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July 1986

Solid Waste

EPA

Criteria for Identifying Areas of Vulnerable Hydrogeology Under the Resource Conservation and Recovery Act

Appendix B

Ground-Water Flow Net/Flow Line Construction and Analysis

Interim Final

GUIDANCE CRITERIA FOR IDENTIFYING AREAS OF VULNERABLE HYDROGEOLOGY

APPENDIX B

GROUND-WATER FLOW NET/FLOW LINE CONSTRUCTION ANALYSIS

Office of Solid Waste
Waste Management Division
U.S. Environmental Protection Agency
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DISCLAIMER

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ABSTRACT

This Technical Resource Document (TRD) is an appendix to the Guidance Criteria for Identifying Areas of Vulnerable Hydrogeology, and discusses the procedures necessary to construct ground-water flow nets. It was developed to assist EPA permit writers and permit applicants in evaluating the suitability of locations selected for hazardous waste disposal facilities. The focus of this manual is on the construction of vertical flow nets.

The document discusses the step-by-step construction of flow nets and is designed for persons with a limited background in hydrology. The manual is divided into five sections. Section 1 is an introduction which discusses the background of location guidance development and presents important definitions. Ground-water flow theory is descussed in Section 2. Graphical construction of flow nets is discussed in Sections 3 and 4 through the use of several practical examples. Section 5 discusses mathematical techniques used to construct flow nets.

Given the complexity of geohydrologic systems, the reader is cautioned that the proper development of a flow net is more complex than it may first appear. The reference list at the end of the manual should be used as an aid to better understanding flow nets and their construction.

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SECTION 1

INTRODUCTION

BACKGROUND

The EPA Office of Solid Waste is issuing a series of guidance documents designed to encourage safe and proper siting of hazardous waste management facilities subject to regulation under RCRA. This document on flow net construction and analysis is an appendix to the Guidance Criteria for Identifying Areas of Vulnerable Hydrogeology. The scope of this program is introduced below.

Under Section 202 of the Hazardous and Solid Waste Amendments of 1984 (Minimum Technology Requirements), the Environmentatl Protection Agency (EPA) is required to develop regulations that account for improvements in land disposal system technology and address the location of hazardous waste management facilities. With regard to facility location, the regulations must specify criteria for the acceptable location of new and existing treatment, storage, or disposal facilities, as necessary to protect human health and the environment. Further, EPA is required to publish guidance criteria identifying areas of vulnerable hydrogeology within 18 months after the enactment of the Amendments.

To address these requirements, the U.S. EPA Office of Solid Waste (OSW) is developing guidance manuals to assist permit writers and permit applicants in assessing the acceptability of physical locations for hazardous waste treatment, storage, and disposal facilities. EPA has developed RCRA site selection criteria on the basis of ground-water vulnerability, as defined by the estimated time of travel (TOT) of ground water at the site in question. For all land disposal facilities and for land-based storage facilities, current policy defines ground water to be vulnerable if the calculated TOT along a 100 ft flow path (TOT_{100}) is less than on the order of 100 years.

For land-based storage facilities, current policy establishes ground water as vulnerable if TOT_{100} is estimated to be less than the time necessary to detect a release and implement corrective action.

This report, on the use of flow nets for determining ground-water flow direction and time of travel (TOT), documents analytical procedures that are essential tools in assessing ground-water vulnerability. If sufficient hydrologic data are available, a flow net can be constructed to determine the flow path offering the least resistance to ground-water flow and, thus, highest flow velocity; TOT can then be calculated along that path. This use of flow nets provides a conservative approach to assessing ground-water vulnerability beneath a hazardous waste management facility.

This Technical Resource Document (TRD) provides RCRA permit applicants and permit writers with guidelines for constructing vertical ground-water flow nets as a means of estimating TOT; thus, the construction of horizontal flow nets is not discussed to a large extent in this manual. Introductory examples presented in Section 3 assume horizontal flow conditions to illustrate flow net construction procedures and concepts. Practical examples that follow assume more realistic ground-water conditions (e.g., vertical gradients, heterogeneity, anisotropy) and illustrate the usefulness of flow nets under these circumstances. Flow nets can be constructed using either graphical or mathematical techniques. Graphical techniques are the simplest and most commonly used and receive primary emphasis.

The use of flow nets has been applied in other areas of geotechnical engineering and is an established procedure for asssessing seepage through earth fill dams. For application to subsurface conditions at RCRA facilities, the concepts are the same but the data needs are quite different. These special considerations are explained in forthcoming sections of this document.

ORGANIZATION OF DOCUMENT

The manual is divided into five sections. The remainder of Section 1 presents technical definitions that should be understood before proceeding through the manual. In development of this guidance manual, it was assumed that the user has a limited knowledge of the basic concepts of geology and hydrology. Section 2 provides a general introduction to flow net theory as a means of understanding flow net construction concepts. Graphical construction of vertical flow nets for different hydrologic systems is discussed in Section 3 and includes examples to demonstrate flow net construction techniques. Section 4 illustrates the construction of flow nets in special hydrologic settings, also by example. Mathematical methods used to construct flow nets are reviewed in Section 5. It is recommended that the user of this manual attempts to work through the examples provided in Sections 3 and 4 to practice methods of flow net construction.

DEFINITION OF TERMS

Several useful definitions are described below, in alphabetical order, to assist in enabling a thorough understanding of subsequent sections of this guidance document. These terms are commonly used in the field of ground water hydrology and are of importance in the application of flow nets. A more complete glossary is provided in Appendix A.

Aquifer is defined as a geologic formation, group of formations, or part of a formation capable of yielding a significant amount of ground water to wells or springs (EPA, 1984c). The uppermost aquifer is the aquifer nearest to the ground surface.

Discharge velocity or velocity (v) is calculated based on the quantity of water that percolates per unit time across a unit area of a section oriented at right angles to the flow lines. For laminar flow conditions (smooth, uniform flow), velocity is defined by Darcy's Law (see Section 2) as $v = ki$, where k is the coefficient of hydraulic conductivity and i is the hydraulic gradient. The units of velocity are commonly cm/sec or ft/day. Seepage velocity (see below) is equal to the discharge velocity divided by the effective porosity.

Effective porosity is the volumetric percentage of the total volume of a given mass of soil or rock that consists of interconnecting pore spaces through which flow can occur.

Elevation head (z) is the elevation difference between the point of interest and the measurement datum point (see Figure 1.1).

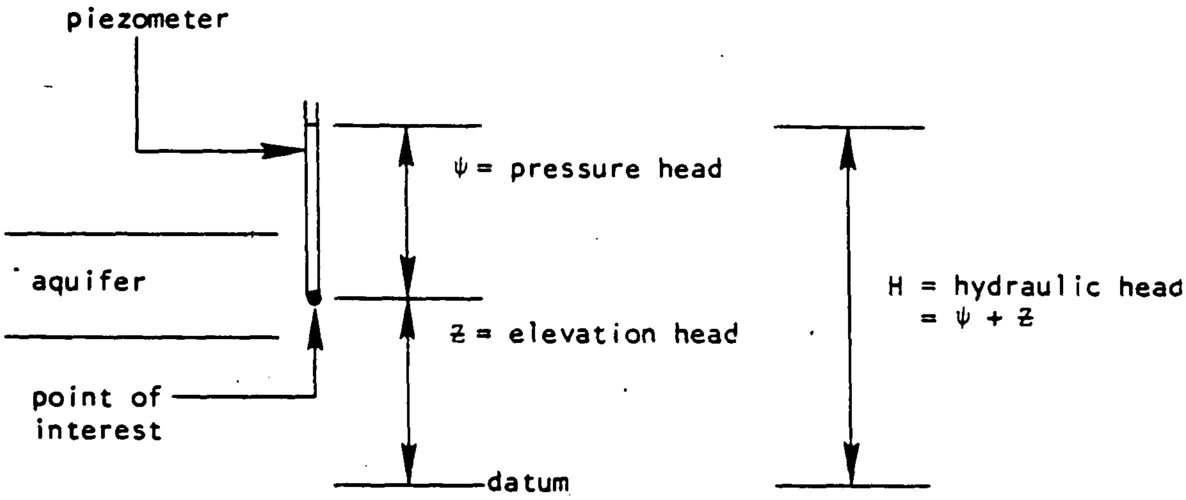


Figure 1.1. Measurement of subsurface water pressure.

Equipotential lines are one of two sets of curves that make up a flow net. These lines are perpendicular to the flow and pass through points of equal head. They are representative of the head or driving force for ground water flow.

Equipotential space is the space between adjacent equipotential lines and represents the incremental drop in head through that distance.

Flow lines comprise the other set of curves that form a flow net. Flow lines represent the path that particles of water follow in passing through subsurface materials.

Flow path is the space between two flow lines and is sometimes referred to as a flow tube or a flow channel.

Ground water exists below the earth's surface in saturated and unsaturated formations. The water table is the division between the unsaturated zone and the saturated zone. It is the point in the vertical dimension where the pressure head is equal to atmospheric pressure. In confined aquifers (artesian aquifers), the pressure head is greater than atmospheric and the potentiometric surface extends above the confining layer. If a well were placed through such a confining layer, the ground water would rise to the level of the potentiometric surface.

Hydraulic conductivity is an expression of a material's ability to transmit water. The coefficient of hydraulic conductivity (k) is dependent on the properties of the flowing liquid. It is equivalent to the volumetric rate of flow of water through a cross-sectional area under a unit hydraulic gradient. The units of the coefficient of hydraulic conductivity are length divided by time (L/T), normally expressed as cm/sec or ft/day.

Hydraulic gradient (i) is the change in hydraulic head per unit length in the direction of flow. For example, if the hydraulic head drops 1 m over a 100 m distance, the gradient is 0.01 m/m. The hydraulic gradient has both horizontal and vertical components. Nested piezometers must be used to determine the vertical component of the hydraulic gradient.

Hydraulic head or total head (H) is the sum of the pressure head (ψ), the elevation head (z), and the velocity head ($v^2/2g$) at the measuring point of interest. For ground water flow, the velocity head term is generally neglected so that $H = \psi + z$ (see Figure 1.1). The hydraulic or total head is the value measured in a well or piezometer.

Piezometer is a field apparatus consisting of a standpipe with a porous tip (to keep soil out and let water in), which is used to measure subsurface water pressure. It operates by converting pressure head to a readily measurable elevation head. The level to which water rises in the piezometer tube represents the hydraulic head as referenced to the selected datum point.

Potentiometric surface is the plane that describes the level to which water will rise in a series of piezometers drilled into a confined aquifer with horizontal flow. Freeze and Cherry (1979) point out that a potentiometric surface is basically "a map of hydraulic contours on a two-dimensional horizontal cross section taken through the three-dimensional hydraulic head patterns that exist in the subsurface in [the area of concern]. If there are vertical components of flow, as there usually are, calculations and interpretations based on this type of potentiometric surface can be grossly misleading."

Pressure head (ψ) is the elevation that ground water rises above the point of interest (see Figure 1.1).

Seepage velocity (v_s) is defined as the average velocity at which water percolates through the pores of a porous material and is equal to the discharge velocity divided by the effective porosity of the material ($v_s = v/n_e$). The units of seepage velocity are commonly cm/sec or ft/day.

SECTION 2

FLOW NET THEORY AND HYDROLOGIC CONSIDERATIONS

GENERAL

A ground water system can be represented by a three-dimensional set of equipotential surfaces and orthogonal flow lines. If a plan view or a two-dimensional cross section is drawn to represent this system, the resultant equipotential lines and flow lines constitute a flow net. A flow net can be used to determine the distribution of heads, velocity distribution, flow paths and flow rates, and the general flow pattern in a ground water system (McWhorter and Sunada, 1977).

Four basic types of ground water systems exist based on the distribution of hydraulic conductivity:

- homogeneous and isotropic;
- homogeneous and anisotropic;
- heterogeneous and isotropic; and
- heterogeneous and anisotropic.

Materials are homogeneous if the hydraulic conductivity does not vary spatially, whereas materials are heterogeneous if hydraulic conductivities do vary spatially. If the hydraulic conductivity is independent of the direction of measurement at a point in a geologic formation, the formation is isotropic at that point. If the hydraulic conductivity varies with the direction of measurement at a point (for example, when the vertical hydraulic conductivity is different than the horizontal conductivity), the formation is anisotropic at that point. Figure 2.1 is a graphical representation of the four types of

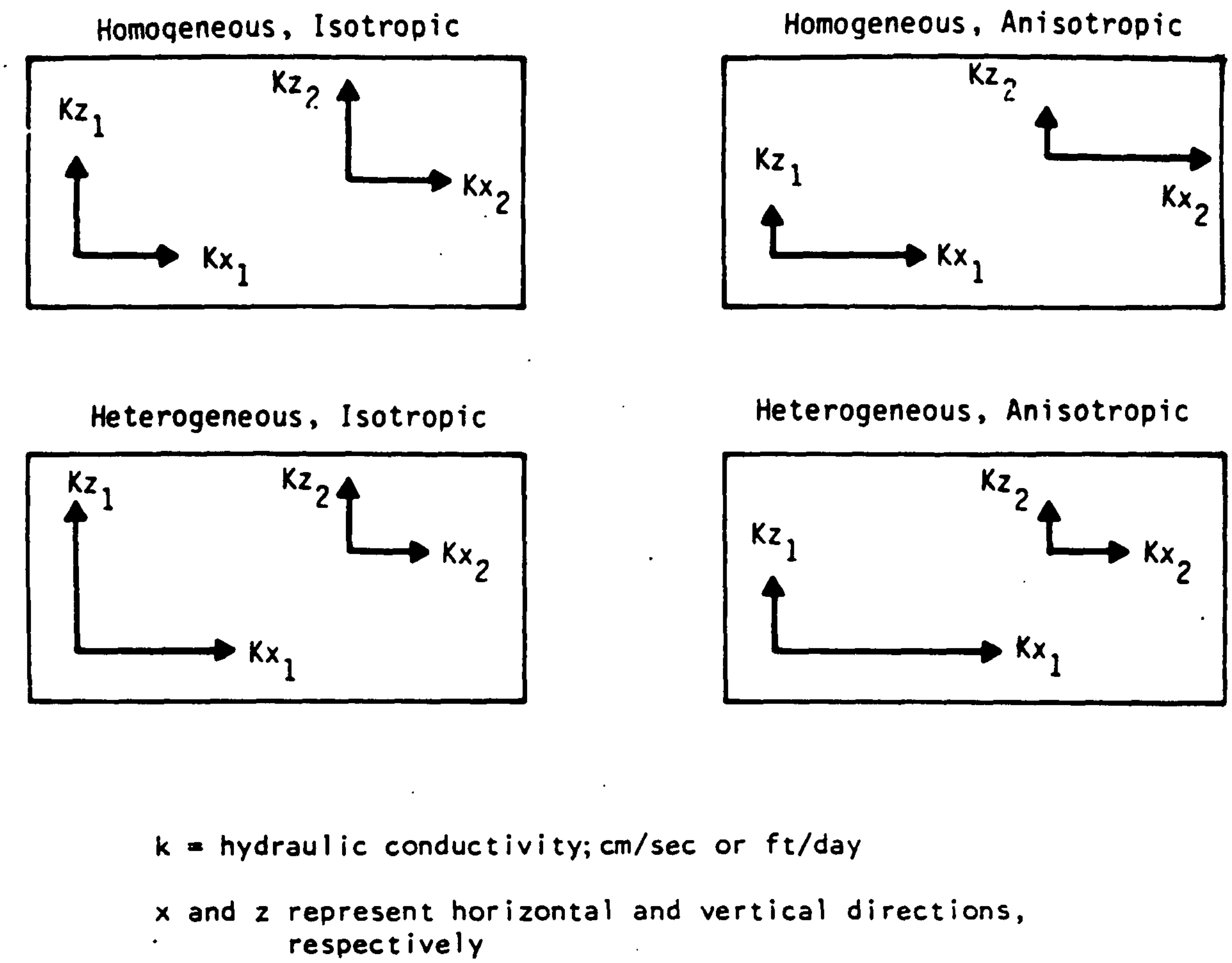


Figure 2.1. Graphical representation of ground water system types. Source: Freeze and Cherry (1979).

systems, where the hydraulic conductivity (horizontal and vertical) is represented in vector form and shown at two different locations within each aquifer.

FLOW NET THEORY

A flow net is a two-dimensional model of the ground water system which, as mentioned above, identifies ground water flow directions and can be used to calculate ground water flow rates. Flow nets can also be used to identify suitable locations for monitoring wells, as well as the screened interval of the wells. The conceptual ground water flow model of a site can be tested using a flow net. A flow net can be constructed for a site to represent the conceptual flow model. The model can be tested by installing additional piezometers at selected locations and comparing the actual head values at these locations with those predicted by the flow net.

The total quantity of water that flows through a given mass of geologic material is equal to the sum of the quantities of water through each flow path in the flow net. A fundamental rule is that each flow path in a flow net must transmit the same quantity of water. Therefore, the total flow, Q, is equal to the flow quantity in each flow path, q, multiplied by the total number of flow paths, F. Similarly, the total head loss, H, experienced in traversing through one flow path of the entire flow net, is equal to the head loss experienced in passing through any equipotential space multiplied by the number of equipotential spaces, N.

Flow, q, through any path in a flow net is defined by Darcy's Law:

$$q = k\ i\ A$$

where k is the coefficient of hydraulic conductivity (cm/sec or ft/day),

i is the hydraulic gradient (dimensionless), and

A is the cross sectional area through which flow occurs (sq. cm or sq. ft).

The calculated value of q is for a unit width in the third dimension orthogonal to the cross section. Thus, the units of q are m^3/sec per meter of width. The total flow through a single flow path is found by multiplying q by the width of interest.

In a flow net consisting of squares of dimension s x l with head loss, h, through a single equipotential space, Darcy's Law reduces to:

$$q = \frac{k\ h\ s}{l}$$

Given that the flow net is comprised of rectilinear spaces that approximate squares, s = l and:

$$q = k\ h$$

From preceeding discussions, it is known that:

$$h = \frac{H}{N}$$

so that:

$$q = \frac{H}{k}$$

Knowing that the flow, q, through any square is described by:

$$q = \frac{Q}{F}$$

where F is the total number of flow paths, it is demonstrated that the total flow, Q, is calculated as follows:

$$Q = kH\frac{F}{N}$$

Accordingly, the total quantity of water that will seep through a unit width of a given subsurface unit can be found by constructing a flow net for the cross section and multiplying its hydraulic conductivity by the total head difference and the ratio of the number of flow paths to the number of equipotential spaces. Again, it should be noted that Q for the full width of interest is determined by multiplying the quantity calculated above by width.

TIME OF TRAVEL (TOT)

Upon construction of a flow net, a conservative determination of time of travel can be calculated along the flow path considered to offer the least resistance to ground water flow and, thus, highest flow velocity. The flow path of least resistance can be identified by inspection once a flow net is constructed for the site in question. This application of flow nets provides a conservative approach to assessing ground water vulnerability beneath a hazardous waste management site.

HYDROLOGIC CONSIDERATIONS

To enable proper construction of a flow net, certain hydrologic parameters of the ground water system must be known, including:

- vertical and horizontal head distribution;
- vertical and horizontal hydraulic conductivity of the saturated zone;
- thickness of saturated layers; and
- boundary conditions.

Head Distribution

Piezometers are used to determine the distribution of head throughout the area of interest. To be valid, head measurements must be time equivalent; that is, all piezometric measurements must be made coincidentally or all measurements must be made for the same ground water conditions. Piezometers should be spatially distributed and placed at varying depths to determine the existence and magnitude of vertical gradients. If vertical flow components exist, the flow direction cannot be derived simply based on inspection of the potentiometric surface in two dimensions. A three-dimensional representation of the potentiometric surface would be required to interpret the flow direction. Ground water will flow, however, from areas of high hydraulic head to areas of low hydraulic head.

Hydraulic Conductivity

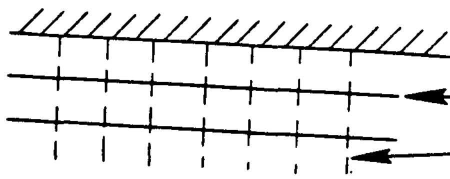
Hydraulic conductivity is a measure of a material's ability to transmit water. Generally, clayey materials have low hydraulic conductivities, whereas sands and gravels have high conductivities. Several laboratory and field methods can be used to determine the saturated and unsaturated hydraulic conductivity of soils including tracer tests, auger-hole tests and pumping tests of wells (Todd, 1980; EPA, 1984b). Methods used to determine hydraulic conductivity above and below the water table are often classified by the range of hydraulic conductivity and the medium being tested.

Aquifer Thickness

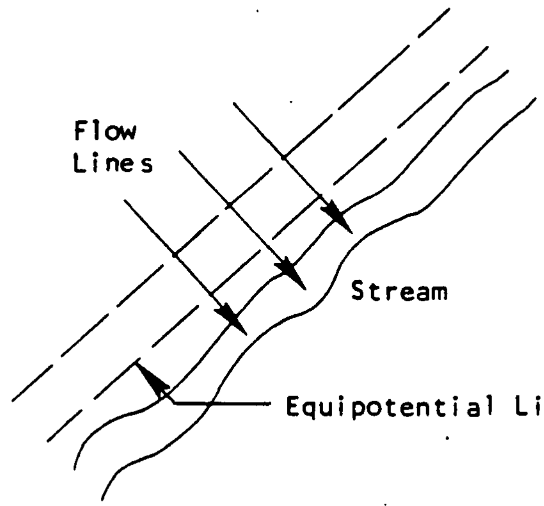
The thickness of an aquifer can be determined by evaluation of geologic logs or by geophysical techniques. Geologic logs from boreholes may show changes in lithology (the characteristics of the geologic material) indicating the relative hydraulic conductivity of materials. Various geophysical techniques, both downhole and surface, have been documented in many textbooks and EPA guidance manuals (1983a and 1983b) and can be used to determine the thickness of geologic units.

Boundary Conditions

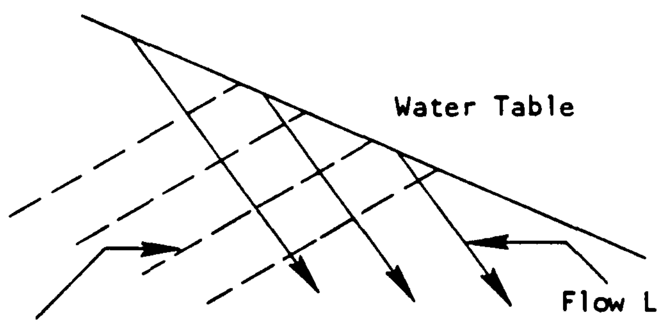
The boundary conditions of the area of investigation must be known to properly construct a flow net. The boundary conditions are used as the boundaries of the flow net. The three general types of boundaries are: (1) impermeable boundaries; (2) constant-head boundaries; and (3) water table boundaries (Freeze and Cherry, 1979). Ground water will not flow across an impermeable boundary; it flows parallel to these boundaries. Unfractured granite is an example of an impermeable boundary (Figure 2.2a). A boundary where the hydraulic head is constant is termed a constant head boundary.



a. Impermeable (No Flow) Boundary Condition



b. Constant-Head Boundary Condition



c. Water-Table Boundary Condition in Recharge Area

Figure 2.2. Types of Boundary Conditions.
Source: Freeze and Cherry (1979).

Ground water flow at a constant-head boundary is perpendicular to the boundary. Examples of constant-head boundaries are lakes, streams, and ponds (Figure 2.2b). The water table boundary is the upper boundary of an unconfined aquifer, and is a line of known and variable head. Flow can be at any angle in relation to the water table due to recharge and the regional ground water gradient (Figure 2.2c). The boundary conditions of an aquifer can be determined after a review of the hydrogeologic data for a site.

Guidance for determining the above parameters is provided in:

- Permit Writer's Guidance Manual for Subpart F, Ground Water Protection (EPA, 1983b);
- Permit Applicant's Guidance Manual for Hazardous Waste Land Treatment, Storage, and Disposal Facilities (EPA, 1984c);
- Method 9100, Saturated Hydraulic Conductivity, Saturated Leachate Conductivity, and Intrinsic Permeability Methods (EPA, 1984b);
- Ground Water Monitoring Assessment Programs at Interim Status Facilities (EPA, 1982); and
- Soil Properties, Classification, and Hydraulic Conductivity Testing (EPA, 1984d).

After assessing the hydrologic parameters of the ground water system at the site of concern, construction of the flow net and subsequent determination of ground water flow direction and time of travel can proceed.

SECTION 3

FLOW NET CONSTRUCTION

BASIC RULES

The simplest ground water system is one which is homogeneous and isotropic. This type of geologic medium serves as a simple basis for describing the basic rules of flow net construction, despite the fact that homogeneous, isotropic media rarely occur in nature. Regardless of the type of medium, the basic rules must be applied and necessary modifications are made throughout the procedure to account for heterogenity or anisotropic conditions.

The fundamental rules and properties of flow nets are summarized below:

1. Flow lines and equipotential lines intersect at 90° angles;
2. The geometric figures formed by the intersection of flow lines and equipotential lines must approximate squares;
3. Equipotential lines must meet impermeable boundaries at right angles (impermeable boundaries are flow lines);
4. Equipotential lines must be parallel to constant-head boundaries (constant-head boundaries are equipotential lines);
5. The head difference (h) between any pair of equipotential lines is constant throughout the flow net;
6. Each flow path in a flow net must transmit the same quantity of water (q); and
7. At any point in the flow net, the spacing of adjacent lines is inversely proportional to the hydraulic gradient (i) and the seepage velocity (v_s).

Procedures that can be used for flow net construction include:

1. Trial sketching
2. Mathematical solution

3. System modeling

4. Electrical analogy

Considering the specialized knowledge required for use of the latter three, trial sketching is generally considered the best method for the novice and is often the practice of choice by those who are knowledgeable of the other methods. Flow net sketching can be sufficiently accurate, if conducted according to the basic rules outlined above with patience and a certain degree of intuition that will develop with practice. The precision associated with flow net sketching is likely comparable to that associated with defining the hydraulic conductivity of the media of concern.

STEPS IN FLOW NET CONSTRUCTION

A relatively small number of flow lines are necessary to adequately characterize flow conditions at the site in question. The use of three to five flow lines will generally be sufficient. With this in mind, the following steps should be used to construct a flow net:

1. Draw a cross section, on a convenient scale, of the geologic mass of concern in the direction of flow.

2. Identify all points of known hydraulic head amd draw tie lines between them by traversing the shortest possible distances and avoiding crossing of lines.

3. Use the tie lines constructed in Step 2 to interpolate other hydraulic head values for the purpose of sketching equipotential contour lines. Clearly, the accuracy of this interpolation procedure will depend upon the number and location of points of known hydraulic head.

4. Establish two boundary flow lines based on geologic information.

5. Using a trial-and-error method, sketch intermediate flow and equipotential lines, making sure that right angles and squares are formed.

6. Continue to sketch these lines until inconsistencies start to develop in the shape of the resulting flow net. For example, angles other than right angles, or rectangles rather than squares are considered inconsistencies.

7. Make successive trials until the flow net is consistent throughout. Each inconsistency noted will indicate the direction and magnitude of change for the next trial.

It is reiterated that only a few lines should be used in constructing the net. Further, all transitions that exist in the net should be smooth and the size of the spaces should change gradually.

As the flow net is constructed, the head distribution should be checked. One should expect a greater head loss occurring in materials with low hydraulic conductivity than in materials with high hydraulic conductivity. Flow lines tend to follow or parallel zones of contact between materials that have differences in hydraulic conductivity of 100 or more. Flow nets drawn for materials with a difference in hydraulic conductivity of a factor of 100 will look the same if the ratio of conductivities is 10^{-7} to 10^{-5} or 10^{-3} to 10^{-1}. However, variations will be evident in the quantity of flow and the TOT. Directional differences in hydraulic conductivity within the same geologic layer (i.e., anisotropy) are also of importance in flow net construction.

At most facilities, vertical and horizontal head data are obtained from well and piezometer measurements, and from free surfaces such as springs, lagoons, ponds and swamps. Often, piezometers or wells have long, open screened sections or have slotting below the water table to measure fluid pressure. The open interval on a piezometer should be as short as possible with the midpoint of the interval being the measuring point.

Wells with long screened sections can be used to obtain approximate piezometer readings if the midpoint of the open interval is used. The head measured in such a well is the integrated average of all the different heads over the entire length of the open interval. In this instance, it is important to note that if vertical gradients are present, the measured head can be a function of the screened length of the well. This must be considered when piezometric data are collected from such wells and are interpreted for the purpose of establishing hydraulic head conditions.

A simple case of two-dimensional seepage is shown in Figure 3-1 to demonstrate the basic characteristics of a flow net. The flow lines are parallel to each other. In reality, there are a large number of flow lines through a given cross section because each particle of water will follow its own flow line. For practical applications, however, a smaller number of flow lines are drawn for problem resolution. Generally, only four or five flow lines are necessary to adequately describe flow conditions at the site. Flow lines are spaced so that the quantity of water flowing in each flow path is the same.

