RI 8981

PB86-151842

Bureau of Mines Report of Investigations/1985

Fracture Zone Dewatering To Control Ground Water Inflow in Underground Coal Mines

By Robert D. Schmidt

UNITED STATES DEPARTMENT OF THE INTERIOR

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SPRINGFIELD, VA. 22161

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UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	h	hour
ft^2	square foot	h/d	hour per day
ft/yr	foot per year	in	inch
gpd	gallon per day	mg/L	milligram per liter
gpd/ft	gallon per day per foot	m/h	meter per hour
		min	minute
gpd/ft^2	gallon per day per square foot	min/d	minute per day
gpm	gallon per minute	pct	percent

Library of Congress Cataloging in Publication Data:

Schmidt, R. D. (Robert D.)

Fracture zone dewatering to control ground water inflow in underground coal mines.

(Bureau of Mines report of investigations ; 8981)

Bibliography: p. 33-34.

Supt. of Docs. no.: I 28.23:8981

1. Mine drainage. 2. Mine water. 3. Coal mines and mining—Appalachian Region. I. Title. II. Series: Report of investigations (United States. Bureau of Mines) ; 8981.

TN23.U43 [TN321] 622s [622'.334] 85-600016

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By Robert D. Schmidt [1]

ABSTRACT

This Bureau of Mines investigation focuses on the identification and control of ground water inflow problems that occur in the active sections of underground Appalachian coal mines. A fracture inflow survey of eight underground mines was conducted. Three types of mine fracture intercepts were identified, which are typical of wet section mining conditions. A mine in Preston County, WV was selected as the site for a fracture zone dewatering experiment. Fracture trace analysis was used to site dewatering wells in a fracture valley setting ahead of mine development. The design, implementation, and results of this dewatering experiment are presented.

A hydrology simulator was also developed and applied to the fracture zone flow problem at the field site. The model uses a semianalytic, boundary integral technique to simulate fracture zones as discrete regions of high average permeability. Comparisons are made between simulated and actual dewatering results.

This investigation suggests that fracture zones are responsible for the sudden release of stored ground water, which often occurs as mining sections advance beneath fracture valley topography. It is concluded, therefore, that dewatering operations that are designed to intercept the component of ground water that is stored in fracture zones will be most effective in controlling infiltration to active mine sections.

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INTRODUCTION

Ground water flow into underground coal mines has been a problem for miners since the inception of the industry. As underground mining operations remove coal, the void space created by the workings acts as an open drain, intercepting or otherwise disrupting normal ground water flow.

High-volume inflows at the active mining face are of special concern. They contribute directly to reduced mine productivity by creating difficult, uncomfortable, and sometimes hazardous working conditions for miners, and by reducing machine efficiency. Mine operating costs are further affected by the necessity for in-mine water handling and subsequent treatment of acidic mine discharge.

Controlling mine infiltration by using pumped wells to dewater aquifer source beds adjacent to mine development is a fairly common surface mining practice. Few published accounts exist, however, of dewatering methods applied to underground mines, particularly to underground Appalachian coal mines. The reluctance of the industry to attempt underground mine dewatering in Appalachia is due in part to discouragingly low permeabilities of many aquifer units (1).[2] Tightly interbedded and well cemented sandstone and shale units are commonly associated with eastern U.S. coal seams. The low intergranular permeability of these units restrict the pumping capacity of water wells, while the cost effectiveness of mine dewatering is closely tied to individual well pumping capacity. Mine dewatering quickly becomes prohibitively expensive if a large number of low yield wells are necessary to adequately dewater source beds in the vicinity of underground mine development.

The complexity of the hydrogeologic setting throughout much of Appalachia is another factor that has deterred mine dewatering attempts. Inhomogeneities in aquifer porosity and permeability resulting from naturally occurring geologic fracture development contribute much to this complexity.

This paper will report on a Bureau of Mines investigation into the occurrence and control of underground mine water inflows in the Appalachian coal regions, where ground water flow in sandstone aquifers with low primary permeability is dominated by the relatively high secondary permeability of rock fracture zones.[3]

This investigation includes the following:

1. A survey of fracture related water inflow problems occurring in eight eastern U.S. underground coal mines.

2. The application of fracture trace analysis, a hydrogeologic technique for siting high yield municipal water wells, to the positioning of mine-aquifer dewatering wells in the vicinity of an active underground mine.

3. The application of a computer modeling technique for simulating the effect of dewatering wells sited on highly permeable zones of concentrated rock fracturing.

4. The design, implementation, and monitoring (at one of the eight mines surveyed) of a mine-aquifer dewatering attempt intended to exploit naturally occurring geologic fracture zones, as preferred sites for dewatering wells.

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

[3]Throughout this report, the terms primary and secondary permeability are used. Primary permeability refers to the natural intergranular permeability of a rock unit, while secondary permeability refers to that which results from a network of closely spaced rock fractures. The terms intergranular and fracture permeability will also be used.

APPALACHIAN HYDROGEOLOGIC SETTING

In early models of ground water flow in the Appalachian plateau (2-5), conglomerates, sandstones, coal seams, and some siltstones were considered to be aquifers, with shales, clay, and siltstones considered aquitards. The dissected upland areas of this plateau, are considered hydrologically isolated, with each hill having in general the following characteristics:

Infiltration zones occurring in upland areas.

Downward vertical percolation of ground water occurring slowly through aquitards.

Lateral flow above an aquitard resulting in sidehill springs and seeps.

Local ground water discharge zones occurring along the base of hills in stream valleys.

Regional ground water flow continuing in a longer, deeper path toward more deeply incised stream valleys.

Underground mines acting as underdrains that greatly alter the natural flow systems that existed prior to mining.

The hydrologic system of the Appalachian plateau is one of multiple perched water tables, overlying deeper regional aquifers.

