologic Overburden

From the standpoint of mine land reclamation the following questions should be addressed in mining and reclamation plans and environmental reports: What are the nature and magnitude of both the beneficial and the adverse affects resulting from the proposed surface mining activity? What actions must be taken to mitigate or minimize any possible environmental damage (adverse effects)?

Specific adverse effects that might need addressing in mining, reclamation and environmental reports include:

1. Handling of overburden rock units that are highly acidic, saline, or sodic and units that contain high levels of phytotoxicants (particularly heavy metals).

2. Constitution of a suitable soil or subsoil material from overburden rock units should mining operations result in excessive disruption of marginal surface soils.

3. Final contouring of surface and reestablishment of surface drainage after backfilling operations are completed to minimize subsequent erosion and to optimize surface runoff from the mined area (Keefer and Hadley 1976).

The geologic data base that should be available to aid in answering these questions and in recognizing and addressing these adverse effects includes:

1. Maps of the exploration area showing the surface topography and the location of boreholes, pits, roads, etc.

2. A detailed geologic map showing the types of surface materials, location of potential borrow deposits, and geologic hazards.

3. Lithologic and geophysical logs of boreholes. Photographs of cores and lists of all retained cores and/or cuttings, and methods used for backfilling all boreholes and pits.

4. Geologic cross-sections showing soil and rock types and rock structure within the proposed mine area.

5. Isopach maps of the topsoil, the overburden and interburden, and the host rock or coal seam. Ratios of overburden to host rock or coal seam thicknesses.

6. Structural contour maps showing the subsurface elevations of the floor of the host rock or coal seam and the subsurface elevations of major rock units that contain high levels of toxic or undesirable materials.

7. Records of all geochemical, mineralogical, and textural analyses.

8. A narrative summary of the conditions of the exploration site to include: regional geology and seismicity; surface conditions and topography; physical, mineralogical, and geochemical characteristics of the overburden and interburden material; nature and extent of toxic materials present in the overburden; and geologic hazards.

It is readily apparent from a review of the literature that there is a lack of information concerning the physical and chemical characteristics of geologic overburden materials in many potential surface mine areas in the Western United

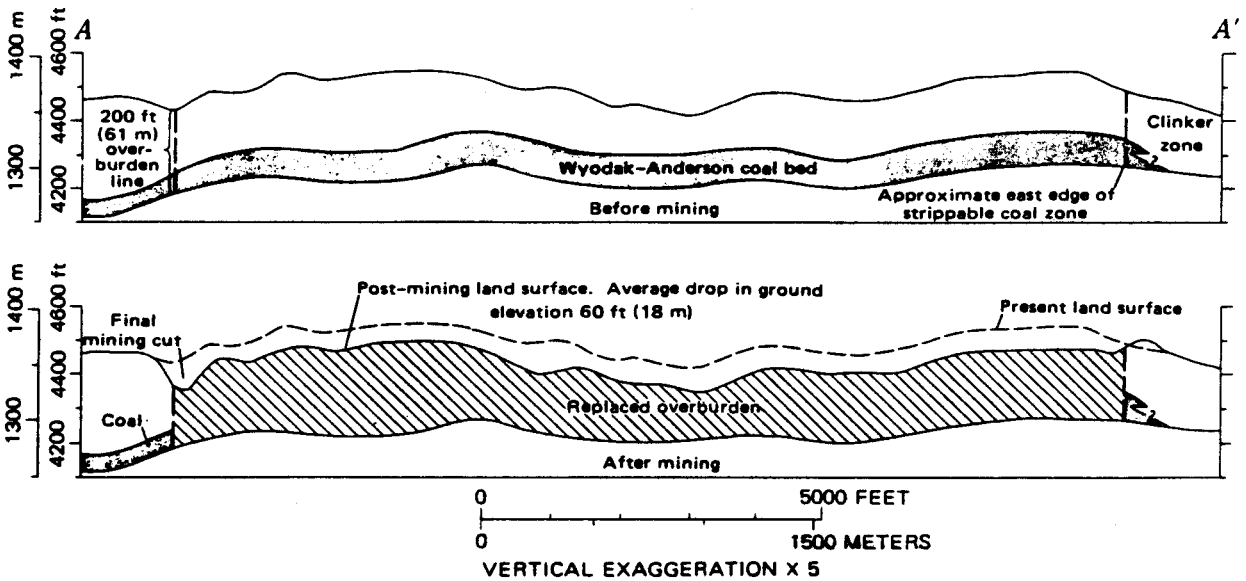

Figure 13. Cross-section showing potential changes in topography resulting from surface mining in the Gillette area, Wyoming. Lower section is based on assumption that overburden is replaced on a cut-by-cut basis with 200 ft wide (60-m-wide) cuts, spoils are smoothly graded, high walls, are graded to a 3:1 slopes, and overburden expands 20 percent. (from Keefer and Hadley 1976, fig. 14, p. 19)

States such as the Fort Union region in North Dakota. Most of the overburden in this area, as well as in other areas of the Western United States, appears to be saline and sodic shales and claystones which create severe problems in rehabilitation. Scoria, sandstone, and gravel, while more desirable for rehabilitation, are also more scarce. Some of the shales and claystones might be less saline, and if so, more easily rehabilitated. An inventory of these more preferred substrata is certainly desirable and warranted (Thorne Ecological Institute 1975).

In some surface mine areas of the Western United States these types of inventories are presently under way by State and Federal agencies. One particular area that has received considerable attention is west central North Dakota (Moran and others 1978). Another such area is the Gillette area in Wyoming. The U.S. Geological Survey is gathering data on the topography, landforms, geology, coal reserves, geochemistry, surface water, erosion and sediment yield, and groundwater to ascertain the potential effects of surface mining of coal (Keefer and Hadley 1976).

One inevitable effect of surface mining is the alteration of the surface topography as a result of surface mining operations. This alteration depends on factors such as depth and thickness of the coal being mined and the manner in which the overburden is being replaced in the mined-out pits. A cross-section showing the potential changes in topography in the Gillette area as a result of surface mining of coal is given in fig. 13. Knowledge of the postmine landscape is especially important in areas where the strippable coal is thick in comparison to the overburden material. Such reconstructions are essential to determining the potential distribution of surface drainage and predicting changes in erosion and sediment yield patterns. Because of the thickness of the coal in this area, the ground surface will be lowered considerably (fig. 13). As a result, extensive closed depressions may be created and gullying along stream course upstream from high walls and increased erosion and sediment yield may result if proper reclamation procedures are not followed.

Potential environmental problems such as those found in the North Dakota and Gillette areas can only be recognized if a sufficient data base from overburden and hydrology studies exists. Solution to some potential environmental

problems must be based on a regional as well as a site-by-site basis.

Soil and Overburden

FIELD INVENTORY DATA APPLICATION

The field inventory maps and accompanying descriptive information will be directed toward answering the following basic question: How much soil material is available that is suitable as plant growth media and what is the distribution of these materials on the site?

The field inventory data base should include the following information for answering the above question:

1. Adequate soil profile descriptions so that topsoil and subsoil isopach maps can be developed to calculate the amount of material.

2. Soil map at a scale sufficient to portray the extent and distribution of the different kinds of soils which occur.

3. Adequate soil mapping unit description to determine the relative homogeneity of soils within a mapping unit and to provide adequate information for making land capability interpretations.

4. Interpretive classifications should be made for each soil mapping unit with regard to land capability classification, important and unique farmlands, range-site classification, erosion susceptibility, and other soil and/or land classification interpretations that might be useful in developing a reclamation plan.

Most of the interpretive classifications can be developed very easily if the field data are collected using the procedures outlined in this report and the interpretation guidelines, which are available from agencies such as the Soil Conservation Service, USDA; Bureau of Reclamation, USDI; Forest Service, USDA; and Bureau of Land Management, U.S. Department of the Interior.

LABORATORY DATA APPLICATION

The major problem facing land planners, relative to use of laboratory data, is identifying data needs and interpreting the data once obtained. The diversity of management goals, controlling specifications, variability in physical and plant system environments, and lack of interpretive correlation data makes this task somewhat difficult. Further, the complexity of these interrelated factors renders impractical any attempt to develop or apply uniform criteria. In addition, definable and applicable criteria are more reliable for dealing with some factors as compared to others.

This section is an attempt to present the "state of the art" in interpreting and applying laboratory data in mined-land reclamation and to provide a basis for knowing what to look for in differentiating what is important and what is not in relation to individual projects.

This section is written to present information that can be useful for evaluating and applying laboratory data to the following concerns: (1) soil fertility relationships, (2) soil salinity and/or sodium relationships, (3) soil textural relationships, (4) mineralogical relationships, (5) trace element deficiency and toxicity relationships, (6) soil erosion relationships, and (7) developing a soil and geologic overburden laboratory characterization program.

Use has been made in this section of many sources of unpublished as well as published information.

Soil Fertility Relationships

The uptake of nutrients by plants is one obvious criterion for assessing their availability. No two species of plants growing on the same soil, however, take up the same quantity of the various nutrients. These variations in uptake are the result of such things as pH of the soil, moisture status, overall fertility status, nature of the plant, and content in the soil of the nutrients.

The above interrelationships have been resolved (at least to a satisfactory degree) for many soil-plant systems through soil test corre-

lation research programs. Most of these investigations have, however, been carried out for agronomic crops under soil moisture regimes quite different from those in which surface mining is taking place in the Western United States. Although agronomic and/or introduced forage crops will be used in some areas in reclamation for which some existing soil test correlation data will be applicable, native vegetation, as well as drier soil moisture regimes, will be the more common soil-plant system for which fertility assessments are made.

Thus, the "state of the art" for evaluating potential soil fertility needs associated with most reclamation efforts is based primarily on judgment.

Data shown in table 15 identifies the soil test-fertilizer recommendation criteria currently being used by the Colorado State University Soil Testing Laboratory. The fertility interpretations provided are thought to be those which most closely approach mined-land reclamation interpretive needs. It must be remembered, however, that these relationships are based on correlation data for a given soil chemical extraction method and for specific crops. (Soil test methods are indicated in table 15.) The purpose for providing this information is not to suggest that the fertilizer treatments recommended be universally applied. This would be undesirable because the recommendations do not have regional application because of crop, climatic, and soil differences. Rather, the information is provided to serve as a first approximation in attempting to identify and/or isolate potential fertility problems associated with a mined-land reclamation effort, recognizing that what might be considered a low soil P level for one type of plant may not be low for another type of plant and/or soil moisture regime.

N and P are recognized as being the most potentially limiting plant nutrients in soils of reclaimed areas in the arid and semiarid West. The degree of deficiency, however, varies greatly due to soil properties, plant type, prevailing climatic conditions, etc.

Although there are little data available, the following is a summary of the present "state of the art" for evaluating the status of several other nutrients in addition to those listed in table 15 and/or discussed in the section which follows:

Sulfur. — Deficiency very unlikely to occur but usually is potentially limiting in very coarse, well-drained, low organic matter soils.

Calcium. — Generally present in sufficient quantities; however, may be important from the standpoint of plant nutrition because of the ratio of Ca to Mg. When Mg exceeds Ca on an equivalent basis, plant yields may be influenced. High Mg to Ca ratios have been found for a number of geologic overburden materials. Specific criteria for evaluating this relationship are not well developed.

Boron. — Deficiency, if it occurs, is probably restricted to isolated situations. Toxicities are likely to be more common than deficiencies.

Molybdenum. — Because of the alkaline nature of most soils found in arid and semi-arid regions, deficiency of this element is unlikely to occur.

In summary, research is being carried out in various parts of the Western United States by State, Federal, and private groups in an attempt to develop interpretive data for evaluating nutrient deficiencies. Thus, soil fertility evaluations can best be made through contact with persons having ongoing research programs.

Soil Salinity and Sodium Relationships

Excessive salinity and exchangeable sodium in soil and geologic overburden are found to be problems hindering revegetation of strip-mines in many areas in the arid and semiarid western regions. General guidelines for evaluating suitability of topsoil (A horizon), subsoil (B and C horizons) and geologic overburden for revegetation of regraded mined lands under nonirrigated conditions are given in table 16. Since irrigation water and soil amendments can ameliorate salt and sodium conditions and present a large array of interpretive problems, the guidelines are limited to nonirrigated conditions except where salt and sodium reach "undesirable" levels. Similarly, plants have a wide range in salt tolerance characteristics which cannot even begin to be covered

Table 15. – Fertilizer recommendations

Small grains

Nitrogen

(1) NO_3–N soil test p/m	Soil organic matter – % 0–1.0	1.1–2.0	>2.0
	Fertilizer N lb/acre		
0-6	50	40	30
7-12	30	20	10*
13-18	10*	0	0
19-24	0	0	0
>24			

10 lb N is recommended only when phosphorus and/or potassium is also required.

Phosphorus

(2) Phosphorus (P) soil test p/m		Fertilizer phosphorus lb/acre P_2O_5
0-7	low	40
8-14	medium	20
14	high	0

Potassium

(3) Postassium (K) soil test p/m		Fertilizer potassium lb/acre K_2O
0-60	low	30
>60	high	0

Native and improved range grasses

Nitrogen

NO_3–N soil test p/m	Soil organic matter – % 0–1.0	1.1–2.0	>2.0
	Fertilizer N lb/acre		
0-6	40	20	0
7-12	20	0	0
12	0	0	0

Phosphorus

Phosphorus (P) soil test p/m		Fertilizer phosphorus lb/acre P_2O_5
0-7	low	30
>7	high	0

Potassium

Postassium (K) soil test p/m		Fertilizer potassium lb/acre K_2O
0-60	low	30
>60	high	0

(1) Phenoldisulfonic acid method
(2) Sodium Bicarbonate Extractable P levels
(3) Ammonium Acetate Extractable

The above soil test values can be interpreted only for soils tested by the respective methods listed.