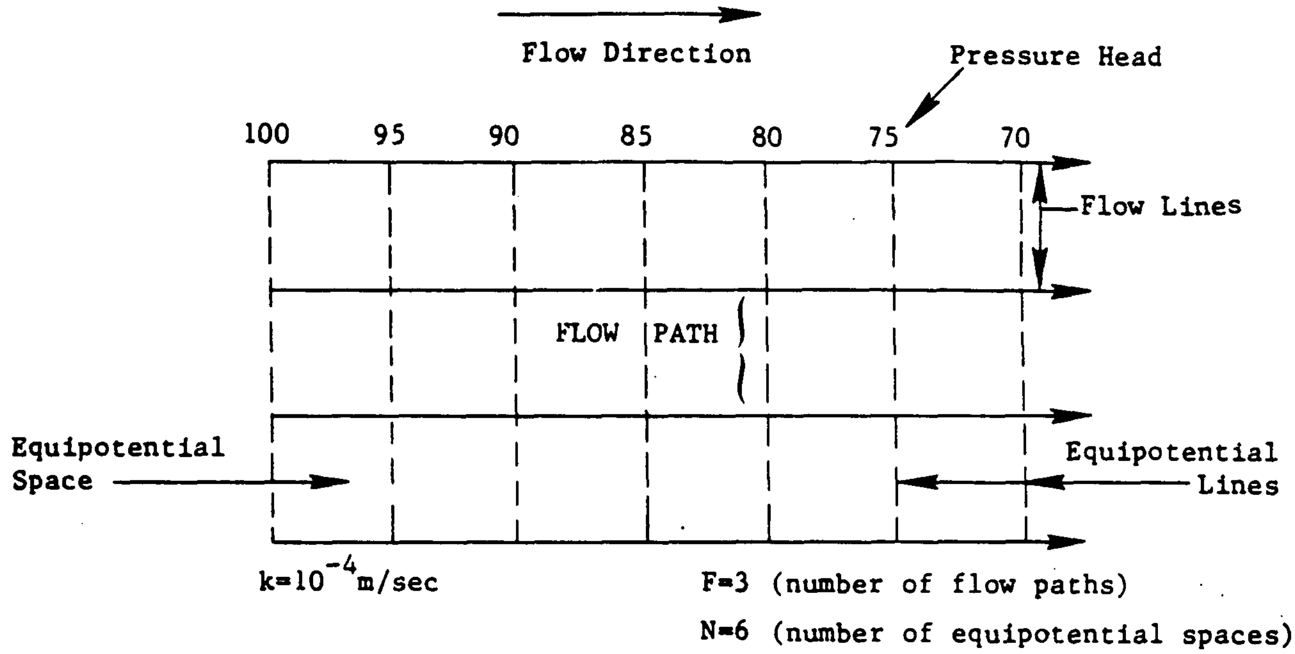


Figure 3.1. Hypothetical flow net.

EXAMPLE OF A HOMOGENEOUS ISOTROPIC FLOW SYSTEM

Figure 3.2a shows a cross section of a homogeneous, isotropic system with no vertical hydraulic gradients to introduce flow net analysis procedures. The cross section is drawn parallel to the direction of flow. The water level elevation is 102 m in Well 1 and 100 m in Well 2. The aquifer consists of fine sand with a hydraulic conductivity of 10^{-5} m/sec. Because this is an idealized hydraulic system, the top and bottom of the aquifer are considered impermeable (no-flow) boundaries and represent flow lines. These flow lines form a single flow path, which is sufficient in this simple case to construct a flow net. For this example, it is assumed that flow is horizontal, so that vertical equipotential lines can be drawn at Wells 1 and 2. Intermediate equipotential lines are drawn by equally dividing the space between Wells 1 and 2 into squares (Figure 3.2b). Once the flow net has been constructed, the flow rate can be calculated using the equation:

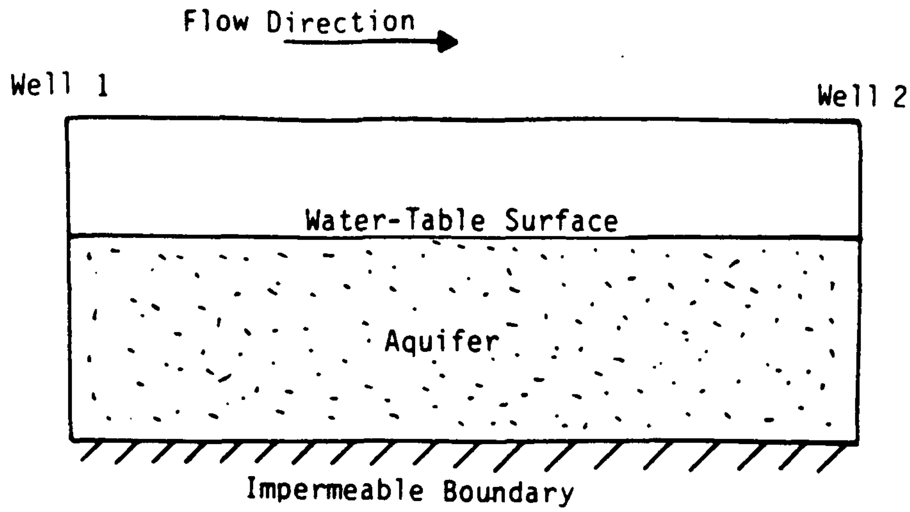


Figure 3.2a. Cross section of a homogeneous, isotropic aquifer; Parallel to the flow direction.

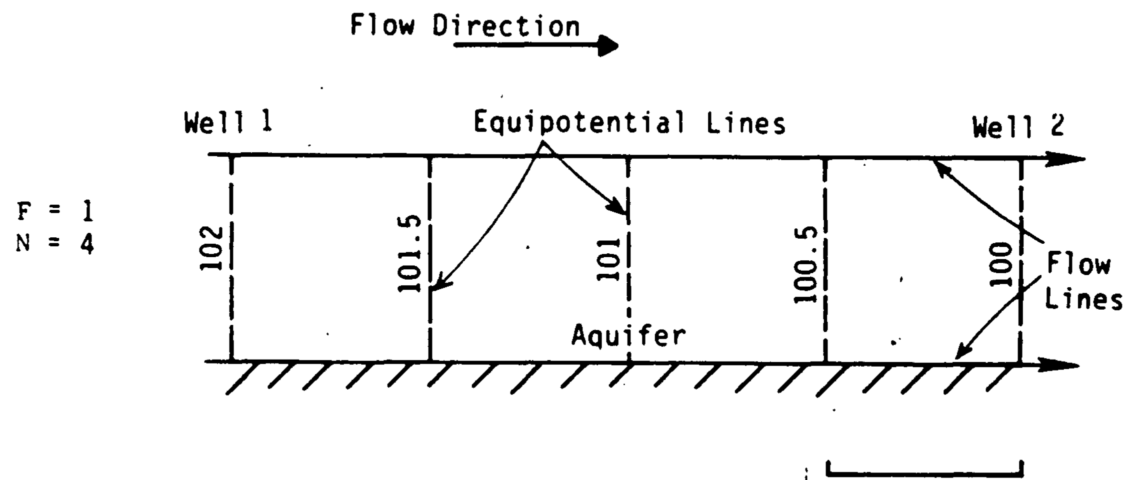


Figure 3.2b. Construction of a simple flow net for the system shown in Figure 3.2a; Squares are formed by the equipotential lines and flow lines.

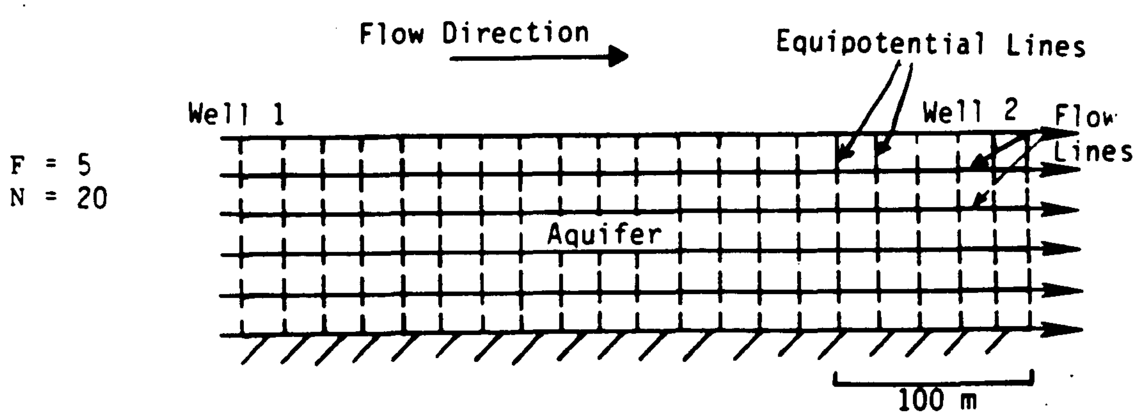


Figure 3.2c. A more detailed flow net for the system shown in Figure 3.2a.

Figure 3.2. Introductory Example - Homogeneous Isotropic flow system with no vertical gradient.

$$Q = \frac{k\ F\ H}{N}$$

where Q = flow rate

k = coefficient of hydraulic conductivity = 10^{-5} m/sec

F = number of flow paths = 1

H = total head drop = 2 m

N = number of equipotential spaces = 4

Using the flow net constructed for this problem,

$$Q = \frac{(10^{-5} m/sec)(1)(2m)}{4}$$

$$Q = 5 \times 10^{-6}\ m^3/sec \text{ per meter of width}$$

It is important to note that N is the number of equipotential spaces in one flow path rather than the number of equipotential lines; N is one less than the number of equipotential lines.

The flow net in Figure 3.2b is the simplest one that can be drawn to represent the system. A more detailed flow net (Figure 3.2c) can be constructed for this system, but the calculated flow rate is the same. From the flow net in Figure 3.2c, there are 5 flow paths and 20 equipotential spaces. Thus, the calculated flow rate is:

$$Q = \frac{(10^{-5}\ m/sec)(5)(2m)}{20}$$

$$Q = 5 \times 10^{-6}\ m^3/sec \text{ per meter of width}$$

and is equal to the value calculated from the flow net in Figure 3.2b.

SECOND EXAMPLE OF HOMOGENEOUS ISOTROPIC FLOW SYSTEM

Another example of a homogeneous isotropic ground water system is shown in Figure 3.3. The facility is a landfarm at a petroleum refinery. The locations of four monitor wells are shown in Figure 3.3. Well I is located upgradient of the landfarm disposal area and Wells II, III, and IV are located downgradient. Water level data from nested piezometers indicate that ground water flow at the site is primarily horizontal. Drilling logs indicate that this site lies on interbedded layers of unconsolidated clay, silt, sand, and gravel. The silty clay unit ranges in thickness from 14 m to more than 27 m. Beneath this unit is a layer of fine-to-medium sand with a thickness ranging from 1 m to more than 10 m. Underlying the sand unit is an impermeable till. All wells are screened in the sand unit.

Table 3.1 shows water level elevation data collected at the site on July 19, 1983. Plotting and contouring of these data indicates that ground water flow is to the northwest (Figure 3.4). The data are contoured by interpolating between the known hydraulic head elevations. Using data from Wells I and IV (Table 3.1), a cross section can be drawn parallel to the direction of flow, southeast to northwest (Figure 3.5).

A flow net (Figure 3.6) can be constructed to determine the rate of ground water flow beneath the site. Because the aquifer is relatively thin, the entire flow system between Wells I and IV can be drawn as one flow path, with the upper flow line representing the water table surface and the lower flow line representing the impermeable till. Equipotential lines can then be drawn between these flow lines to form squares. The closer spacing of equipotential lines near Well I results from the change in aquifer thickness and indicates a steeper hydraulic gradient near Well I.

No hydrologic tests (i.e., slug or pump tests) were conducted at the monitoring wells, so an average hydraulic conductivity for fine-to-medium grained sand (10^{-4} m/sec) was selected from the literature (Freeze and Cherry, 1979) for use in calculating the flow rate. The flow rate is calculated from the equation:

$$Q = \frac{k\ F\ H}{N}$$

$$Q = \frac{(10^{-4}\ \text{m/sec})(1)(1.77\text{m})}{95}$$

$$Q = 1.9 \times 10^{-6}\ \text{m}^3\text{/sec per meter of width}$$

Figure 3.6b shows an expanded portion of the flow net shown in Figure 3.6a. The flow rate for this section is calculated below:

TABLE 3.1. DATA FOR REFINERY MONITOR WELLS

Monitor well No.	Ground surface elevation[a]	Water level elevation[a]	Elevation of bottom of sand unit[a]	Elevation of top of sand unit[a]
I	32.3	3.81	3.1	4.0
II	19.8	2.16	1.2	5.9
III	19.5	2.15	2.7	12.2
IV	22.6	2.04	-2.4	7.3

[a]All elevations are in meters, vs. mean sea level.

Note: Wells I and IV are approximately 223 m apart.

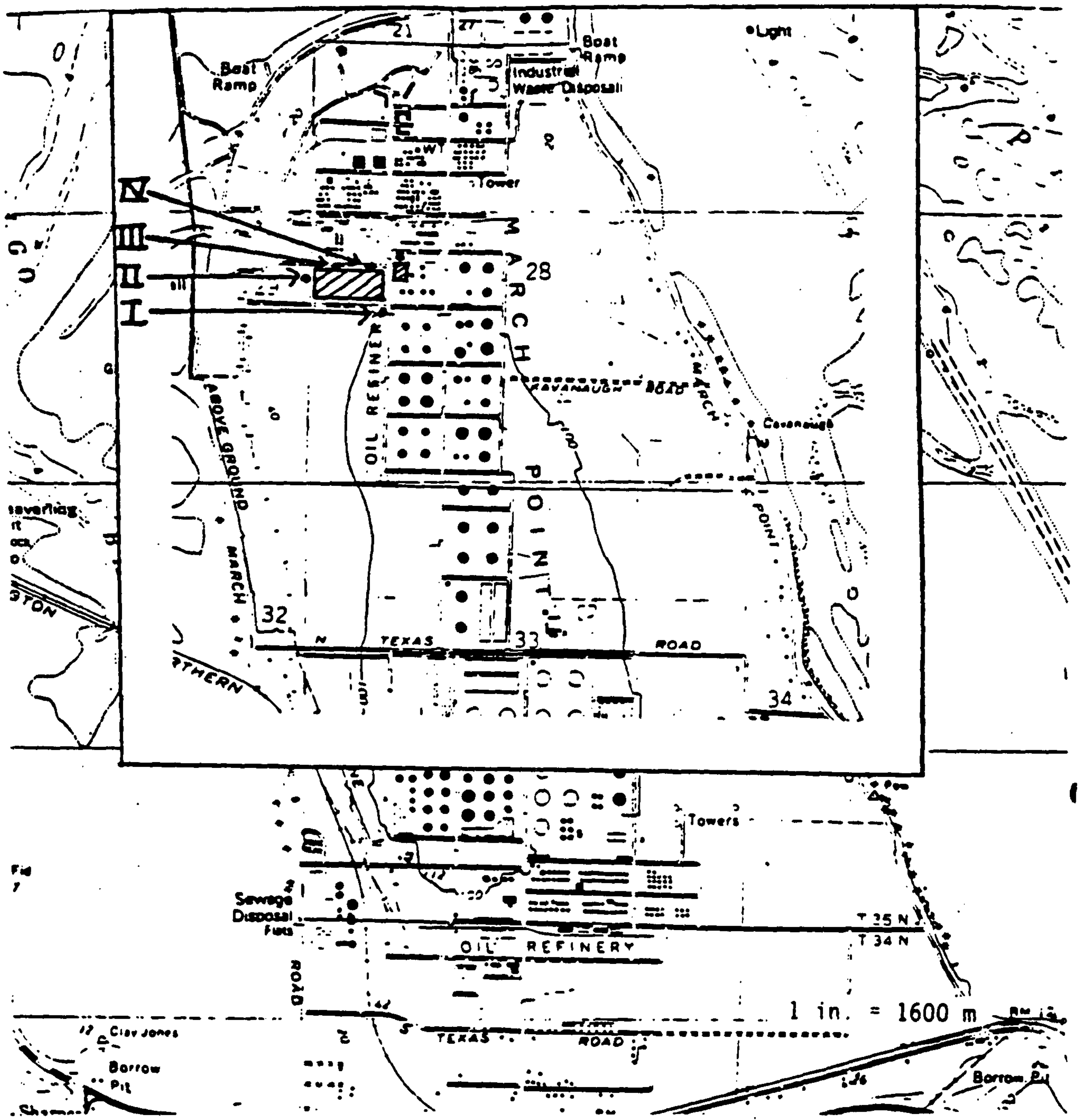


Figure 3.3. Location map of Refinery Site and Monitor Wells.

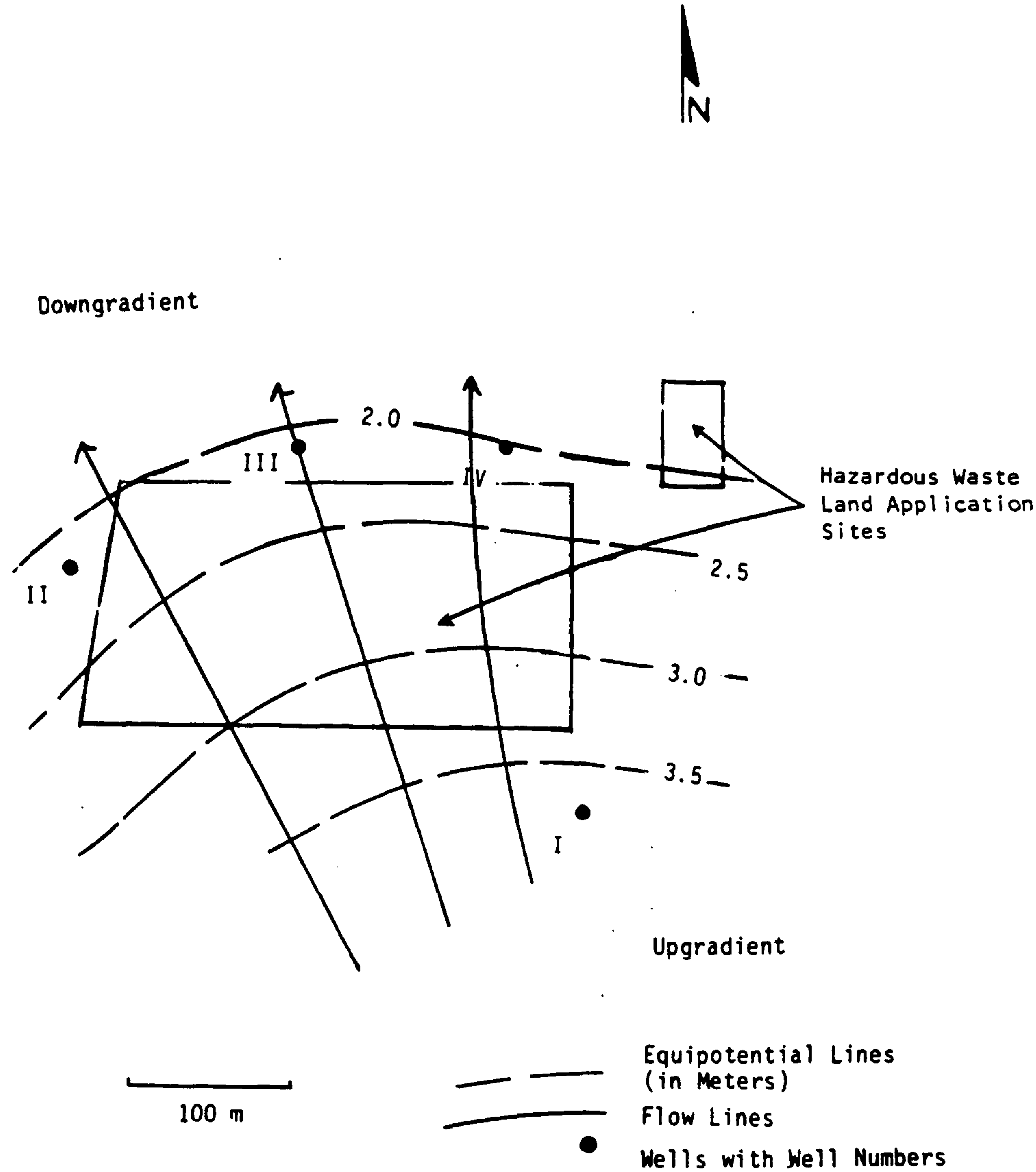


Figure 3.4. Potentiometric surface showing flow direction.

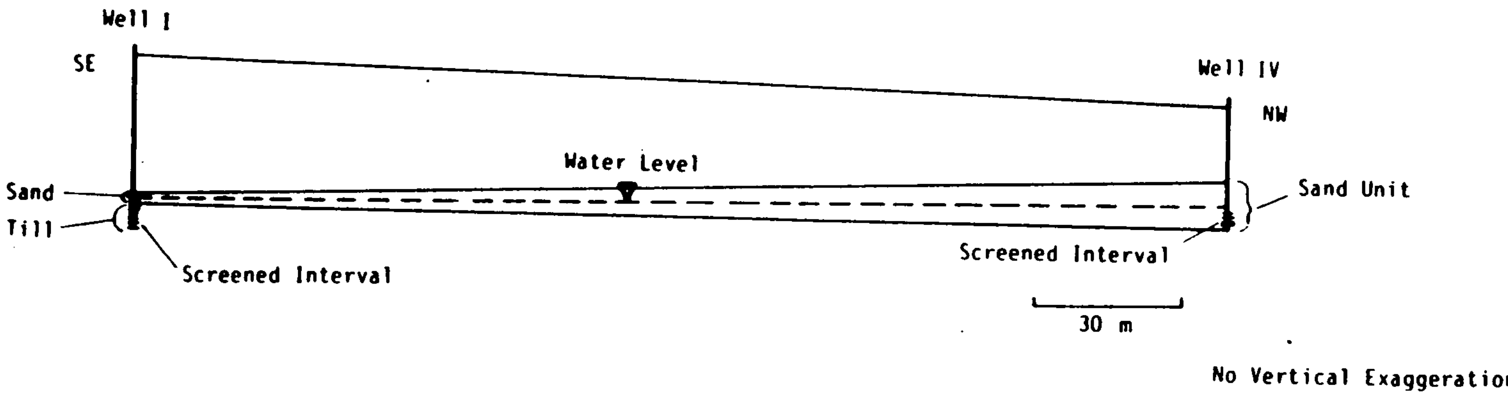


Figure 3.5. Cross section through the site between wells I and IV.

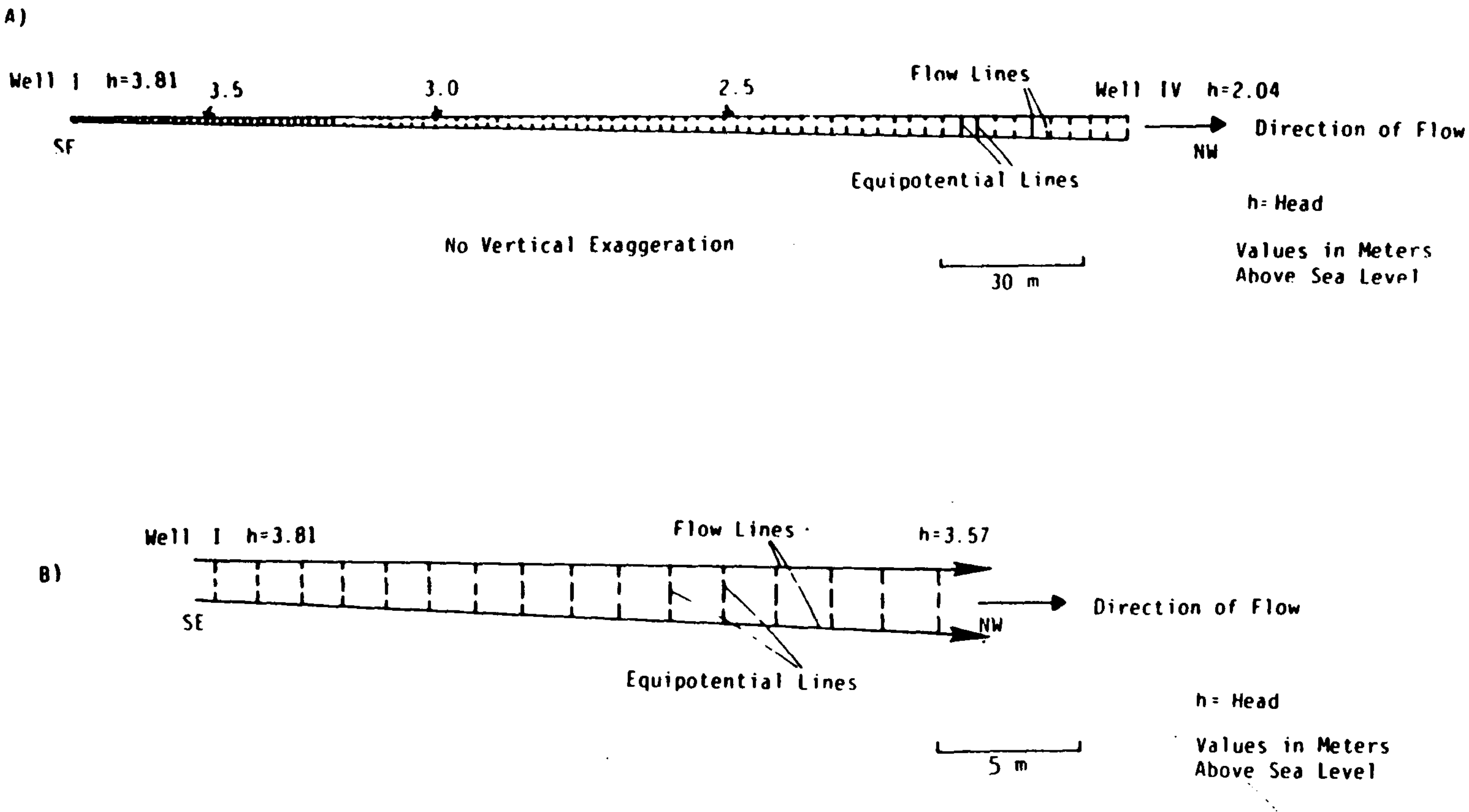


Figure 3.6. Flow net for the refinery.

$$Q = \frac{k\ F\ H}{N}$$

$$Q = \frac{(10^{-4}\ m/sec)(1)(0.24\ m)}{15}$$

$$Q = 1.6 \times 10^{-6}\ m^3/sec \text{ per meter of width}$$

The flow rate resulting from this calculation is virtually the same as the flow rate calculated using the entire length of the flow net.

The flow net in Figure 3.6a indicates that the potentiometric surface in Figure 3.4 is incorrect; the contour lines should be more closely spaced near Well I. This can be corrected by inspection of the flow net. Because there are 95 head drops (N) representing 1.77 m of total change in head (H), 26.8 head drops represent 0.5 m change in head. With this information the location of the 2.5, 3.0, and 3.5 m equipotential lines can be approximated (see Figure 3.6a) and used to adjust the potentiometric surface (Figure 3.7).

These introductory examples indicate the basic concepts of flow net construction. The remaining discussions and examples are practical in nature and show the influence of heterogeneity and anisotropy and the importance of evaluating the vertical component of hydraulic gradient. Procedures for estimating time of travel are also documented.

CONSTRUCTION OF FLOW NETS IN HETEROGENEOUS, ISOTROPIC SYSTEMS

Heterogeneous, isotropic ground water systems usually consist of two or more layers of materials with different lithologies and different hydraulic conductivity. This heterogeneity may result from vertical layering, sloping strata, fault zones, igneous injection, or the existence of man-made structures such as slurry walls. Ground water flow in heterogeneous, isotropic systems is controlled by the hydraulic conductivity of the layers, as well as by boundaries within the system.