The previously cited studies emphasized the importance of sandstones, conglomerates, and coals as layered hydrogeologic units in the northern Appalachian coal fields. Each of these early studies mentioned the presence of fractures and their possible influence on permeability, vertical flow through confining layers, and interconnections between aquifers. However, fracture flow was apparently considered of secondary importance when compared with intergranular flow. More recent studies (6-7) have indicated ground water flow in shallow aquifer units is greatly affected by zones of concentrated rock fracturing.

FRACTURE ZONES

Naturally occurring zones of concentrated rock fracturing, commonly called fracture zones, are important elements in understanding the hydrogeologic effects of underground mining operations in Appalachian coal regions.

Fracture zones are comparatively narrow regions of intensely fractured rock. They are generally less than 1 mile in length, 20 to 50 ft across, and extend to depths of 100 to 300 ft. For the most part, fracture zones are oriented vertically (8). Typically, it is believed that the increasing overburden pressures with depth reduce the frequency and size of rock fractures.

Fracture permeability is a particularly significant if not a dominant consideration in the shallow rock strata of northern Appalachia at depths that range from 50 to 250 ft. Fracture zone permeability may be 10 to 1,000 times greater than the intergranular permeability of sandstone units. It is estimated that 5 to 10 zones of fracture concentration exist in any 100-acre area (9).

Fracture zones often coincide with stream valley topography, however they appear to be independent of regional structural trends.

Intense fracturing occurs beneath valley bottoms, supposedly because fracture zones are zones of structural weakness in the Earth's crust that are susceptible to erosion and valley formation (10). Thus the aquifer beneath a narrow, deeply incised valley can be broadly viewed as a highly permeable zone of concentrated rock fracturing (11-12). Not surprisingly, the water inflow problems of underground coal mines occur most often when mining activity is conducted beneath valley settings.

Figure 1 depicts the fracture pattern of an idealized zone of fracture concentration. Zones consist of vertical joints, faults, and cracks that are connected horizontally by bedding plane fractures (9).

In multiple aquifer settings, fracture zones may act as vertical hydraulic connections between separate aquifer units. In contrast to the low permeability shale units through which very little vertical

leakage would ordinarily occur, the potential for vertical leakage via fracture zones (including direct surface infiltration) is much greater. With mining activity, the intersection of fracture zone and coal seam is potentially an area of concentrated inflow to the mine workings.

Figure 2 is an example of a fracture zone, seen in cross section at an abandoned limestone quarry in Preston County, WV. Although this photograph does not show the land surface, left and right boundaries of the fracture zone are apparent, as is increased weathering of fractured rock due to enhanced surface infiltration.

FRACTURE ZONE DETECTION AND USAGE

Fracture traces are the surface expression of underlying zones of fracture concentration. Discerning these traces using stereopaired aerial photographs was first reported in reference 13 where they were used to locate fracture zones in limestone formations.

Reference 13 distinguishes between two types of linear features visible on aerial photographs as follows:

> A photogeologic fracture trace is a natural linear feature consisting of topographic (including straight stream segments), vegetation, or soil tonal alignments, visible primarily on aerial photographs, and expressed continuously for less than one mile. Only natural linear features not obviously related to outcrop pattern of tilted beds, lineation and foliation, and stratigraphic contacts are classified as fracture traces.
>
> A photogeologic lineament is similarly defined, except that it is expressed continuously for at least one mile, and more likely expressed continuously or discontinuously for many miles.

Fracture trace analysis refers specifically to the process of locating and assessing the hydrologic significance of linear features less than a mile in length. Stereopaired, low-level aerial photographs (1 in = 2,000 ft) are the principal means of discerning these linear features.

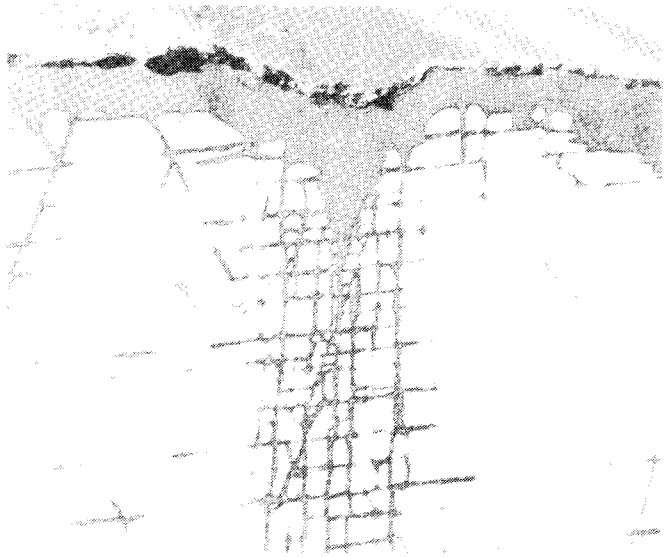

FIGURE 1. - Fracture zone cross-sectional representation (9).

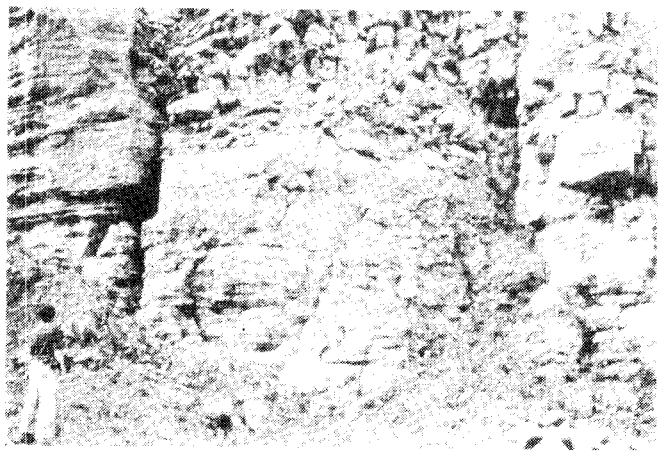

FIGURE 2. - Fracture zone in exposed highwall.