Remarks

Experience and test results to date indicate that N and P are the elements most likely to be deficient in soils on mined land reclaimed areas. However, responses to fertilizers which are applied to correct these deficiencies are not always obtained because other factors such as soil moisture may be more limiting than these nutrients. The likelihood of a response to added K even at low K soil test values is probably minimal except possibly on very sandy soils.

The authors of this manual know of no available data which can be used to evaluate other nutrient deficiencies.

Below are listed critical levels at which Fe, Mn, Cu, and Zn are considered to be potentially deficient for those agronomic crops which are sensitive to deficiency of these elements and in many cases for those crops grown under irrigated conditions. They cannot and should not be interpreted as being critical for most of the plants grown on most soils/spoils and soil moisture regimes in the Western United States. However, if the levels fall much below those identified below, further evaluation may be necessary.

Element	DTPA extractable p/m (critical level)
Zn	<0.25
Fe	<2.5
Mn	<1.0
Cu	<0.2

Table 16. — Suitability of topsoil, subsoil, and overburden for revegetation of regraded surface mines under non-irrigated conditions in arid and semiarid regions

Factor	Material	Highly suitable (excellent to good)	Suitable (fair)	Undesirable except with amelioration (poor)	Amelioration
$EC_{se} \times 10^3$ mmhos/cm	Topsoil (A-horizon)	<2	2-4[1]	>4[1]	Leaching to reduce to <4
ESP	Topsoil (A-horizon)	<5	5-10	>10	Amendment to reduce[2] ESP to <10
$EC_{se} \times 10^3$ mmhos/cm	Subsoil (B & C horizons)[3]	<4	4-8	8	Leaching to reduce to <8
ESP	Subsoil (B & C horizons)	<10	10-15	15-30[4]	Amendment to reduce[2] ESP to <15
ESP	Subsoil (B & C horizons) 2:1 swelling clay content >65% of <2 μ fraction	<5	5-10	10-15	Amendment to reduce[2] ESP to <10
$EC_{se} \times 10^3$ mmhos/cm	Overburden (B & C horizon contact material)	<4	4-8	>8[1]	Leaching
ESP	Overburden (B & C horizon contact material)	<10	10-15	15-30[4]	Amendment to reduce[2] ESP to <15
$EC_{se} \times 10^3$ and ESP	Overburden as a substitute for topsoil or subsoil (B & C horizon)	Same EC & ESP criteria as topsoil and subsoil			

[1]Changes to suitable with supplementary irrigation water having $EC \times 10^6$ <1000 μ mhos/cm and SAR <5 or annual precipitation >18 inches.

[2]Amendment alternatives: native gypsum, commercial gypsum, commercial low-B $CaCl_2$.

[3]Minimum thickness of overlying A not <6 inches (15 cm).

[4]2:1 swelling clay content 65% of <2μ fraction — reduce to topsoil value if > 65%.

adequately within the purpose and intent of these guidelines. The guidelines for salinity were approached on the basis of difficulty in obtaining plant stands on saline soils under nonirrigated conditions. Most plant seeds will germinate under quite saline soil conditions but a great many will fail to emerge and, if emergence takes place, many die during the seedling stage, especially if drought conditions exist simultaneously.

The excellent to good suitability rating for soil salinity and sodium are those levels that should result in little or no difficulty in establishing stands of plants usually used for revegetation and would qualify for "prime-land" category, with respect to salinity and sodium. Also, little or no decrease in plant production after stand establishment would be expected as a result of soil salinity or exchangeable sodium. Lower levels of salt and sodium are recommended for A horizon topsoil placed on the surface. Higher salt levels can be tolerated in the lower depth because plants usually increase in salt tolerance after establishment. Lower exchangeable sodium levels are recommended for A horizon topsoil or topsoil substitute because the soil surface is critical for maintenance of good water-soil-plant relationships. It is necessary to maintain an acceptable infiltration rate to prevent excessive runoff and erosion especially on steep slopes, a 10 percent Exchangeable Sodium Percentage (ESP) probably will not be significant in reducing infiltration rates especially on sandy-textured soils. Some downward movement of exchangeable sodium can be expected, however, even in arid areas. Downward movement of exchangeable sodium can affect the permeability of subsoil layers. Also, translocation of clay can be initiated at relatively low Exchangeable Sodium Percentage (ESP) levels with rainwater. Translocation of clay would reduce the moisture retention of the surface soil and reduce the permeability of lower depths. Loss of clay from the surface layer could result in an increased wind-erosion susceptibility. Thus, the long-term effects of ESP may be more important than immediate effects.

The "fair" suitability rating for salinity levels is in the range where difficulties in establishing a stand under nonirrigated conditions and reduced plant production might be expected, especially if agronomic species were grown. The "fair" rating for exchangeable sodium would be in the range where some adverse effects on physical properties might be expected, especially on finer-texture materials. Expected adverse effects might be reduced infiltration and permeability, reduced aggregation, and increased water or wind erosion. Migration of salt or sodium, either upward by capillarity or downward by leaching, is possible also.

The "undesirable" rating does not necessarily mean that the soil or overburden could not be used. It may be that the material represents the "best available" in some cases. It does mean, however, that it would probably be necessary to develop water for irrigation and to use amelioration procedures to decrease salt and/or exchangeable sodium to levels that would insure successful revegetation. An arbitrary upper limit of 30 percent exchangeable sodium was imposed for economic considerations; the application of amendments and leaching to dissolve the amendments is a costly and time-consuming process. For example, about 1.7 tons of gypsum (100 percent purity) per acre are necessary to reduce exchangeable sodium by 1 meq/100 g in a 1-ft depth of soil. On the average, it will require that about a 1 to 1.4 ft depth of water be applied per acre to dissolve the 1.7 tons of gypsum so that calcium can replace sodium. An amendment, such as calcium chloride, is much more soluble but it is also much more expensive than gypsum. The water requirement for leaching of soil salts alone is usually much lower than for dissolving an amendment.

As with other aspects of strip-mine reclamation, considerable site-specific judgment needs to be exercised.

Soil and Geological Overburden Textural Relationships

Texture is an important soil property to evaluate in surface mine reclamation planning. In general, texture should not be examined from the standpoint of sand, silt, and clay distribution, per se, but the evaluation should be based upon several important properties that are closely related to texture. A list of factors affected by or related to texture are given in table 17. A generalized rating for each property is given for

Table 17. — Generalized rating of factors probably needing assessment in surface mine reclamation as affected by texture of soil or overburden

Factors Affected by Texture	[1]s	ls	lfs	sl	fsl	vfsl	l	scl	sicl	cl	sc	sic	c
1. Water Infiltration	rapid	rapid	rapid	mod. rapid	mod. rapid	mod.	mod.	mod. slow	mod. slow	mod. slow	slow	slow	very slow
2. Moisture Retention	very low	very low	very low	low	low	mod.	mod.	mod. high	mod. high	mod. high	high	high	very high
3. Potential for Water Stable Aggregate Formation from Dispersed Material	very low	very low	low	low	low	low	mod.	mod.	low	high	high	mod.	high
4. Sodium Dispersion Susceptibility	very low	very low	low	low	low	mod.	mod.	mod.	high	high	high	very high	very high
5. Tendency for Crust Formation on Soil Surface	very low	very low	very low	low	low	mod.	mod.	mod.	high	high	high	very high	very high
6. Wind Erosion Susceptibility	[2] high	mod.[2] high	mod. high	mod. low	mod.	mod. high	low	mod. low	low	low	mod. low	low	low
7. Water Erosion Susceptibility	very low	very low	low	low	low	mod.	mod.	mod.	high	high	high	very high	very high
8. Aeration	very good	very good	good	good	good	good	good	good	fair	fair	fair	poor	poor
9. Inherent Fertility	low	low	low	mod.	mod.	mod.	mod.	high	high	high	very high	very high	very high
10. Fertilizer Retention	low	low	low	mod.	mod.	mod.	mod.	high	high	high	very high	very high	very high

[1]s-sand, ls-loamy sand, lfs-loamy fine sand, sl-sandy loam, fsl-fine sandy loam, vfsl-very fine sandy loam, l-loam, scl-sandy clay loam, sicl-silty clay loam, cl-clay, sc-sandy clay, sic-silty clay, c-clay.

[2]very fine, fine and medium sands and dune sand.

each textural class. Textures most suitable or amenable to reclamation and revegetation generally fall between the sandy loam to clay loam textures. However, a primary consideration should also be maintenance of the integrity of the soil profile developed under natural conditions, in so far as possible. Thus, criteria for determination of suitability with respect to texture is largely "site-specific" and rigid guidelines cannot easily be made. It is suggested that an attempt be made to rank order properties of different materials that are available according to relative importance for a specific climatic and topographical setting and assign a score to each textural class available as topsoil, subsoil, or overburden to arrive at a total quantitative score for each material available. The material with the highest quantitative score would be considered as most suitable at that specific site. Properties to evaluate include infiltration, permeability, structures, water holding capacity, stoniness, salt and exchangeable sodium, surface crusting susceptibility, wind and water erosion susceptibility, fertility, and possibly others. Salt and exchangeable sodium ratings and erosion equations are discussed in another section. The amount of different materials available for regrading or soil reconstruction is also an important factor to be considered. Qualitative suitability ratings of several factors were used by McKall and Associates (1978) to obtain an overall rating of soil suitability for stripmine rehabilitation.

The "slaking test" (table 14) is used to evaluate consolidated overburden as a potential soil substitute material. If 65 percent or more of the consolidated core sample passes through a 5-mm sieve opening after being wet under vacuum and then shaken for 15 minutes in a horizontal shaker, it can be considered that the strata will weather rapidly and be suitable as plant growth media. The infiltration and/or permeability of soil and overburden materials after disturbance are difficult to predict except on a general basis of texture or to measure after regrading. It is expected that infiltration and permeability of soil materials will be higher than measured values in the field after regrading but will gradually decrease until they approach the value obtained before disturbance. Laboratory measurements of "hydraulic conductivity" (table 14) probably represent the best approach for screening different textured overburden materials. The "shrink-swell" test (table 14) should provide additional information for evaluating expected permeability changes under saturated conditions.

The following general rules can be applied in relation to other texturally related properties. Field capacity gravimetric moisture content can be closely estimated as: 1/2 paste saturation, percent. Volumetric field capacity can be estimated as: gravimetric moisture, percent times bulk density. Wilting point can be estimated as: 1/4 paste saturation, percent. The difference between field capacity moisture content and wilting point can be used as an estimate of "plant available water".

Better plant stands, more vigorous growth, and higher production of plant material are normally obtained on A horizon topsoil if it is not mixed with subsoil layers or overburden. Germination and emergence of seedlings are usually better on a coarse-textured A horizon than on a structureless fine-textured A horizon, unless moisture is very limiting. Fine-textured materials have a greater tendency to form surface crusts, which decrease the emergence of seedlings.

In general, a fine-textured A horizon should be stripped and stockpiled separately from finer-textured textural B and/or C horizons even though the A horizon is relatively thin. Mixing a textural B horizon (B_2t) with a fine-textured A horizon, for example a clay loam, is apt to markedly decrease water infiltration and increase erosion. Mixing a textural B horizon with a greater or equal amount of sandy A horizon usually will not decrease infiltration to seriously low rates and may be beneficial by increasing moisture retention capacity.

Other considerations with respect to soil profile reconstruction during regrading operations are as follows. In general, a coarser-textured A horizon placed over a finer-textured subsoil is more suitable for promoting surface infiltration and for maximizing moisture storage while reducing surface runoff and erosion. Placing materials with a large textural difference over one another is undesirable, especially fine-textured material over coarse-textured material, because it acts to interrupt downward moisture flow and creates "perched water tables". Compacted zones should be eliminated when placing one material

over another because compaction impedes moisture flow.

Illustrations of regrading operations, seed bed preparation, and various erosion control techniques are shown in publications by Mills and Clar (1976) and USDA Soil Conservation Service (1977).

Mineralogical Relationships

Pyrite mineralogy. — Pyrite (FeS_2), formed in overburden materials under reducing conditions, oxidizes to form sulfuric acid when exposed to atmospheric oxygen or oxygenated waters. The rate of this reaction is increased as the particle size of the pyrite decreases and in the presence of sulfur-oxidizing bacteria (species of *Thiobacillus*). Framboidal pyrite, a fine-grained pyrite occurring in aggregates of individual crystals, usually $< 2\ \mu$ in size, oxidizes rapidly whereas large crystals react slowly. The overall reaction is shown in equation 1 below. When soil and overburden contains alkaline earth carbonates, such as lime, the acidity produced by pyrite is neutralized as shown in equation 2.

(1)

$$2FeS_2 + 7\text{-}\tfrac{1}{2}\ O_2 + 4H_2O \rightarrow 4H_2SO_4 + Fe_2O_3$$

(2)

$$H_2SO_4 + CaCO_3 \rightarrow Ca^{++} + SO_4 = + CO_2 + H_2O$$

Pyrite is detected in overburden materials by the qualitative method of Neckers and Walker (1952). The total acid potential of pyrite-bearing strata is quantitatively determined by analysis for total sulfur (Bardsley and Lancaster 1965) from which gypsum and water soluble sulfates are subtracted. The acid neutralization potential is determined on the basis of the overburden lime content. An "acid-base account" procedure (Smith and others 1976) is used to determine whether sufficient lime is present to neutralize the total potential acidity. Thus, pyrite in overburden materials should not be present in amounts sufficient to produce acid soil and acid drainage water if overburden is used as a soil substitute or is in contact with regraded subsoil. Prevention of acid soil formation is especially important because heavy metals, in general, become more available to plants and heavy metal concentrations increase in ground water as the soil becomes more acidic. Also, if the sulfuric acid produced by pyrite-oxidation is neutralized by lime, this can result in detrimental effects on ground water by raising the salinity content as soluble calcium and sulfate ions. The bicarbonate ion content may be reduced, however. A more thorough discussion of acidity development follows in volume II.