The rules for construction of flow nets for heterogeneous, isotropic systems are the same as for homogeneous, isotropic systems, except that the "tangent law" (see below) must be satisfied at geologic boundaries. If squares are created in one portion of a formation, squares must be created

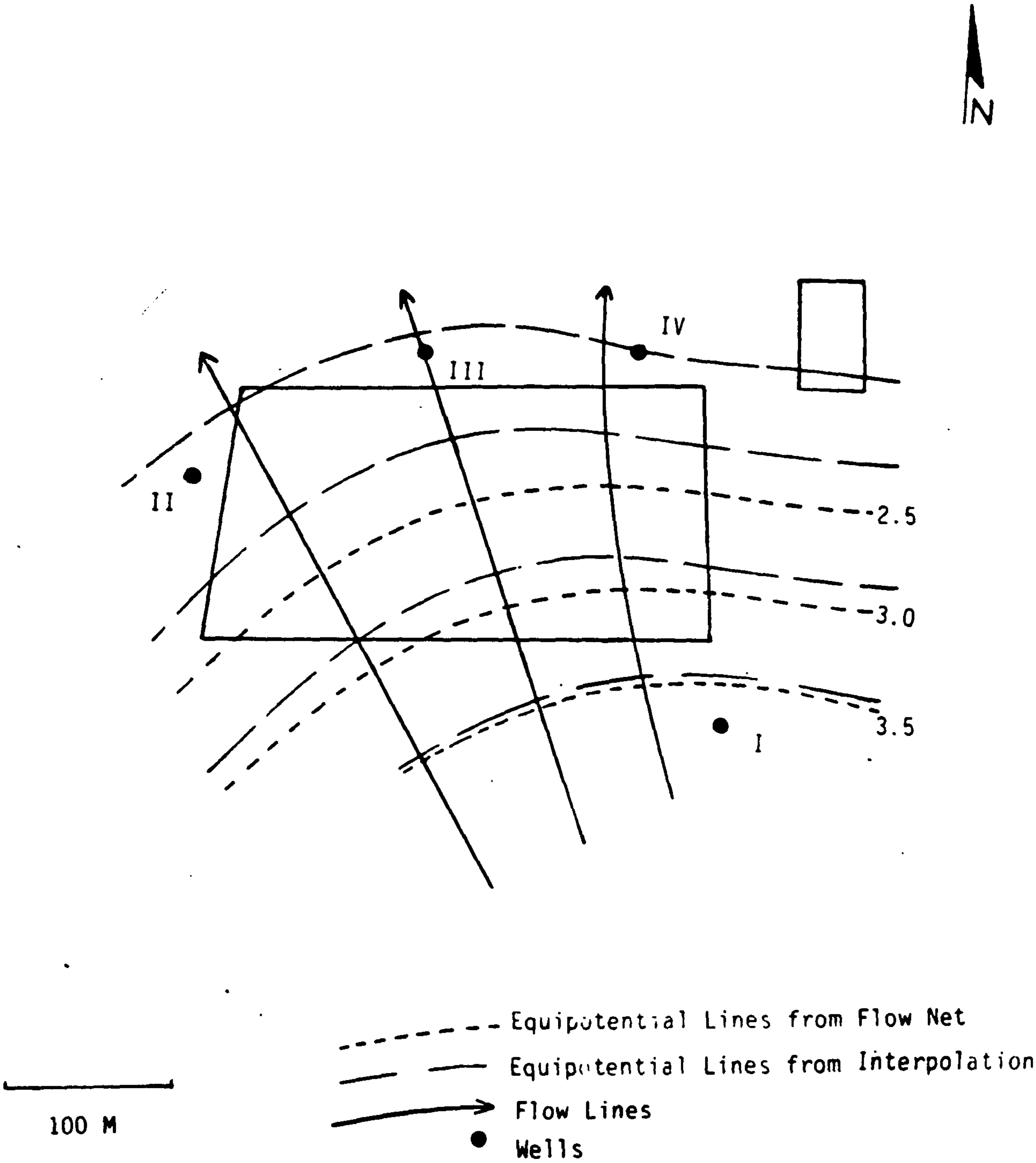


Figure 3.7. Reconstructed potentiometric surface for refinery example.

throughout that formation and throughout other formations that have the same hydraulic conductivity. Rectangles will be created in associated formations that have different hydraulic conductivities (Freeze and Cherry, 1979).

When a flow line crosses from a material of one hydraulic conductivity to another, the flow line is deflected and the flow velocity changes. Flow lines tend to be parallel to the zone of contact between materials in the medium with higher hydraulic conductivity, and perpendicular to contacts between materials in the medium with lower hydraulic conductivity (Figure 3.8). Flow paths will be narrower in layers with high conductivity because less area is necessary to conduct the same volume of water. In media of lower conductivity, flow paths will be wider in order to conduct the same volume of flow (Cedergren, 1977).

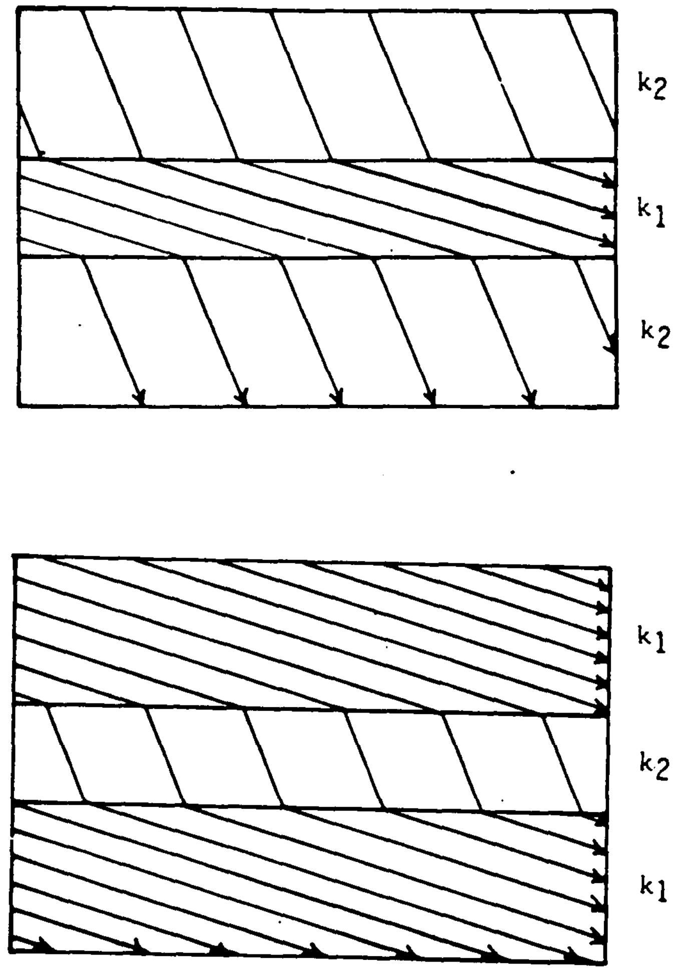
Tangent Law

The deflection of flow through geologic boundaries is similar in concept to the refraction of light through zones of different velocity. It can be shown through application of Darcy's Law and by geometry that the ratio of the hydraulic conductivities of two different geologic materials is equal to the ratio of the tangents of the two angles formed by the ground water flow lines (Figure 3.9). The tangent law states that:

$$\frac{k_1}{k_2} = \frac{\tan \sigma_2}{\tan \sigma_1}$$

Figure 3.9a shows the deflection of a flow line passing from a material of higher hydraulic conductivity (sand) to one of lower hydraulic conductivity (silt). Deflection of a flow line passing from a low to a high hydraulic conductivity zone is shown in Figure 3.9b. The illustration also shows the shape of the rectangles that exist in the downstream material.

Equipotential lines are also deflected when they cross conductivity boundaries because they are perpendicular to flow lines. It is impossible to construct a flow net for a heterogeneous, isotropic system in which only squares are created. However, the intersections of flow lines and equipotential lines must still form right angles (the flow net will consist of squares and rectangles).



For both cases, $k_1 > k_2$

Figure 3.8. Deflection of flow lines across materials of different hydraulic conductivity.

Source: Freeze and Cherry (1979).

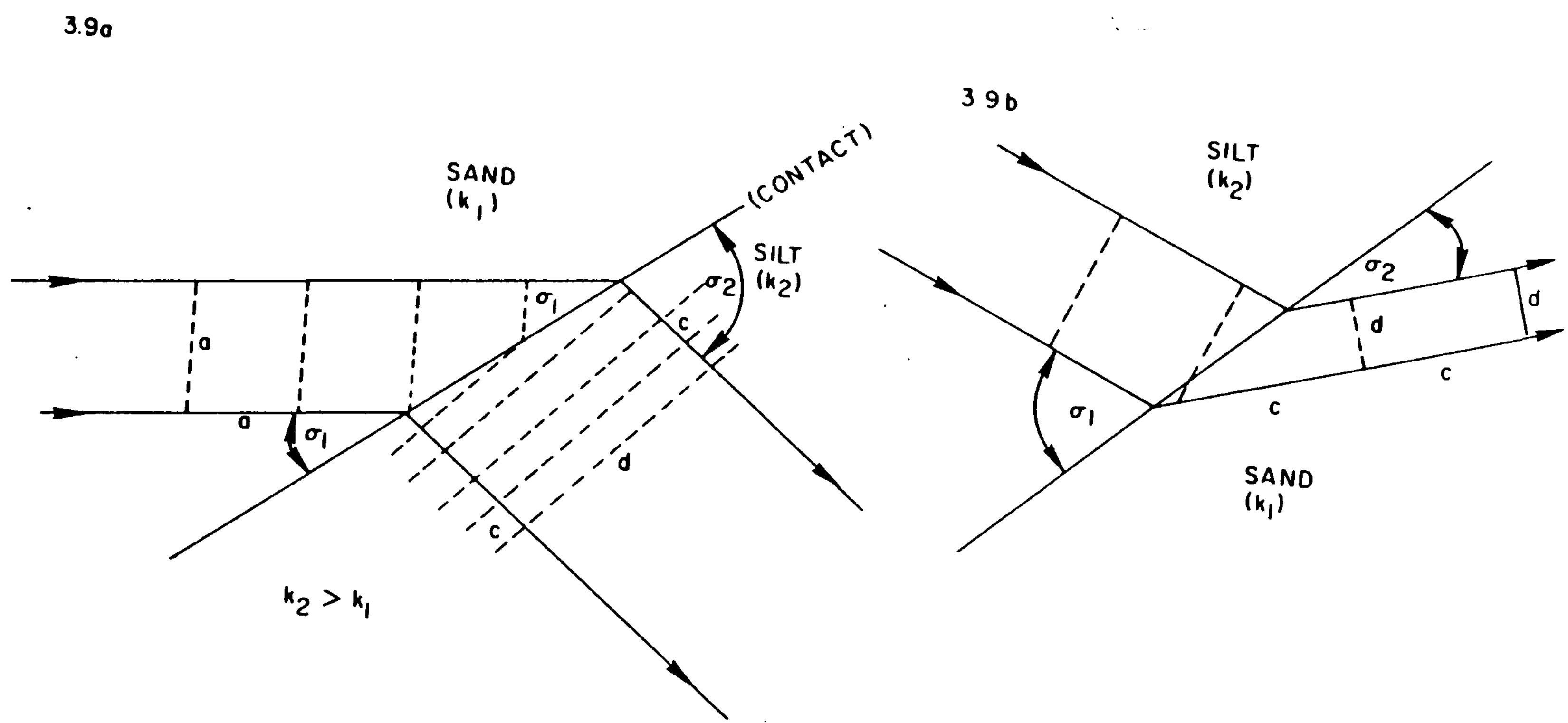


Figure 3.9. Deflection of flow lines and illustration of the tangent law.

A simple example of a heterogeneous, isotropic ground water system is shown in Figure 3.10. The conductivity of the slurry wall is a factor of 20 less than that of the sand. For ground water to flow from the sand through the slurry wall, the equipotential spaces of the flow net must compress in the slurry wall section to 1/20th of the equipotential space in the higher conductivity sand layer. Figure 3.11 shows that there are five equipotential spaces (or five equal units of head loss) between points A and B and C and D, or a total of ten equipotential drops for flow through the sand zones. Flow through the slurry wall from B to C consumes 20 equipotential drops because there is one equipotential drop for each equipotential space. Thus, the total number of equipotential drops is 30 and the head loss through any equipotential space is 1/30th of the head loss through the system. In addition, flow through the slurry wall results in a head loss equal to two thirds of the head loss through the system. Most importantly, if piezometers were installed in the soils along this cross section, the hydraulic head profile or potentiometric surface would closely follow A'-B'-C'-D', shown in Figure 3.11.

Example of a Heterogeneous Isotropic Ground Water System

The hazardous waste facility shown in Figure 3.12 is located over a heterogeneous aquifer in a recharge area. The site geology is composed of two layers of material. The upper layer is a 10 m thick layer of silt with a hydraulic conductivity of 10^{-6} m/sec (k_1). The lower layer is a 5 m thick layer of sand with a hydraulic conductivity of 10^{-5} m/sec (k_2). The head distribution for the system of water table wells and piezometers at the site can be constructed by drawing tie lines between the measuring points, shown in Figure 3.13a, making sure that the tie lines do not cross each other. The tie lines can be used to interpolate equipotential head values of interest. For example, the distance along tie line 1 (Well P-8 to Well P-9) on Figure 3.13a is 18 m and the head drop is 1 m. In order to contour the flow net at 1/2 meter head loss intervals, it is necessary to determine where the 10 m equipotential contour intersects the tie line. This is determined from the ratio:

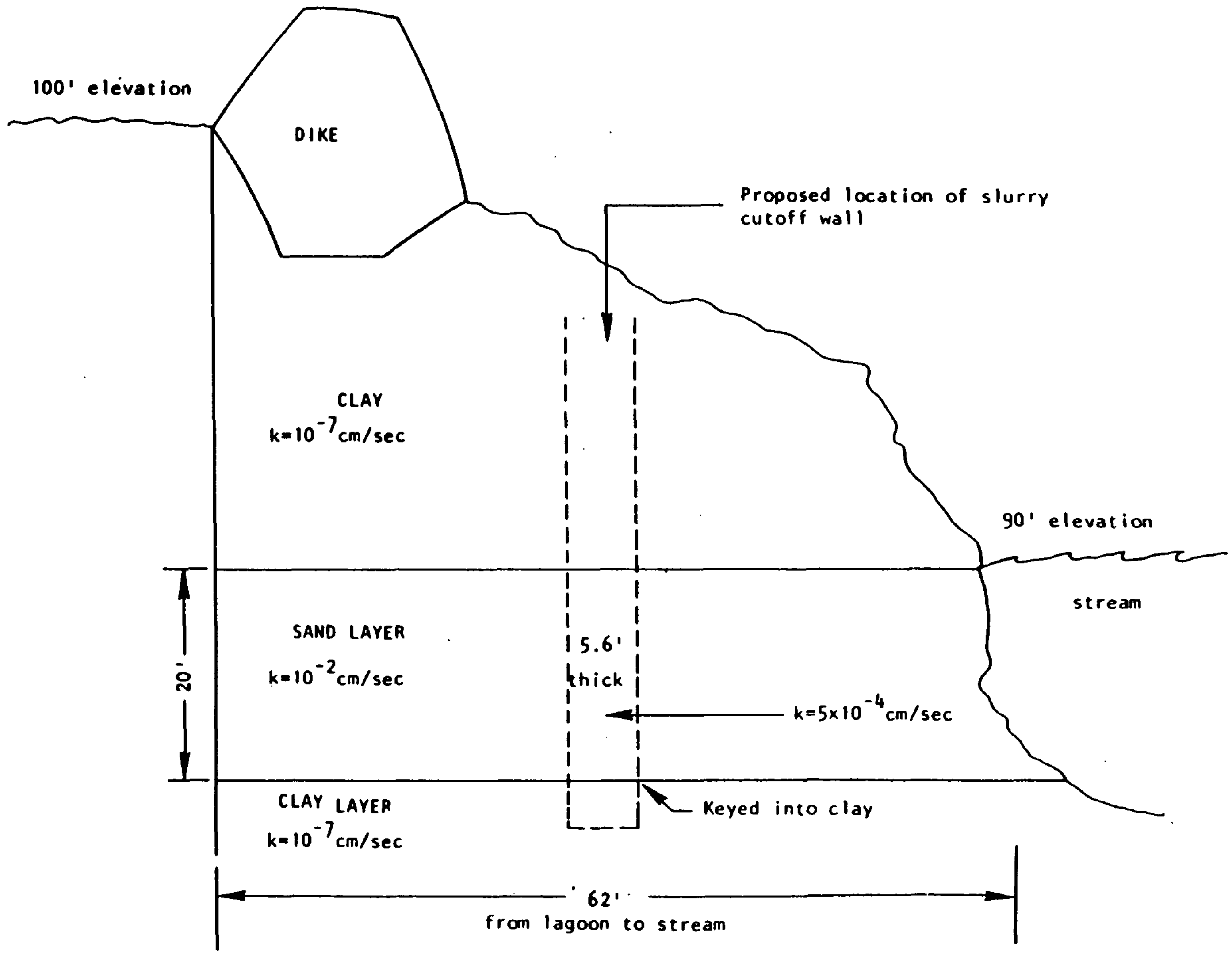


Figure 3.10. Cross section of Heterogeneous Isotropic ground water system with slurry wall.

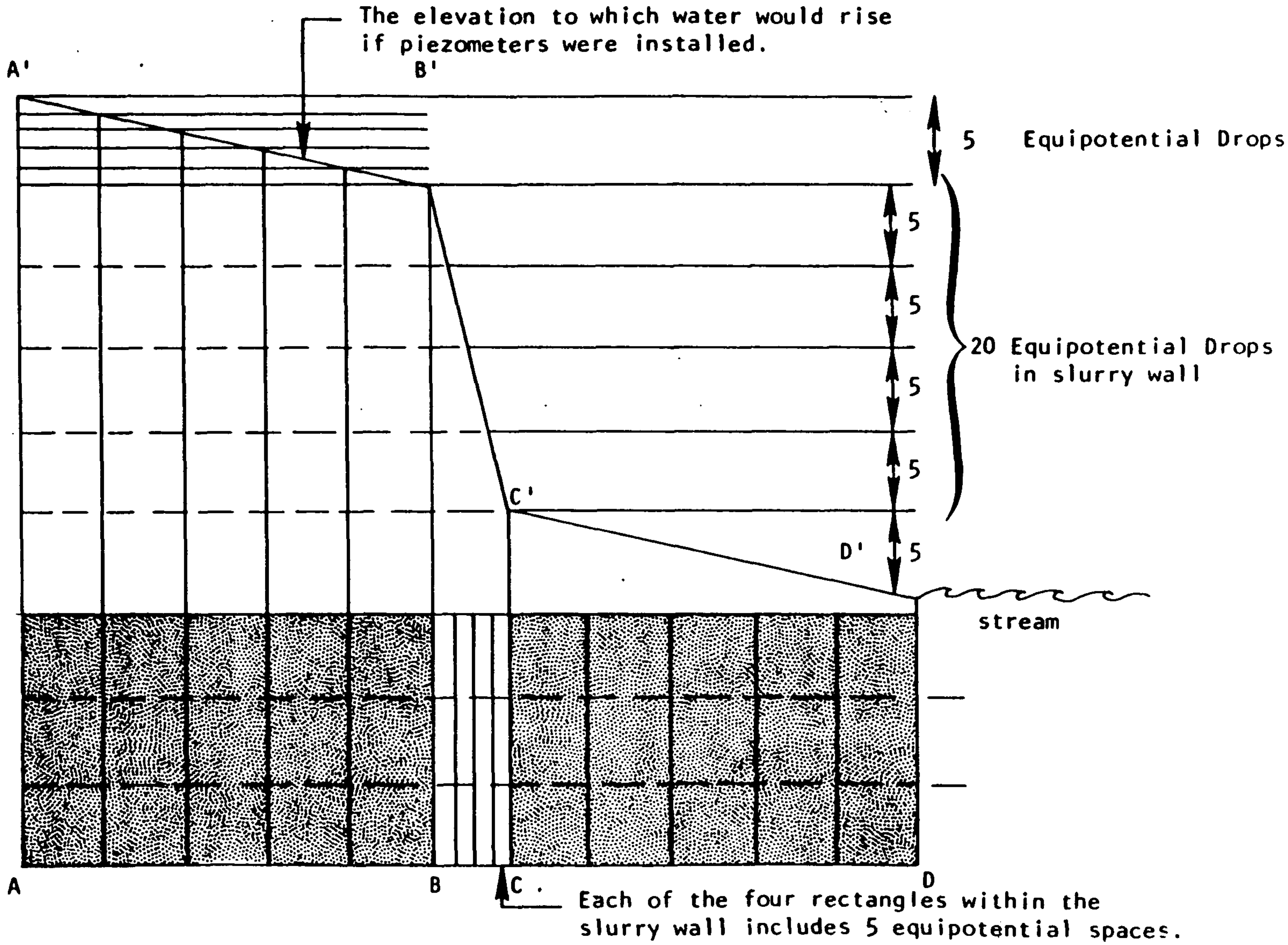


Figure 3.11. Flow net developed to analyze the effect of slurry wall.

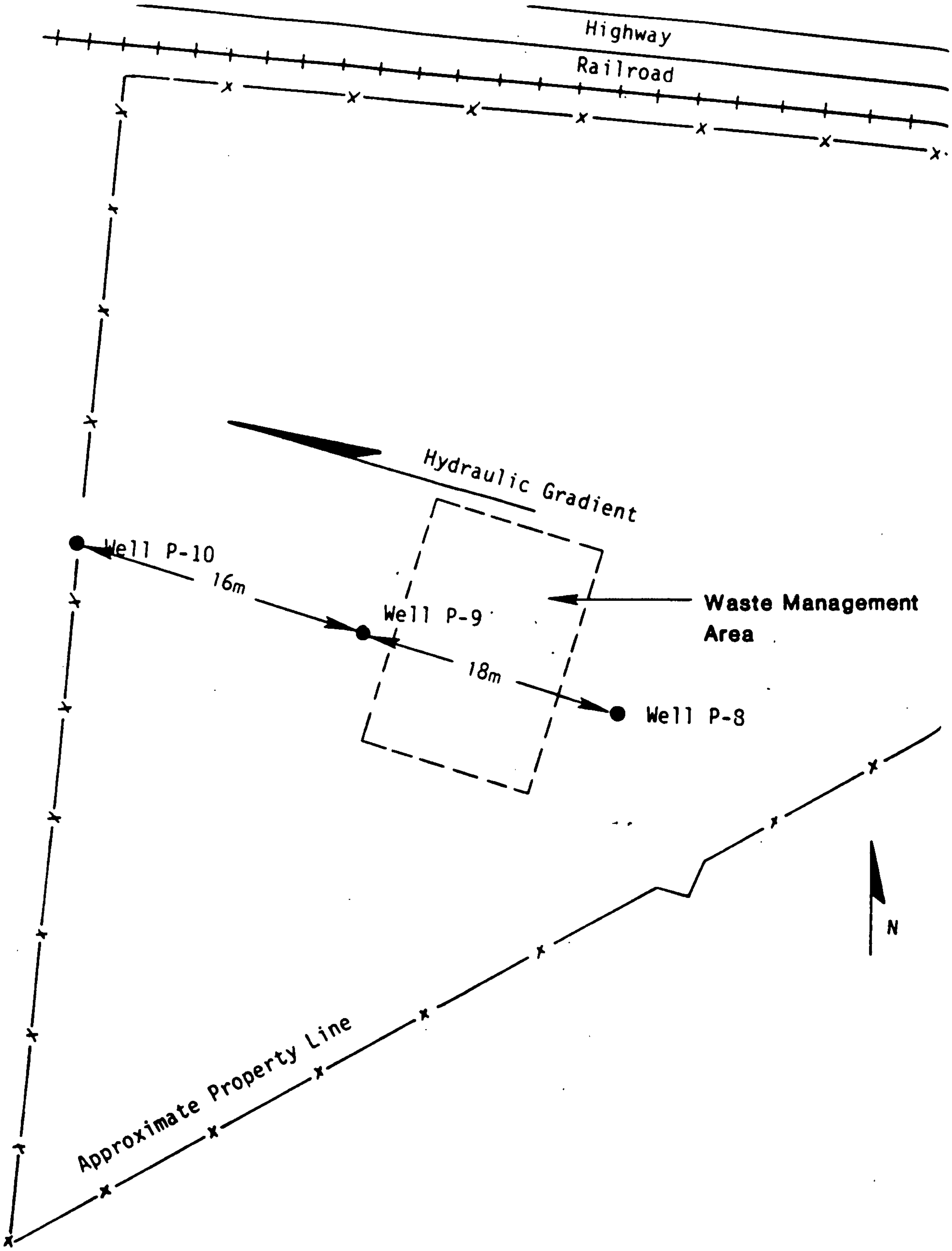


Figure 3.12. Well location map for example of heterogeneous isotropic ground water system.

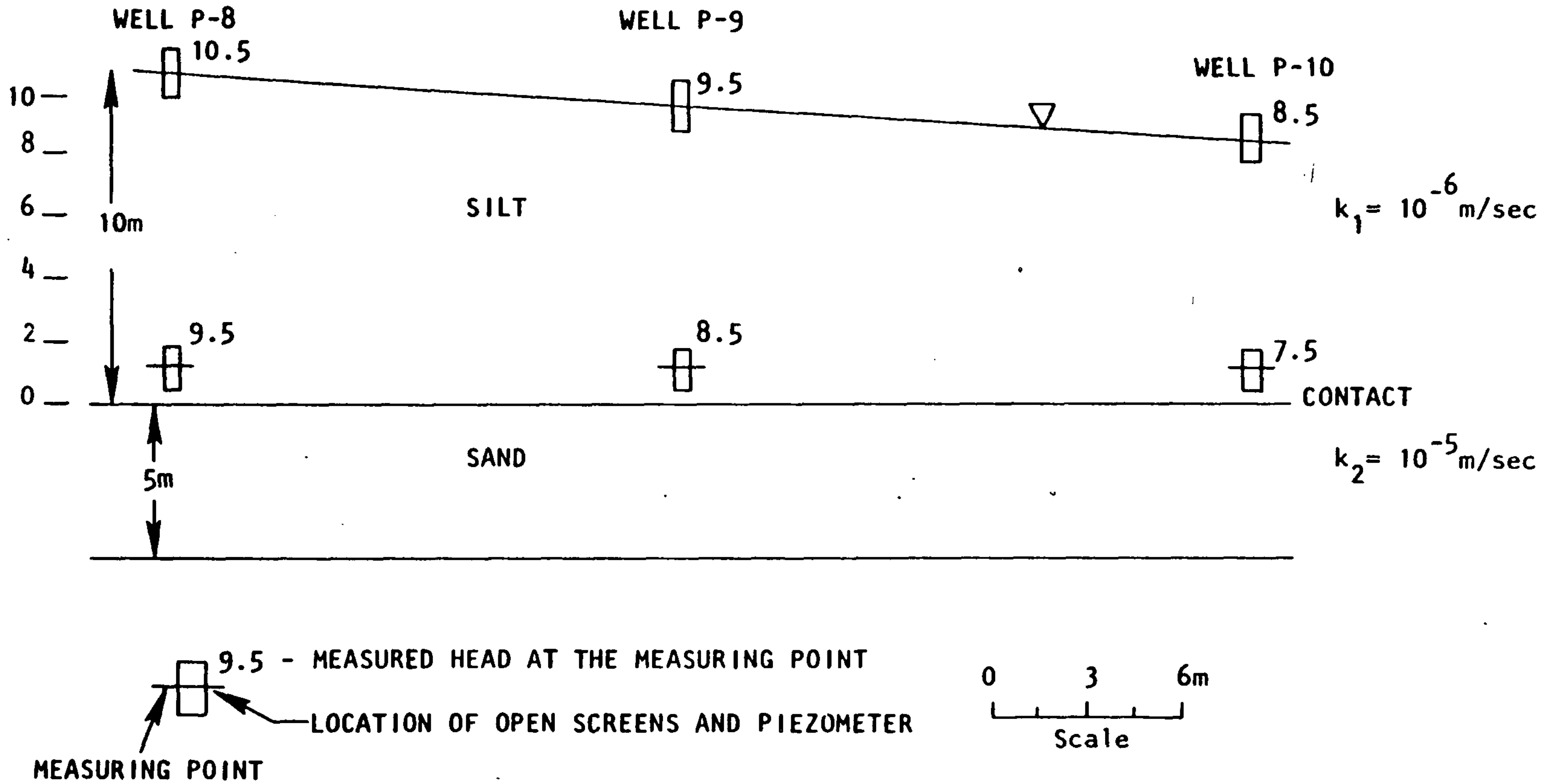


Figure 3.13a. Distribution of heads in silt layer.

$$\frac{18\ m}{1\ m} = \frac{X}{0.5\ m}$$

where X is the distance from the intersection to the measuring point and is equal to 9 m. Thus, the 10 m contour intersects the tie line at a distance of 9 m from Well P-8 and is located by measuring along tie line 1 (see Figure 3.13b). Each equipotential contour of interest is located along the tie line in the same fashion. Upon completion, all points of equal head (from the top of the layer to the base of the layer) are connected to form the equipotential lines. The relationship of equipotential lines to tie lines is shown in Figure 3.13b.

Flow lines are added at right angles to the equipotential lines so that squares are formed (see Figure 3.13c). At the contact of the silt layer with the sand layer, the flow lines form an acute angle, σ_1. This angle is used in the tangent law to determine the angle of deflection, σ_2:

$$\frac{k_1}{k_2} = \frac{\tan \sigma_2}{\tan \sigma_1}$$

From Figure 3.13d, σ_1 is 65°. Therefore,

$$\frac{10^{-6}\ m/sec}{10^{-5}\ m/sec} = \frac{\tan \sigma_2}{\tan 65°}$$

and $\tan \sigma_2 = 0.21$

$$\sigma_2 = \tan^{-1} 0.21$$

$$\sigma_2 = 12.1°$$

After determining this angle, the flow lines through the sand layer can be drawn, as shown in Figure 3.13d.