Fracture trace analysis has been used by private concerns and various government agencies in the siting of municipal and domestic water wells and also in attempting to identify high risk roof fall areas in underground mines (14).

The intersections of fracture zones have been found to be particularly productive sites for water wells. As of 1979, at least 123 municipal water wells in Pennsylvania had been sited on fracture zone intersections. The average yield of fracture sited wells was 10 to 1,000 times greater than nonfracture sited wells (9).

A recent publication (6) details the technique of locating fracture zones and the procedures and problems unique to fracture sited water well drilling.

UNDERGROUND COAL MINE WATER-RELATED PROBLEMS

Two water-related problems are most commonly associated with active operation of an underground coal mine in northern Appalachia (15-16).

1. Formation of acid mine drainage (AMD).
2. High-volume ground water inflows that interfere with mining activity.

The AMD problem has been thoroughly researched. AMD results from the oxidation and dissolution of sulfides commonly associated with coal and adjacent rock. Pyrite is the most common sulfur mineral, and the source of nearly all the acidity, iron, and sulfate in mine discharges (15). Most acidic mine water is generated in the inactive and abandoned portion of underground mine workings. Federal and State regulations prohibit the discharge of mine drainage pollutants into surface waters, and the costs of handling and treating acidic discharges are a substantial economic burden to coal mining companies. Control of acid mine water has been the focus of two recent dewatering experiments conducted in inactive and abandoned underground mines in Appalachia (1, 17).

The second water-related problem associated with mining is a quantity rather than a quality problem. It is far less well documented than AMD, but it is equally as important to the economics of coal mining. The present study indicates that ground water interference with mining activity is especially severe when sources of mine inflow are concentrated in active coal producing sections of a mine.

In a typical five-entry room and pillar coal mining section the continuous miner, roof bolter, and shuttle car operations are concentrated in an area that is seldom more than 300 ft^2 (18). Significant inflows of ground water, which impact mining conditions at the developing coal face, will have a far greater effect on coal production than ground water inflow almost anywhere else in the mine. A section experiencing ground water inflow to the point where mining operations are significantly impeded is commonly termed a wet section.

Typical wet sections experience many of the following water-related problems (19):

1. High-volume inflow in an operating section--

   Can cause temporary or permanent shutdown of the section.

   Requires labor to move extra pumping and pipe equipment to flooded section.

   Requires extra water handling capacity to deal with peak inflow.

2. Reduced floor stability causes--

   Restricted equipment and miner maneuverability.

   Soft fireclay to become viscous fluid, floor heaving, and roof falls.

   Equipment and labor to be used for removal of muddy floor material along haulageways and manways.

3. Increased equipment wear, maintenance, and loss of efficiency caused by--

   Dirt and clay washed into mechanical parts, increased frictional resistance and wear, increased maintenance, and shorter life expectancy.

   Wet floor, lateral movement of rails and ties, and extra maintenance of rail system.

   Reduced traction and increased rolling resistance of rubber-tired vehicles.

   Equipment and labor used to extract machines that become bogged down in muddy sump areas.

4. Decreased safety, comfort, and productivity of miners caused by--

   Water in contact with worn trailing cable splices, which trips breakers and makes reset difficult.

   Muddy wet floors that cause slippery footing.

Wet, cold working conditions that increase miner fatigue, reduce efficiency and alertness, and increase absenteeism.

5. Decreased coal quality caused by--

Higher water content, which decreases BTU's.

Sediment washed into coal, which decreases BTU's and increases ash.

These particular water-related problems have long been recognized by the coal industry on a qualitative basis. However, in contrast to the AMD problem there appears to be little if any comprehensive and quantitative analysis of their impact reported in published literature.

Significant leakage into underground workings can occur in roof strata, floor strata, or the coal seam, although significant roof inflow is apparently the most common. A survey of 10 wet mines (1) indicated that rock fractures in the mine roof and floor rock were the dominant sources of ground water inflow in all 10 mines.

MINE INFLOW SURVEY

As part of this investigation, eight underground mining operations experiencing ground water problems were visited. An initial telephone survey was made to identify mines (primarily in Appalachia) experiencing serious water problems. A distinction was made between water problems that were entirely of a quality nature (AMD) and those that were primarily caused by the quantity of water entering mine workings.

During each on-site visit, mines were qualitatively noted as exhibiting strong, moderate, or weak evidence of fracture controlled inflow. These subjective criteria were defined as follows:

Strong criteria.--Multiple examples of leakage from obvious cracks, fractures or roofbolt holes with many sources flowing in a steady stream (5 gpm or greater). Numerous reports from mining personnel of similar inflows.

Moderate criteria.--Multiple examples of leakage from cracks, fractures, and boltholes. A few flowing in steady streams but mostly drippers (1 gpm or less). Some reports from mining personnel of seasonal affects and past point source inflow.

Weak criteria.--Leakage from cracks, fractures, and boltholes evident only as drippers. Few reports of past point source inflow, no seasonal affects, no wet sections.

A summary of the results of this survey appears in table 1.

Of the eight underground mines visited, five were placed in the strong fracture inflow category, and three in the moderate category. One surface operation was judged to be in the weak category. Fracture inflow was most evident in the roof rock of the eight underground mines.

This small sampling of mines revealed that the high volume point sources of inflow occur primarily at recently exposed workings whereas diffuse leakage is more common in older workings. In six of eight underground mines, mine and section foremen expressed their greatest concern about water problems at the active face, despite the fact that in most cases the inflow rate in these wet sections was a very small proportion of total mine inflow. Apparently most mine operators do not interpret a water problem as serious until it interferes directly with the operation of the continuous miner, shuttle car, or roof bolter, i.e., with coal production.