Clay mineralogy. — Swelling or expanding (2:1 type) clay minerals in soils and geologic overburden with excessive absorbed sodium undergo dispersion and decrease soil permeability to a greater degree than nonswelling clays. Identification and quantification of the less than $2\ \mu$ clay mineral fraction could be used as an additional criteria for determining critical exchangeable sodium levels. If the soil clay contains more than 65 percent 2:1 lattice swelling clays, lower limits of ESP could be imposed for the particular suitability class. Clay mineral analysis can be helpful in determining the suitability of overburden as a soil substitute. Overburden with a combination of both nonswelling and swelling clays would be preferable for soil profile reconstruction.

It is recommended that clay mineral analyses be run on only a few cores per site. Lateral variation in the clay mineral suite is generally not great within the area of a proposed surface mine. The possibility exists for greater vertical variation within different depositional strata or rock formations.

Sandstone mineralogy. — Microscopic examination of thin section samples of sandstone overburden units, although not a common practice, can provide useful data to aid in the correlation of overburden strata and to supplement other physical and chemical data on the friability, resistance to mechanical breakdown, weatherability, and pyrite content of these units. Little work has been completed on the petrographic characteristics of overburden in the western states. Studies of the mineralogical and textural characteristics and weatherability of Eocene (Wasatch) sandstones of the Powder River Basin, Wyoming, are presently under way by the authors of this report. In the Eastern United States, petrographic studies of Pennsylvanian

Age Sandstones by Grube and others (1972) have revealed that some aspects of geologic overburden that are important to mine land reclamation.

Petrographic studies of the Lower Mahoning sandstone, coupled with determination of the total sulfur content of pulverized samples revealed sufficient pyrite free rock material to place in the oxidation zone of spoil heaps to avoid acid pollution. These studies also reveal abundant sandstone at depths below 6 m that contain highly toxic materials that would produce prolonged sources of acid water pollution unless protected from oxidation by deep burial or other means (Grube and others 1972).

Petrographic studies of the material filling the pore spaces between framework grains of sandstones revealed that moderately calcareous sandstones while hard at the time of excavation, will break down relatively rapidly when left near the surface so that circulating waters are able to remove the carbonate cement. Sandstones with argillaceous parting and clay matrix may also be hard at the time of excavation but will disintegrate rapidly near the surface. The argillaceous sandstone are particularly useful where additional sand would be beneficial in the soil (Smith and others 1974).

Trace Element Toxicity Relationships

Zinc and iron were considered in a general way from the standpoint of deficiency to plants in section a. These same elements, with the exception of iron, as well as other trace elements (some of which are necessary for plant growth and others which are not) are discussed further in this section because of their environmental importance. In addition to some of these elements being important as required plant nutrients, they are also of concern from the standpoint of toxicity to plants, animals and humans.

The trace elements considered in this section do not include all elements having potential impact on the environment. Those included are recognized as perhaps being the most important and/or likely to be a problem. In general, interest in trace elements tends to be based on the following:

1. Those that are toxic to plants and/or animals (boron, selenium, and molybdenum).

2. Those that are toxic to fish (zinc).

3. Those that are toxic to humans and animals (selenium, arsenic, cadmium, and nickel).

This is not to say that other elements may not be of importance. Those listed are of highest interests, however, and, in general, may be the most likely to occur in quantities in available forms to plants and animals to cause problems.

Evaluation of potential trace element problems is complicated by the same sets of factors as those we find associated in soil fertility evaluations. Although plant uptake of these metals is one criterion for assessing their effects, different plants take up different quantities and the availability of these elements to plants and their mobility in environment is controlled by soil pH, drainage, moisture regime, and amount present in the soil. Also, nutrient interactions within the plant and/or animal control whether or not deficiency and/or toxicity may occur. Toxicity levels for plants, animals, and in soils have been reported for some elements, while critical levels for other elements have not yet been established.

Evaluation of trace element and plant nutrient relationships for geologic overburden is further complicated by the fact that if the deeply buried materials, that are relatively unaltered, are brought closer to the surface and subjected to the natural bio-geochemical weathering process, significant changes may occur in their chemical and physical properties through time. These changes may not be identifiable either through "total" or "available" chemical analysis performed on fresh materials.

Geologic material identification through mineralogical analyses can be a useful tool for identifying minerals having weathering reaction products that might be significant to the plant-soil-water environments. If mineralogical analyses are not performed, then other measures are needed to identify potential changes in geologic materials as a result of weathering, i.e., long term leaching effects and plant growth and plant tissue analyses.

It appears that a logical approach to the problem at the present time is (1) to know some-

thing about the kinds of soil or geologic materials in which these elements are likely to occur in high amounts, (2) to make some arbitrary assessment as to the availability of these elements to plants and/or animals based on an interpretation of the soil systems that occur or are likely to occur on the site, and (3) if a problem is suspected, to make an appropriate choice of a chemical extractant which will indicate the potential availability to plants and/or mobility of the element in the bio-geochemical environment.

The data provided in table 18 show, in general, the amounts of some trace elements found in rocks that form soil parent materials. This information enables us to anticipate with some degree of confidence the approximate amount of a trace element that might be present if we identify the nature of the geologic material(s) with which we are working.

In addition, the data in table 18 identifies the soil conditions in which the various trace elements may be potentially more available to plants, and also more mobile in the soil, and thus subject to leaching.

Soil Erosion Relationships

Some accepted procedures for evaluating wind and water erosion potential, and identifying regraded and stockpiled areas follows:

The methods discussed have certain limitations. It is suggested that the references listed be carefully reviewed to ensure that the methods are not misinterpreted relative to their applicability for assessing erosion for a given condition. The procedures outlined can be an excellent tool for assessing the relative erosion potential that might exist, but must be used with discrimination and with adequate background information relative to the values that are used for assessing the impact of a particular variable.

Wind erosion. — Overall susceptibility to wind erosion has been demonstrated to be the result of a number of variables and has been expressed in the form of the equation

$$E = f(I\ K\ C\ L\ V)$$

where:

E = the predicted average annual soil loss expressed in tons/acre/year.

I = soil erodibility. This is the inherent potential of the soil to erode under a "bare" surface condition.

K = a soil surface roughness factor. Many times, roughening of the soil surface by mechanical means can, on some soils, completely stop wind erosion for at least a short term period. This factor should be seriously considered as a "short term" practice as part of an erosion control plan. Guides are available for calculating surface roughness for specific site situations. This practice would be most useful on soils having "moderate" wind erosion susceptibility because they generally leave a cloddy, as well as roughed surface condition after treatment, both of which are effective in controlling wind erosion.

C = climatic factor. This factor is evaluated based on the average wind velocity and on the precipitation-evaporation index for a given area.

L = The unsheltered distance along the prevailing wind direction. Attempts should be made to avoid creating unsheltered or bare soil areas which are moist subject to prevailing winds. For example, creating a bare area on the windward side of a knoll greatly increases susceptibility to wind erosion and stabilization procedures would have to recognize this situation if it exists. Otherwise, stabilization efforts often will fail.

V = vegetative cover. This variable in wind erosion evaluation considers three conditions: (1) quantity of residue, (2) kind of residue, and (3) the orientation of the residue.

Water erosion. — Factors important for evaluating water erosion potential and a basis for developing erosion control management practices have also been combined in the form of the following equation-like expression:

$$A = R\ K\ L\ S\ C\ P$$

where:

A = computed soil loss expressed in tons/acre/year.

Table 18. — General relationships of occurrence and availability of trace elements in soil and/or geologic overburden

General abundance and occurrence of trace elements in geologic and soil materials in p/m (Bowen 1966; Swain 1955; Taylor 1961) (Total concentration)

	Mn	B	Zn	Cu	As	Pb	Mo	Se	Cd	Ni
Earth crust	950	10	70	55	1.8	12.5	1.5	.05	.2	75
Sedimentary rocks										
Shale	850	100	95	45	13.0	20.0	2.6	.60	.30	68
Sandstone	50	35	16	5	1.0	7.0	.20	.05	.05	2
Limestone	1100	20	20	4	1.0	9.0	.4	.08	.035	20
Soils										
Range	100-4000	2-100	10-300	2-100	1.0-50	2.0-200	.2-5.0	.01-2.00	.01-7.00	—
Mean	850	10	50	20	6.0	10.0	1.0	.20	.06	40

Concentrations of trace elements in the surface layers of soils in Powder River Basin — in p/m (after Keefer and Hadley 1976)

	Mn	B	Zn	Cu	As	Pb	Mo	Se	Cd	Ni
Depth 0-1 inch (0-2.5 cm)										
Range	70-1000	<2.0-70	28-93	3-30	—	10-30	<3-20	—	—	<5-30
Mean	280	31	62	16	7.2	18	—	.20	—	15
Depth 6-8 inches (15-20 cm)										
Range	100-700	<20-70	25-104	5-50	—	10-100	<3-5	—	—	<7-50
Mean	250	28	64	18	8.2	18	—	.14	—	16

[1] Providing specific criteria for evaluating potential toxicity and/or deficiency of these elements is impractical and even dangerous because of the variability in tolerance to these elements by different plants, even within the same species — animals and humans. The only appropriate manner for handling these questions at the present time is to review recent literature and determine if data that are available actually apply to a particular situation. Suggested references are: Chapman and others 1966; Mitchell 1964; Connor and others 1975; Cannon and others 1972; Shacklette 1972; Hemphill 1973; Prabhakarannair 1969; Connor and others 1976; Cragg 1971; Norman and others 1968.

General soil conditions where elements are mobile or available to plants

Element	Soil condition	Remarks[1]
Mn	Most available under acid soil conditions; neutral or alkaline soil conditions may cause deficiencies.	Manganese toxicities in plants generally occur on very acid soils. Deficiencies may occur on neutral or alkaline soils. Excess Mn may restrict plant growth.
B	Low precipitation, alkaline soil conditions.	Boron toxicity can occur in arid areas where sodium and calcium borates occur in soils. The safe limits of available Boron content between deficiency and toxicity are narrow.
Zn	Soil low in $CaCO_3$; acid soil conditions.	Zinc toxicities can occur on acid soils that are heavily fertilized with zinc fertilizers. Zinc tends to accumulate at or near the surface of the soil.
Cu	Acid soil conditions.	Deficiency of copper occurs on sandy alkaline soils that have been well leached. Toxicity of copper can occur on soils that have been subject to applications of sprays containing copper.
As	Alkaline soil conditions.	No evidence that arsenic is essential for plant growth. Toxicity generally occurs in areas that have accumulated arsenic in the soils through foliar spray compounds.
Pb	Acid soil conditions.	Lead accumulated in surface horizons of many soils does not appear to be readily available to plants. Lead may be absorbed by plants from pollution and then be toxic to animals.
Mo	Wet soils and neutral to alkaline soil conditions.	Heavy applications of phosphatic fertilizers will increase molybdenum uptake by plants. Excessive amounts of molybdenum are toxic to grazing animals.
Se	Alkaline soil conditions with well oxidized environment.	Selective plants such as Astragalus and Sium generally accumulate selenium and may cause poisoning in grazers. Associated with sedimentary rocks.
Cd	Mildly alkaline to acid soil conditions.	Not usually toxic to plants. Cadimum may be absorbed by plants from pollution and may cause toxicity to grazing animals.
Ni	Acid soil conditions.	Nonessential for plants and animals. The amount of nickel absorbed ranges widely among species.

R = the rainfall factor. An index which is the measure of the erosive force of specific rainfall. This value can be expressed as a mean over an annual period or for short periods of time.

K = the soil erodibility factor. A relative value expressed from 0 to 1.0 which reflects the inherent potential of soil to erode by water when exposed.

LS = slope length and degree factor.

C = crop cover or management factor.

P = erosion control practice factor such as contouring, terracing, etc.

Numerical values for each of the six factors have been determined from field experience and research data. Values for use in the wind erosion equation also are available (USDA Soil Conservation Service 1977 a, b, c).

Developing a Soil and Geologic Overburden Laboratory Characterization Program

The main objective in developing a soil and geologic overburden laboratory characterization program is to avoid mass sample characterization by minimizing the number and/or kinds of analyses that are performed. This is done without sacrificing quality and kinds of data needed for making the assessments necessary.

The Bureau of Reclamation, U.S. Department of the Interior, has for many years based the level and intensity of laboratory characterization on an approach called "screenable soil characterization as related to land reclamation" (personal communication, Mr. Richard Piper, U.S. Bureau of Reclamation, Denver, Colo.). In screenable characterization a multiphase program is developed which minimizes the number and kinds of analyses to be performed. This approach emphasizes that the number and types of laboratory studies to be carried out will be determined by area conditions, particularly variability of soils and land types, and the controlling specifications and needs. Thus, the laboratory characterization must be coordinated from the very beginning with the field investigations. Using this concept, the information in table 19 was developed as an example for determining data needs for evaluating soil and/or geologic overburden material as plant growth media and effects on environmental quality. The approach, as presented in table 19, may require modification based on present Federal, State, and local regulations, as well as particular site characteristics. It does, however, provide a basic framework for developing a data needs plan.

Interpretation and Application of Ground and Surface Water Data

The interpretation and uses of ground and surface water data relative to surface mining are highly site specific. Here it is possible to provide only general guidelines and procedures. A general description of research and interpretation procedures for ground water and ground water chemistry is provided by Freeze and Cherry (1979).