The dimensions of the rectangles in the sand layer can be determined by considering the ratio of hydraulic conductivities. If c is the length of the rectangle and d is the width:

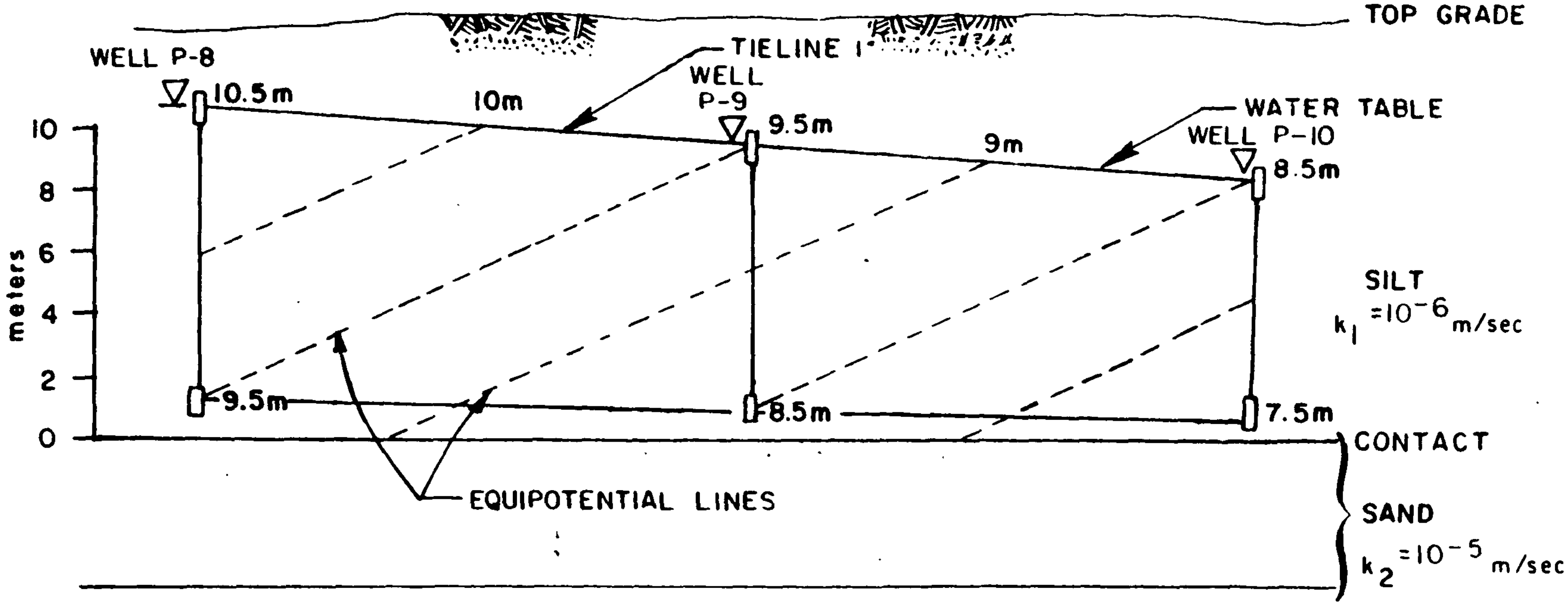


Figure 3.13b. Interpolation and plotting of equipotential lines.

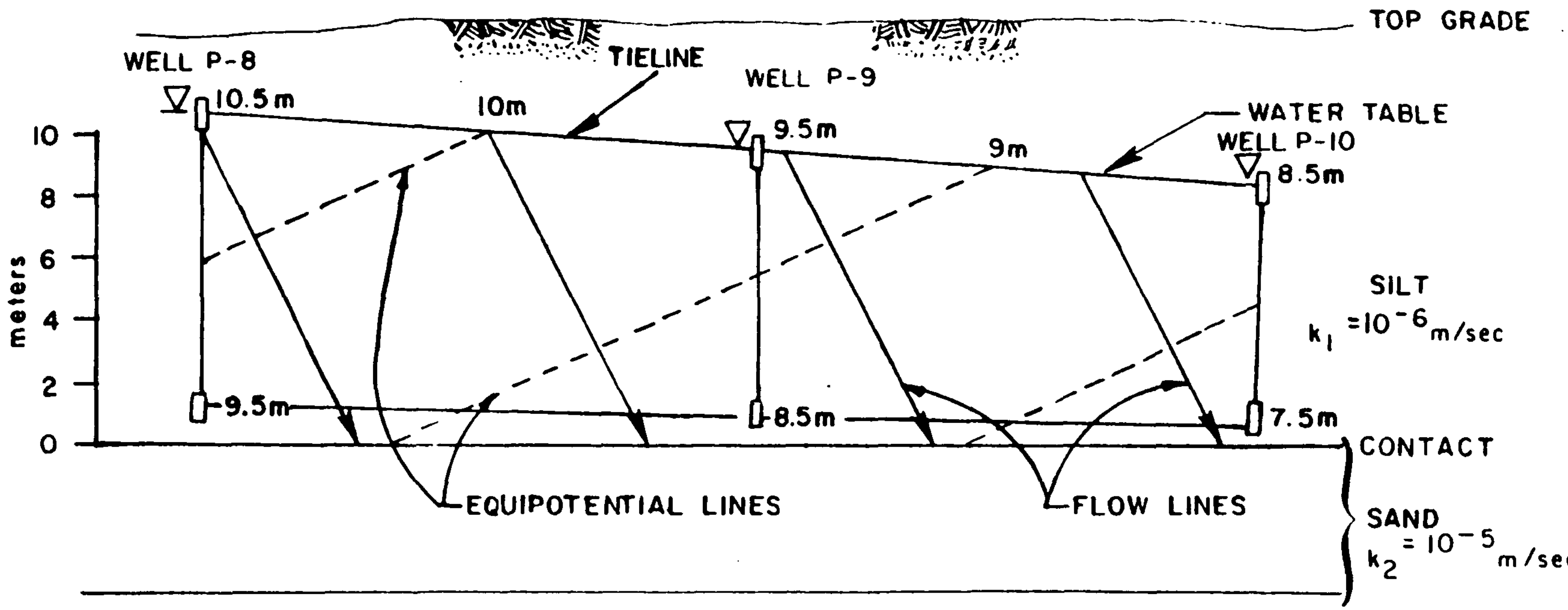


Figure 3.13c. Development of flow net.

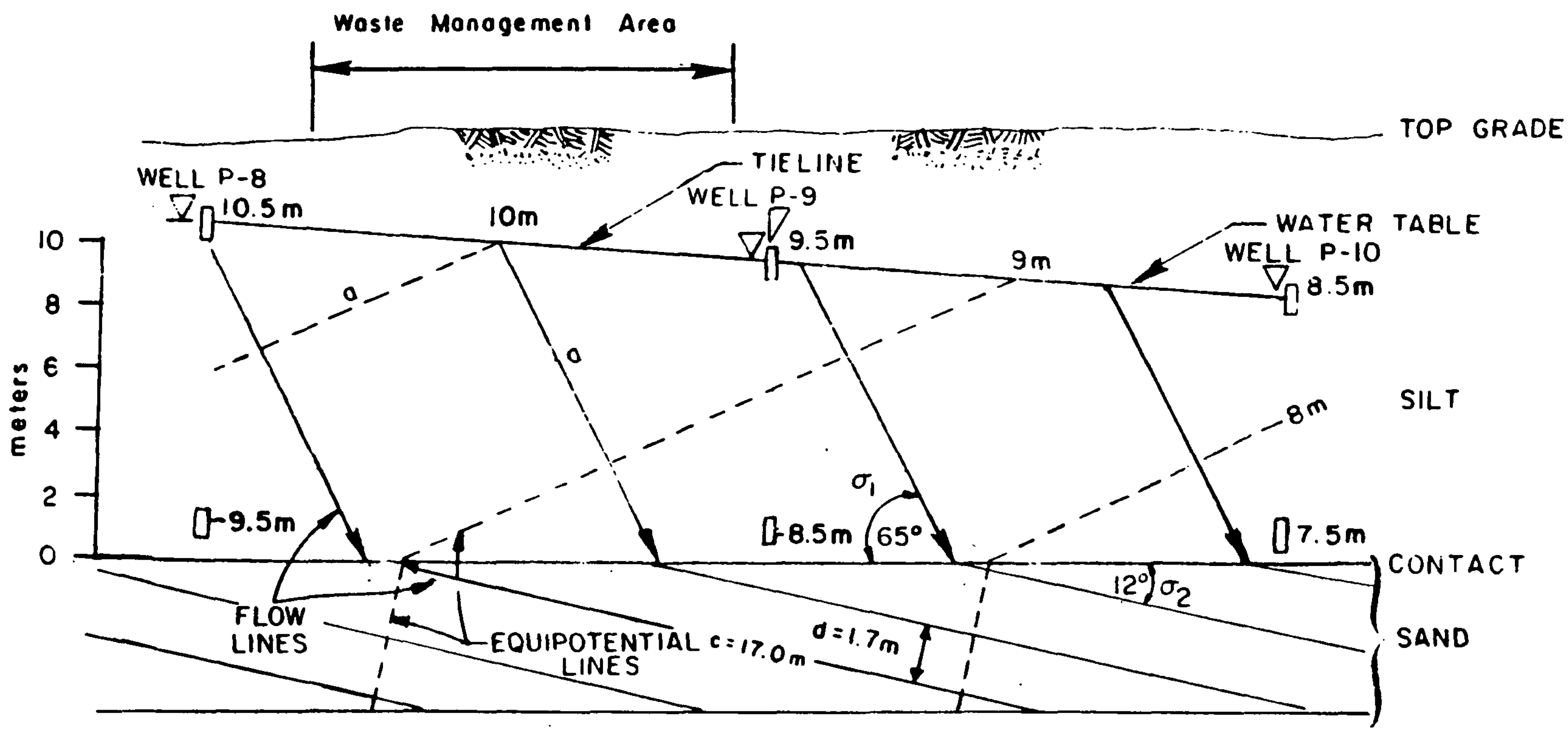


Figure 3.13d. Flow net for silt and sand layers.

$$\frac{c}{d} = \frac{k_2}{k_1}$$

Thus, by calculating the ratio of conductivities, the proportional relationship between rectangle length and width can be determined, as follows:

$$c/d = k_2/k_1 = 1 \times 10^{-5}/1 \times 10^{-6}$$

Therefore, the width, d, of the rectangles in the sand is equal to 1/10th of the length, c. By measuring the distance between adjoining flow lines, the distance, d, is approximately 1.7 m while the distance, c, is approximately 17.0 m, as shown in Figure 3.13d.

The flow net (Figure 3.13d) can now be used to determine the appropriate flow path for TOT determination. The flow path exhibiting the lowest gradient and highest velocity is selected to determine TOT_{100}. In this case, the selected flow path is located at the downgradient edge of the WMA through the silt. The flow path shown in Figure 3.13e does not correspond to any of the flow lines that were used to construct the flow net, but there are an infinite number of flow lines and equipotential lines that could have been used to construct the flow net.

TOT_{100} is based on the seepage velocity in each layer and the length of the flow line in that layer. The seepage velocity is:

$$v_s = \frac{ki}{n_e}$$

The effective porosity (n_e) is given as 0.2 for both layers in this example. The hydraulic gradient, i, for each layer is determined by measurement from the flow net, with the following results:

$$i_{silt} = \frac{\Delta h}{L} = \frac{1 \text{ m}}{7.3 \text{ m}} = 0.137$$

$$i_{sand} = \frac{\Delta h}{L} = \frac{1 \text{ m}}{17 \text{ m}} = 0.059$$

Therefore, the seepage velocity, v_s, for each layer is:

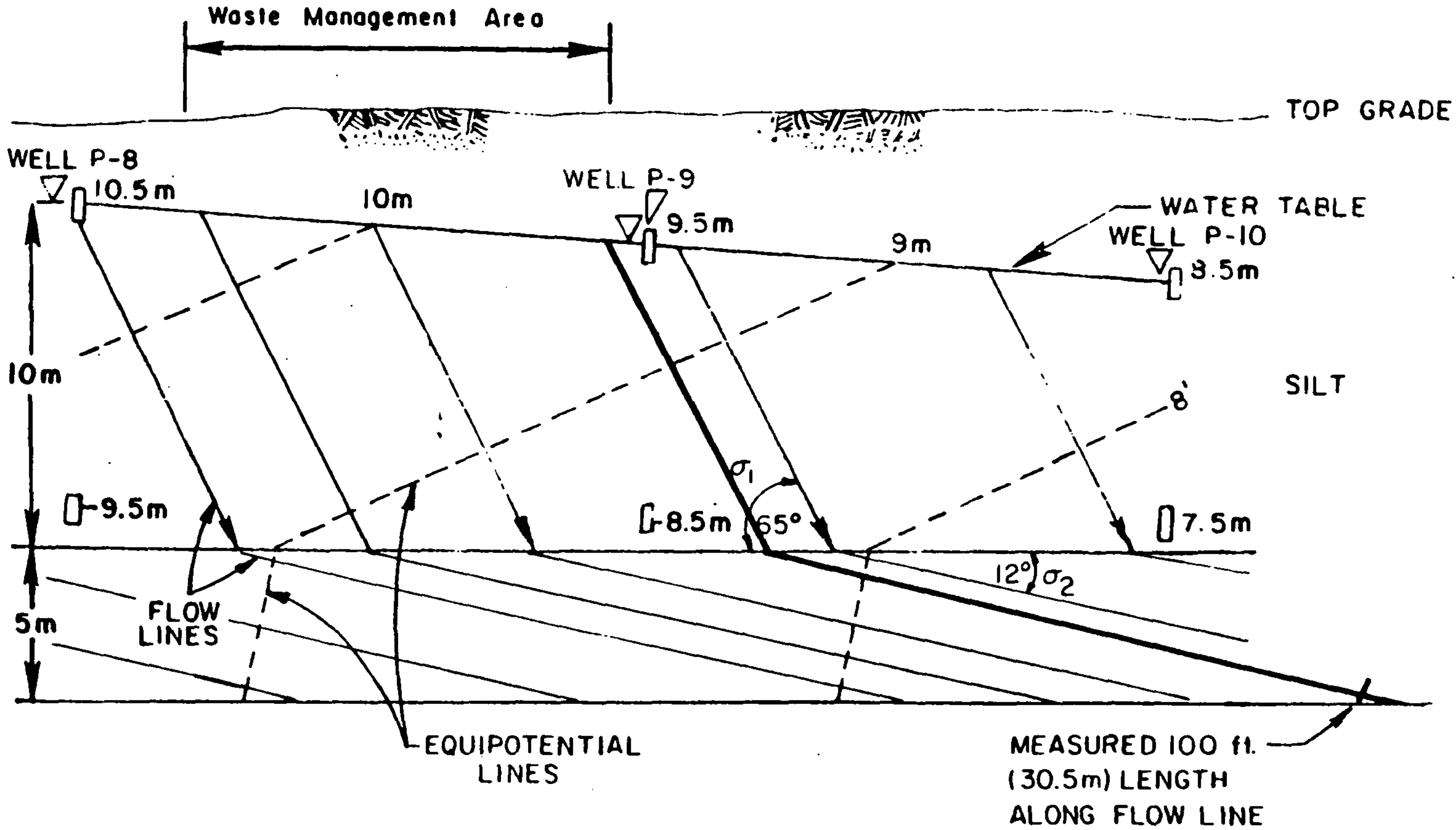


Figure 3.13e. Selection of flow line for use in TOT calculation.

$$v_s(\text{silt}) = \frac{10^{-6}\ \text{m/sec}\ (0.137)}{0.2} = 6.9 \times 10^{-7}\ \text{m/sec} = 0.06\ \text{m/day}$$

$$v_s(\text{sand}) = \frac{10^{-5}\ \text{m/sec}\ (0.059)}{0.2} = 3.0 \times 10^{-6}\ \text{m/sec} = 0.26\ \text{m/day}$$

The flow path of highest velocity includes a sector of 10.5 m in the silt and 20 m in the sand. TOT_{100} is calculated as follows:

$$TOT(\text{silt}) = L/v_s(\text{silt}) = 10.5\ \text{m}/0.06\ \text{m/day} = 175\ \text{days}$$

$$TOT(\text{sand}) = L/v_s(\text{sand}) = 20\ \text{m}/0.26\ \text{m/day} = 77\ \text{days}$$

$$TOT_{100} = TOT(\text{silt}) + TOT(\text{sand}) = 252\ \text{days}$$

According to current policy, the site would be considered vulnerable because the calculated ground water TOT along a 100 ft flow path is less than 100 years.

The volumetric flow rate through this system can be calculated using the flow net constructed for the silt. It is best to calculate the flow rate for one square of the flow net and multiply this value by the total number of flow paths in the system. The flow rate through one flow path is:

$$Q = \frac{k\ F\ H}{N}$$

$$Q = \frac{(10^{-6}\ \text{m/sec})(1)(1\text{m})}{1}$$

$$Q = 1 \times 10^{-6}\ \text{m}^3/\text{sec per meter of width}$$

Because there are approximately three flow paths in this system, the total flow across the flow net is $3 \times 10^{-6}\ m^3$/sec per meter of width.

CONSTRUCTION OF FLOW NETS IN HOMOGENEOUS, ANISOTROPIC SYSTEMS

The previous example assumed that hydraulic conductivity within the flow system was the same in all directions at any given point, but in nature many geologic formations are anisotropic. In some sediments, such as clays and silts, anisotropy is due to particles being flat instead of spherical. These particles are usually deposited with the flat side down, producing sheet-like beds. These beds decrease vertical hydraulic conductivity and result in relatively higher horizontal hydraulic conductivity. Anisotropy can also result from lenses or pockets of material of different hydraulic conductivity within a matrix. A medium which is predominantly clay but includes sand stringers will have a higher horizontal conductivity than clay without the sand stringers.

To construct flow nets for anisotropic media, it is necessary to shrink the dimensions of the cross section in the direction of the higher hydraulic conductivity, or expand the dimension of the cross section in the direction of the lower hydraulic conductivity. If the horizontal hydraulic conductivity, k_h, is greater than the vertical hydraulic conductivity, k_v, then the reconstructed section can be reduced to a narrower horizontal dimension or expanded to increase the vertical dimension. If the reverse is true ($k_v > k_h$), the section could be lengthened horizontally or reduced vertically (Cedergren, 1977). Referring to Figure 3.14a, the expression $\sqrt{k_v/k_h}$ is multiplied by the horizontal dimension (x) to transform the cross section (Figure 3.14b). To transform the cross section vertically, one would multiply the vertical dimension by the expression, $\sqrt{k_h/k_v}$. After the cross section has been transformed, the flow net may be drawn as if it were in isotropic media. The dimension which has not been transformed remains the same.

After the flow net has been constructed, it may be desirable to view it in its original dimensions. This is done by dividing the dimension that was transformed by the expression used in the transformation, $\sqrt{k_v/k_h}$ or $\sqrt{k_h/k_v}$. When the cross section has been returned to its original dimensions, the flow net can then be reconstructed using the same number of flow lines and equipotential lines. Transforming the flow net in this way will not change the ratio of F to N and will not change any of the calculations made on the transformed section. The new flow net should be composed of rectangles elongated in the direction of high hydraulic conductivity. Note that the intersections between flow lines and

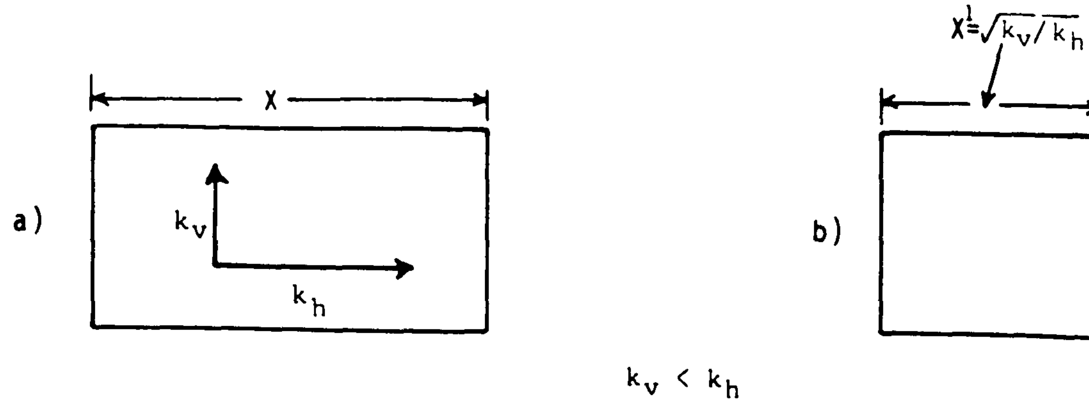


Figure 3.14. Shrinking of Anisotropic flow net.

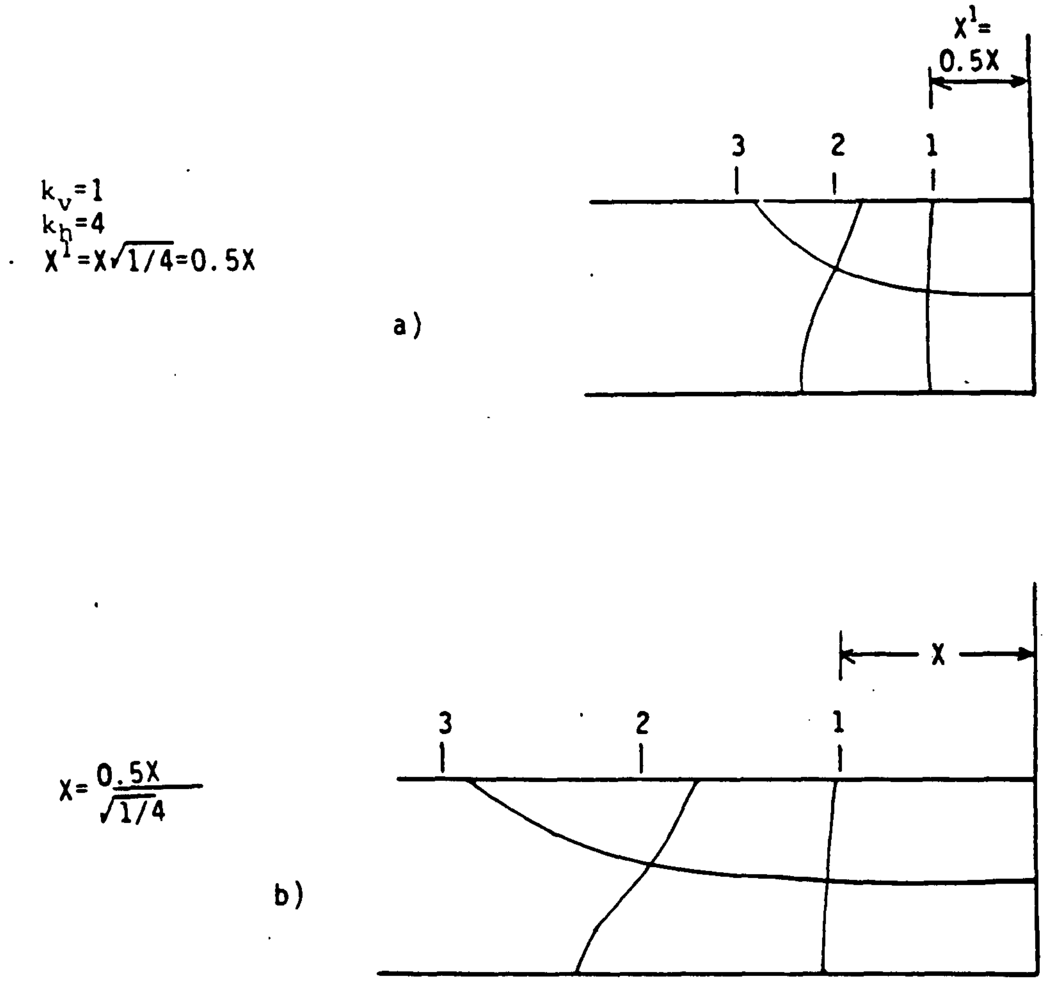


Figure 3.15. Elongation of flow net to original dimensions.

Source: Freeze and Cherry (1979).

equipotential lines will not necessarily be at right angles in this reconstructed view. Figure 3.15 demonstrates the procedure of returning a flow net to its original dimension, using a value of horizontal hydraulic conductivity which is four times greater than the value of vertical hydraulic conductivity. Figure 3.15a is the transformed flow net and Figure 3.15b is the flow net in the original scale.

After the flow net is transformed, it must be double checked to make sure that it appears to be reasonable. The rectangles should be elongated in the direction of greatest hydraulic conductivity. The ratio of F to N will remain the same and the expression $\sqrt{k_v \, k_h}$ will be used as the effective hydraulic conductivity in the transformed section.

Example of a Homogeneous Anisotropic Flow System

The geology and orientation of the site are the same as that shown earlier in Figure 3.13a with the same head distribution but different hydraulic conductivitites. For this example, only the upper silt layer is considered. The silt layer has sediments which are anisotropic, and the vertical hydraulic conductivity is 1/10th of the horizontal conductivity.

The hydraulic properties of the silt layer are:

$$k_v = 10^{-7} \text{ m/sec}$$

$$k_h = 10^{-6} \text{ m/sec}$$

$$n_e = 0.2$$

The value of $\sqrt{k_v/k_h}$ for the section is 0.316. The horizontal scale could be reduced to 31.6 pecent of the original, and/or both the horizontal and vertical scales could be increased or decreased so that the ratio of these dimensions is 0.316. In this example, the horizontal scale is 1 in. = 6 m and the vertical scale is 1 in. = 1.896 m (note that 1.896/6 = 0.316). Figure 3.16a shows the transformed geologic section.

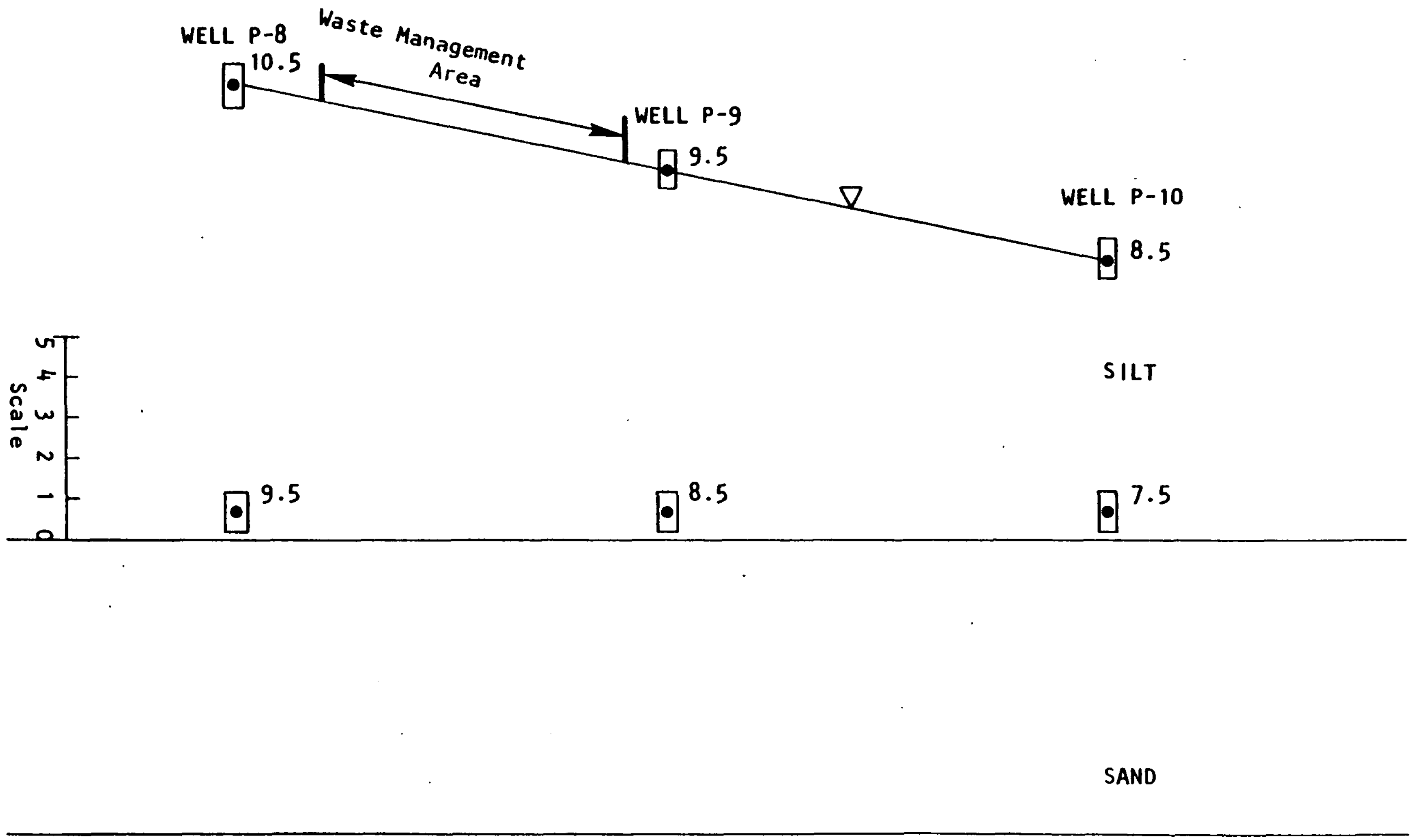


Figure 3.16a. Transformed section using available well data.