If major sources of inflow to the mine were diffuse or located in caved, abandoned, inactive, or other old workings in the mine, the problem was more likely to be seen entirely as an AMD problem that added to production expenses but was not considered serious enough to merit any special attention or preventive measures. Conventional methods of collection, pumping, and treatment were employed to deal with this water.

The most acidic water in a mine often was flowing from the caved or abandoned workings. Water flowing from active workings became degraded primarily as a result of mixing with more acidic water, in various mine sumps.

TABLE 1. - Coal mine water inflow survey

Location and coal seam	Depth to coal, ft	Mining method	Sections visited	Observed most inflow from--			Fracture involvement		
				Roof	Coal	Floor	Weak	Moderate	Strong
Preston County, WV,[1] Upper Freeport	100- 300	RP	1	X		X			X
Clearfield County, PA, Brookville	200- 250	RP	2	X	X				X
Greene County, PA, Pittsburgh	200- 400	RP	2	X		X		X	
Indiana County, PA, Upper Freeport	250- 450	RP	2	X					X
Cambria County, PA,[2] Lower Kittanning	500- 550	RP	1	X					X
Clearfield County, PA, Middle Kittanning	100- 300	RP	1	X				X	
Tuscaloosa, AL, Pratt	550- 650	RP LW	2	X					X
Carbondale, CO, A	200-1,000	RP LW	1	X				X	
Rockdale, TX, unknown	100- 150	OP	3	HW	HW	HW	X		

Location and coal seam	Serious water problems--		Floor deterioration observed	Water quality, pH	
	At face	Elsewhere		At source	Mine discharge
Preston County, WV,[1] Upper Freeport	X		X	6.5-7.0	3.0-3.5
Clearfield County, PA, Brookville	X		X	[3]4.4	[3]3.0
Greene County, PA, Pittsburgh		X	X	6.5-7.0	2.9-3.0
Indiana County, PA, Upper Freeport	X	X	X	7.0-8.5	NT
Cambria County, PA,[2] Lower Kittanning	X		X	[3]7.4	[3]3.0-3.0
Clearfield County, PA, Middle Kittanning		X		NM	NM
Tuscaloosa, AL, Pratt	X	X	X	7.0-8.5	NT
Carbondale, CO, A	X	X		8.5-9.5	NT
Rockdale, TX, unknown	X			NM	NT

HW Highwall. NT No treatment.
LW Longwall. OP Open pit.
NM No measurement. RP Room and pillar.

[1]Bureau of Mines dewatering project.
[2]EPA-Wahler Associates dewatering project.
[3]From literature.

POINT SOURCES OF INFLOW

Point inflow sources in the active sections, especially in the roof rock, appeared to be very much fracture dependent. Inflow sources were observed most often to occur in one of three ways:

1. Contact between the mine workings and a natural geologic joint or fault.
2. Localized mining induced roof fractures that connect the mine workings with natural fracturing.

3. Roof bolt holes, which happen to be drilled into joints or bedding plane fractures.

Figure 3 is a simple schematic showing the three types of mine-fracture intercepts in cross section. Figure 4 shows an example of the roof bolt hole intercept. Note in this figure that adjacent roof bolts are producing no water whatsoever.

The roof bolt hole source is very much like a well drilled (4 to 6 ft) upside down, inside the mine. It also causes the most difficulty for miners (bolter crews especially) since they are required, in the drilling and bolting process, to work directly beneath a hole which may initially produce a 20- to 25-gpm inflow.

Fracture inflow in the mines surveyed occurs in two phases, similar to water well inflow. In the initial time-dependent phase, ground water stored in the intercepted fracture zone is released into the mine. This phase is characterized by an initially very high inflow rate which then tapers off over a period of days, weeks, or sometimes months. This time dependent interval of mine inflow is believed to depend on the following:

1. The areal extent of saturated rock fracturing (or the extent of the fracture zone) that has been tapped.

2. The recharge rate to the fracture zone (direct surface recharge could be occurring).

3. The direction and extent of mine development which may subsequently intersect the same fracture zone at a lower elevation, creating a preferred flow path for ground water inflow.

Generally, after a period of time, a steady state infiltration pattern develops at the fracture-mine intercept. In the steady-state phase, inflow is constant, though often considerably diminished from its initial rate. The steady-state inflow rate is for the most part determined by the rate at which the intercepted fracture (network) is recharged, either by ground water from the surrounding unfractured rock or by surface inflow from streams.

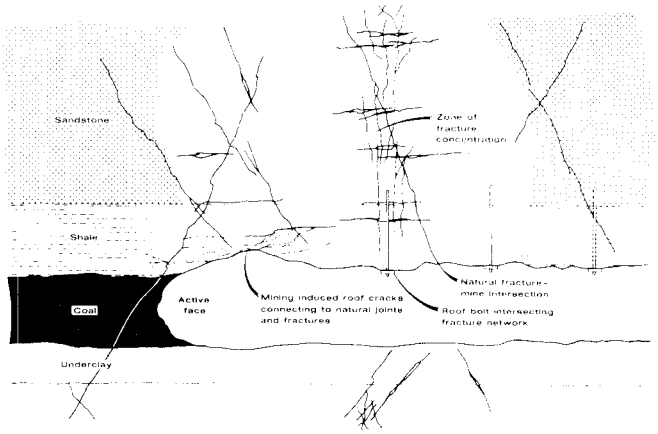

FIGURE 3. - Three types of mine fracture intercepts.