SURFACE AND GROUND WATER QUALITY

An important purpose of collecting data on the quality of surface and ground waters is to provide a baseline from which changes attributable to mining can be detected. For purposes of premining and postmining planning and decision making, it is necessary to identify and understand, quantitatively, the role that the study site plays in determining the quality of waters used internal and external to the study site. Only then is it possible to rationally project potential changes caused by the mining operations. A number of specific steps must be accomplished.

A first step is to combine the water quality data with the estimated discharges of ground and surface waters to determine chemical discharge from the site to potential receiving waters. The chemical discharge can be computed in terms of specific ions of particular concern, in terms of total dissolved solids, or both. Knowledge of the quality and discharge of the receiving waters below the points of inflow from the study site assist in determining the contribution from the study area. The framework in which

Table 19. — Example of an approach for determining interpretative data needs

Situation	Data needs
	A. Soil resources
1. Identify current soil resource status.	a. Federal Register (Jan. 31, 1978) and any State criteria available through the Soil Conservation Service (SCS).
a. Important and prime farmlands. b. Land capability.	b. Identify management practices needed to maintain or increase productivity by utilizing existing soil and land interpretive classifications utilized by the SCS, the United States Bureau of Reclamation, and other agencies.
2. Determine plant growth media potential of given soil resource.	a. Soil isopach maps developed from soil inventory are used to determine distributions and extent of soil materials.
	b. Laboratory analyses needed to determine quality of soil resources: salinity, sodium, pH, organic matter, texture, available N, P and K, percent calcium carbonate, and percent saturation (water). Other laboratory analyses for trace elements or heavy metals in the soil should be considered dependent on type of material and in which soil has developed and the chemical status of existing soil systems. Table 18 shows normal levels in rock and soils. This will aid in determining whether or not particular elements may be suspect.
3. Determine current and potential erosion.	Variables for determining wind and water erosion should be identified (USDA Soil Conservation Service 1977a,b,c).
	B. Geologic overburden resouces
4. Evaluate geologic overburden for plant growth media. (This step would be carried out if the soil resource evaluation indicates that it is necessary to utilize these materials as plant growth media.)	a. Identify distribution and extent of geologic strata from lithological core data. Sampling according to variances as shown by lithologica core characterization.
	b. Laboratory analyses of select geologic overburden to determine quality as a plant growth media: salinity, sodium, pH, organic matter, texture, available N and P, pyrite, percent saturation (water), percent calcium carbonate, percent gypsum, and erosion potential.
5. Evaluate geologic overburden for environmental concerns such as placement effects on ground water quality.	Select geologic overburden to determine effect on environmental quality: salinity, sodium, pH, organic matter, pyrite, percent calcium carbonate, and percent gypsum. Additional analyses for other factors such as heavy metals can initially be determined based on the data shown in table 18.

the analysis is applied is that of a combined expression for water and chemical mass balance (Rowe and McWhorter 1978; Kunkle 1965; Pinder and Jones 1969; Visocky 1970). It is sometimes possible to refine estimates of surface and ground water inflow to the receiving waters by this procedure. For example, suppose the discharge and total dissolved solids (TDS) concentration are measured at both ends of a stream reach receiving ground and surface water inflows from the area of concern. The measured gain of water over the reach must be accountable by surface and ground water inflows, taking into account such factors as diversions, evaporation, and transpiration. Similarly, the measured gain in chemical discharge (TDS multiplied by water discharge) must be accountable by chemical discharge from surface and ground water inflows. Ideally, an overall balance of both water and chemical discharge should be achieved. This is rarely possible without making reasonable adjustments of contributing factors. Often it is advantageous to perform such analyses for selected sub areas and reaches of receiving waters and over selected time intervals, when one or more contributing factors can be set to zero.

Once a satisfactory water and chemical balance has been achieved, the investigator is in a position to predict how the quality and quantity of the receiving waters will be changed by changes in the quality and quantity of inflow from the study area. At this point it is necessary to estimate the changes that can reasonably be expected to occur as the result of mining. Among the factors that must be considered are changes in recharge and storage as a result of mining, interception of surface and ground water by the pit, changes in evapotranspiration, modifications of the routes and quantities of surface runoff, and the pick up of additional contaminants.

Accurately predicting such changes is difficult, and only some very general guidelines can be provided. Discussion of potential changes in the quantities of recharge, ground and surface water runoff, and evapotranspiration are contained in the next subsection. The following is a brief presentation of one method for estimating postmining quality of combined surface and ground water runoff.

The disturbance of the naturally occurring sequence of strata exposes fresh surfaces for contact by water and, therefore, enhances the opportunity for water to pick up additional soluble materials. Experience at one site in Colorado showed that the TDS concentration (as indicated by electrical conductivity) in water that had passed through the spoils was about equal to that in extracts from saturated samples of the spoil (Rowe and McWhorter 1978). Other experience in Montana and North Dakota has not verified the equality of these measurements, however. The present state of knowledge seems to support only the rough rule of thumb that the dissolved solids concentration in spoil water will be on the order of 1 to 3 times the concentration in extracts from saturated pastes prepared from the overburden (Rowe and McWhorter 1978; Van Voase 1978).

In general, the quality (with respect to dissolved solids) of overland flow from disturbed lands is not greatly different from that in the undisturbed state (Rowe and McWhorter 1978). This is particularly true if existing topsoil is replaced on the spoils following mining. Apparently, pick up of dissolved solids by overland flow is not as great as for subsurface flows because the thin layer of material in contact with overland flow is rapidly leached and, because of smaller contact times, among other reasons.

Rowe and McWhorter (1978) present a simple model based upon the concepts of mass balance described in the foregoing paragraphs that may be useful for making rough estimates of the anticipated effect of mining on the TDS in combined surface and ground water runoff. Their model is

$$P_t = \frac{KR\ f_{sn}P_{sn} + (1-f_{sn})P_{gn} + f_{sm}P_{sm} + (1-f_{sm})P_{gm}}{1 + KR}$$

where:

P_t = the mean TDS in combined surface and groundwater runoff from the total watershed comprised of both mined and natural lands.

K = The ratio of total drainage per unit area (including both surface and ground water

runoff) on the undisturbed portion of the watershed to the total drainage per unit area from the mined land.

R = The ratio of the area of undisturbed land to the area disrupted by mining.

P_{sm} = mean TDS concentration in surface runoff from the mined area.

P_{gm} = mean TDS concentration in ground water runoff from the mined area.

f_{sm} = the fraction of total drainage from mined area that is overland flow.

P_{sn} = mean TDS concentration in surface runoff from the natural area of the watershed.

P_{gn} = mean TDS concentration in ground water runoff from the natural area of the watershed.

f_{sn} = the fraction of total drainage from the natural area that is overland flow.

This model is based on the assumption of zero net change in watershed storage and, therefore, all parameters represent means over a period for which this assumption is approximately true. A minimum of 1 year is recommended.

A brief example follows. Suppose that premine monitoring of the quality and quantity of ground and surface water flows on the watershed to be mined yielded P_{sn} = 210 mg/l, P_{gn} = 900 mg/l, and that f_{sn} = 0.10. Also, saturation extracts prepared from overburden samples exhibited a mean TDS of 2 300 mg/l, from which it is estimated that the TDS of ground water in the spoils will be 4 600 mg/l. Thus, P_{gm} = 4 600 mg/l. Topsoiling is planned so it is resonable to assume P_{sm} = P_{sn} = 210 mg/l. Reclamation plans call for revegetation that can be expected to be about equal to the premining vegetation. Grading of the mined lands is not expected to reproduce the premining drainage patterns, however. Numerous small basins with no outlet are formed and this causes reduced surface runoff, longer surface retention of water, and increased infiltration opportunity relative to undisturbed land. Thus, it is anticipated that total combined surface and ground water runoff from the mined land will be reduced relative to the undisturbed area by 15 percent. This yileds K = 1/0.85 = 1.18. The difference is accounted for by increased transpiration by plants due to the increased quantity of water available in the root zone. Also, because of the lack of good surface drainage on the regraded mined land, it is estimated that the fraction of total drainage from the mined land that is overland flow will be reduced relative to the natural condition. Therefore, f_{sm} is set equal to 0.05. Finally, the mining plans call for 22 percent of the watershed to be mined. This yields R = 0.78/0.22 = 3.55.

Values for all of the parameters on the right side of the equation are now available. Substituting and carrying out the computations yields P_t = 1 515 mg/l. This is the anticipated postmining value for the mean annual, discharge weighted, TDS concentration in total drainage from the watershed in which the mine is located. The corresponding premining value is 831 mg/l. In this case, mining 22 percent of the watershed nearly doubles the mean TDS concentration in the watershed drainage.

The foregoing is a demonstration of one way in which water quality and overburden data can be utilized in premine planning and decision making. The model is not applicable in all cases, of course, and other analysis procedures may be required for particular studies.

Water quality data is sometimes very useful for assisting in the understanding of the subsurface hydrologic system. For example, the proportion of surface water and ground water in the discharge of a pumping well can sometimes be determined by knowing the quality of the surface water, the quality of the unmixed ground water, and the quality and discharge of the mixture from the well (Hem 1970). Sudden changes in water quality during a pumping test can sometimes be interpreted as contributions from different zones with dissimilar water quality. Water quality in different zones may provide insight into the degree of interconnection between adjacent aquifer zones, as another example.

PIEZOMETRIC SURFACE MAPS AND FLUCTUATIONS

Ground water level data from a network of observation wells can be used to construct piezometric surface and water table maps. Such maps are prepared by connecting points of equal water level elevation to form a pattern of contours similar to those on a topographic map. These maps provide information concerning ground water flow direction, quantities of flow (when combined with transmissivity), and likely areas of recharge and discharge. Geologic information on stratigraphy, structure, faults, etc., should be fully utilized during the preparation and interpretation of piezometric surface maps.

An important use of such maps is to compute the quantities of ground water entering and leaving the study area, or possibly, to and from surface water bodies. These quantities are required for use in the water and chemical mass balances discussed in the previous subsection. Premining flow patterns, displayed as a piezometric map, are an aid to the determination of inflow to the mining pit, the estimation of the area over which the piezometric surface can be expected to be disturbed in both the mining and postmining phases, and the postmining flow pattern. The elevation of water levels in wells relative to the elevation of streams, ponds, springs, etc., often provides the most significant information available concerning the interrelationships between surface and ground waters. Similarly, relative elevation of water levels in different aquifers at the same location provides information on the degree of hydraulic interconnection between aquifers, especially when one of the aquifers is being pumped.

Figure 14 is an example of a piezometric surface map prepared for and overburden aquifer at a potential mine site. The direction of ground water flow is toward the northeast in this case. Comparision of piezometric surface elevations in the potential mine area with those in a shallow alluvial aquifer adjacent to the site on the east and north sides indicated that ground water discharged from the potential mine site into the alluvial aquifer. The gradient (slope) of the piezometric surface is about 0.006. These data, together with measured values for transmissivity of 7×10^{-3} ft^2 per min, and the area through which flow is occurring, yields an estimated 5.4 acre-ft/yr of ground water discharge into the alluvial aquifer. Knowledge of the quality of the ground water in the overburden aquifer and the alluvial aquifer permits the estimation of the influence of the overburden waters on both the quantity and quality of the waters contained in the alluvial aquifer.

Water level fluctuations can sometimes be used to estimate recharge when values for the storage coefficient or apparent specific yield are known. Multiplying the observed change in water level by the storage coefficient or the apparent specific yield gives the volume of water per unit area that has been added or removed from the aquifer. Factors other than recharge and discharge sometimes cause water levels in wells to fluctuate, however. Barometric pressure changes often cause water levels in wells penetrating confined aquifers to change by as much as several centimeters. Water levels should be correlated with barometric pressure and precipitation to help assure a correct interpretation.

Figure 15 shows measured water levels in three wells in a potential mine site. The fluctuations apparent in the lower two graphs correlate well with each other, and these short term fluctuations represent response to atmospheric pressure fluctuations indicating that both wells are completed in a confined aquifer. The upper graph shows the water level in a well penetrating an unconfined aquifer in the same area. The conclusions drawn from these records was substantiated by geophysical and geological data at the site. The time period over which these data were collected is too short to draw any conclusions concerning the indicated trends relative to recharge or discharge. Nevertheless, this example demonstrates how water level fluctuation data can assist in the interpretation of geologic and geophysical information.