Flow net construction proceeds as if the sediments are isotropic, as shown in Figures 3.16b and 3.16c. Figure 3.16c shows the portion of the flow net that could originate under the waste management area. This occupies approximately one-fourth of a flow path. The upper boundary of this area is used as the flow path to determine TOT_{100}.

To determine TOT in the silt, the completed flow net is transformed back to its original dimensions (Figure 13.16d). The hydraulic gradient is determined from this transformed section and is equal to 0.09. The equivalent hydraulic conductivity of the silt layer is required to determine the seepage velocity through it. This value is determined by:

$$k_e = \sqrt{k_v \ k_h} = \sqrt{(1 \times 10^{-7})(1 \times 10^{-6})} = 3.16 \times 10^{-7} \text{ m/sec.}$$

The seepage velocity is:

$$v_s = \frac{k_e i}{n_e} = \frac{(3.16 \times 10^{-7} \text{ m/sec})(0.09)}{0.2} = 1.42 \times 10^{-7} \text{ m/sec or } 1.23 \times 10^{-2} \text{ m/day}$$

The associated TOT_{100} is 2480 days or 6.8 years. Thus, the estimated TOT has increased by two orders of magnitude as conditions have changed from isotropic to anisotropic, with vertical conductivity an order of magnitude less than horizontal conductivity.

Flow Net Construction in Heterogeneous, Anisotropic Systems

Construction of flow nets in heterogeneous, anisotropic systems follows the previously discussed rationale for flow net construction in homogeneous, anisotropic systems with the additional factor that the ratio between vertical hydraulic conductivity and horizontal hydraulic conductivity in the uppermost layer of the system is assumed to be representative of the directional ratio of conductivities in the lower layers. This assumption is based on the likelihood that, in most sedimentary material, the horizontal hydraulic conductivity is expected to be larger than the vertical hydraulic conductivity. In terms of practicality, if the assumption is made that the

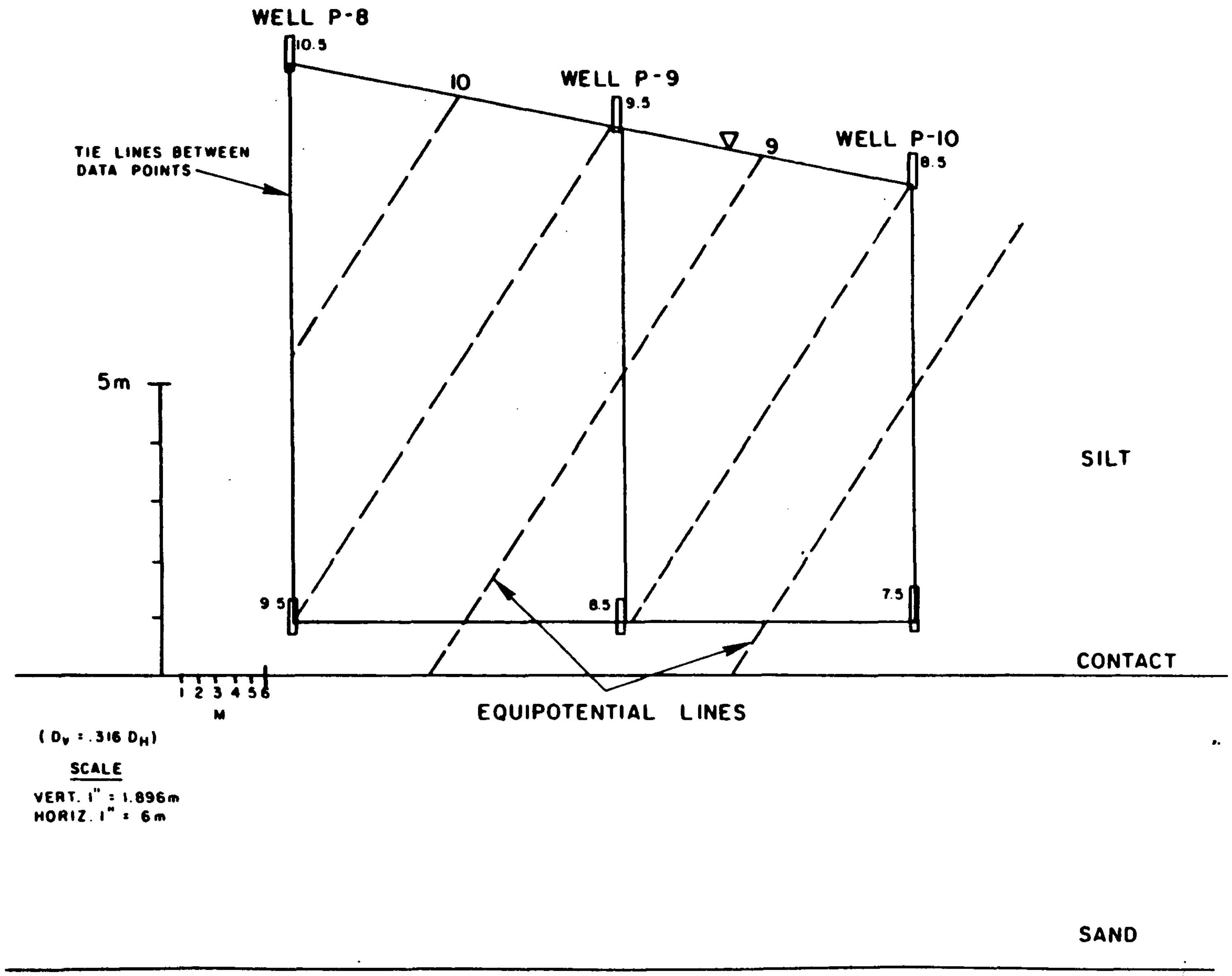


Figure 3.16b. Contouring to determine placement of equipotential lines.

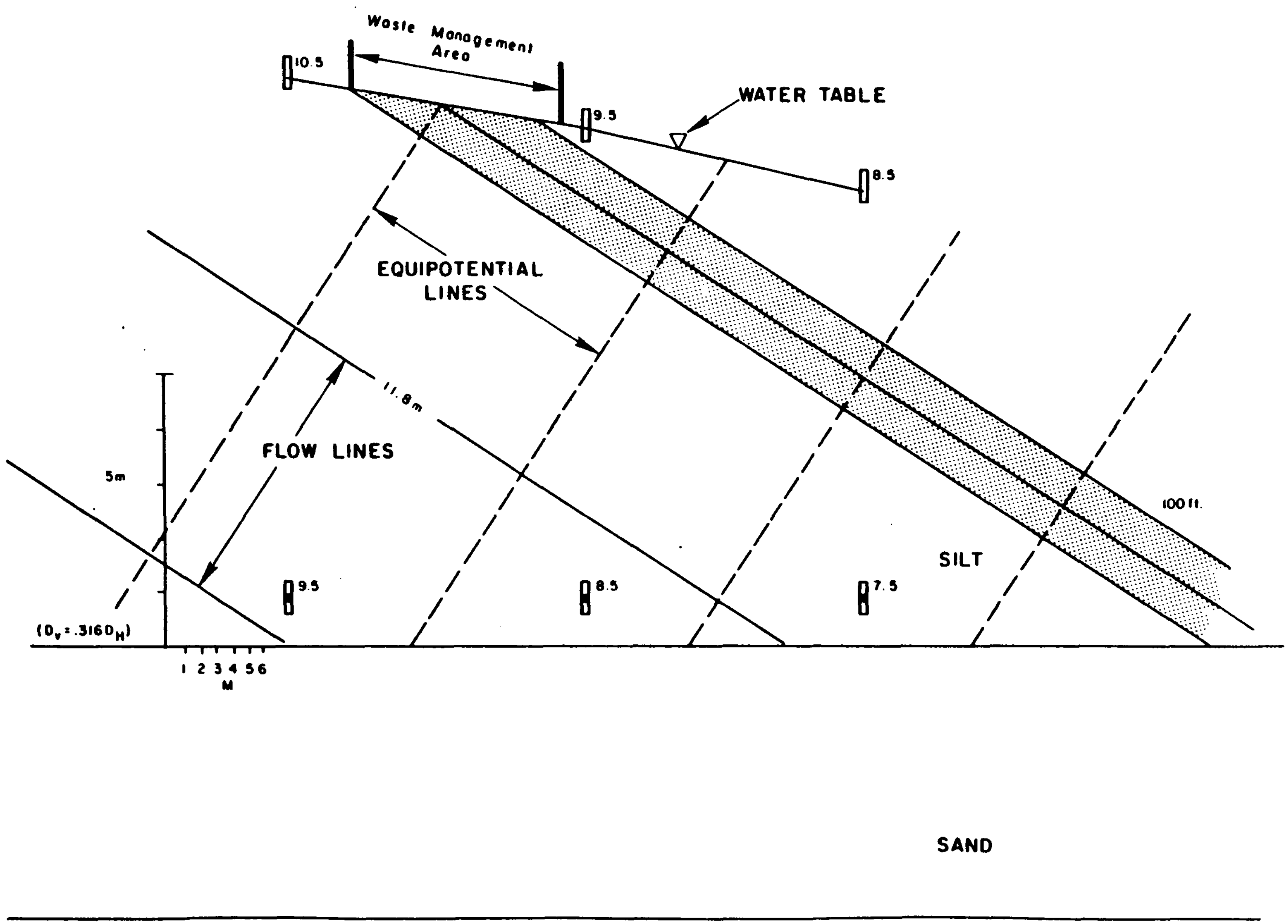


Figure 3.16c. Flow net construction in the silt layer.

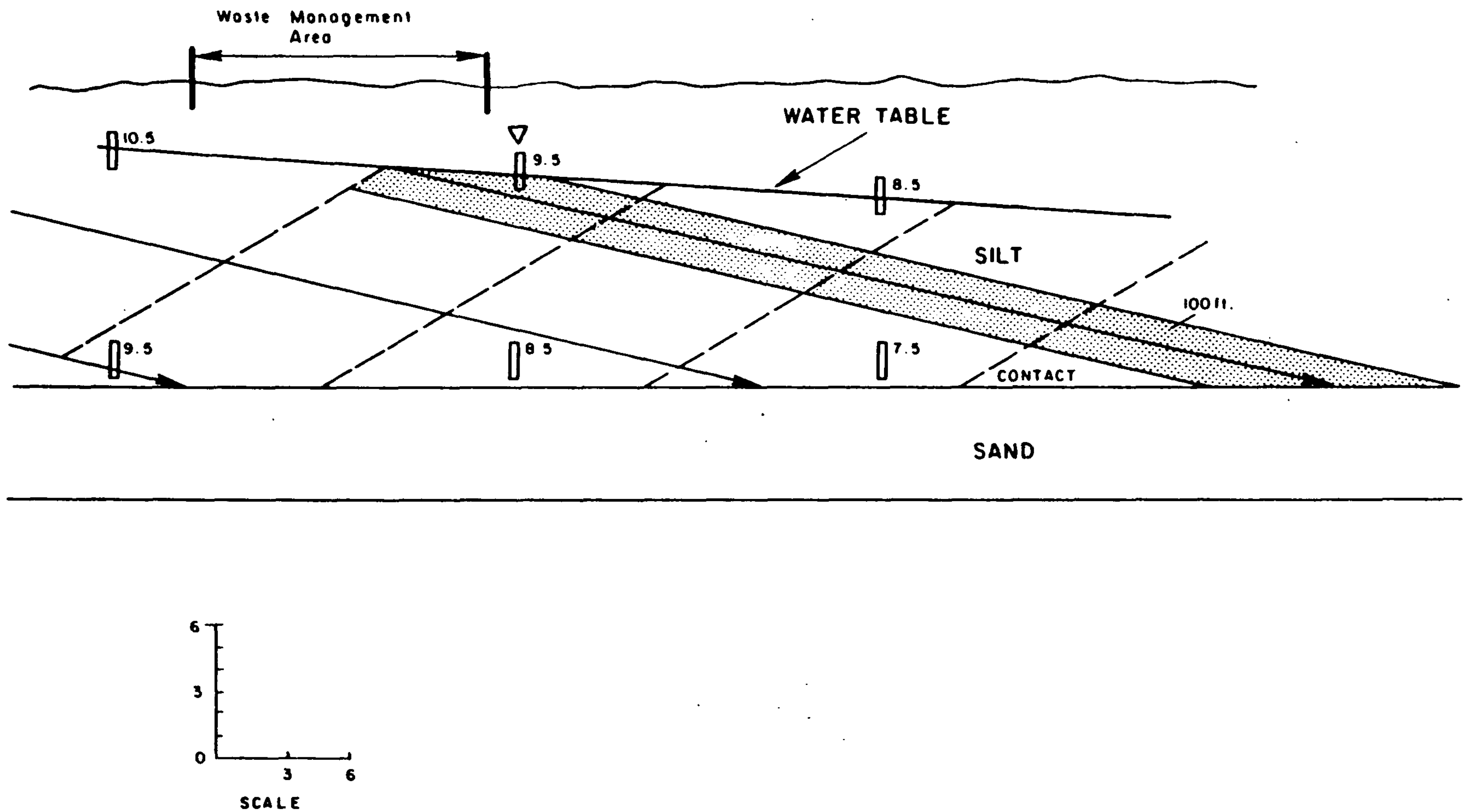


Figure 3.16d. Flow net for silt layer returned to original dimensions.

ratio of horizontal to vertical hydraulic conductivity is different from that of the overlying sediments, then separate flow nets would have to be constructed for each layer by using information from the upper layer as the starting point for construction of the lower layer. Additionally, the dimensions of this new flow net would have to be adjusted to the conductivity ratio in the next layer and so on throughout the system. The latter approach should be followed, however, if geologic data indicate that such conditions occur in reality and the 100 foot flow line of concern passes into such media.

SECTION 4

CONSTRUCTION OF FLOW NETS IN SPECIAL SETTINGS

This section provides examples for the construction of flow nets and the calculation of TOT_{100} for special geologic settings. The settings include a ground water mound over a leaking lagoon, complex hydrogeology in an arid region, fractured bedrock environments, seepage face flow conditions, and free surface flow conditions.

EXAMPLE OF A GROUND WATER MOUND OVER A LEAKING LAGOON

The waste management unit of concern is an existing lagoon which was used for disposal of waste water from a metal plating and finishing plant. The lagoon was considered to be an evaporation lagoon by the owner because it did not overflow and did not require pumping. Consequently, the owner elected not to monitor the lagoon. During site closure, however, the possibility of subsurface leaking was noted.

Figure 4.1 provides a plan view of the site, and the location of the ground water investigation well and piezometers. Site geology consists of 40 to 60 feet of glacial outwash sand overlying a layer of glacio-lucustrin silt/clay of unknown depth. The outwash sands are believed to be part of a delta formed from an ice-dammed lake. The presence of the clay has been determined from one short boring and shallow seismic refraction work. No piezometers have been installed in the clay.

Based on review of the Part B permit application, it is evident that the applicant considers the ground water in the sand to be perched above the clay and asserts that ground water flow is basically horizontal. The applicant also believes that there is no basis for the placement of monitoring wells in the clay or any need to investigate below the clay sediments. Additionally, the applicant stated that by drilling into or through the clay, connections may be created between the upper sand layer and deeper aquifers.

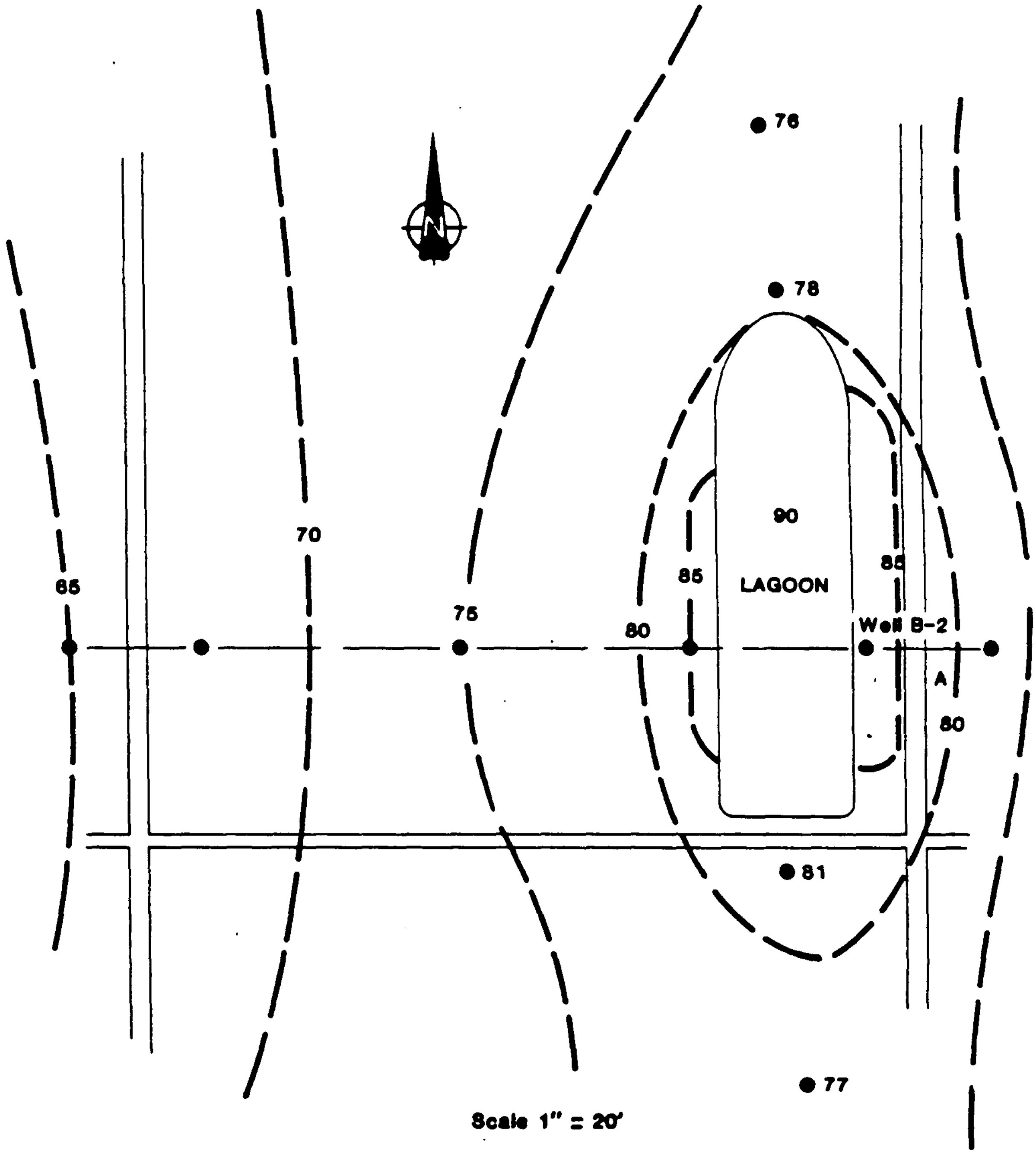


Figure 4.1. Well location and water table contour map for sand/gravel underlain by clay.

The intent of drawing the vertical flow net is to investigate the claims made by the applicant, determine the vulnerability of the site, and to determine the need for additional work.

Figure 4.2a presents a cross section through the subsurface below the waste management area indicating the measuring points determined for each well and piezometer. The tie lines between each data point are shown. Several points should be noted about the cross section. First, the bottom of the lagoon forms a fixed head boundary. The head at this boundary is the elevation of the liquid in the lagoon which is 90 feet. The bottom and the sides of the lagoon below the water level represent an equipotential line. Flow lines that emerge from the lagoon will be at right angles to the bottom of the lagoon. Second, any equipotential line that intersects the water table does so at its characteristic hydraulic head. Third, because the clay sediments have a lower hydraulic conductivity than the overlying sand, the flow lines entering the clay will bend toward an imaginary line normal to the contact between the two sediments.

Contouring the head data gives an approximate equipotential map as shown in Figure 4.2b. Five-foot contour intervals were selected for the equipotential drops. This map gives some idea of the final shape of the flow net but cannot, at this point, be used to determine the quantity of flow or TOT_{100}.

Flow lines are now added to the equipotential map. The flow lines and the equipotential lines are shifted as needed to form squares. Depending on the complexity of the head distribution, 3 to 20 iterations can be expected. The equipotential lines cannot be moved in any way that would violate the known data points at each well or piezometer location.

Figure 4.2c is the final flow net. The right hand side of the figure, where the mound flow merges with the natural ground water, has not been completed because of the lack of data in this area. One large square has been subdivided to provide the necessary detail in shaping the squares in this area. By doing so, the 75 foot contour enters the bottom of the same layer even though data are not available in this area.

The flow net indicates that:

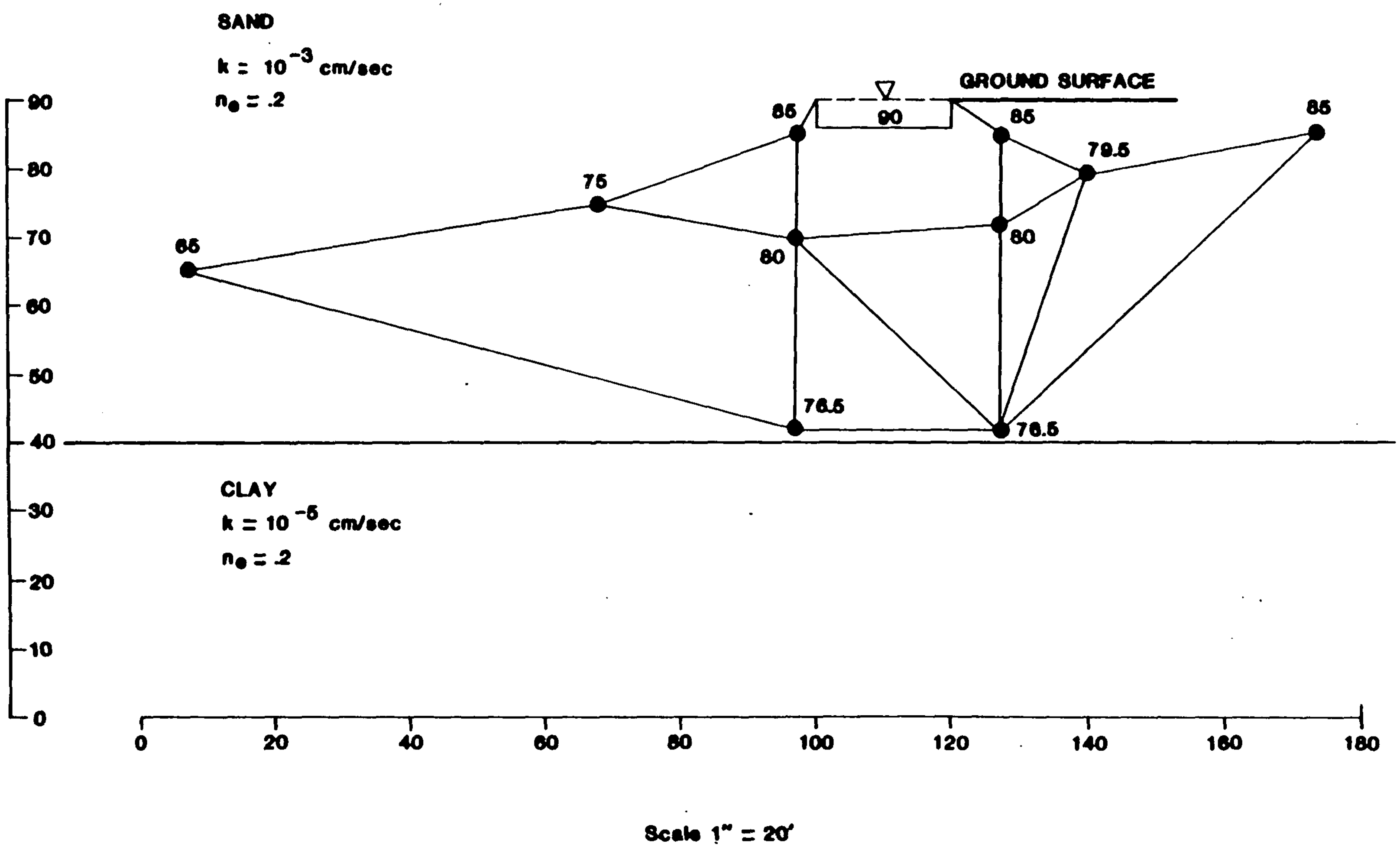


Figure 4.2a. Construction of tie lines to allow contouring to determine equipotential lines.

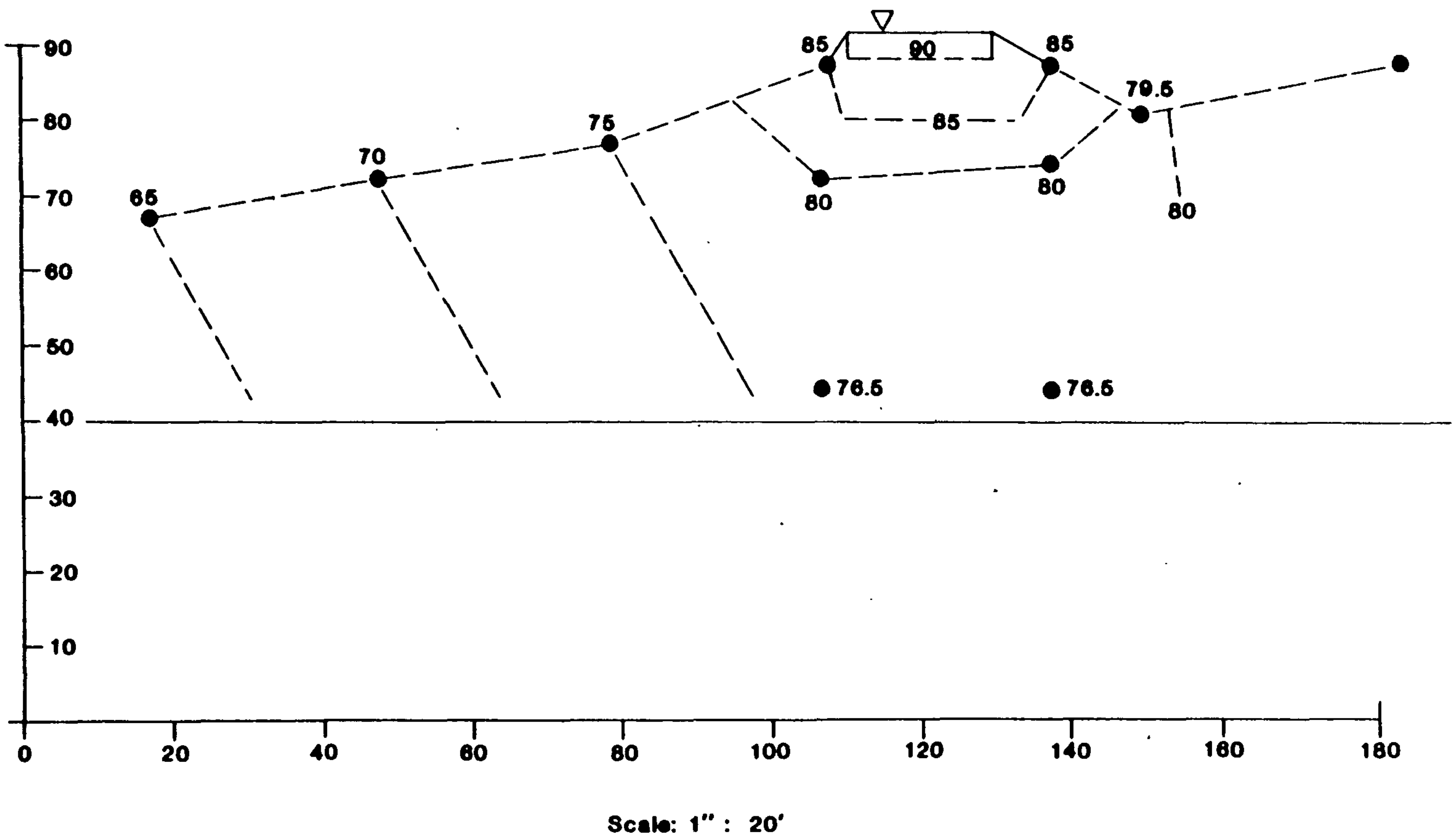


Figure 4.2b. Approximate equipotential map based on contouring of data points.