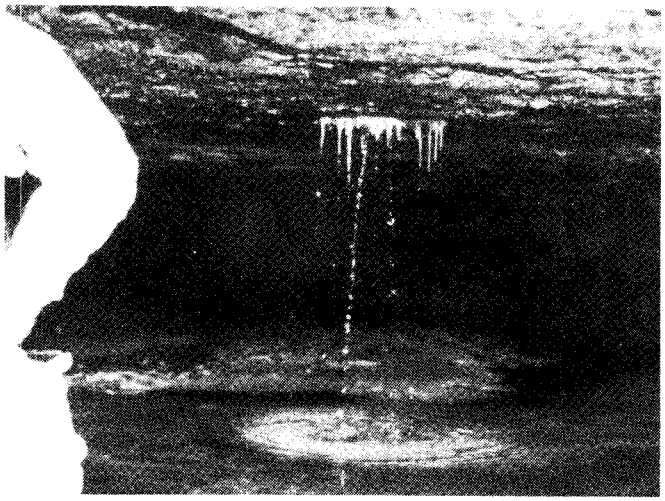

FIGURE 4. - Roof bolt hole inflow source.

In this survey, mine operators reported that it was not uncommon for a steady-state mine inflow source to intermittently revert to its initial high flow rate during periods of heavy rain or during spring snowmelt, where a good surface connection apparently existed.

The pattern of inflow in a mine influenced by fractures is therefore very often a transient one, with the highest inflow sources generally concentrated at the newly exposed workings, i.e., the active face. These sources then diminish as the face advances away from them but new sources closer to the face continually develop. Miners refer to this as water that "follows the face." This pattern of mine infiltration is characteristic of a wet section.

The occurrence of mine-fracture intercepts was observed most often in the roof, although mine-fracture intercepts in lower aquifer units are likely to occur in similar fashion. Very often, however, if the floor material is a soft fireclay, it forms an effective seal (aquitard) above the aquifer units that are below the mine. This clay seal rapidly deteriorates however, when exposed to the combined effects of roof leakage and heavy vehicle traffic.

FLOOR CONDITIONS IN A WET SECTION

As indicated previously, the severity of a mine water problem is related only partly to the quantity of water entering the mine workings. The location of inflow sources in the mine coupled with the affects of inflow on mine working conditions (mainly floor conditions) are equally important in determining the serious nature of a mine water problem.

In this survey, floor conditions near the face were the principal water-related problem reported by section foremen, especially in mines with a fireclay underlayment. Soft fireclay deteriorates when water from roof leakage causes swelling, and constant traffic churns the clay material into mud. Ruts, sumps, and low wet areas tend to develop on haulage routes. To compound the problem, as the fireclay aquitard deteriorates, piezometric pressures in the underlying aquifer cause an increase in infiltration through the mine floor. Figure 5 shows the development of this often observed floor problem.

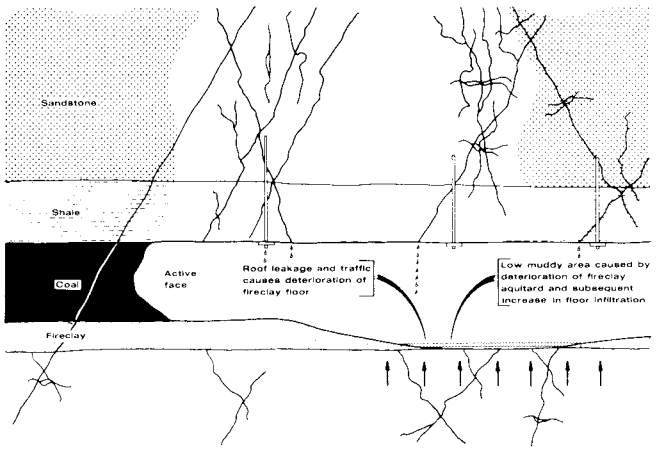

FIGURE 5. - Development of poor floor conditions at an active face.

Fireclay material scraped from the floor was often seen piled in abandoned entries after it had been churned into mud and was impeding rubber tired haulage between face and belt head. Crushed rock and planking in troublesome areas were also observed to be common temporary fixes, as was simply loading the fireclay material out with the coal.

Very little information of a quantitative nature is available in the literature concerning the effects of ground water inflow on coal mine production. However, it has been reported (16) that production may be higher by 50 to 75 tons per shift in a dry section than in a wet section with poor floor conditions.

A question asked of two section foremen during this survey may shed some light on the reason for the mine operator's concern with water at the active face. Section foremen in two of the mines that had recently experienced wet condtions were asked to estimate the number of minutes in an 8-h day (480 min) in which the continuous miner in their section was actually cutting coal. They were then asked to estimate the effect high inflow at the face (50 to 100 gpm) and bad floor conditions would have on coal cutting time. Table 2 summarizes their responses.

TABLE 2. - Probable effects of high inflow on coal cutting time per 8-h shift

	Mine 1	Mine 2
Cutting time, min:		
Dry conditions.....	90-100	120-150
Wet conditions.....	<15- 30	<15- 45
Lost production...pct..	17- 30	13- 30

These foremen attributed the lost production time to slower response of shuttle cars traveling over muddy and deeply rutted floors, increased electrical problems, and slower, less efficient performance of equipment operators and helpers working in wet muddy conditions. One of these foremen added that persistently wet mining conditions were often accompanied by higher than average miner absentee rates as well.

WATER QUALITY IN A WET SECTION

The mine inflow survey revealed that in four of the five eastern U.S. underground mines surveyed, the pH of water at the point of inflow ranged from 6.5 to 8.5. Fracture inflow in one mine had a pH of 4.4 and was known to be coming from an overlying abandoned mine. Four of five mines treated their water for acidity prior to discharge, with mine effluent pH ranging from 3.0 to 4.5.