ANALYSIS OF AQUIFER TEST DATA

It is apparent from the discussions in the foregoing subsections that values of transmissivity, storage coefficient, and apparent specific yield are required for several of the computa-

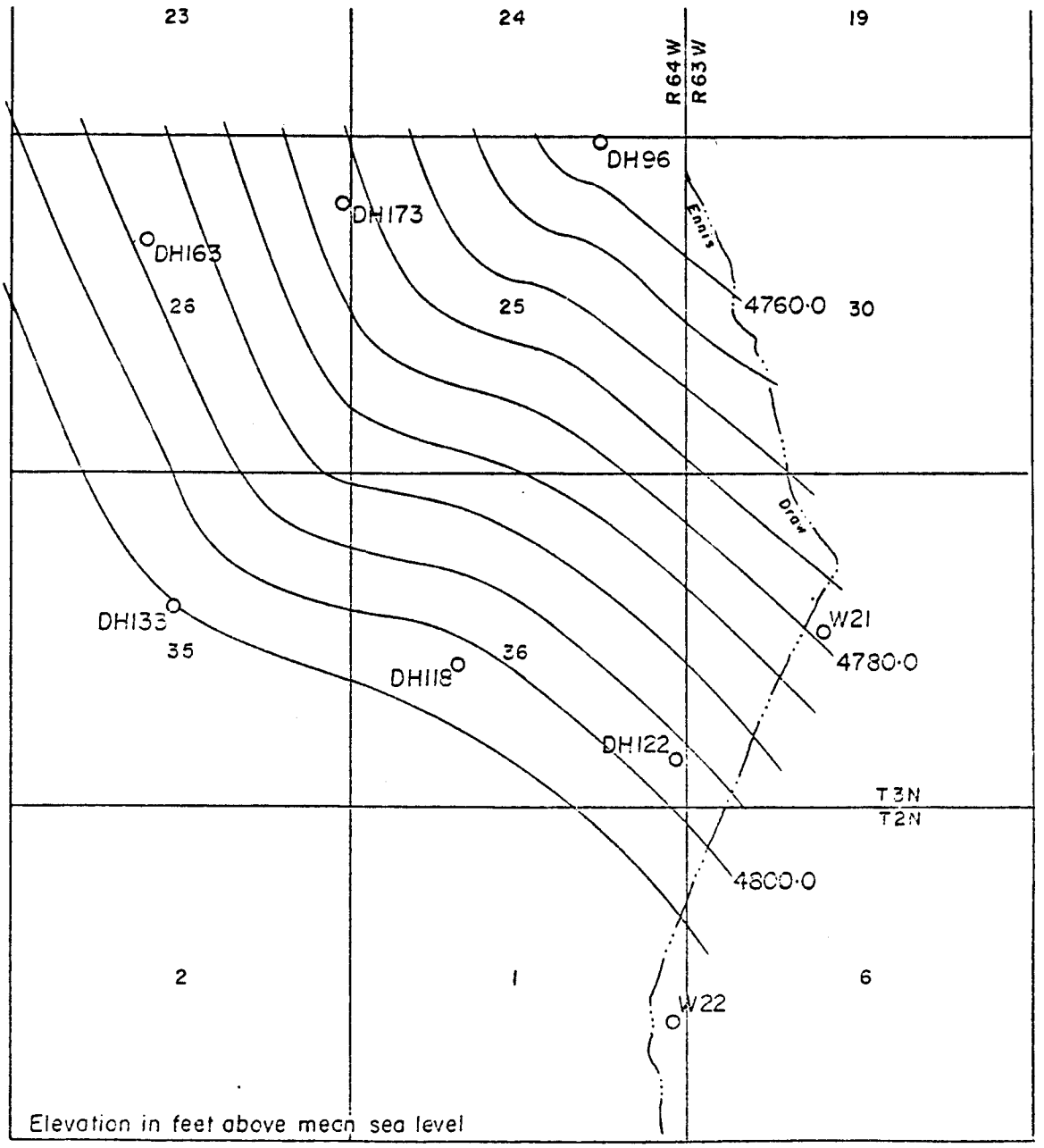

Figure 14. Piezometric surface of overburden aquifer in October 1978.

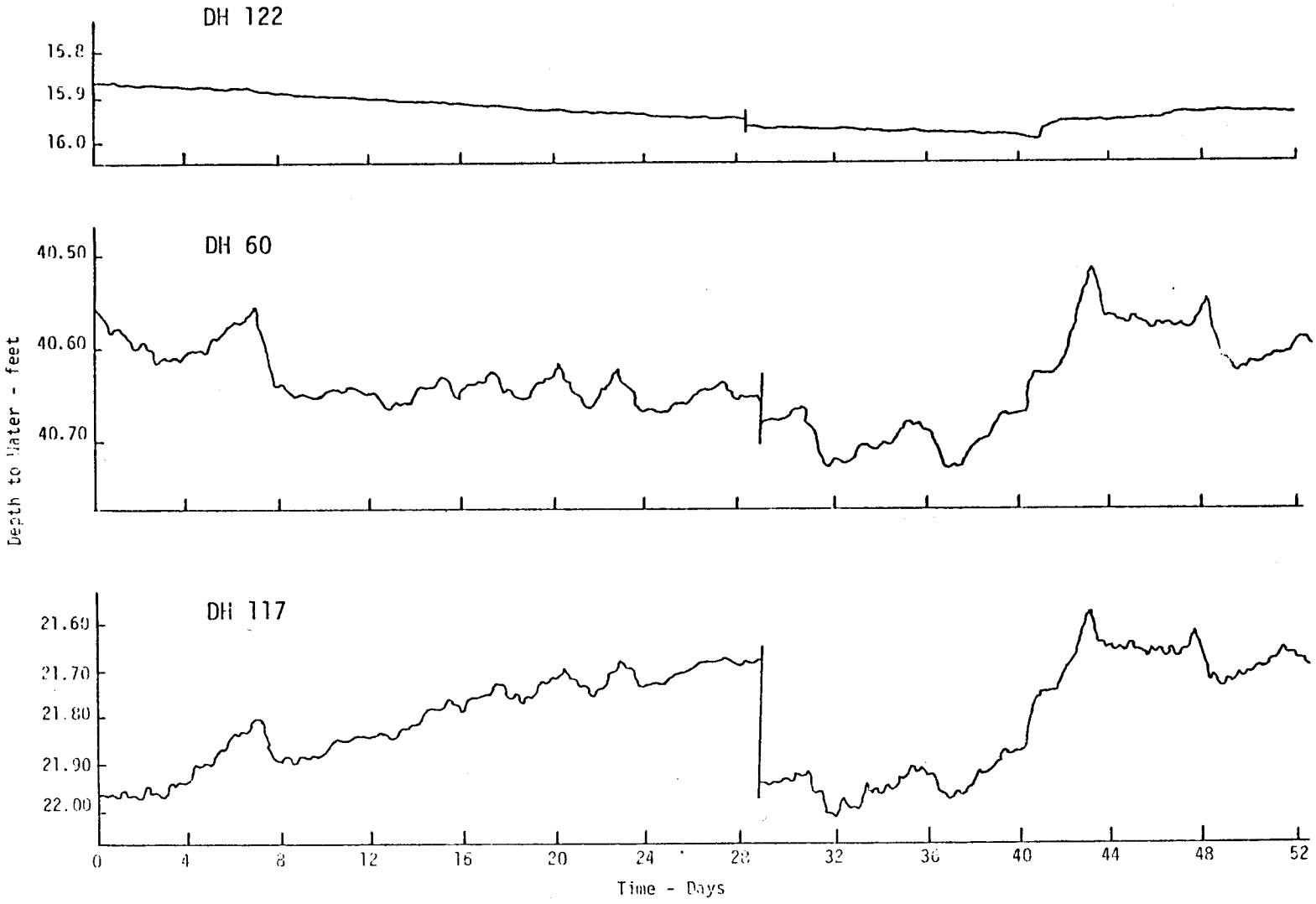

Figure 15. Water table fluctuation recordings.

tions. Other important questions such as mine inflow, the extent of disturbance of the piezometric surface, and recovery time also require knowledge of the hydraulic coefficients. The use of the hydraulic coefficients in such calculations is outlined subsequently. In the present subsection, the analysis of the aquifer test data from which the coefficients are derived is discussed.

Aquifer test data analysis involves the graphical transformation of raw field data into calculated values of the aquifer parameters (Stallman 1971). These aquifer parameters may be obtained from the observation of two relationships that occur during an aquifer test (Johnson, Inc. 1974): (1) The rate of drawdown with respect to time at any point within the cone of depression (time-drawdown graph); and (2) shape and position of the cone of depression with respect to distance at some time during the aquifer test (distance-drawdown graph).

The Theis, Jacob, recovery, and slug test methods are based on observation of the time-drawdown relationship, and the distance-drawdown test method is based on observations of the distance-drawdown relationship. All methods of aquifer test data analysis discussed herein are based on the following assumptions (Stallman 1971; Johnson, Inc. 1972).

1. The aquifer is homogeneous and isotropic.

2. The aquifer is of uniform thickness.

3. The pumping well completely penetrates the aquifer.

4. The natural ground water gradient is negligible.

5. Laminar flow conditions exist throughout the aquifer.

6. The aquifer is of infinite areal extent.

7. The well has been properly developed.

8. The well discharge is equal to the aquifer discharge.

The impact of boundary effects and well development on aquifer test data analysis is discussed later. Certain additional assumptions are invoked for particular types of analyses.

Theis analysis (adapted from McWhorter and Sunada 1977). — The Theis method of aquifer test analysis uses the following procedures:

1. On transparent log-log paper, plot drawdown vs r^2/t (r is the distance between the pumping and observation wells). This is known as the field curve.

2. From table 20 prepare a log-log plot of W(u) vs u. This is known as the type curve. Note: both the field and type curves must be plotted on the same size log-log paper.

3. Superimpose the field curve over the type curve, keeping both axes parallel. Adjust the position of the field curve until a best fit is made between the field data and the type curve.

4. Select any arbitrary "match" point and record its related coordinates W(u), u from the type curve and s, r^2/t from the field curve (fig. 16).

5. The values of W(u), u, s, r^2/t corresponding to the match point are inserted into the following formulas to determine the transmissivity and storage coefficient (or apparent specific yield):

$$T = \frac{QW(u)}{4\pi s} \qquad S = \frac{4Ttu}{r^2}$$

where:

Q	=	well discharge during the pump test
s	=	drawdown
S	=	storage coefficient or apparent specific yield
T	=	transmissivity
r	=	distance between pumping and observation wells
W(u),u	=	match point coordinates from the type curve.

Table 20. — Values of W(u) (From McWhorter and Sunada 1977)

N/u	$N\times10^{-15}$	$N\times10^{-14}$	$N\times10^{-13}$	$N\times10^{-12}$	$N\times10^{-11}$	$N\times10^{-10}$	$N\times10^{-9}$	$N\times10^{-8}$	$N\times10^{-7}$	$N\times10^{-6}$	$N\times10^{-5}$	$N\times10^{-4}$	$N\times10^{-3}$	$N\times10^{-2}$	$N\times10^{-1}$	N
1.0	33.9616	31.6590	29.3564	27.0538	24.7512	22.4486	20.1460	17.8435	15.5409	13.2383	10.9357	8.6332	6.3315	4.0379	1.8229	0.2194
1.5	33.5561	31.2535	28.9509	26.6483	24.3458	22.0432	19.7406	17.4380	15.1354	12.8328	10.5303	8.2278	5.9266	3.6374	1.4645	0.1000
2.0	33.2684	30.9658	28.6632	26.3607	24.0581	21.7555	19.4529	17.1503	14.8477	12.5451	10.2426	7.9402	5.6394	3.3547	1.2227	0.04890
2.5	33.0453	30.7427	28.4401	26.1375	23.8349	21.5323	19.2298	16.9272	14.6246	12.3220	10.0194	7.7172	5.4167	3.1365	1.0443	0.02491
3.0	32.8629	30.5604	28.2578	25.9552	23.6526	21.3500	19.0474	16.7449	14.4423	12.1397	9.8371	7.5348	5.2349	2.9591	0.9057	0.01305
3.5	32.7088	30.4062	28.1036	25.8010	23.4985	21.1959	18.8933	16.5907	14.2881	11.9855	9.6830	7.3807	5.0813	2.8099	0.7942	0.006970
4.0	32.5753	30.2727	27.9701	25.6675	23.3649	21.0623	18.7598	16.4572	14.1546	11.8520	9.5495	7.2472	4.9482	2.6813	0.7024	0.003779
4.5	32.4575	30.1549	27.8523	25.5497	23.2471	20.9446	18.6420	16.3394	14.0368	11.7342	9.4317	7.1295	4.8310	2.5684	0.6253	0.002073
5.0	32.3521	30.0495	27.7470	25.4444	23.1418	20.8392	18.5366	16.2340	13.9314	11.6280	9.3263	7.0242	4.7261	2.4679	0.5598	0.001148
5.5	32.2568	29.9542	27.6516	25.3491	23.0465	20.7439	18.4413	16.1387	13.8361	11.5330	9.2310	6.9289	4.6313	2.3775	0.5034	0.0006409
6.0	32.1698	29.8672	27.5646	25.2620	22.9595	20.6569	18.3543	16.0517	13.7491	11.4465	9.1440	6.8420	4.5448	2.2953	0.4544	0.0003601
6.5	32.0898	29.7872	27.4846	25.1820	22.8794	20.5768	18.2742	16.9717	13.6691	11.3665	9.0640	6.7620	4.4652	2.2201	0.4115	0.0002034
7.0	32.0156	29.7131	27.4105	25.1079	22.8053	20.5027	18.2001	15.8976	13.5950	11.2924	8.9899	6.6879	4.3916	2.1508	0.3738	0.0001155
7.5	31.9467	29.6441	27.3415	25.0389	22.7363	20.4337	18.1311	15.8280	13.5260	11.2234	8.9209	6.6190	4.3231	2.0867	0.3403	0.0000658
8.0	31.8821	29.5795	27.2769	24.9744	22.6718	20.3692	18.0666	15.7640	13.4614	11.1589	8.8563	6.5545	4.2591	2.0269	0.3106	0.0000376
8.5	31.8215	29.5189	27.2163	24.9137	22.6112	20.3086	18.0060	15.7034	13.4008	11.0982	8.7957	6.4939	4.1990	1.9711	0.2840	0.0000216
9.0	31.7643	29.4618	27.1592	24.8566	22.5540	20.2514	17.9488	15.6462	13.3437	11.0411	8.7386	6.4368	4.1423	1.9187	0.2602	0.0000124
9.5	31.7103	29.4077	27.1051	24.8025	22.4999	20.1973	17.8948	15.5922	13.2896	10.9870	8.6845	6.3828	4.0887	1.8695	0.2387	0.0000071

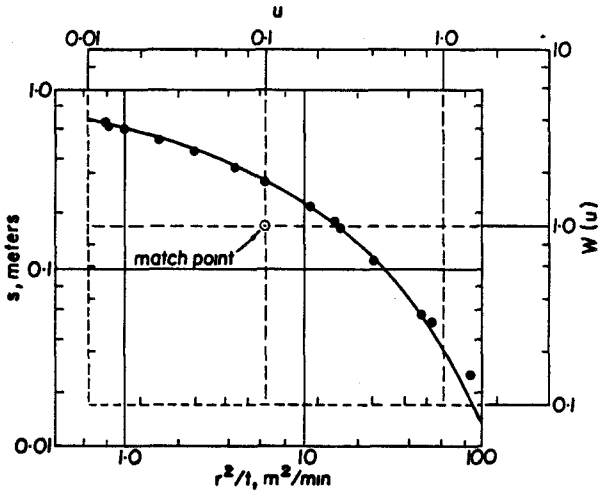

Figure 16. Matching the type curve with drawdown data.