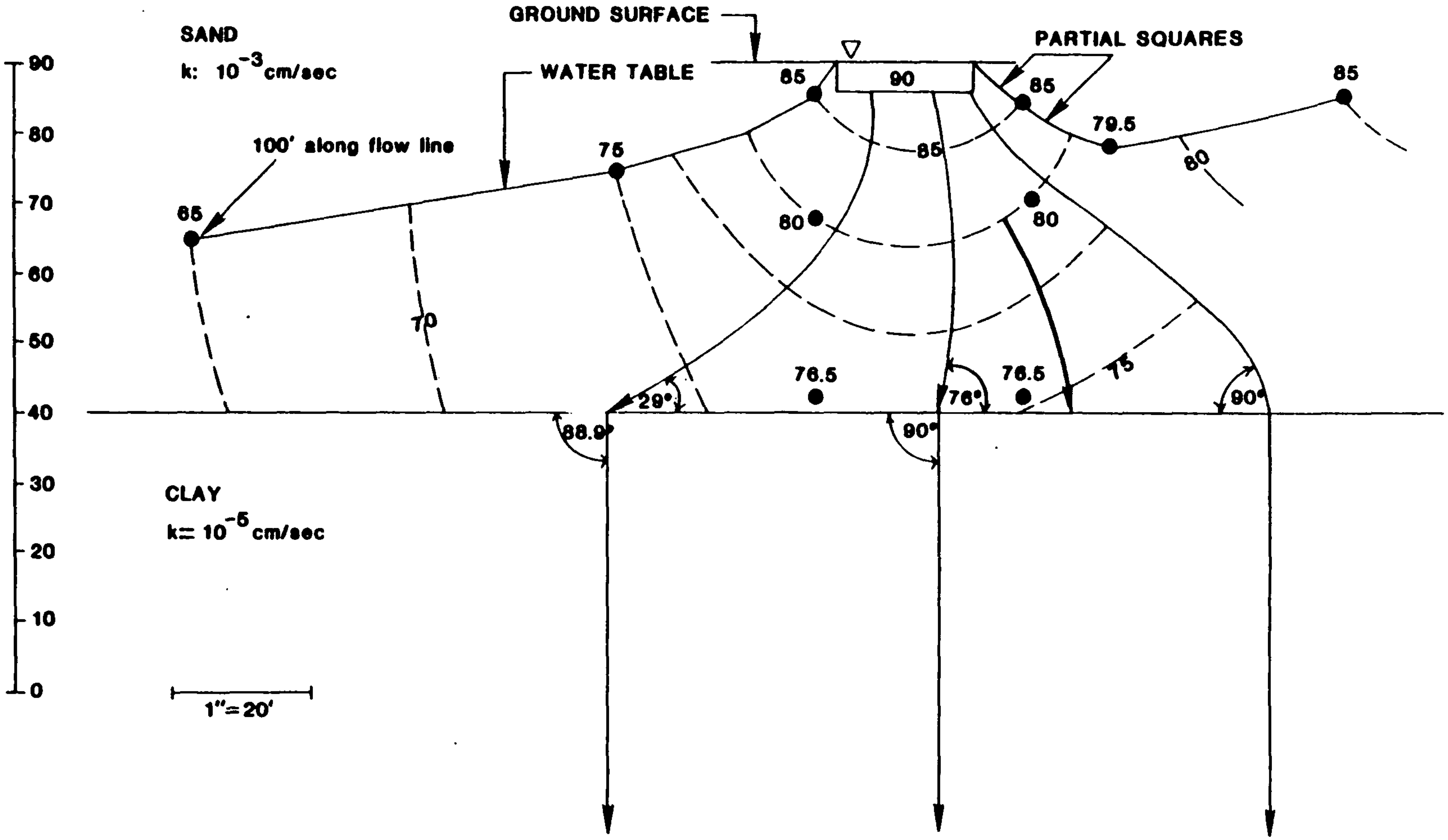


Figure 4.2c. Flow net for mound example.

- approximately 3.5 flow paths emerge from the lagoon,
- the influence of the lagoon extends to the base of the sand layer and probably through the clay layer, and
- the majority of the flow from the lagoon enters the clay strata and only about one-half to one flow path remains in the sand at the left side of the flow net.

By considering that 3.5 flow paths leave the base of the lagoon and by calculating the flow through one square, the total leakage from the lagoon can be determined. Using $i = 0.56$, $A = 8\ ft^2$, and $k = 2.83$ ft/day; flow through one square of unit thickness is:

$$q = kiA = (2.83)(0.56)(8) = 12.7 \text{ cubic feet /day.}$$

Leakage from the lagoon bottom through all flow paths in the cross section is:

$$Q = (3.5)(12.7) = 44.5 \text{ cubic feet/day.}$$

The calculated Q applies to a 1-foot thickness of lagoon bottom. Considering the lagoon length of 700 feet, the total flow from the lagoon is:

$$Q(\text{lagoon}) = (700)(44.5) = 31{,}200 \text{ cubic feet/day.}$$

TOT_{100} is determined by locating the flow line in the sand layer that represents the highest ground water velocity. A flow line near the water table was selected. Knowing that the effective porosity is 0.2, the seepage velocity and TOT_{100} along this flow line are calculated as:

$$v_s = \frac{ki}{n_e} = \frac{(2.83)(0.56)}{0.2} = 7.9 \text{ ft/day}$$

$$TOT_{100} = \frac{L}{v_s} = \frac{100}{7.9} = 12.7 \text{ days}$$

The tangent law indicates that the ground water flow will be nearly vertical, directed downward through the clay layer. The shape of the flow net in the clay strata will be rectangles with the length of the rectangle 100 times the width (47 feet to 0.47). This follows from the ratio, (k_{sand}/k_{clay}).

In assessing the applicant's claim that any leakage from the lagoon would stay in the sand, the flow net indicates that the majority of the lagoon leakage enters the clay layer.

EXAMPLE OF COMPLEX HYDROGEOLOGY IN AN ARID REGION

The following example points out typical problems that may be encountered in drawing flow nets for cases with complex geology and hydrology. Additionally, the example shows that in complex areas where construction of a complete flow net is not possible, TOT can still be estimated.

The cross section of the proposed site shows a 50 to 60 ft thick gravel deposit above a 10 to 20 ft thick vetric tuff layer which overlies a 150 to 200 ft thick water worked tuffaceous layer which overlies a series of basalt flows with interflow deposits. The first continuous saturated zone lies in the water worked tuff, 150 to 170 ft below the ground surface. The thickness of the saturated zone varies from 0 to over 100 ft depending upon the topography and the amount of fracturing in the underlying basalt flow.

Figure 4.3 indicates the locations of the wells that were installed during site investigations, and shows the proposed point of compliance wells. The location of the cross section selected for flow net analysis is also shown. Figure 4.4a indicates the location of the midpoints of the wells and piezometers, all of which are in the tuff deposit or the underlying basalt. Table 4.1 provides horizontal hydraulic conductivity data based on slug tests and packer tests conducted in wells along the cross section.

Pump tests were conducted to measure the vertical hydraulic conductivity of the tuff and basalt, indicating an average of about 2.7×10^{-7} cm/sec in each medium or about one to two orders of magnitude below the horizontal

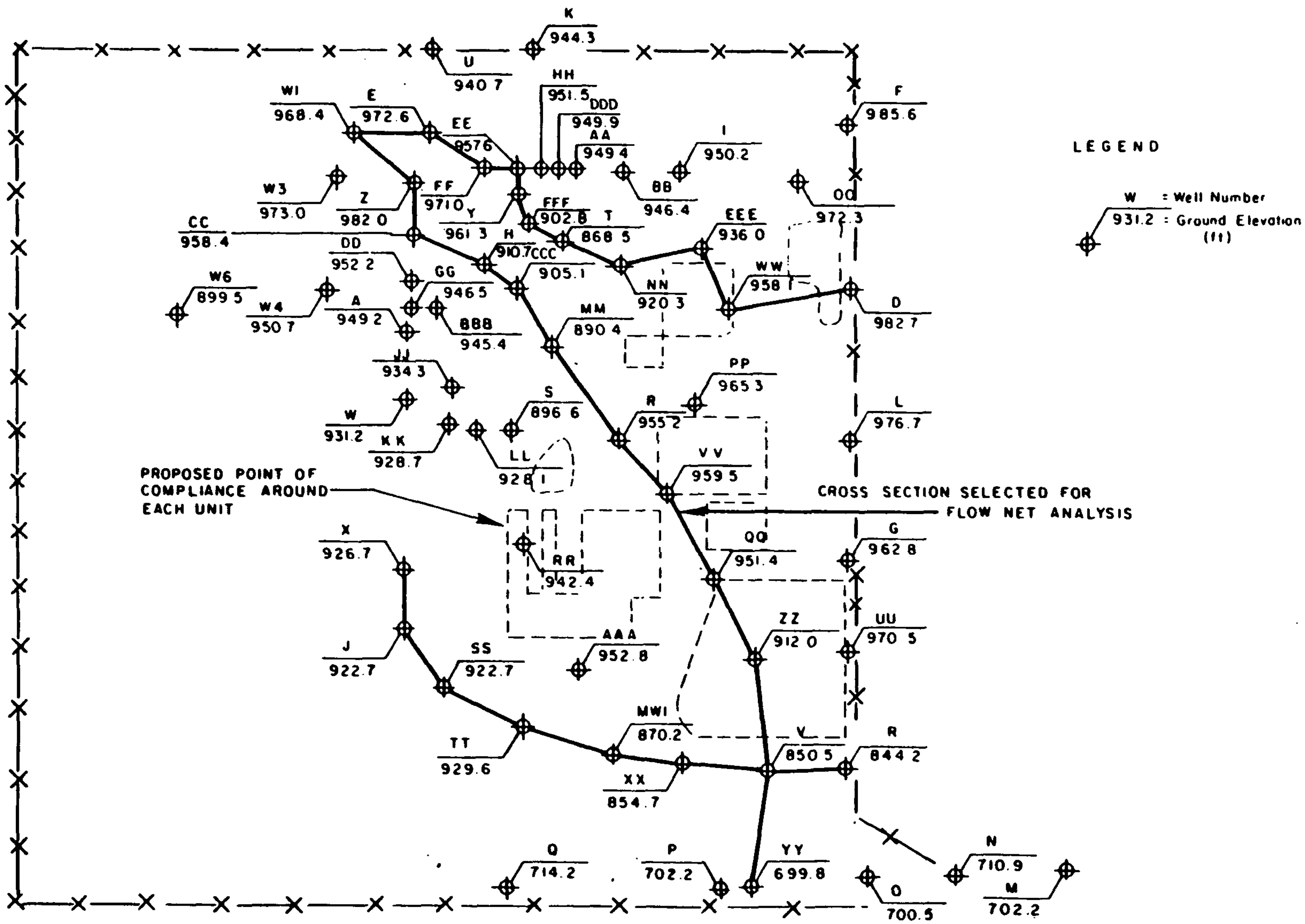


Figure 4.3. Well location map.

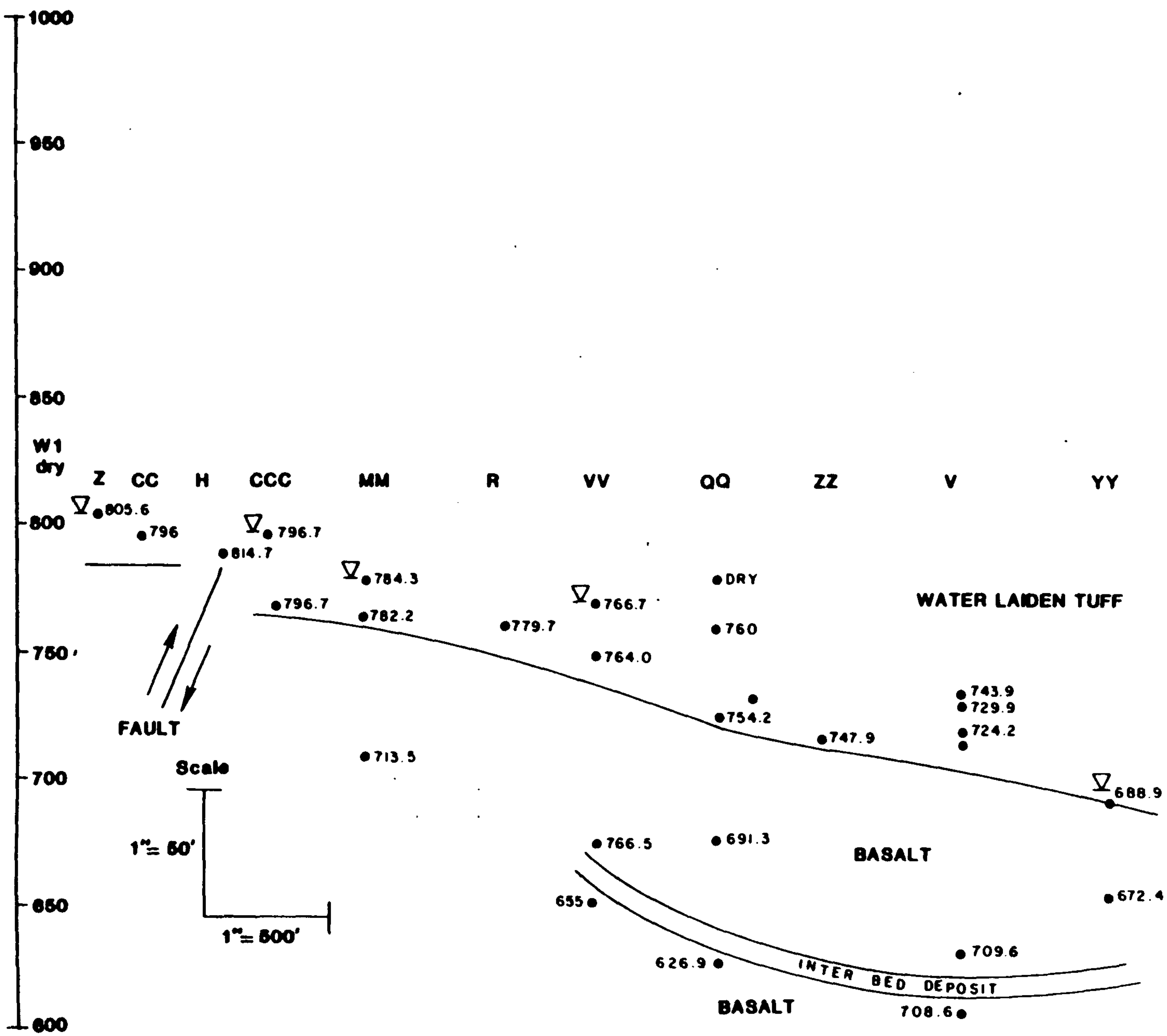


Figure 4.4a. Cross section showing hydraulic head data.

TABLE 4.1. HORIZONTAL HYDRAULIC CONDUCTIVITY DATA FROM SLUG TESTS AND PUMP TESTS

Well I.D.	Geologic unit	k-cm/sec
V	Basalt	$2.99x10^{-5}$ (average from
	Tuff	$2.31x10^{-6}$ slug tests)
QQ	Tuff	$7.52x10^{-6}$
	Basalt (top 30')	$2.64x10^{-4}$
	Basalt (bottom)	$6.34x10^{-7}$
YY	Basalt	$2.11x10^{-4}$
VV	Basalt	$9.61x10^{-5}$ to $1x10^{-8}$
R	Tuff	$1.89x10^{-4}$
MM	Tuff	$7.73x10^{-5}$
	Basalt	$2.64x10^{-4}$ to $4x10^{-6}$

hydraulic conductivities given in Table 4.1. Based on the conductivity difference of 100:1, the horizontal axis of Figure 4.4 has been reduced by a factor of 10:1 (e.g., $\sqrt{k_h/k_v}$). The flow net is now drawn as if the subsurface materials were isotropic.

The system of tie lines drawn between data points is shown in Figure 4.4b. The tie lines can now be used for interpolation without consideration of site layering. A 10 foot contour interval is considered reasonable for this system. After interpolating to determine the location of intermediate equipotential lines, an approximate equipotential map can be drawn as shown in Figure 4.4c. Upon completion, the geologic layering is superimposed onto the map.

The approximate equipotential map indicates that the gradients in the tuff are generally less than those in the basalt. In the basalt, however, there are zones of very low gradients and very steep gradients. These variations reflect the changes in hydraulic conductivity noted in Table 4.1.

The equipotential lines in the tuff layer have unusual shapes. These lines are probably artifacts of the contouring process because some lines would require discharge of ground water upward to the unsaturated sediments, which is not possible. In Figure 4.4d, many of these unusual equipotential lines have been smoothed, such that the orientation of the equipotential lines is consistent with the downward gradients present in the ground water mound between wells MM and R.

The next step in the flow net construction process for this site is to add flow lines, as shown in Figure 4.4d. In a geologic setting where the hydraulic conductivity varies over a wide range within the same layer, it is impossible to determine where a boundary is crossed and the accompanying degree of flow line deflection. In such cases, it is generally useful to inspect the flow in a limited portion of the whole system. Flow lines will continue to cross the equipotential lines at right angles because the section is already transformed. To construct the flow net, a number of representative flow lines can be placed on the equipotential map. The majority of the flow will be in areas other than the low hydraulic conductivity areas of basalt with the highest gradients. The equipotential map indicates that there are two

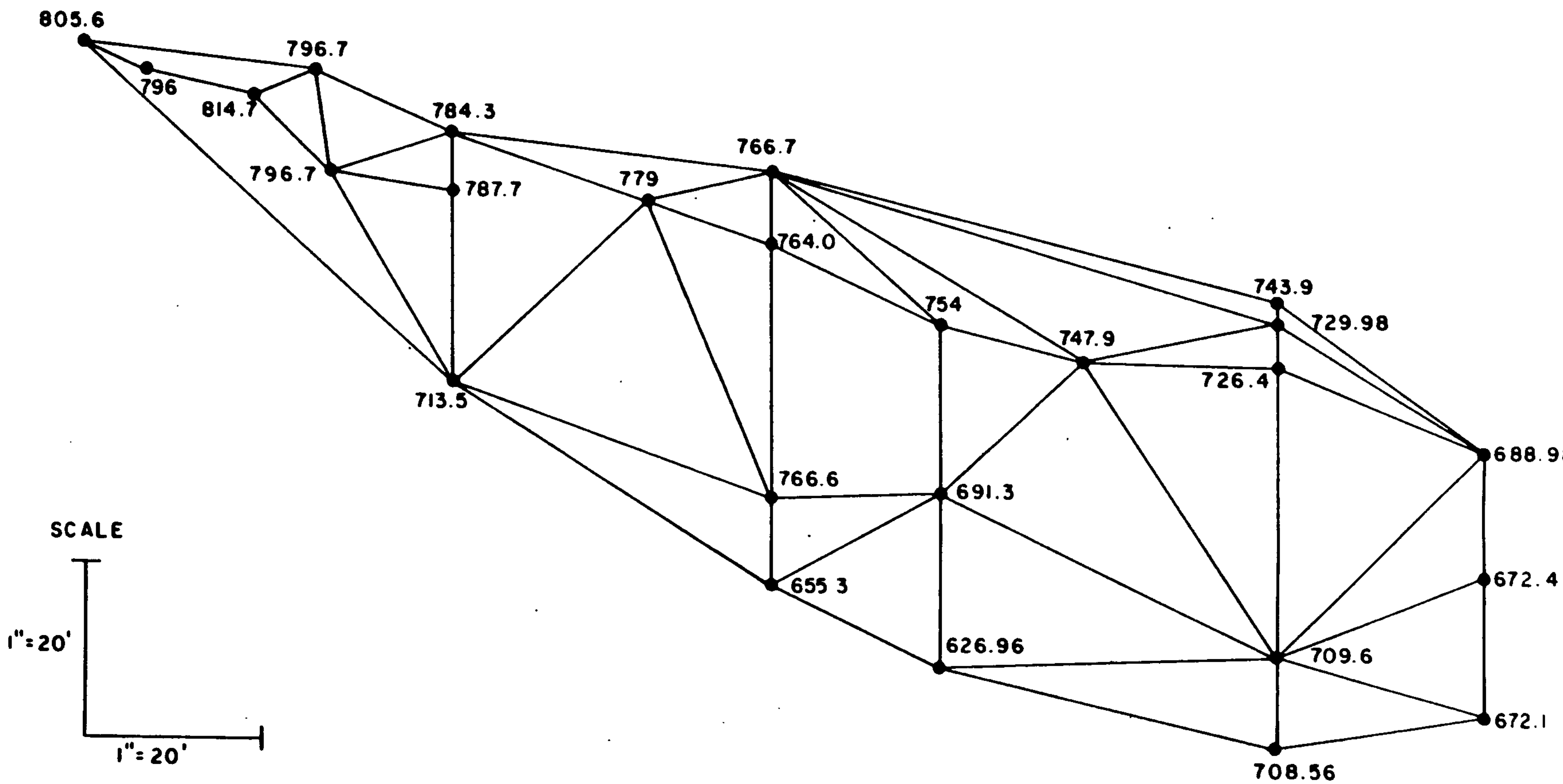


Figure 4.4b. Construction of tie lines for interpolation of equipotential head values.

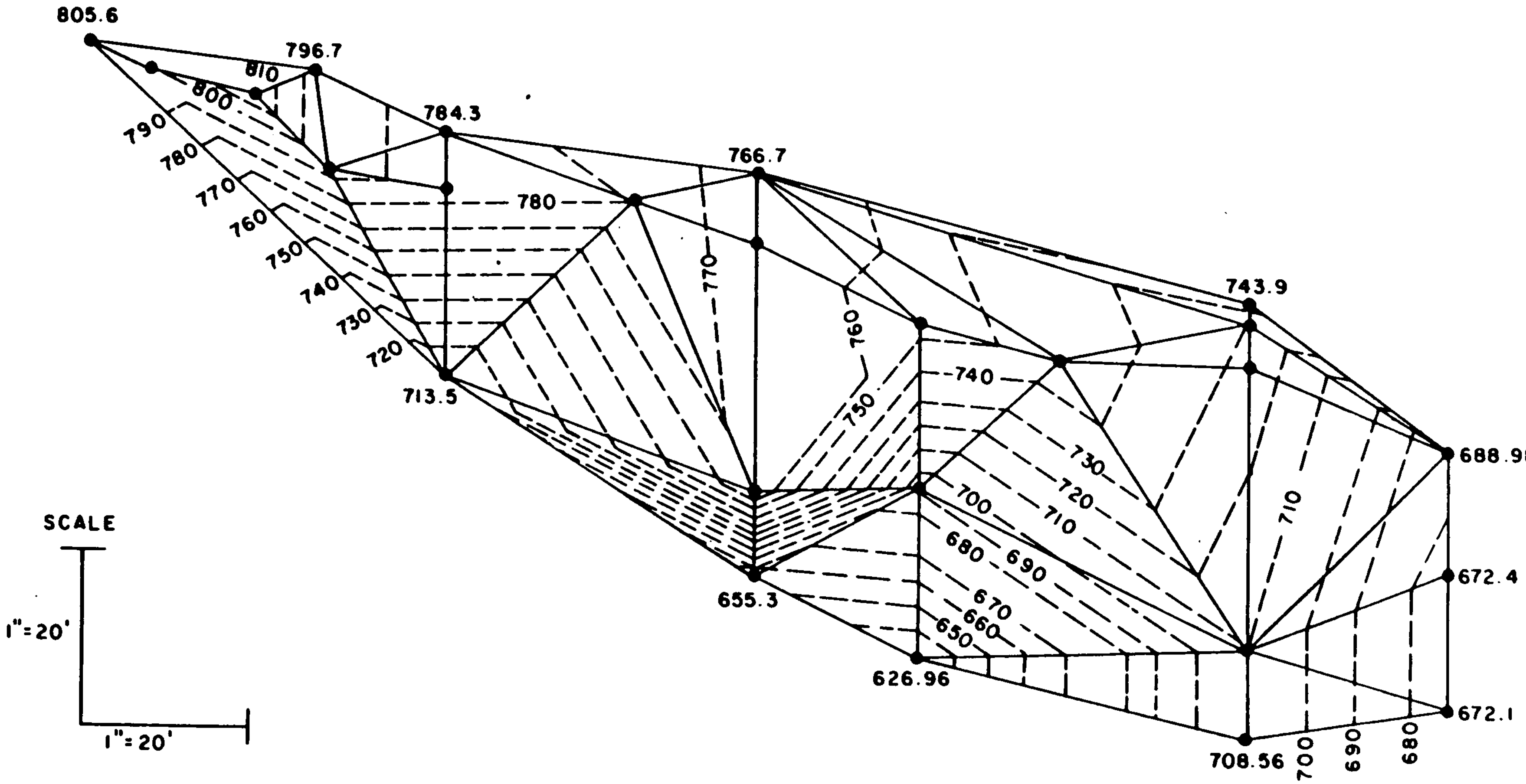


Figure 4.4c. Approximate equipotential map.

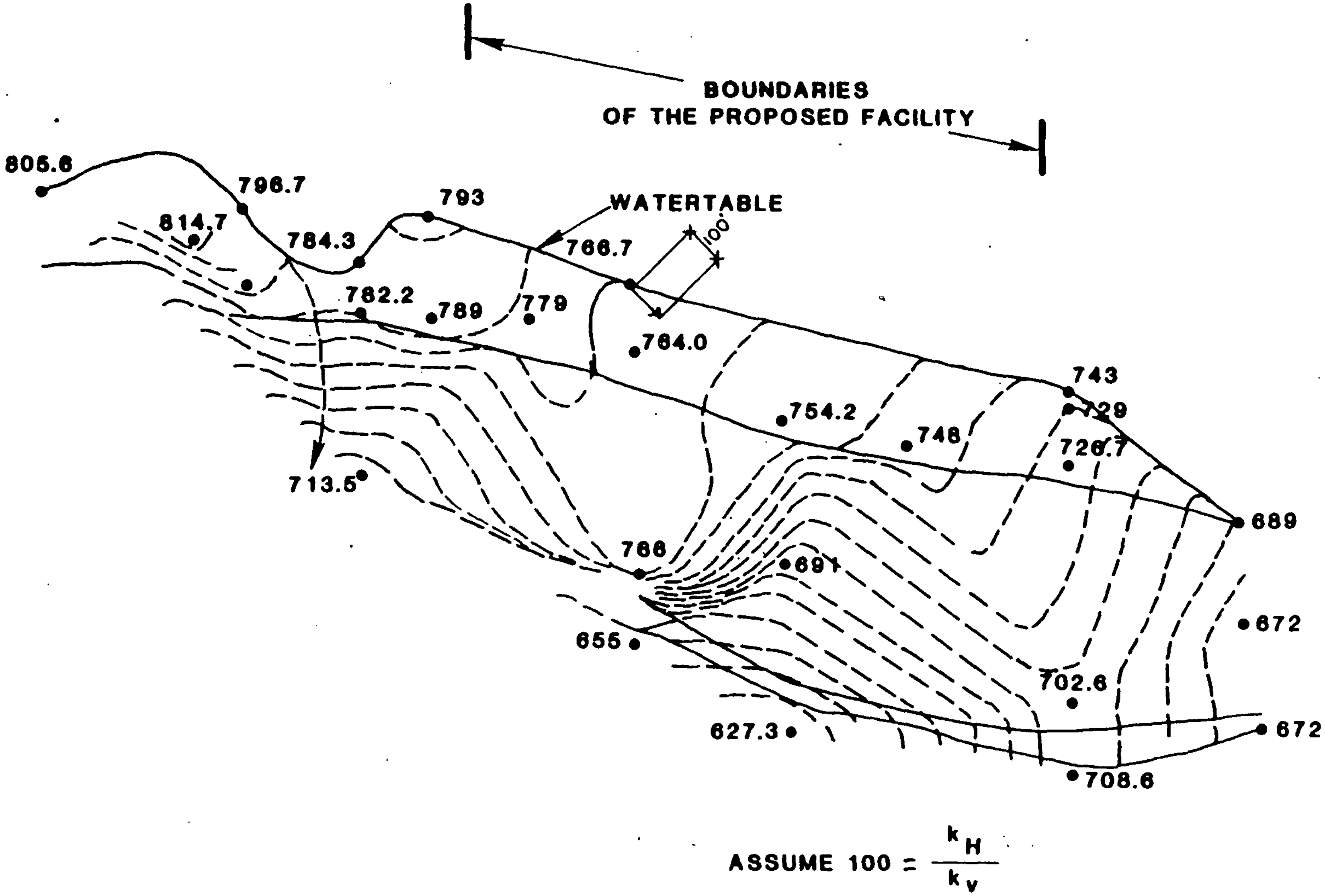


Figure 4.4d. Approximate flow net.

zones in the basalt that have significantly higher hydraulic conductivities than the medium as a whole. These areas probably represent zones of fracturing in the basalt.

TOT_{100} can be determined by selecting the flow path that represents the highest ground water velocity. This path will be the zone that has tha lowest hydraulic gradient and could be represented by the flow path that passes near well W and well Q in the tuff. By measuring along this flow line in the basalt, the hydraulic gradient is determined to be 0.025 (10/400). Because there are no hydraulic conductivity data for the tuff at well W (the area of lowest gradient), the highest hydraulic conductivity for the tuff, as documented in Table 4.1, will be assumed.

Geophysical logging results indicate that the porosity of the tuff is about 40 percent. However, the storage coefficient ranges from 0.01 to 0.1 based on pump test data. Because the saturated zone in the tuff is unconfined, it is reasonable to assume that the effective porosity, n_e, is approximately equivalent to the storage coefficient determined in the pump test.