With respect to acidity and iron content, mine water at the point of infiltration was comparatively high quality if it had a more or less undisturbed ground water source. Undisturbed sources of fracture water included the surrounding unfractured aquifer material, glacial or alluvial deposits, or direct surface infiltration, i.e., streams, rainfall, snowmelt, etc. Mine inflow coming from disturbed sources such as abandoned mine workings or mine spoils was often degraded at the point of infiltration to the mine.

APPROACHES AND PROBLEMS OF PAST MINE DEWATERING EFFORTS

Several possible well dewatering schemes to control leakage into underground mines have been studied. One of the first proposed exploiting highly permeable fracture zones as possible high yield well sites for dewatering underground mines (20). A second study (21) discussed the benefits that might be achieved by reducing head levels in bedrock aquifers located immediately above and below underground coal mines. The concept of connector wells or gravity wells for mine dewatering was also introduced in these reports.

The dewatering methods proposed by these studies are intended entirely as a means of reducing acidic mine drainage from abandoned and inactive mine workings. The development and production problems that result from localized high inflows in active mine sections are not addressed, and the dewatering methods proposed are not readily adapted to deal with the transient flow conditions that occur in active mining sections.

Of the several different coal mine dewatering schemes proposed, pumped well dewatering of sandstone aquifers to control AMD in inactive mine workings was only recently attempted (1).

Exploration and pump tests of wells revealed that ground water flows into the study area of the mine were concentrated along two fracture zones that appeared to intersect in the area of greatest inflow. These preferred and rather narrow flow paths were not revealed until after completion of observation wells and dewatering wells.

MODELING THE FRACTURE ZONE FLOW PROBLEM

The justification for including fracture zones in the siting process for dewatering wells may arise from a number of past research experiences including the following:

1. The apparent importance of mine-fracture intercepts as inflow sources in both active and inactive underground workings.
2. Past dewatering attempts that describe the prohibitively high cost of mine dewatering with wells of comparatively low yield (i.e., wells drilled without regard to preferred flow paths).
3. The more or less well established technique for locating fracture zones (fracture trace analysis) and the past use of fracture-sited wells to obtain the high-capacity pumping necessary of municipal water wells.
4. The association of high volume storage water release in wet sections with the high storage and transmissive properties of fracture zones.
5. Computer models that describe the advantageous flow pattern and higher yield of wells sited on high permeability fracture zones.

Of particular interest is the analytical justification for fracture dewatering revealed by computer modeling of fracture zone-dewatering well problems.

Depending on how the fracture flow problem is conceptualized, models of flow in fractured media generally take one of three basic approaches, termed, equivalent porous media, double porosity, or discrete fracture (22).

The equivalent porous media approach treats the fractured rock mass as statistically equivalent to a continuous and homogeneous porous medium. This is perhaps the simplest characterization of fracture flow processes.

The double porosity approach is a continuous approach also. In this approach, the fractured medium is represented by porous blocks of material surrounded by a porous network of fissures. The two systems are linked by an equation that describes flow from blocks to fissures, which involves the pressure differential between the two systems at any point (23-24).

Discrete fracture models focus attention on the geometry of individual fractures, attempting to duplicate such features as aperture size, orientation, roughness, etc. Models that conceive of fractures as parallel planer plates (25) fall into this category.

This approach was combined with boundary element methods to model uniform flow in a porous medium incorporating multiple intersecting fracture channels (26).

For the fracture zone flow problem of this investigation, a modeling approach must be selected that is consistent with the following:

1. The geologic characterization of fracture zones.
2. The availability of field data for describing a particular fracture zone network.
3. What is considered to be the scale of the dewatering problem area, or region of hydrologic interest.

In keeping with these guidelines, the computer code developed for this investigation is a straightforward application of a semianalytical technique (27) for simulating flow regions incorporating discrete zones of differing permeability. As such, program DWATR can be classified as an equivalent porous media model of a fractured rock mass.

MODEL DEVELOPMENT

In this approach to the modeling of dewatering activity, zones of concentrated rock fracturing are treated as discrete regions of high average permeability. Flow in the aquifer is treated as two dimensional in the horizontal plane.

The modeling approach is based on superposition of elementary analytic solutions to features such as uniform flow, flow toward a well, and flow across a discontinuity in permeability. Program DWATR is also equipped with streamline tracing routines in order to track ground water particle movement.

The following section contains a summary of the basic equations for flow in a homogeneous confined or unconfined aquifer, followed by a presentation of the elementary solutions for uniform flow, flow toward a well, and flow across a discontinuity in permeability.

BASIC EQUATIONS

The components q_x, q_y, and q_z of the specific discharge vector [L/T] in an isotropic porous medium are given by Darcy's law,

$$q_x = -k \frac{\partial \phi}{\partial x}, \quad q_y = -k \frac{\partial \phi}{\partial y}, \text{ and}$$

$$q_z = -k \frac{\partial \phi}{\partial z}, \tag{1}$$

where k is the permeability [L/T] and ϕ is the piezometric head [L] as measured from the bottom confining layer, which is taken to be horizontal. Continuity of flow yields

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = 0. \tag{2}$$

Substitution of equation 1 into equation 2 gives the LaPlace equation

$$\nabla^2 \phi = 0. \qquad (3)$$

Equation 3 is the differential equation for steady-state flow in an isotropic porous medium.