Example (McWhorter and Sunada 1977)

Estimate the transmissivity and apparent specific yield of an aquifer from the following data.

r = 20 m Q = 1.872 m^3/min

s(meters)	0.025	0.050	0.055	0.110
r^2/t (m^2/min)	88.9	53.3	47.1	25.0
s	0.170	0.180	0.220	0.300	0.370
r^2/t	16.7	15.1	11.1	6.25	4.12
s	0.450	0.530	0.620	0.640	0.650
r^2/t	2.47	1.55	0.98	0.82	0.78

Following the procedures described previously, the data are plotted on log-log paper then superimposed on the type curve. Figure 16 illustrates the field curve superimposed on the type curve with a selected match point. The match point coordinates are:

$$W(u) = 1.0,\ u = 0.1,\ s = 0.183,\ r^2/t = 6.2.$$

From before,

$$T = \frac{QW(u)}{4\pi s} = \frac{(1.872)\ (1.0)}{4\pi(0.183)}$$

$$= 0.814\ m^2/min$$

$$S_{ya} = \frac{4Ttu}{r^2} = \frac{4(0.814)\ (0.1)}{6.2} = 0.053.$$

In addition to the assumptions listed prevously, this method assumes that the aquifer discharge is constant. In applications where the transmissivity is very low, the aquifer discharge to the well may not be constant, even for a constant pump discharge. This is because the pump derives a portion of its discharge from water standing in the well bore. Correction of the pump discharge, using measured drawdowns in the pumped well, may be necessary to determine an acceptably accurate value for Q in the above equations.

Jacob analysis (adapted from McWhorter and Sunada 1977). — The Jacob method is subject to the same restrictions as the Theis analysis. An additional restriction imposed on this method is that the test must be conducted for a sufficiently long time such that $u < 0.01$, where $u = r^2/4\alpha t$ and $\alpha = T/S$ for confined aquifers; $\alpha = T/S_{ya}$ for unconfined aquifers.

The Jacob method uses the following procedures.

1. Using semi-log paper, plot drawdown on the coordinate axis vs. time on the logarithmic axis (fig. 17). The plot will be a straight line if the test was conducted for a sufficiently long period.

2. From this plot, compute the change in drawdown over one log cycle.

3. The change in drawdown over one log cycle is inserted into the following equation along with the other field data to determine transmissivity.

$$T = 2.303Q/4\pi\Delta s$$

where:

Q = discharge

Δs = change in drawdown over one log cycle.

4. To determine the storage coefficient or apparent specific yield, extrapolate the straight line portion of the data plot to the horizontal axis (s=0). Determine the value of t_o where the straight line intersects the horizontal axis.

5. Insert the value of t_o along with the appropriate data into the following formula:

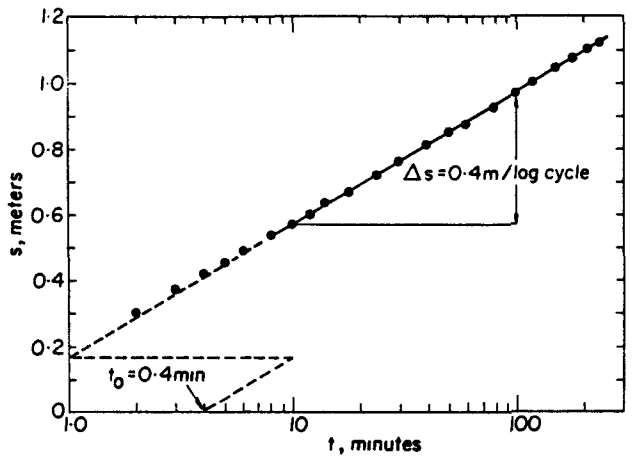

Figure 17. Example of the Jacob method for determining aquifer properties.

$$S = 2.246Tt_o/r^2$$

where:

- r = radial distance between the observation well and the pumping well
- T = transmissivity determined previously
- t_o = time where drawdown = 0
- S = storage coefficient (confined) or apparent specific yield (unconfined).

Example (McWhorter and Sunada 1977)

Given the following data, determine the transmissivity and the storage coefficient.

$r = 61$ m $\qquad Q = 1.844\ m^3/min$

t(min)	1	2	3	4	5
s(meters)	0.200	0.300	0.370	0.415	0.450
t	6	8	10	12	14	18
s	0.485	0.530	0.570	0.600	0.635	0.670
t	24	30	40	50	60	80
s	0.720	0.760	0.810	0.850	0.875	0.925
t	100	120	150	180	210	240
s	0.965	1.000	1.045	1.070	1.100	1.120

The data are plotted as shown in fig. 17. From the foregoing,

$$T = 2.303Q/4\pi\Delta s$$
$$= [2.303(1.894)]/[4\pi(0.4)]$$
$$= 0.868\ m^2/min.$$

Extrapolation of the straight line yields $t_o = 0.4$ minutes at $s = 0$.

$$S = 2.246Tt_o/r^2$$
$$= [2(2.246)(0.868)(0.4)]/(61)^2$$
$$= 2.0\times10^{-4}.$$

Before we can accept these results, we must be sure that $u \leq 0.01$. For a confined aquifer $u = Sr^2/4Tt$. The minimum test duration time for which $u \leq 0.01$ is given by $t = r^2S/4Tu = [(61)^2(2.0\times10^{-4})]/[4(0.868)(0.01)] = 21$ min. Therefore, only data points for $t>21$ min should be used in the determination of the straight line. Using data for which $u<0.01$ causes a deviation of about 6 percent from the Theis analysis results.

Because of the restriction that u must be less than 0.01 for the Jacob method of analysis to be applicable, this procedure is usually used to analyze drawdown data collected on the pumped well itself. Thus, it is often used for the analysis of data from the drawdown/specific capacity type test that was discussed previously. Again, well-bore storage is likely to be a significant source of error in very tight aquifers, unless the pump discharge is appropriately corrected.

Specific capacity analysis (adapted from Walton 1970; USDI 1977). — No attempt is made in this method to obtain values for the storage coefficient or apparent specific yield. Rather the procedure is to estimate an appropriate value for the storage coefficient based upon whether the aquifer is confined or unconfined, and from experience in the area (if any). A storage coefficient of 10^{-4} and an apparent specific yield of 0.1 will suffice, if no information is available. Transmissivity T is plotted against corresponding values for specific capacity Q/s on log-log paper from the equation

$$Q/s = 4T/[\ln(\frac{4\pi T}{Sr_w^2} - 0.5772)],$$

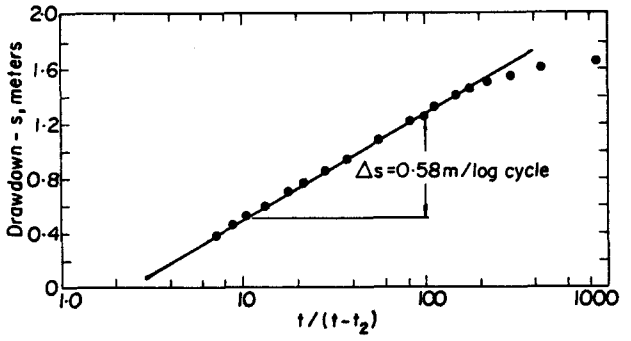

Figure 18. Water levels in a recovery test.

using the estimated value for S and a number of arbitrary values of T. The radius of the well is r_w. The value of time used in the computation is the pumping time at which the drawdown *s* was measured. The value of transmissivity that corresponds to the observed specific capacity is read from the graph.

The USDI (1977) reference presents a table from which the transmissivity can be estimated from knowledge of only specific capacity. The value so obtained is only a rough estimate.

Recovery test analysis (adapted from McWhorter and Sunada 1977). — The recovery test is conducted immediately after the pump is shut off at the end of the pump test. An additional restriction imposed on this method is that the value of u must be less than 0.01, where $u = r^2/4\alpha t$ as stated previously.

The recovery test uses the following procedures:

1. Record the total length of pumping time when the pump is shut off (t_p).

2. Using semi-log paper, plot drawdown on the coordinate axis vs $t/t\text{-}t_p$ on the logarithmic axis (fig. 18). Note, t is the time since pumping began, t_p is the total pumping time ($t>t_p$).

3. From this plot, compute the change in drawdown over one log cycle.

4. Insert the change in drawdown over one log cycle into the following equation to determine transmissivity:

$$T = 2.303Q/4\pi\Delta s$$

5. To determine the storage coefficient or apparent specific yields, extrapolate the straight line portion of the data plot to the horizontal axis. Determine t_o at the intersection of the straight line and horizontal axis.

6. Insert the value of t_o into the following formula:

$$S = 2.246Tt_o/r^2$$

where:

r	=	distance between observation and pumping wells
T	=	transmissivity
t_o	=	time when drawndown = 0
S	=	apparent specific yield or storage coefficient.

Example (McWhorter and Sunada 1977)

Given the following data determine the transmissivity and the storage coefficient.

Q = 1.79 m^3/min, r = 4.6 m, pumping time t_p = 443 min.

s(meters)	1.640	1.595	1.535	1.490	1.445
t(min)	443.5	444	444.5	445	445.5
s 1.400	1.305	1.235	1.200	1.060	0.930
t 446	447	447.5	448.5	451	455
s 0.845	0.755	0.700	0.590	0.521	0.451
t 459	464	469	479	489	499
s 0.384					
t 514					

Calculate $t/t\text{-}t_p$ for each of the above data points and plot as shown in fig. 18. From the foregoing,

$$T = 2.303Q/4\pi\Delta s$$
$$= [2.303(1.79)2/[4\pi(0.58)]$$
$$= 0.566\ m^2/min.$$

Extrapolation of the straight line yields $t/t\text{-}t_p$ = 2.2 min. From before,

$$S = 2.246Tt_o/r^2$$
$$= [2.246(0.566)(2.2)]/(4.6)^2 = 0.13.$$

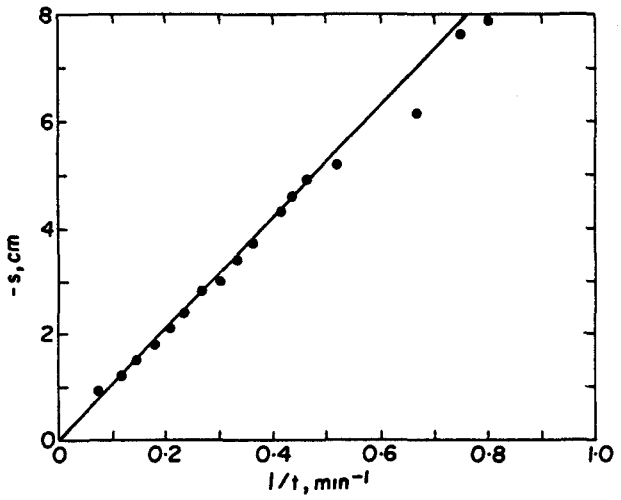

Figure 19. Response to a slug injection.

Again the pump discharge may require correction to determine an appropriate value for Q in tight aquifers.

Slug test analysis. — Three methods of slug test analysis as proposed by Papadopulos and others (1973), Cooper and others (1967), and by Hvorslov (1951), are treated in this section.

The method proposed by Papadopulos and others (1973) is as follows (adapted from McWhorter and Sunada 1977).

1. On rectangular coordinate paper plot the residual buildup of the water level due to a slug injection vs inverse time (fig. 19).

2. Select any arbitrary point on the curve of $-s$ vs $1/t$. The coordinate of the point ($-s$, $1/t$) is inserted into the following equation to determine T.

$$T = V/4\pi\, t(-s)$$

where:

v = slug volume

t = time

s = buildup due to the slug injection.

Example (McWhorter and Sunada 1977)

Determine the transmissivity from the following data.

$V = 0.148\ m^3$

-s(cm)	7.9	7.6	6.1	5.2	4.9
$1/t(min^{-1})$	0.800	0.750	0.667	0.521	0.461
-s 4.6	4.3	3.7	3.4	3.0	2.8
1/t 0.435	0.413	0.361	0.333	0.300	0.265
-s 2.4	2.1	1.8	1.5	1.2	0.9
1/t 0.231	0.212	0.183	0.146	0.117	0.077

These data are plotted on coordinate paper as shown in fig. 19. A point on the line is fig. 19 is selected arbitrarily; in this case the coordinates of the point are $-s = 6.3$ cm, $1/t = 0.6$. From the foregoing,

$$T = V/4\pi\, t(-s)$$

$$= 0.148/[4\pi(0.6)(6.3/100)$$

$$= 0.11\ m^2/min.$$

Note this method does not provide a reliable determination of the storage coefficient (Cooper and others 1967) and does not account for changes in well-bore storage.

The method of analysis as proposed by Cooper and others (1967) is as follows.

1. On semi-log paper plot H/H_o on the arithmetic axis vs time on logarithmic axis (field curve) where

H_o = the buildup of the water level at time t=0 due to a slug injection,

H = the residual water table buildup some time t after injection.