The seepage velocity and TOT_{100} for the site can be determined as follows:

$$v_s = \frac{ki}{n_e} = \frac{(1.89 \times 10^{-4} \text{ cm/sec})(0.25)}{0.01} = \frac{(0.535 \text{ ft/day})(0.025)}{0.01} = 1.34 \text{ ft/day}$$

$$TOT_{100} = \frac{100 \text{ ft}}{v_s} = \frac{100 \text{ ft}}{1.34 \text{ ft/day}} = 74.7 \text{ days}$$

CONSTRUCTION OF FLOW NETS FOR FRACTURED BEDROCK ENVIRONMENTS

In order to construct a flow net for a fractured bedrock ground water system, it must be assumed that the system hydrology behaves similar to granular porous media. This would be the case if the fracture density of the system was high, but variations in fracture spacing may cause the material to exhibit heterogeneity or anistropy. Therefore, it is necessary to evaluate the fracture density of the system before constructing the flow net to ensure that the assumption of porous media flow conditions is valid for the system. If the fracture density of a system is low, it may be necessary to attempt to analyze the flow in terms of individual fractures. However, in systems where the fractures are large and turbulent flow conditions exist, Darcy's Law is not valid. For these sytems, a method other than flow net construction must be used to calculate ground water flow rates (Bear, 1972).

An example of a hazardous wate management site overlying fractured bedrock is shown in Figure 4.5. The ground water system is comprised of a permeable basalt flow overlying fractured basalt which overlies impermeable basalt. The permeable basalt layer has a measured hydraulic conductivity of 10^{-7} m/sec at well 5, based on pump tests. The fractured basalt has a measured conductivity of 10^{-5} m/sec. For the purpose of demonstration, porous media laminar flow is assumed. The basalts are assumed to be isotropic. Ground water flows through the aquifer in a northerly direction as determined from measurements at several wells in the area. Using well data from Table 4.2 and the map in Figure 4.5, the flow through the aquifer can be calculated by following the rationale noted below.

A cross section is constructed based on the map and well data, using a scale of 1 in = 25 m. An approximate equipotential map of the head data and a flow net for the permeable basalt are drawn using the water level elevations indicated in Table 4.2.

The approximate equipotential map indicates a relatively low gradient in the top of the upper basalt flow layer. A zone of higher hydraulic conductivity at the top of basalt flows is common. The noted low gradient zone probably corresponds to a higher conductivity zone. Because the low hydraulic conductivity, high gradient zone in the center of the basalt flow controls the flow in the system, the flow net analysis focuses on this region.

The squares shown in Figure 4.6 represent a head drop of 30 m between equipotential lines with 25 m wide flow paths. The hydraulic conductivity varies between the upper zone and the center zone by a factor of about 30 to 1 (3×10^{-6} m/sec vs. 1×10^{-7} m/sec). Because flow in the basalt is approximately perpendicular to the contact between the two zones, no deflection of the flow lines occurs. However, the tangent law is used to calculate the angle of flow line deflection, σ_2, as ground water flows into the fractured basalt:

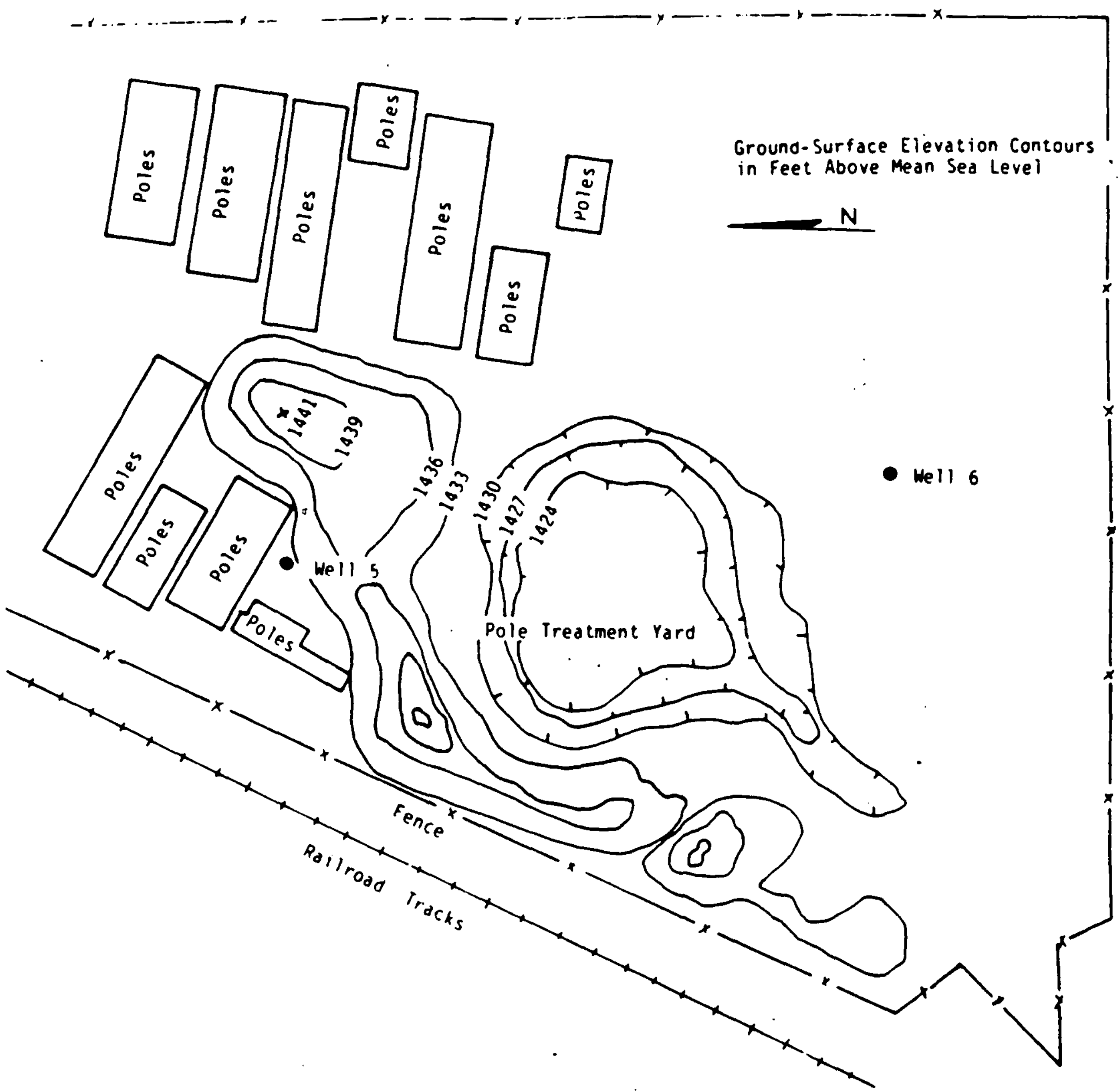


Figure 4.5. Well location map and ground-surface elevations for fractured bedrock example.

TABLE 4.2. WATER LEVEL AND STRATIGRAPHY FOR MONITOR WELLS IN FRACTURED BEDROCK EXAMPLE

Well Data	Well No. 5A (m)[a]	Well No. 5B (m)	Well No. 6 (m)
Ground Surface Elevation	1,431	1,431	1,432
Elevation of First Encountered Water During Drilling[b]	1,412	1,412	1,413
Water-Level Elevation in Wells (Screened portion is shown in Figure 4.6)	1,410	1,380	1,410
Fractured Basalt Layer Elevation (Top)	1,374	1,374	1,374
Fractured Basalt Layer Elevation (Bottom)	1,364	1,364	1,366

All elevations in meters AMSL.

[a]A well is shallow; B well is deep.

[b]Assumed equal to the water-table surface because the aquifer is unconfined.

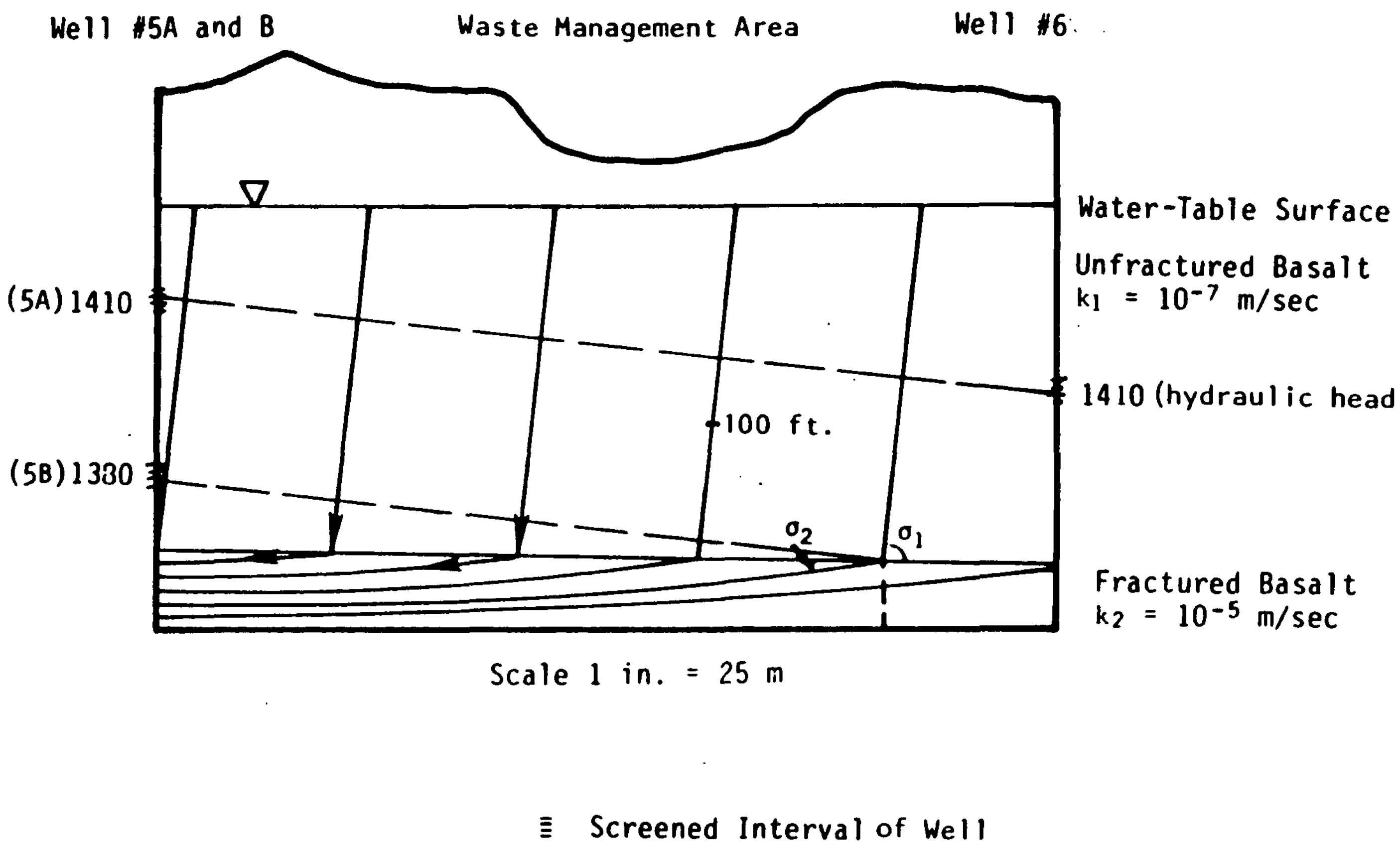


Figure 4.6. Flow net for fractured bedrock example.

$$\frac{k_1}{k_2} = \frac{\tan \sigma_2}{\tan \sigma_1}$$

where:

$$\sigma_1 = 85°$$

then:

$$\frac{1 \times 10^{-7} \text{ m/sec}}{1 \times 10^{-5} \text{ m/sec}} = \frac{\tan \sigma_2}{\tan 85°}$$

$$\sigma_2 = 6.5°$$

Construction of the flow net is continued into the fractured basalt as shown in Figure 4.6. Distance between equipotential lines in the fractured basalt is 100 times greater than that in the unfractured basalt based on the difference in conductivity of a factor of 100.

The total flow through the system can be calculated using the flow net in the upper basalt. The flow through one square is multiplied by the number of flow paths in the upper basalt layer to estimate the flow through the system. In this example:

$F = 5$	(from flow net)
$k = 1 \times 10^{-7}$ m/sec	(from data)
$H = 30$ m	(from data)
$N = 1$	(from flow net)

Total flow for the cross section of unit width is calculated below:

$$Q = \frac{(1 \times 10^{-7} \text{ m/sec})(5)(30 \text{ m})}{1}$$

$$Q = 1.5 \times 10^{-5} \text{ m}^3\text{/sec}$$

TOT_{100} is calculated based on a hydraulic gradient of approximately 1.2, as determined from Figure 4.6 or the data presented in the text. The applicant has indicated an effective porosity for the unfractured basalt of 0.1.

The seepage velocity is:

$$v_s = \frac{ki}{n_e} = \frac{1 \times 10^{-7}(1.2)}{0.1} = 1.2 \times 10^{-6} \text{ m/sec}$$

$$\text{or } 3.4 \times 10^{-1} \text{ ft/day}$$

The associated TOT_{100} is:

$$TOT_{100} = \frac{100 \text{ ft}}{0.34 \text{ ft/day}} = 294 \text{ days}$$

CONSTRUCTION OF FLOW NETS IN SEEPAGE FACE CONDITIONS

A seepage face develops when a saturated-unsaturated flow system exists at a free outflow boundary, such as a stream bank. In this case, the ground water flow will leave the system across the seepage face. The intersection of the water table and the ground surface at the stream bank defines the upper boundary of the seepage face. Freeze and Cherry (1979) provide an indepth explanation of this phenomenon and ramifications for drawing flow nets.

Consider the case of a landfill located high on the bank of a river. In this example, an irrigation ditch upgradient from the landfill introduces water which seeps through the landfill. After the water passes through the landfill, it flows through a layer of sand and silt that forms the top portion of the river bank. The water table and river bank intersect at a point, the elevation of which measures 315 m (the top of the seepage face). Impermeable bedrock is located below the sand and silt and acts as a boundary to ground water flow.

A monitoring well installed 78 m downgradient from the irrigation ditch shows that the ground water level is at the ground surface during the summer months when the irrigation ditch is in operation. Through use of the cross section shown in Figure 4.7, ground water discharge into the river can be calculated. The flow net is drawn, as presented in Figure 4.8. The irrigation ditch is a constant-head boundary, the underlying bedrock is impermeable, and the water flows out of the seepage face. The top exit point

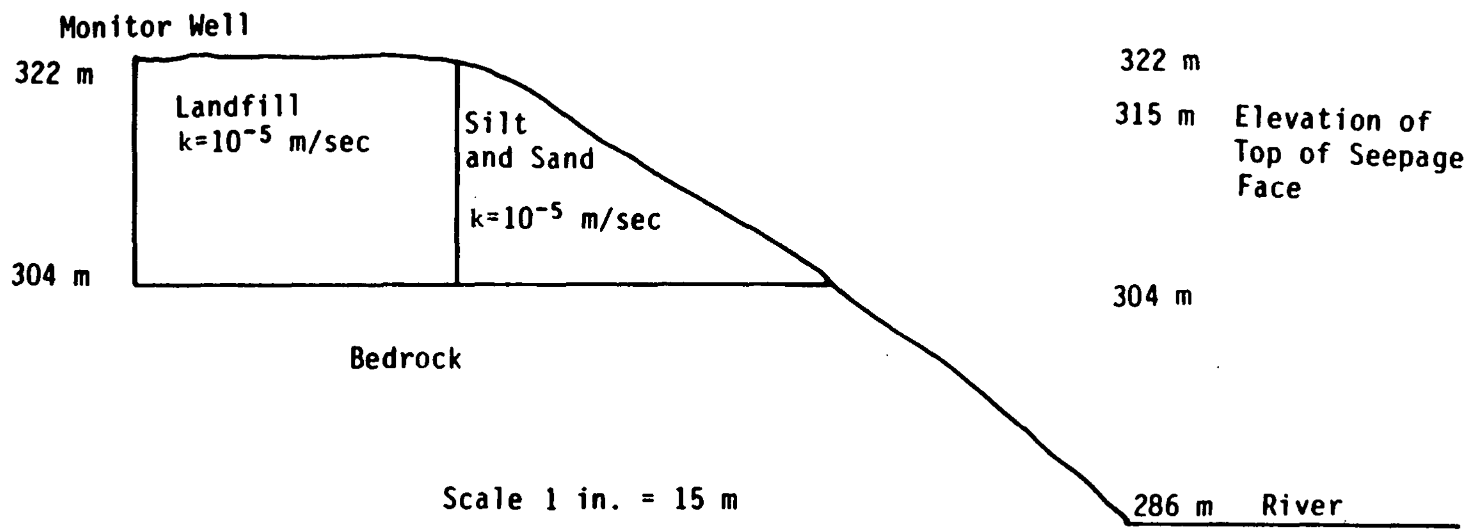


Figure 4.7. Cross section for seepage face.

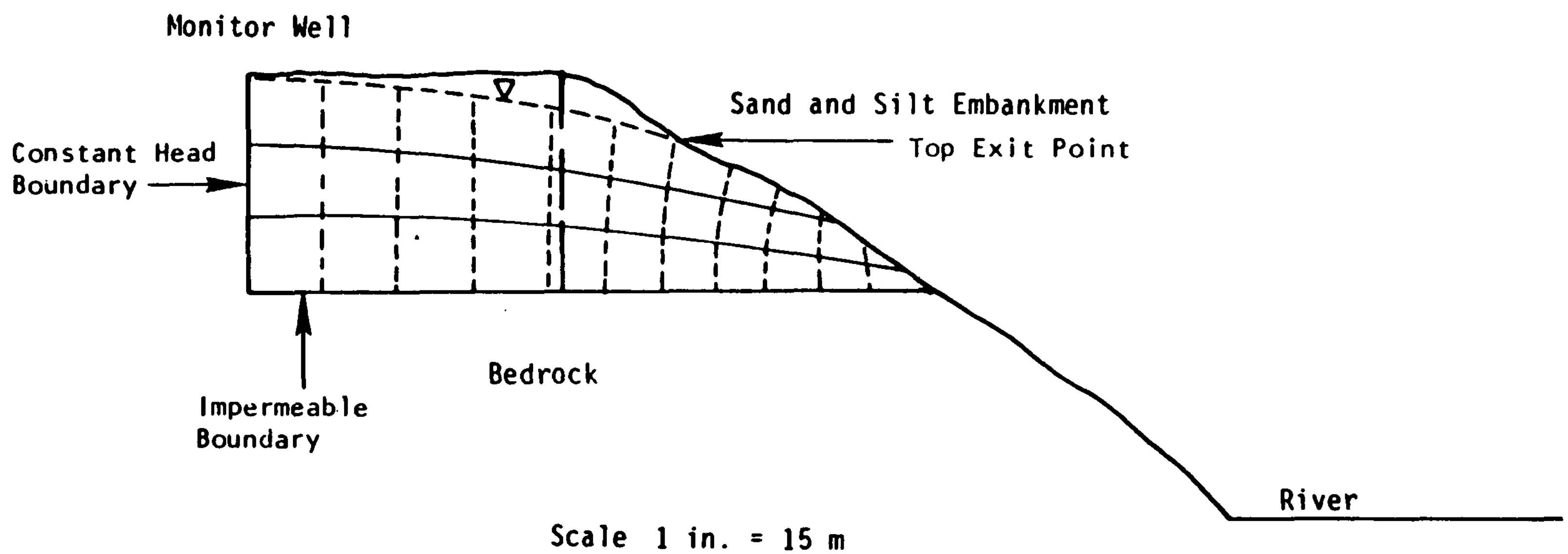


Figure 4.8. Flow net for seepage face.

(see Figure 4.8) is unknown unless solved for by trial and error or approximated from observations in the field, the complicating factor in solving this type of example.

The flow through a unit width represented by the cross section is determined from:

$$Q = \frac{k\ F\ H}{N}$$

where, in this example:

$F = 3$	(from flow net)
$k = 1 \times 10^{-5}$ m/sec	(from data)
$H = 18$ m	(from flow net)
$N = 11$	(from flow net)

Therefore,

$$Q = \frac{(1 \times 10^{-5}\ \text{m/sec})(3)(18\ \text{m})}{11}$$

$$Q = 4.9 \times 10^{-5}\ \text{m}^3/\text{sec per meter of width}$$

FLOW NET CONSTRUCTION FOR FREE-SURFACE FLOW CONDITIONS

If the water table itself approximates a flow line, no vertical gradients exist and this unusual condition is referred to as free-surface flow. There are two methods that can be used to calculate flow for free-surface flow conditions. The first method is to construct a flow net and calculate the flow as previously discussed. However, the position of the entire free surface may not be known. To solve the flow problem in this case, the Dupuit-Forchheimer theory of free-surface flow is used. This theory is based on two assumptions:

1. Flow lines are assumed to be horizontal and equipotential lines are assumed to be vertical; and

2. The hydraulic gradient is assumed to be equal to the slope of the free surface and to be invariant with depth.

With these assumptions, an empirical approximation can be used to calculate flow, as follows:

$$Q = k\ h(x)\frac{dh}{dx}$$

where h(x) is the elevation of the water table above the datum used for the flow system at x, and the gradient dh/dx is the slope of the free surface, $\Delta h/\Delta x$ at x (Figure 4.9). In theory, this equation is representative of a free surface that forms a parabola. Calculations using the Dupuit-Forchheimer theory produce the most accurate results when the slope of the free surface is small and when the depth of the concqnfined aquifer is shallow (Freeze and Cherry, 1979).

Figure 4.10 shows a subsurface cross section in the direction of ground water flow at a site where free-surface flow occurs. The figure is vertically exaggerated by a factor of 100. Based on Figure 4.10, a Dupuit-Forchheimer flow net can be constructed. One flow path can be used and each equipotential line represents the same drop in head (Figure 4.11).

The flow rate is calculated using the Dupuit-Forschheimer solution at point x_1, where h(x) = 3.9 m. The quantity dh/dx, at x_1, is measured from the figure, resulting in dh = 0.6 m and dx = 115 m. Therefore, dh/dx = 5.2×10^{-3} m/m. Using the equation:

$$Q = k\ h(x)\frac{dh}{dx}$$

$$Q = (1 \times 10^{-5}\ m/sec)(3.9\ m)(5.2 \times 10^{-3}\ m/m)(1\ m)$$

$$Q = 2 \times 10^{-7}\ m^3/sec$$

SITUATIONS IN WHICH FLOW NETS ARE DIFFICULT OR NOT APPROPRIATE

There are situations in which the construction and use of flow nets is difficult or impossible. These situations occur when there are scaling problems, when the geology is complex, when there is a lack of

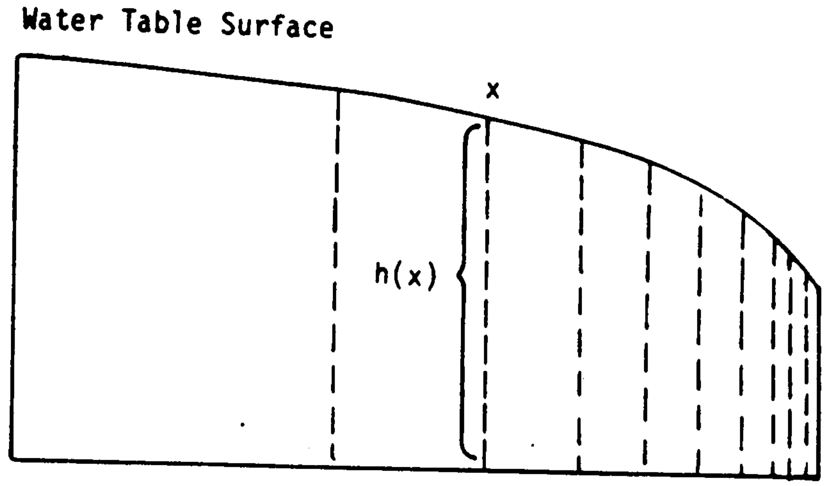


Figure 4.9. Diagram showing x and h(x) for Dupuit-Forchheimer calculation.

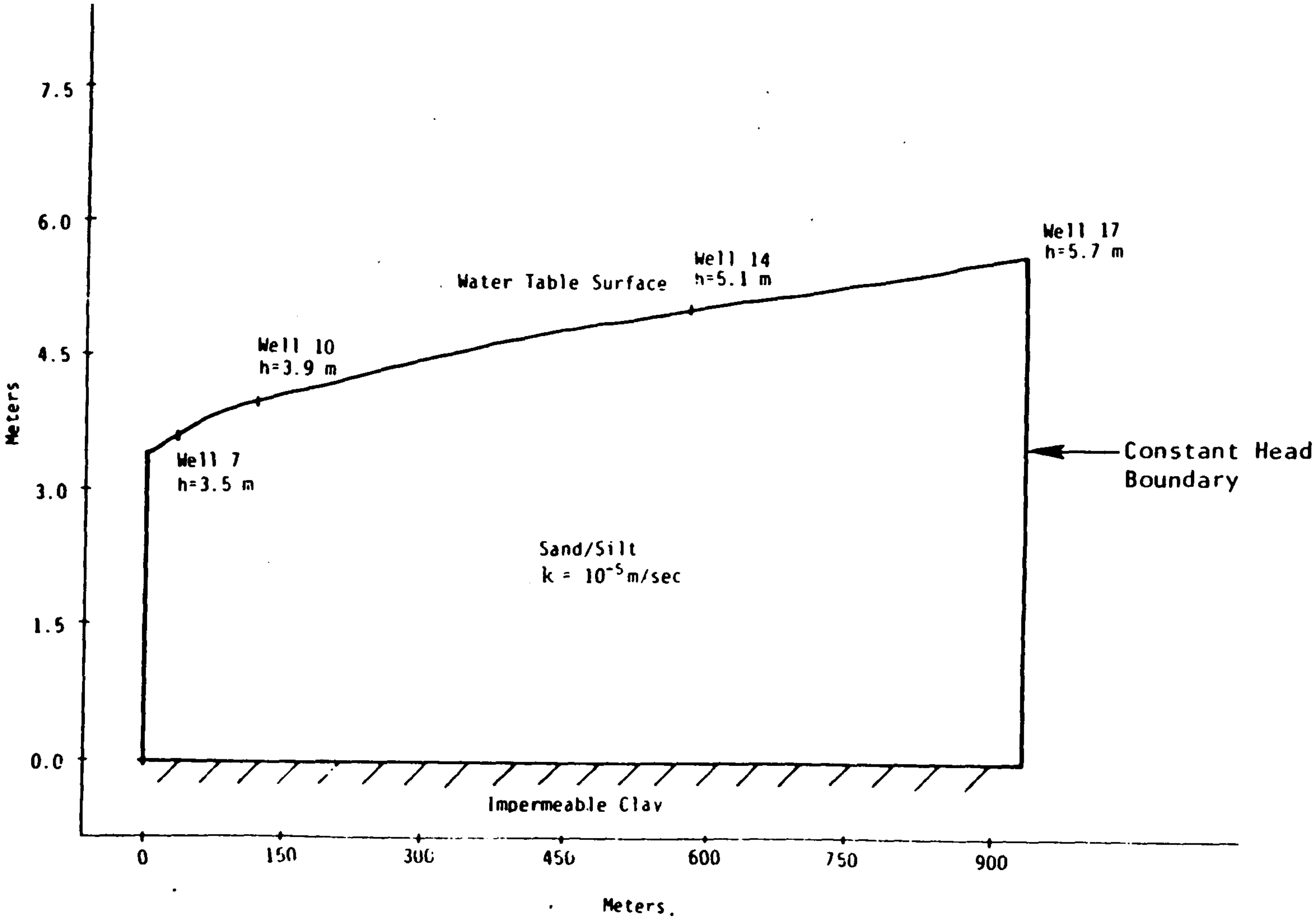


Figure 4.10. Cross section for free-surface flow.