Regional Confined Flow

For the case of two-dimensional confined ground water flow, as illustrated in figure 6, a discharge vector with components Q_x and Q_y $[L^2/T]$ is introduced, which represents the flow of ground water through planes of unit width, normal to the x and y axis and extending over the height, H, of the aquifer, so that

$$Q_x = \int_o^H q_x \, dz = H \cdot q_x \text{ and}$$

$$Q_y = \int_o^H q_y \, dz = H \cdot q_y. \qquad (4)$$

In writing equation 4, use is made of the Dupuit-Forchheimer assumption whereby the piezometric head, ϕ, does not vary with z, so that q_x and q_y do not vary with z. Substituting Darcy's law (equation 1) into equation 4 gives

$$Q_x = \frac{-\partial kH\phi}{\partial x} \text{ and } Q_y = \frac{-\partial kH\phi}{\partial y}. \qquad (5)$$

A discharge potential, $\Phi[L^2/T]$, is introduced whereby

$$\Phi = kH\phi + C_c, \qquad (6)$$

so that the components of the discharge vector follow from

$$Q_x = \frac{-\partial \Phi}{\partial x} \text{ and } Q_y = \frac{-\partial \Phi}{\partial y}. \qquad (7)$$

The constant C_c is arbitrary and vanishes from Q_x and Q_y.

Regional Unconfined Flow

For the case of unconfined flow, illustrated in figure 7, the components Q_x and Q_y of the discharge vector follow from

$$Q_x = \int_o^H q_x \, dz = q_x \cdot \phi \text{ and}$$

$$Q_y = \int_o^H q_y \, dz = q_y \cdot \phi, \qquad (8)$$

where the piezometric head, ϕ, is measured from the aquifer base, and where use is again made of the Dupuit-Forchheimer assumption. Equation 8 becomes, with equation 1,

$$Q_x = -k\phi \cdot \frac{\partial \phi}{\partial x} \text{ and } Q_y = -k\phi \cdot \frac{\partial \phi}{\partial y} \qquad (9)$$

or

$$Q_x = \frac{-\partial (1/2k\phi^2)}{\partial x} \text{ and } Q_y = \frac{-\partial (1/2k\phi^2)}{\partial y}. \qquad (10)$$

The discharge potential, Φ, for unconfined flow is then defined as

$$\Phi = 1/2k\phi^2 + C_u, \qquad (11)$$

where again C_u is an arbitrary constant that vanishes from Q_x and Q_y.

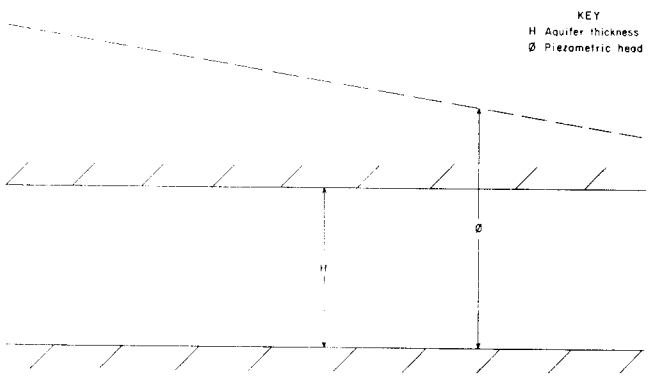

FIGURE 6. - Confined flow setting.

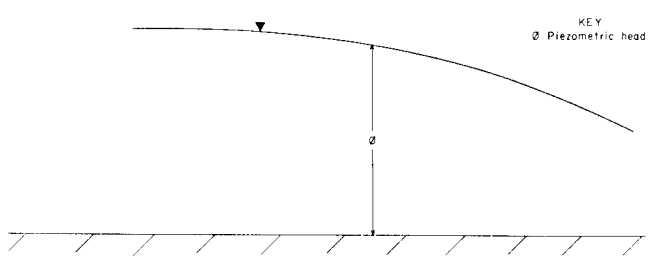

FIGURE 7. - Unconfined flow setting.

Combined Confined and Unconfined Flow

Along the boundary between regions of confined and unconfined flow in figure 8, $\phi = H$, since ϕ is continuous. The constants C_c and C_u can be chosen to ensure that the discharge potential, Φ, is also continuous at this interegional boundary (28).

Setting $\phi = H$ in equations 6 and 11, continuity of Φ gives

$$k \cdot H \cdot H = 1/2k\phi^2 + C_u, \qquad (12)$$

selecting $C_c = 0$, it follows for C_u that

$$C_u = 1/2kH^2. \qquad (13)$$

Thus a discharge potential, Φ, in a aquifer involving both confined and unconfined flow, may be defined as

$$\Phi = \begin{cases} kH\phi \text{ if } \phi \geqslant H \\ 1/2k\phi^2 + 1/2kH^2 \text{ if } 0 \leqslant \phi < H \end{cases}. \qquad (14)$$

Alternatively, the expression for piezometric head, ϕ, is given as

$$\phi = \begin{cases} \Phi/kH \text{ if } \Phi \geqslant kH^2 \\ \sqrt{\dfrac{\Phi - 1/2kH^2}{1/2k}} \text{ if } 1/2kH^2 < \Phi < kH^2 \end{cases}. \qquad (15)$$

In a Dupuit-Forchheimer model, the continuity equation formulated in terms of discharge vectors becomes

$$\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = 0, \qquad (16)$$

so that La Place's equation becomes

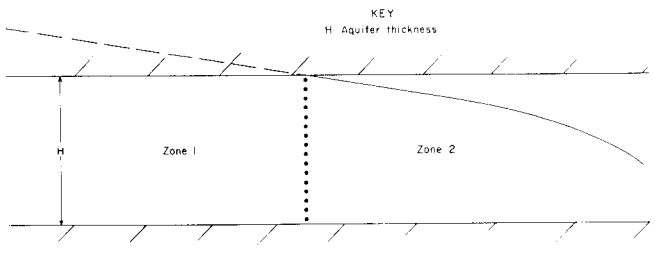

FIGURE 8. - Confined and unconfined flow, combined.

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} = 0, \qquad (17)$$

where Φ is defined by equation 14.