2. From table 21 prepare a semi-log plot of H/H_o vs Tt/r^2 (type curve), where r = radius of well casing, T = transmissivity, and t = time.

3. Superimpose the field curve on the type curve keeping the horizontal axes coincident. Adjust the position of the field curve so as to achieve the best fit of data to the type curves (see fig. 20).

4. Select an arbitrary "match" point and read the corresponding values of t (from the field curve) and Tt/r^2 (from the type curve).

5. Insert the corresponding match point values for t and Tt/r^2 into the following equation and solve for T.

Table 21. — Values of H/H_0 for a Well of Finite Diameter (from Cooper and others 1967).

Tt/r_c^2	H/H_0				
	$\alpha = 10^{-1}$	$\alpha = 10^{-2}$	$\alpha = 10^{-3}$	$\alpha = 10^{-4}$	$\alpha = 10^{-5}$
1.00×10^{-3}	0.9771	0.9920	0.9969	0.9985	0.9992
2.15×10^{-3}	0.9658	0.9876	0.9949	0.9974	0.9985
4.64×10^{-3}	0.9490	0.9807	0.9914	0.9954	0.9970
1.00×10^{-2}	0.9238	0.9693	0.9853	0.9915	0.9942
2.15×10^{-2}	0.8860	0.9505	0.9744	0.9841	0.9888
4.64×10^{-2}	0.8293	0.9187	0.9545	0.9701	0.9781
1.00×10^{-1}	0.7460	0.8655	0.9183	0.9434	0.9572
2.15×10^{-1}	0.6289	0.7782	0.8538	0.8935	0.9167
4.64×10^{-1}	0.4782	0.6436	0.7436	0.8031	0.8410
1.00×10^{0}	0.3117	0.4598	0.5729	0.6520	0.7080
2.15×10^{0}	0.1665	0.2597	0.3543	0.4364	0.5038
4.64×10^{0}	0.07415	0.1086	0.1554	0.2082	0.2620
7.00×10^{0}	0.04625	0.06204	0.08519	0.1161	0.1521
1.00×10^{1}	0.03065	0.03780	0.04821	0.06355	0.08378
1.40×10^{1}	0.02092	0.02414	0.02844	0.03492	0.04426
2.15×10^{1}	0.01297	0.01414	0.01545	0.01723	0.01999
3.00×10^{1}	0.009070	0.009615	0.01016	0.01083	0.01169
4.64×10^{1}	0.005711	0.005919	0.006111	0.006319	0.006554
7.00×10^{1}	0.003722	0.003809	0.003884	0.003962	0.004046
1.00×10^{2}	0.002577	0.002618	0.002653	0.002688	0.002725
2.15×10^{2}	0.001179	0.001187	0.001194	0.001201	0.001208

Table 22. — Rise of water level in Dawsonville well after simultaneous withdrawal of weighted float (r-7.6 cm) (from Cooper and others 1967).

t (sec)	$1/t$	Head (m)	H (m)	H/Ho
-1		0.896		
0		0.336	0.560	1.000
3	0.333	0.439	0.457	0.816
6	0.167	0.504	0.392	0.700
9	0.111	0.551	0.345	0.616
12	0.0833	0.588	0.308	0.550
15	0.0667	0.616	0.280	0.500
18	0.0556	0.644	0.252	0.450
21	0.0476	0.672	0.224	0.400
24	0.0417	0.691	0.205	0.366
27	0.0370	0.709	0.187	0.334
30	0.0333	0.728	0.168	0.300
33	0.0303	0.747	0.149	0.266
36	0.0278	0.756	0.140	0.250
39	0.0256	0.765	0.131	0.234
42	0.0238	0.784	0.112	0.200
45	0.0222	0.788	0.108	0.193
48	0.0208	0.803	0.093	0.166
51	0.0196	0.807	0.089	0.159
54	0.0185	0.814	0.082	0.146
57	0.0175	0.821	0.075	0.134
60	0.0167	0.825	0.071	0.127
63	0.0159	0.831	0.065	0.116

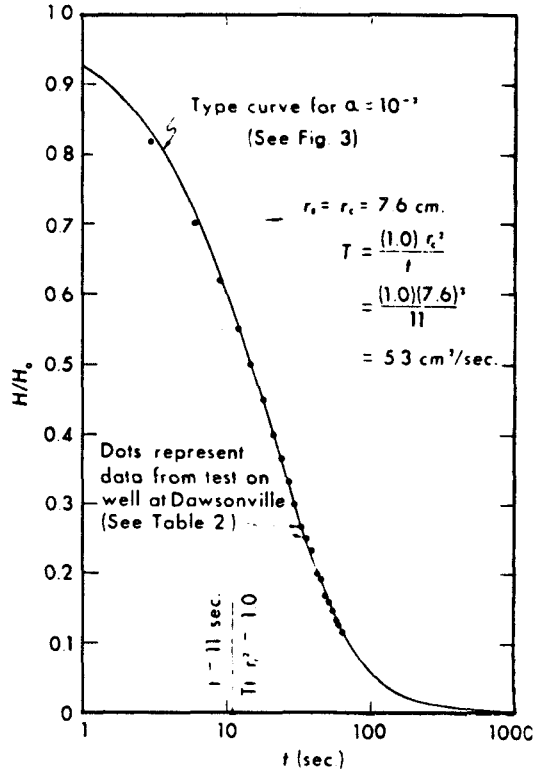

Figure 20. Plot of data from test at Dawsonville, Georgia, superposed on type curve (from Cooper and others 1967).

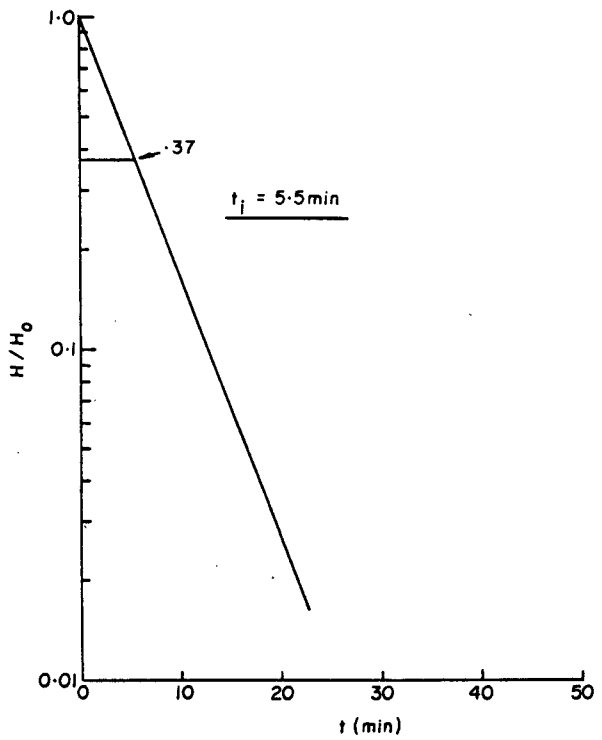

Figure 21. Time lag plot.

$$T = [(Tt/r^2)r^2]/t$$

where:

T = transmissivity

r = well casing radius

t = time coordinate on the field curve of the match point

Tt/r^2 = the value of Tt/r^2 on the type curve corresponding to the match point.

Example (Cooper and others 1967)

Given the test data listed in table 22, determine the transmissivity. A plot of H/H_o vs t superimposed on the type curve is shown in fig. 20. The coordinates of the match point are determined from fig. 20 to be $Tt/r^2 = 1.0$, t = 11 sec. From the foregoing,

$$T = [(Tt/r^2)r^2]/t = [1(7.6)^2]/11$$

$$= 5.3\ cm^2/sec = 5.3x10^{-4}\ m^2/min.$$

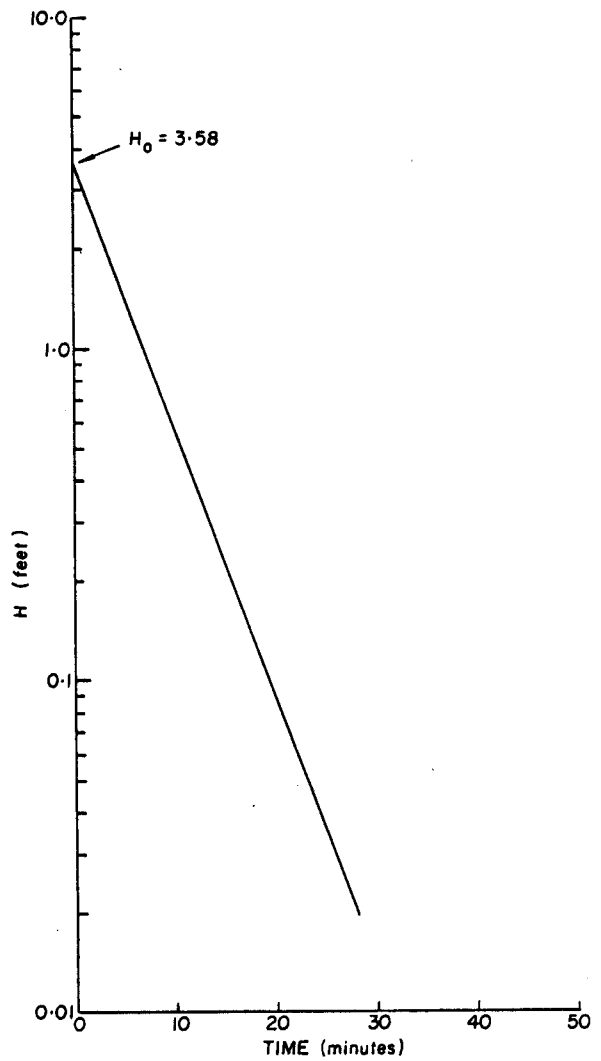

Figure 22. Plot the buildup H vs time.

Note: this method does not provide a reliable determination of the storage coefficient, S (Cooper and others 1967).

Slug test as proposed by Hvorslev (1951) is as follows:

1. On semi-log paper plot H/H_o on the logarithmic axis vs time on the arithmetic axis as shown in fig. 21. H_o, the buildup of water level at time zero, is best determined as follows. Plot the buildup H vs time on semi-log paper as illustrated in fig. 22. Extrapolate the straight line position of the plot to time t=0 to determine H_o, the initial buildup due to a slug injection at time zero. Once H_o is determined, values of H/H_o can be calculated and plotted as in fig. 21.

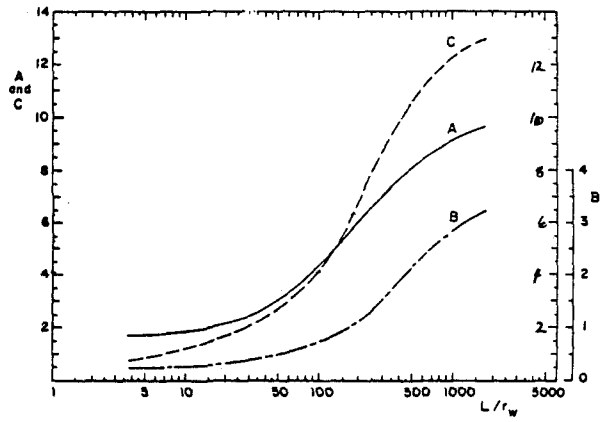

Figure 23. Curves relating coefficients A, B, and C to L/r_w.

2. From the semi-log plot of H/H_o vs t, determine the coordinates of t_L, the time lag, corresponding to $H/H_o = 0.37$ (fig. 21).

3. Determine the coefficient C (fig. 23) corresponding to value of L/r_w derived from the well construction data where L = screen length, r_w = well radius or radius of well plus the gravel pack.

4. Insert the coefficient C into the following equation to determine $\ln R_e/r_w$.

$$\ln R_e/r_w = \left[\frac{1.1}{\ln H_w/r_w} + \frac{C}{L/r_w} \right]^{-1} \text{ (Bouwer and Rice 1976)}$$

where R_e = the effective radius of buildup, r_w = well radius or radius of well and aquifer pack (if known), L = screen length, and H_w = distance between the bottom of the well and the static ground water surface (see fig. 24 for the relation between H_w, r_w, L).

5. Insert the values of time lag (t_L), $\ln R_e/r_w$, and the well casing diameter into the following equation to determine K (for completely penetrating well).

$$K = \frac{d^2 \ln R_e/r_w}{8Lt} \text{ (Hvorslev 1951)}$$

where:

d = well casing diameter

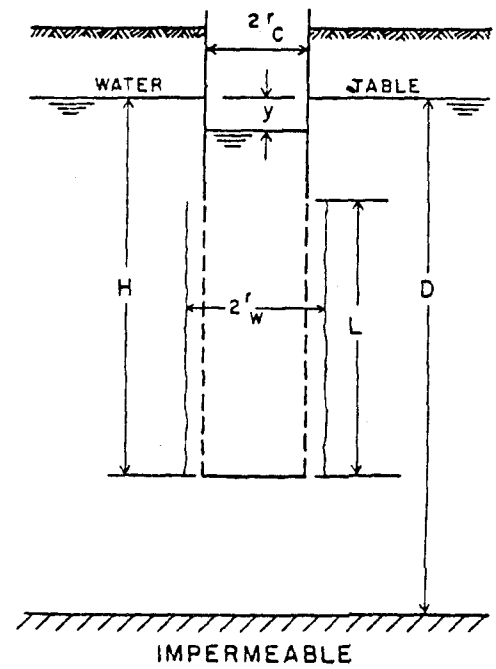

Figure 24. Geometry and symbols of a partially penetrating, partially perforated well in unconfined aquifer with gravel pack or developed zone around perforated section.

$\ln R_e/r_w$ = described in steps 3 and 4

L = screen length

t = time

K = hydraulic conductivity.

Example

Given the following well construction and slug test data, determine the hydraulic conductivity.

d = 0.42 ft, L = 20 ft, r_w = 0.21 ft,

H_w = 94.08 ft.