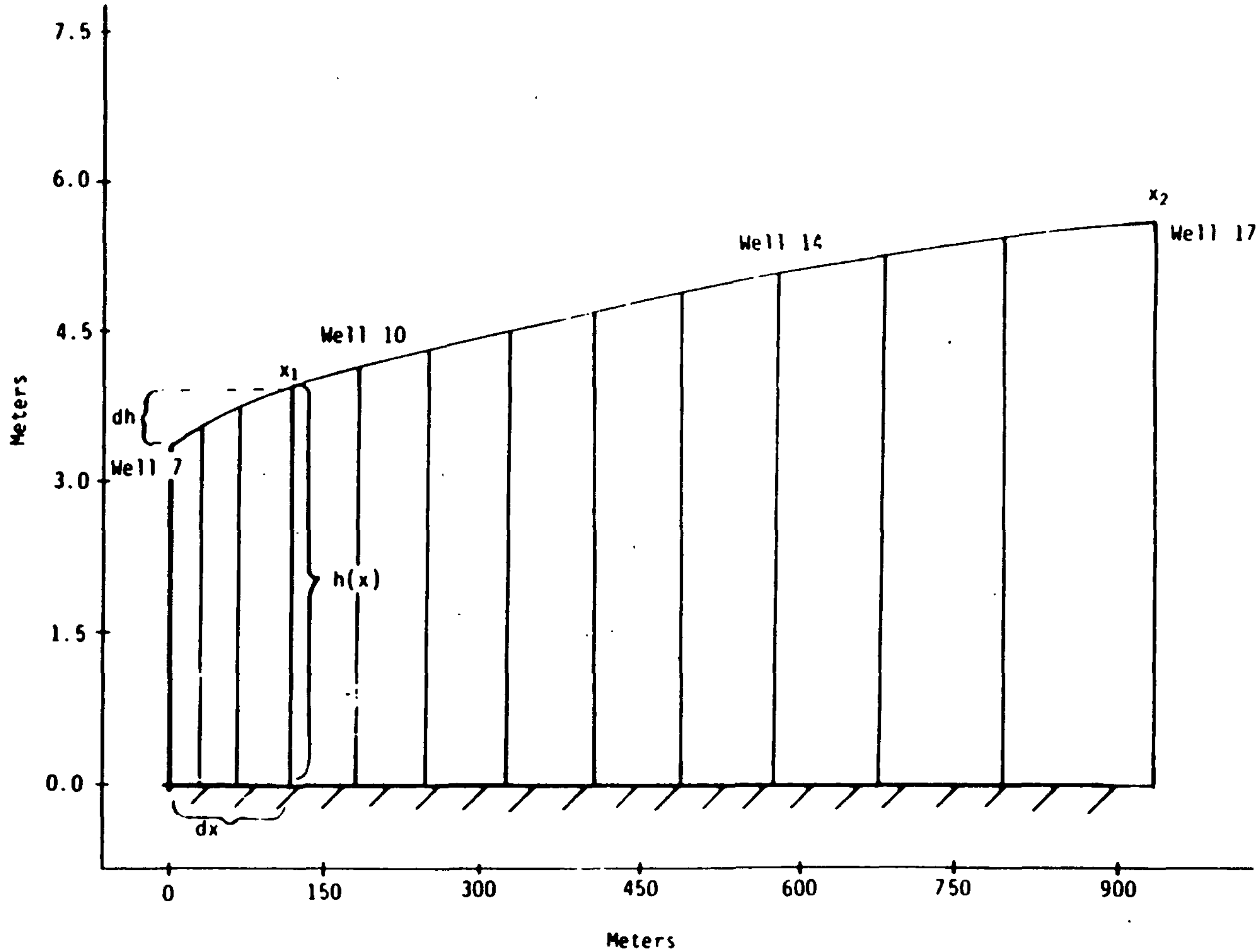


Figure 4.11. Dupuit-Forchheimer solution scheme for free-surface flow.

three-dimensional hydrologic data for the ground water system, and when ground water flow conditions do not conform to the principles expressed by Darcy's Law.

Scaling problems occur when the aquifer and/or geologic layers associated with a particular ground water system are thin in relation to the length of the flow net. If a flow net is constructed for this situation, the flow net will be made up of squares that are too small to work with unless the scale is exaggerated.

Lack of three-dimensional hydrologic data or hydrologically equivalent data for a ground water flow system makes proper flow net construction impossible. Hydrologic testing at various depths within an aquifer and determination of the vertical hydraulic conductivity and vertical gradient in the aquifer are essential to provide reliable interpretive results. These data must be available before a flow net can be constructed.

There are two types of ground water systems in which the principles expressed by Darcy's Law do not apply. The first is a system in which ground water flows through materials with low hydraulic conductivities under extremely low gradients (Freeze and Cherry, 1979) and the second is a system in which a large amount of flow passes through materials with very high hydraulic conductivities. Darcy's Law expresses linear relationships and requires that flow is laminar (flow in which stream lines remain distinct from one another). In a system with high hydraulic conductivity, flow is often turbulent when it has a high velocity. Turbulent flow is characteristic of karstic limestone and dolomite, cavernous volcanics, and fractured rock systems. Construction of flow nets for areas of turbulent flow would not provide accurate results.

SECTION 5

MATHEMATICAL CONSTRUCTION OF FLOW NETS

Two-dimensional, steady-state, boundary-value problems can be solved mathematically, as well as by use of flow nets. Freeze and Cherry (1979) discuss the theory and mathematics of the problem. It is clear that the time and effort required to determine a mathematical solution is greater than the effort to graphically construct a flow net. Leliavsky points out that, "... the analytical method, although rigorously precise, is not universally applicable", because the number of known functions on which it depends is limited. However, except in a few elementary cases, the analytical method lies beyond the mathemetics of practicing design offices" (in Cedergren, 1977). Given the complexity of developing flow nets using mathematical techniques, they are recommended only for experienced technicians, and should be used only if several flow net iterations would be necessary to calibrate parameters or test hypotheses.

The basic equation for saturated, steady-state, confined flow through isotropic and homogeneous porous media (Laplace equation) in two dimensions is:

$$\frac{\partial^2 h}{\partial x^2} = \frac{\partial^2 h}{\partial z^2} = 0$$

The solution of this equation for given boundary conditions is presented in Appendix III of Freeze and Cherry (1979). This equation describes a homogeneous, isotropic medium, but it can be modified for heterogeneous and anisotropic materials. This equation is solved iteratively to calculate the head at various points along a flow net. A graphically constructed flow net is a solution of the Laplace equation. A complete discussion of mathematical solutions for flow in one, two, and three dimensions is included in Freeze and Cherry (1979) and Bear (1972).

With the advent of powerful calculators and personal computers that are "user friendly" and relatively inexpensive, a number of simpler ways to determine direction and velocity of flow have been developed. The data collected to construct a flow net can be used to calculate flow direction and velocity.

Calculators and micro-computers greatly reduce the amount of work that must be performed by the user, and thereby increase the speed of problem solving. They can perform a large number of repetitive calculations in minutes and present the output in numerical or graphical form. They also eliminate the need for tables or graphs that are required for hydraulic computations. Integration schemes that require complicated calculations can be solved quickly and easily.

Calculators and micro-computers also feature peripheral devices that aid in calculation and presentation of hydrologic data. The data and the programs to solve the mathematical expressions for flow problems can be recorded on magnetic cards, tapes, or disks. The programs and data can be stored until such time as they are needed, and then can be readily loaded onto the computational system. Printers, plotters, and the software required to run them are also available. These devices can be used to plot, contour, display, and present analyses in a way that can be easily understood.

The largest number of available programs are for well hydraulics problems. These programs can be useful to permit writers and applicants in situations where the effects of pumping wells in the vicinity of a site must be determined. Table 5.1 lists several of these programs and some of their characteristics.

Several simple contaminant transport programs possess the capability to track contaminated water and predict time of travel. The draft TRD on Leachate Plume Migration (Pettyjohn, et al., 1982) discusses mathematical solutions for calculation of plume movement. That document also includes a TI-59 hand-held calculator program for calculating plume migration. Table 5.2 lists several other programs for contaminant transport and some of their capabilities.

No attempt has been made to discuss the hydraulic or transport codes for hand-held calculators or micro-computers in this document. These techniques are not difficult, but they must be diligently pursued if they are to become a

TABLE 5.1. AVAILABLE HAND-HELD CALCULATOR PROGRAMS FOR GROUND WATER FLOW AND TRANSPORT (BROWN, 1983)

Ground Water Systems Characterized with Well Data

	Aquifer Characteristics			Well Configuration					
Program Title	Type	Properties	Extent	Number	Penetration	Time-frame	Program Output	Calculator Type	Reference
General Aquifer Analysis for Nonsteady Theis Conditions	C	H,I	IN	24	FP	TV	D	TI-59	Sandberg et al. 1981 Prickett and Vorhees 1981
Multiple Well, Variable Pumping Rate Problems	C	H,I	IN	1	FP	TV	D	HP-29C	Picking 1979
Constant or Variable Pumping (Injection) Rate, Single or Multiple Fully Penetrating Wells	C	H,I	IN	-	FP	TV	D	TI-59	Warner and Yow 1979
Constant or Variable Pumping (Injection) Rate, Single or Multiple Fully Penetrating Wells	C	H,I	IN	-	FP	TV	D	HP-97	Rayner 1981
Dewatering Well Design	C	H,I	IN	24	FP	TV	D	TI-59	Koch and Associates (1)
Theis Condition Well Field	C	H,I	IN	57	FP	TV	D	HP-41	IGWMC (2)
Point Sink Aquifer Model	C	H,I	IN	50	FP	TV	D	HP-41	Ulrich (3)
Nonsteady State Nonleaky Artesian-Single Production Well	C	H,I	IN	1	FP	TV	D	TI-59	Walton 1983 a & b
AQMODL (4)	C	H,I	IN	60	FP	TV	D	HP-41	Rayner 1983
Nonsteady State Nonleaky Artesian-Partially Penetrating Wells	C	H,I	IN	1	PP	TV	D	TI-59	Walton 1983 a & b

(Continued)

TABLE 5.1 (continued)

Program Title	Aquifer Characteristics			Well Configuration		Time-frame	Program Output	Calculator Type	Reference
	Type	Properties	Extent	Number	Penetration				
Constant Pumping (Injection) Rate, Fully Confined Aquifer, Partially Penetrating Well	C	H,I	IN	1	PP	TV	D	TI-59	Warner and Yow 1980b
Radial Flow to a Constant Drawdown Hemisphere	C	H,I	IN	1	PP	TV	IF	TI-59	Koch and Associates (1)
Analysis of Source or Sink Flow Rates with Drawdown as a Given	C	H,I	IN	7	FP	TV	IF	TI-59	Sandberg et al. 1981 Prickett and Vorhees 1981
Nonsteady Discharge of a Flowing Well	C	H,I	IN	1	FP	TV	IF	TI-59	Koch and Associates (1)
Anisotropic Confined Aquifers	C	H,A	IN	1	PP	TV	D	TI-59 HP-41	Parr et al. 1983
Jacob Leaky Artesian Steady-State	L	H,I	IN	25	FP	SS	D	TI-59	T.A. Prickett and Associates (5)
Steady State Leaky Artesian - Single Production Well	L	H,I	IN	1	FP	SS	D	TI-59	Walton 1983 a & b
Nonsteady State Leaky Artesian - Single Production Well	L	H,I	IN	1	FP	TV	D	TI-59	Walton 1983 a & b
Leaky Aquifer Drawdown	L	H,I	IN	1	FP	TV	D	HP-41	Ulrich (3)
Constant Pumping (Injection) Rate, Single Fully Penetrating Well, Semiconfined Aquifer	L	H,I	IN	1	FP	TV	D	TI-59	Warner & Yow 1980a

(Continued)

TABLE 5.1 (continued)

Program Title	Aquifer Characteristics			Well Configuration		Time-frame	Program Output	Calculator Type	Reference
	Type	Properties	Extent	Number	Penetration				
Hantush "Well Function"	L	H,I	IN	1	FP	TV	D	HP-41	IGWMC(2)
Nonsteady State Two Mutually Leaky Artesian Aquifers - Single Production Well	L	H,I	IN	1	FP	TV	D	TI-59	Walton 1983 a & b
Steady Radial Ground-Water Flow in a Finite Leaky Aquifer	L	H,I	B	1	FP	SS	D	HP-41	IGWMC(2)
Successive Steady States - Constant Head Points - Unconfined Aquifer	WT	H,I	IN	7	FP	TV	IF,D	TI-59	Koch and Associates (1)

(Continued)

TABLE 5.1 (continued)

Regions with Subsurface Drains

Program Title	Aquifer Characteristics				Drain Configuration			Time-frame	Program Output	Calculator Type	Reference
	Type	Properties	Extent	Dimensionality	Number	Penetration	Length				
Steady-State Drawdown Around Finite Line Sinks	C	H,I	IN	X-Y	10	FP	F	SS	D	TI-59	Sandberg et al. 1981 Prickett and Vorhees 1981
Successive Steady States - Constant Head Finite Line Sinks - Compute Drawdowns	C	H,I	IN	X-Y	10	FP	F	SS	D	TI-59	Koch and Associates (1)
Finite Line Sinks for Nonsteady Conditions	C	H,I	IN	X-Y	15	FP	F	TV	D	TI-59	Sandberg et al. 1981 Prickett and Vorhees 1981
Line Sink Aquifer Model	C	H,I	IN	X-Y	15	FP	F	TV	D	HP-41	Ulrich (3)
Study of Steady-State Flow to Finite Line Sources or Sinks with Drawdown as the Given	C	H,I	IN	X-Y	6	FP	F	SS	IF	TI-59	Sandberg et al. 1981 Prickett and Vorhees 1981
Successive Steady States - One Dimensional Inflow to a Line	C	H,I	IN	X	1	FP	IN	SS	IN	TI-59	Koch and Associates (1)
Successive Steady States - Constant Head Finite Line Sinks - Compute Inflows	C	H,I	IN	X-Y	6	FP	F	SS	IF	TI-59	Koch and Associates (1)

(Continued)

TABLE 5.1 (continued)

Program Title	Aquifer Characteristics: Type	Aquifer Characteristics: Properties	Aquifer Characteristics: Extent	Aquifer Characteristics: Dimensionality	Drain Configuration: Number	Drain Configuration: Penetration	Drain Configuration: Length	Time-frame	Program Output	Calcu-lator Type	Reference
One Dimensional, Nonsteady Flow to a Constant Drawdown, Infinite Line Sink or Source	C	H,I	IN	X	1	FP	IN	TV	IF,D	TI-59	Koch and Associates (1)
One Dimensional, Nonsteady Flow to an Increasing Drawdown, Infinite Line Sink or Source	C	H,I	IN	X	1	FP	IN	TV	IF,D	TI-59	Koch and Associates (1)
Boussinesq Solution	WT	H,I	B	X	1	FP	IN	TV	IF,D	TI-59	Koch and Associates (1)
One Dimensional, Nonsteady Flow to a Constant Drawdown, Infinite Line Sink or Source with Recharge	WT	H,I	IN	X	1	FP	IN	TV	IF,D	TI-59	Koch and Associates (1)
One Dimensional Non-Steady Ground Water Flow (3)	WT	H,I	IN	X	1	FP	IN	TV	IN,D	HP-41	IGWMC (2)

(Continued)

TABLE 5.1 (continued)

Models Described by Type of Transport Process

Program Title	Aquifer Characteristics				Transport Processes	Timeframe	Program Output	Calculator Type	Reference
	Type	Properties	Extent	Dimensionality					
Advective Mass Transport - Theis Particle Mover	C	H,I	IN	X-Y	AD	TV	PL	TI-59	Sandberg et al. 1981 Prickett and Vorhees 1981
Streamlines and Travel Times for Regional Ground-Water Flow affected by Sources and Sinks	C	H,I	IN	X-Y	AD	TV	PL	HP-41	IGWMC (2)
Advective Transport Model	C	H,I	IN	X-Y	AD	TV	PL	HP-41	Ulrich (3)
Advection and Dispersion - Regional Flow	C	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	TI-59	Walton 1983 a & b
Ground Water Dispersion	C	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	TI-58/59	Kelly 1982
Plume Management Model	C	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	TI-59	Sandberg et al. 1981 Prickett and Vorhees 1981
Calculator Code for Evaluating Landfill Leachate Plumes	C	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	TI-59	Pettyjohn et al.
Dissipation of a Concentrated Slug of Contaminant	C	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	TI-59	T.A. Prickett and Associates (5)
Advection and Dispersion from a Stream	C	H,I	IN	X	AD, DS	TV	CN	TI-59	Walton 1983 a & b
Advection and Dispersion from a Single Pumping Well	C	H,I	IN	R	AD, DS	TV	CN	TI-59	Walton 1983 a & b
Advection and Dispersion from a Single Solute Well	C	H,I	IN	R	AD, DS	TV	CN	HP-41	IGWMC (2)

(Continued)

TABLE 5.1 (continued)

Pond Sources

Program Title	Aquifer Characteristics: Type	Properties	Extent	Dimensionality	Pond Configuration	Time-frame	Program Output	Calculator Type	Reference
Analysis of Ground Water Mounding Beneath Tailings Ponds	WT	H,I	IN	R	CI	TV	HH	TI-59	Sandberg et al. 1981 Prickett and Vorhees 1981
Circular Recharge Area	WT	H,I	IN	R	CI	TV	HH	TI-59	Walton 1983 a & b
Circular Basin Recharge Mound	WT	H,I	IN	R	CI	TV	HH	HP-41	Ulrich (3)

(1) Programs available as of October 1983 from Koch and Associates, Denver, Colorado

(2) Programs available as of August 1983 from the International Ground Water Modeling Center, Holcomb Research Institute, Butler University, Indianapolis, Indiana

(3) Programs available as of August 1983 from James S. Ulrich and Associates, Berkeley, California

(4) Programs can also consider regional water level changes with time and the effects of a regional gradient

(5) Programs available as of July 1983 from Thomas A. Prickett and Associates, Inc., Urbana, Illinois

(6) Program can consider four boundary conditions for drain: constant head, constant flux, linearly varying head and linearly varying flux

LEGEND:
C - Confined
L - Leaky
WT - Water Table
H - Homogeneous
I - Isotropic
A - Anisotropic
IN - Infinite
B - Bounded
X - Longitudinal
Y - Lateral
F - Finite
R - Radial

FP - Fully Penetrating
PP - Partially Penetrating

TV - Time Varying
SS - Steady State
D - Drawdown
IF - Inflow
CI - Circular
HH - Hydraulic Head
CN - Concentration
PL - Particle Location with Time

AD - Advection
DS - Dispersion
RD - Retardation
DG - Degradation

TABLE 5.2 AVAILABLE MICROCOMPUTER PROGRAMS FOR GROUND WATER FLOW AND TRANSPORT (BROWN, 1983)

Ground Water Systems Characterized with Well Data

Program Title	Aquifer Characteristics				Well Configuration					
	Type	Properties	Extent	Dimensionality	Number	Penetration	Timeframe	Program Output	Computer Type	Reference
General Aquifer Analysis (THEIS)	C	H,I	IN	X-Y	100	FP	TV	D	TRS-80 Apple IBM-PC Osborne	Koch and Associates (1)
THWELLS	C	H,I	IN	X-Y	-	FP	TV	D	Osborne	IGWMC (2)
GWFLOW (3)	C,L	H,I	IN	X-Y	1	FP,PP	TV	D	Sharp PC1500	IGWMC (2)
Nonsteady State Nonleaky Artesian - Single Production Well	C	H,I	IN	R	1	FP	TV	D	TRS-80	Walton 1983 a & b
Nonsteady State Nonleaky Artesian - Partially Penetrating Wells	C	H,I	IN	R	1	PP	TV	D	TRS-80	Walton 1983 a & b
Leaky Aquifer Analysis (LEAKY)	L	H,I	IN	X-Y	100	FP	TV	D	TRS-80	Koch and Associates (1)
Steady State Leaky Artesian - Single Production Well	L	H,I	IN	R	1	FP	SS	D	TRS-80	Walton 1983 a & b
Nonsteady State Leaky Artesian - Single Production Well	L	H,I	IN	R	1	FP	TV	D	TRS-80	Walton 1983 a & b

(Continued)

TABLE 5.2 (continued)

Program Title	Aquifer Characteristics: Type	Aquifer Characteristics: Properties	Aquifer Characteristics: Extent	Aquifer Characteristics: Dimensionality	Well Configuration: Number	Well Configuration: Penetration	Timeframe	Program Output	Computer Type	Reference
Nonsteady State Two Mutually Leaky Artesian Aquifers - Single Production Well	L	H,I	IN	R	1	FP	TV	D	TRS-80	Walton 1983 a & b

(Continued)

TABLE 5.2 (continued)

Models Described by Type of Transport Process

Program Title	Aquifer Characteristics				Transport Processes	Timeframe	Program Output	Computer Type	Reference
	Type	Properties	Extent	Dimensionality					
Advection and Dispersion - Regional Flow	C	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	TRS-80	Walton 1983 a & b
MAP PLUME	C	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	Apple Kaypro II Victor Vector	NCGWR (4)
PLUME	C	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	Super-brain TRS-80	IGWMC (2)
PLUME	C	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	Sharp - PC1500	NCGWR (4)
PLOSBMB	C	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	Osborne	Voorhees (5)
PLUME CROSS-SECTION	C	H,I	IN	X-Z	AD, DS, RD, DG	TV	CN	Apple Kaypro II Victor Vector	NCGWR (4)
RANDOM WALK	C,L, WT	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	Apple Kaypro II Victor Vector TRS-80 Sharp - PC1500	NCGWR (4)
RANDOM WALK	C,L, WT	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	Super-brain Osborne Sharp - PC1500	IGWMC (2)

(Continued)

TABLE 5.2 (continued)

Program Title	Aquifer Characteristics				Transport Processes	Timeframe	Program Output	Computer Type	Reference
	Type	Properties	Extent	Dimensionality					
RWOSBMB	C	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	Osborne	Voorhees (5)
RWMY	C,L, WT	H,I	IN	X-Y	AD, DS, RD, DG	TV	CN	Osborne	Voorhees (5)
Advection and Dispersion from a Stream	C	H,I	IN	X	AD, DS	TV	CN	TRS-80	Walton 1983 a & b
Advection and Dispersion from a Single Pumping Well	C	H,I	IN	R	AD, DS	TV	CN	TRS-80	Walton 1983

(Continued)

TABLE 5.2 (continued)

Pond Sources

Program Title	Aquifer Characteristics				Pond Configuration	Timeframe	Program Output	Computer Type	Reference
	Type	Properties	Extent	Dimensionality					
Circular Recharge Area	WT	H,I	IN	R	CI	TV	HH	TRS-80	Walton 1983 a & b
Mounding	WT	H,I	IN	R	CI	TV	HH	Apple Kaypro II Victor Vector	NCGWR (4)

(1) Programs available as of October 1983 from Koch and Associates, Denver, Colorado

(2) Programs available as of November 1983 from the International Ground Water Modeling Center, Holcomb Research Institute, Butler University, Indianapolis, Indiana

(3) GWFLOW is a series of eight flow solutions, including one for mounding estimation

(4) Programs available as of October 1983 from the National Center for Ground Water Research, Oklahoma State University, Stillwater, Oklahoma

(5) Programs available as of November 1983 from Dr. Michael L. Voorhees of Warzyn Engineering, Inc., Madison, Wisconsin

LEGEND:
- C - Confined
- L - Leaky
- H - Homogeneous
- I - Isotropic
- IN - Infinite
- X - Longitudinal
- Y - Lateral
- R - Radial
- Z - Vertical
- FP - Fully Penetrating
- PP - Partially Penetrating
- TV - Time Varying
- SS - Steady State
- D - Drawdown
- PL - Particle Location with Time
- CN - Concentration
- AD - Advection
- DS - Dispersion
- RD - Retardation
- DG - Degradation

working part of a permit applicant's or permit writer's skills. Walton (1984) discusses 35 codes for micro-computers. Holcomb Research Institute (1983) serves as a source of documentation for hand-held calculator codes. Brown (1983) also discusses hand-held calculator and micro-computer programs for ground water flow and transport.

Large computers are now commonly used to model hydrologic systems at hazardous waste sites. Researchers have found that flow codes can easily be modified to calculate stream function and steady-state potentials. The results can then be plotted into a flow net (Christian, 1980). Fogg and Senger (1984) discuss the use of a finite-element code to draw flow nets for hetergeneous, anisotropic media in the absence of internal sources or sinks.

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APPENDIX A

GLOSSARY*

Anisotropic--Descriptive of a geologic medium that has hydraulic properties (i.e., hydraulic conductivity) that vary with direction.

Aquiclude--Defined as a saturated geologic unit that is incapable of transmitting significant quantities of water under ordinary hydraulic gradients (Freeze and Cheery, 1979).

Aquifer--A geologic formation, group of formations, or part of a formation capable of yielding a significant amount of ground water to wells or springs (EPA, 1984b).

Aquitard--Defined as a stratigraphic sequence of geologic beds that may be permeable enough to transmit water in quantities that are significant in the study of regional water flow, but may not have a permeability sufficient to allow completion of production wells within them (Freeze and Cherry, 1979).

Artesian--Descriptive of ground water that is under sufficient hydrostatic pressure to rise above the aquifer containing it.

Confined Aquifer--An aquifer bounded above and below by impermeable beds; an aquifer containing confined ground water.

Constant-Head Boundary--A boundary along which the hydraulic head is constant. An equipotential line. Flow lines must meet at a constant-head boundary at right angles, and adjacent equipotential lines must be parallel to the boundary (Freeze and Cherry, 1979).

Discharge Velocity--The quantity of water that percolates per unit time across a unit area of a section oriented at right angles to the flow lines. For laminar flow conditions, it is defined by Darcy's Law as the coefficient of hydraulic conductivity multiplied by the hydraulic gradient (Terzaghi and Peck, 1967).

Effective Porosity--The volumetric percentage of the total volume of a given mass of soil or rock that consists of interconnecting pores spaces through which flow can occur.

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*All definitions are after Bates and Jackson, 1980, unless otherwise noted.

Equipotential Line--A contour line on the potentiometric surface; a line along which the hydraulic head of ground water in an aquifer is the same. Flow is perpendicular to these lines in the direction of decreasing ground water potential.

Flow Line--A line that is indicative of the direction of ground water flow, and is perpendicular to equipotential lines (Freeze and Cherry, 1979).

Flow Net-- In the study of ground water phenomena, a graph of flow lines and equipotential lines that represents two-dimensional flow through porous media.

Flow Path-- The area between two adjacent flow lines (Freeze and Cherry, 1979).

Ground Water--Subsurface water that exists in saturated and unsaturated formations.

Head--(a) The elevation to which water rises at a given point as a result of reservoir pressure. (b) Water-level elevation in a well, or elevation to which the water of a flowing artesian aquifer will rise in a piezometer.

Heterogeneous--Descriptive of a ground water formation where hydraulic properties vary spatially (Freeze and Cherry, 1979).

Homogeneous--Descriptive of a ground water formation where hydraulic properties are the same at every point (Freeze and Cherry, 1979).

Hydraulic Conductivity--The volumetric rate of flow of water per unit time through a unit cross-sectional area, under a unit hydraulic gradient, at the prevailing temperature.

Hydraulic Conductivity Boundary--The boundary between two materials having different hydraulic conductivities (Freeze and Cherry, 1979).

Hydraulic Gradient-- The rate of change of total head per unit distance in the direction of flow at a given point.

Hydrostratigraphic Unit--A body of rock having considerable lateral extent and composing a geologic framework for a reasonably distinct hydrologic system.

Hydrostatic Pressure--The pressure exerted by water at any given point in a body of water at rest. The pressure is generally due to the weight of the water at higher levels in the zone of saturation.

Isotropic--Descriptive of the condition in which hydraulic properties of an aquifer are the same in all directions (Fetter, 1980).

Laminar Flow--Smooth, uniform water flow in which the stream lines remain distinct from one another, as distinguished from turbulent flow.

Lithology--The description of rocks on the basis of such characteristics as color, mineralogic composition, and grain size.

Permeability--The capacity of a porous rock, sediment, or soil to transmit fluid. It is a measure of the relative ease of fluid flow under a hydraulic gradient.

Piezometer--A nonpumping well, generally of a small diameter, which is used to measure the elevation of ground water or potentiometric surface. A piezometer generally has a short well screen isolated in the aquifer of interest (Fetter, 1980).

Porosity--The percentage of the bulk volume of a rock or soil that is occupied by pore spaces, whether isolated or connected.

Potentiometric Surface--An imaginary surface representing the areal head of ground water as defined by the level to which the water rises in a group of wells. The water table is an example of a potentiometric surface.

Pressure Head--The distance between the point of measurement (e.g., bottom of a well) and the water level in a well (Freeze and Cherry, 1979).

Seepage Velocity--Defined as the average velocity at which water percolates through porous material and is equal to the discharge velocity divided by the effective porosity of the material (Terzaghi and Peck, 1967).

Stratification--The formation, accumulation, or deposition of material in layers; specifically, the arrangement or disposition of sedimentary rocks.

Tie Line--In the context of flow net analysis, this is a straight line drawn between points of equal pressure head, as measured by a piezometer or a well, on a flow net diagram. It is used to interpolate the magnitude of otherwise unknown hydraulic head values at selected locations.

Turbulent Flow--Water flow in which flow lines cross and intermix at random, as opposed to laminar flow.

Unconfined Aquifer--An aquifer having a water table as the upper boundary; an aquifer containing unconfined ground water.

Uppermost Aquifer--The geologic formation nearest to the natural ground surface that is an aquifer, as well as lower aquifers that are hydraulically interconnected with this aquifer (EPA, 1984b).

Water Table--The surface of a body of unconfined ground water at which the pressure is equal to that of the atmosphere.

Zone of Aeration--A subsurface zone containing water at pressure less than atmospheric, including water held by capillary forces. This zone is limited above by the land surface and below by the water table.

Zone of Saturation--A subsurface zone in which all of the pore spaces are filled with water under pressure greater than that of the atmosphere. Although the zone may contain sporadic gas-filled pore spaces or pore spaces filled with a fluid other than water, it is still considered saturated.