H(feet)	3.27	2.94	2.44	2.01	1.68	1.39
t(min)	0.5	1.0	2.0	3.0	4.0	5.0
H 1.24	0.96	0.81	0.68	0.56	0.38	0.26
t 6.0	7.0	8.0	9.0	10.0	12.0	14.0
H 0.18	0.12	0.08	0.05	0.03	0.02	0.01
t 16.0	18.0	20.0	25.0	26.0	30.0	40.0

A plot of H vs t is shown in fig. 22. H_o is determined by extrapolating the straight portion of this plot to time t=0. From fig. 22 H_o = 3.58 ft.

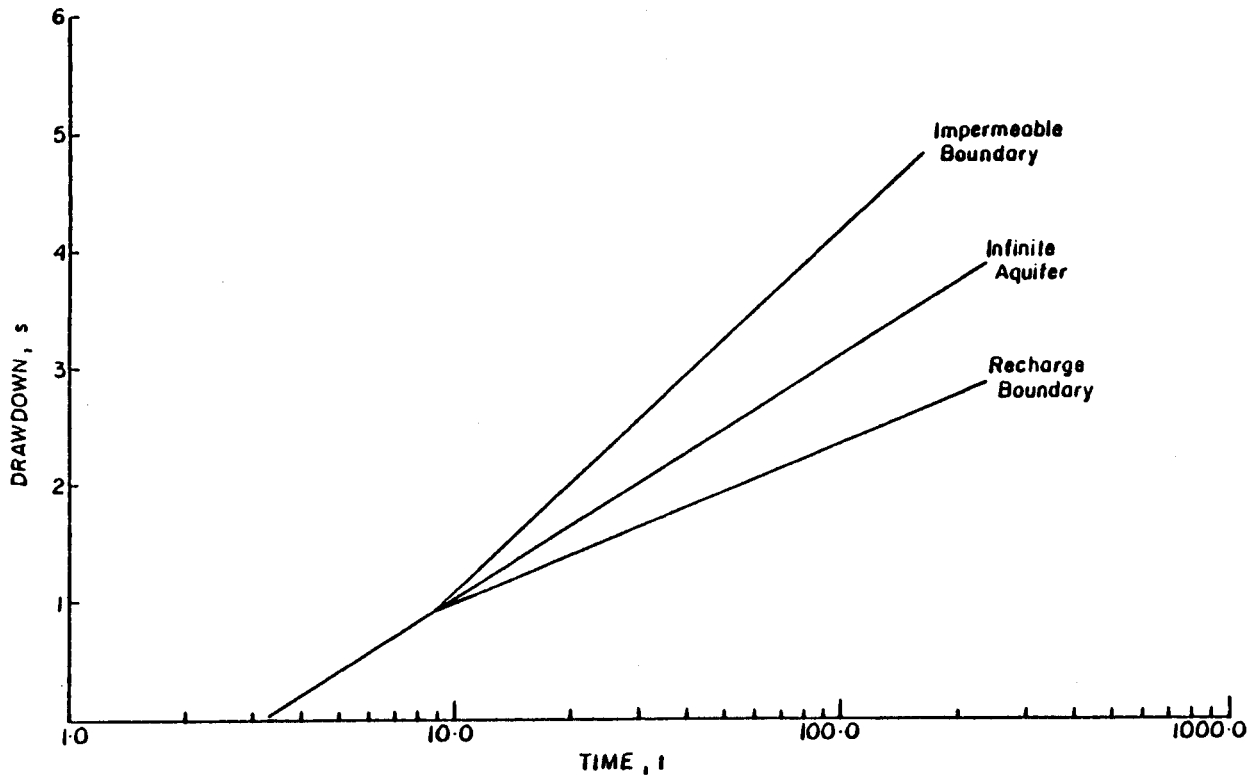

Figure 25. Effects of boundaries on drawdown vs time.

The time lag t_L is 5.5 min as shown in fig. 21. From fig. 22 the value of C corresponding to $L/r_w = 95.2$ is $\simeq 4.25$. From before

$$\ln R_e/r_w = \left[\frac{1.1}{\ln H_w/r_w} + \frac{C}{L/r_w}\right]^{-1}$$

$$= \left[\frac{1.1}{\ln 94.08/0.21} + \frac{4.25}{20/0.21}\right]^{-1}$$

$$= 4.45.$$

Therefore, the hydraulic conductivity is

$$K = [d^2 \ln R_e/r_w]/8Lt_L$$

$$= [(0.42)^2 (4.45)]/[8(20)(5.25)]$$

$$= 9.35 \text{ ft/min} = 1.35 \text{ ft/day}.$$

Note: T = K·b where T = transmissivity, K = hydraulic conductivity, and b = aquifer thickness. If the aquifer thickness is the same as the screen length (L=20 ft), then the transmissivity is

$$T = K \cdot b = (1.35)(20) = 26.9 \text{ ft}^2/\text{day}.$$

EFFECTS OF BOUNDARY CONDITIONS AND WELL CONSTRUCTION ON AQUIFER TEST RESULTS

Aquifer boundary conditions are rarely known at the field site prior to conducting the aquifer test. Any boundary effects must be recognized by the field investigator in order to avoid serious errors in the calculation of the aquifer parameters. Figures 25 and 26 illustrate the effect of recharge and impervious boundary conditions on the time-drawdown and distance-drawdown curves, respectively. The effects of these boundary conditions are summarized in table 23 (Johnson, Inc. 1974, p. 132). Recharge/boundary effects may be caused by nearby rivers or lakes, vertical infiltration from overlying zones, and increases in aquifer thickness or hydraulic conductivity. Impermeable boundary effects may be caused by geologic fault zones, decrease in aquifer thickness (pinch out), decrease in hydraulic conductivity, and impermeable bed-

Table 23. — Comparisons of recharge and boundary effects on semilog diagrams

Recharge effect during pumping test	
Time-drawdown graph	**Distance-drawdown graph**
1. Slope of graph becomes flatter. If transmissibility is calculated on the basis of the flatter slope it will be higher than the true value.	1. Slope of straight line remains almost unchanged. Aquifer transmissibility calculated from the graph is usually close to its true value.
2. Extending straight line of flatter slope results in an erroneous value of t_o making it too low. A calculation using this figure gives a value for the storage coefficient that is smaller than the correct one.	2. Straight line is displaced upward. Extension to zero drawdown gives a value of r_o which when used to compute storage coefficient results in a value higher than the correct one.
Boundary effect during pumping test	
Time-drawdown graph	**Distance-drawdown graph**
1. Slope of graph becomes steeper. If transmissibility is calculated on the basis of the steeper slope it will be lower than the true value.	1. Slope of straight line remains almost unchanged. Aquifer transmissibility calculated from the graph is usually close to its true value.
2. Extending line of steeper slope results in erroneous value of t_o which is too high. A calculation using this figure gives a storage coefficient that is larger than its correct value.	2. Straight line is displaced downward. Extension to zero drawdown gives erroneous value of r_o which makes calculated value of storage coefficient smaller than the correct one.

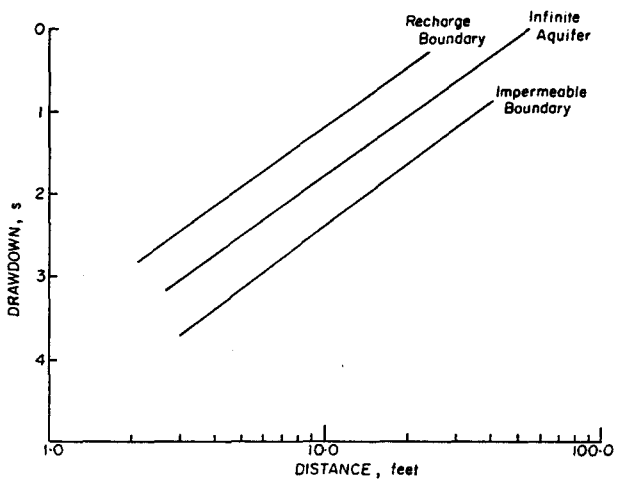

Figure 26. Effects of boundaries on drawdown vs distance.

rock. If boundary effects are apparent during the aquifer test, then the aquifer parameters must be determined from test data collected prior to the time the boundary effects are observable in the data.

Proper well construction is critically important if the aquifer test is to provide data representative of the aquifer. The following well design and construction factors contribute to excessive drawdown during the aquifer test (Johnson, Inc. 1974):

1. Well screens with insufficient open area.
2. Poor distribution of well screens.
3. Insufficient well screen length.
4. Inadequate well development.
5. Improper placement of the well screen.

Any one of these factors can significantly reduce the calculated values of transmissivity or hydraulic conductivity.

Example

Once the hydraulic coefficients are known, they can be used to estimate mine inflow and the extent to which the piezometric surface is disturbed. There are a variety of ways in which this can be accomplished that range from simple idealizations to application of sophisticated

Table 24. — Example of lateral inflow computation

Time	q	Q_1	Q_2	Q_3	Q_4	Q_5	Q_{total}
Years	$ft^3/ft\text{-}d$	ft^3/d					
.25	2.8	4200	–	–	–	–	4200
.50	2.0	3000	4200	–	–	–	7200
.75	1.6	2400	3000	4200	–	–	9600
1.00	1.4	2100	2400	3000	4200	–	11700
1.25	1.3	1950	2100	2400	3000	4200	13650
1.50	1.2	1800	1950	2100	2400	3000	11250
1.75	1.1	1650	1800	1950	2100	2400	9900
2.00	1.0	1500	1650	1800	1950	2100	9000
2.25	0.95	1425	1500	1650	1800	1950	8325

models. The following is an example when the relatively simple idealization of one-dimensional inflow to a pit is applicable.

The inflow to a mine pit that cuts through an aquifer is given by

$$q = 2(12t/S_{ya}Th_o^2)^{-1/2} + q_o \quad ,$$

where:

- q = inflow discharge per unit of pit length (both sides)
- q_o = natural flow in undisturbed aquifer per unit of pit length
- t = time since inflow began
- S_{ya} = apparent specific yield
- T = transmissivity
- h_o = initial saturated thickness of aquifer.

This equation is a special case of a more general result given by Bear (1972). The discharge predicted by this equation is the inflow discharge per unit of open pit. A mining plan is required to convert these values into actual discharges to be expected at any time. For example, suppose $S_{ya} = 0.05$, $T = 10\ ft^2/day$, $h_o = 65$ ft, $q_o = 0$, and the mining plan calls for 1,500 ft of pit to be open every 3 months until a total pit length of 7,500 ft is achieved and the pit length is constant thereafter. Pit inflow as a function of time is computed by calculating the inflow from each segment of the pit, marking time for each segment from the time that the segment was opened. The contributions from each segment at any time after the opening of the first segment are calculated by adding the contributions from each individual section. The computations are summarized in table 24. Q in this table is the discharge per unit of pit length (q) multiplied by the length of the open segment. The subscripts refer to the first, second, etc., segments of the pit. Q_{total} represents the inflow from the total length of open pit at any time. The maximum inflow discharge is 13,650 ft^3/day or about 70 gal/min in this example.

The theory leading to the above equation also provides a means for estimating the distance from the pit to points where the piezometric surface remains essentially undisturbed. The equation is

$$L = (3Tt/S_{ya})^{1/2}$$

where L is the distance from the pit to the point where the drawdown of the piezometric surface is zero. Using the same numbers for T and S_{ya} as above, this equation predicts that inflow to the pit will cause the piezometric surface to be depressed to a distance of about 0.5 miles from the pit after 20 years.

The above equations and computations are presented to demonstrate one possible use of the hydraulic coefficients. Other uses exist and, certainly, there are many other ways to estimate pit inflow during mining. The above constitutes an example, not a recommendation.

Effect of Abandoned Mine on Piezometric Surface. — Another aspect that is sometimes im-

portant in premine planning and decision making is the extent to which the original piezometric surface will remain disturbed after the mine is abandoned. McWhorter and Rowe (1976) and Hamilton and Wilson (1977) provide approaches to this problem. McWhorter and Rowe (1976) idealize the abandoned mine area as a circle of radius R and area equal to the actual mined area. Their equation for the distance to which the postmining piezometric head is different from the premining value by an arbitrary amount is

$$r = \frac{R}{\sqrt{c}} \left(\left| \frac{K_o - K_i}{K_o + K_i} \right| \right)^{1/2}$$

where:

- r = distance from the center of the mined area to points where postmining piezometric head is different from the premining value by an arbitrarily small fraction equal to c.
- R = equivalent radius of the mined area.
- c = ratio of the difference between premining and postmining values of piezometric head to the premining value.
- K_o = hydraulic conductivity outside the mined area.
- K_i = hydraulic conductivity inside the mined area.

Use of the above equation requires that both K_o and K_i are known. Prior to mining, K_i is not known. Nevertheless, the maximum distance can be estimated by putting $K_i=0$ or $K_i=\infty$ for which

$$r = R\sqrt{c}$$

For example, the distance to which the postmining piezometric head differs from the premining value by 10 percent if $r = R/\sqrt{0.10} = 3R$.

The analysis also permits one to establish other limiting values that may be of interest. For example, it is shown that the maximum width of the downstream plume of ground water of modified quality is 4R. Also, postmining flow through the mined area can be no greater than twice the premining flow through the same area, regardless of how permeable the spoils are compared to the undisturbed aquifer.

The conditions under which the foregoing analyses are made are highly idealized relative to the conditions that can be expected to prevail in the field. The results should be expected to yield only order-or-magnitude estimates of the extent to which the long-term, postmining ground water flow differs from the premining condition. Hamilton and Wilson (1977) provide results similar to those discussed above for a variety of mine geometries.