It is noted that the solution to the ground water flow problem formulated in terms of Φ does not distinguish between confined or unconfined flow conditions. Hence the boundaries between regions of confined and unconfined flow need not be known beforehand. Once Φ has been determined as a function of location, these flow conditions simply follow from the value of Φ in equation 15.

ELEMENTARY SOLUTIONS

The solution to a flow problem containing such features as uniform flow, flow toward wells, and discontinuities in the permeability may be obtained by superimposing the elementary solution to each feature. The discharge potential, Φ, for the combined solution still satisfies equation 17, since equation 17 is linear in Φ. The following section presents the elementary solutions used in the present model.

Complex Potential Function

An analytic complex function $\Omega = \Omega(z)$ is introduced here as (see references 29 and 30),

$$\Omega(z) = \Phi(z) + i\Psi(z), \qquad (18)$$

where $(z = x + iy)$. The real part of this complex potential function, $\mathrm{Re}[\Omega(z)]$, is the discharge potential as given by equation 15 and the imaginary part, $\mathrm{Im}[\Omega(z)]$, is termed the stream function.

The stream function is constant along streamlines, and the total discharge between two streamlines is equal to the difference in their stream function values (see reference 30).

$\Phi(z)$ and $\Psi(z)$ are related by the Cauchy-Riemann conditions,

$$\frac{\partial \Phi}{\partial x} = \frac{\partial \Psi}{\partial y} \text{ and } \frac{\partial \Phi}{\partial y} = \frac{-\partial \Psi}{\partial x}. \qquad (19)$$

It follows from equations 19 and 17 that both Φ and Ψ are harmonic functions, whereby Ψ is termed the conjugate harmonic of Φ.

Uniform Flow

The complex potential for uniform horizontal flow, $\Omega_f(z)$ (29), is presented here as

$$\Omega_f(z) = V_\gamma H z e^{-i\gamma} + C, \qquad (20)$$

where V_γ is the natural ground water flux, [L/T], in a direction, γ, measured with respect to the positive x axis. The constant, C, in equation 20 is arbitrary.

Flow Toward a Well

The complex potential, $\Omega_w(z)$, for a single completely penetrating well at a point, z_o, is presented in ground water flow texts (e.g., reference 29) as

$$\Omega_w(z) = \frac{Q}{2\pi} \ln (z-z_o) + C, \qquad (21)$$

where Q is the well strength (discharge rate) [L^3/T].

Separating $\Omega_w(z)$ into real and imaginary parts gives

$$\Phi_w(z) + i\Psi_w(z) = \frac{Q}{2\pi} \ln |z-z_o| + \frac{iQ}{2\pi} \arg (z-z_o) + C, \qquad (22)$$

where the imaginary part

$$\Psi_w(z) = \frac{Q}{2\pi} \arg (z-z_o), \qquad (23)$$

is the stream function for the well. The argument of z is chosen as

$$-\pi \leq \arg (z) \leq \pi.$$

As appears from equation 22, equipotentials are concentric circles around the well, while streamlines are radials from the well. It is noted that the stream function jumps by the amount Q when crossing the negative axis. This discontinuity in Ψ_w for $x < x_o$, $y = y_o$ is termed the branch cut.

The superposition principle enables a multiple well pattern to be modeled simply as the sum of individual well solutions. The general solution for flow toward n wells then follows from

$$\Omega_w(z) = \sum_{j=1}^{n} \frac{Q_j}{2\pi} \ln (z-z_j) + C, \qquad (24)$$

where z_j is the location and Q_j the strength of the jth well.

Flow Across a Permeability Discontinuity

In figure 9, a cross section of a confined aquifer is depicted containing two zones of different permeability. On the left (-) side, of the dotted vertical the permeability is k_o, and on the right (+) side the permeability is k_1. Since the piezometric head is continuous on the boundary between k_o and k_1, it follows from equation 14 that the relation between Φ_o and Φ_1 at the permeability discontinuity is

$$\Phi_1 = \frac{k_1}{k_o} \cdot \Phi_o, \qquad (25)$$

where the subscripts in Φ_o and Φ_1, denote the permeability used in equation 14. As seen from equation 25, the potential is discontinuous across the jump in permeability. The discontinuity, $\Delta\Phi$, may be expressed in terms of Φ_o as

$$\Delta\Phi = \Phi_1 - \Phi_o = \left(\frac{k_1 - k_o}{k_o}\right) \cdot \Phi_o. \qquad (26)$$

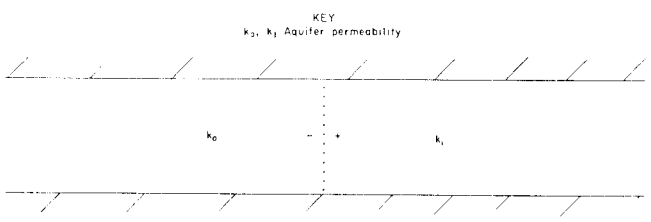

FIGURE 9. - Permeability discontinuity.

In order to model this jump in potential, use is made of line doublets as presented in reference 27 for modeling flow domains containing regions of different permeabilities.

The potential due to a line doublet is discontinuous across the line doublet. This discontinuity in the potential is equal to the doublet strength. Line doublets with varying strengths are distributed along the boundary between zones of different permeability in order to satisfy equation 26. The use of line doublets in the DWATR model is briefly described in the following.

The complex potential due to a line doublet with a second order strength distribution, as given in reference 27, is

$$\Omega_p(z) = - i \frac{S(z)}{2\pi} \ln\left(\frac{z_\ell+1- z}{z_\ell - z}\right) + \mu(z), \quad (27)$$

where S is defined as

$$S(z) = S_\ell\left(\frac{z_\ell+1-z}{z_\ell+1-z_\ell}\right) + S_\ell+1\left(\frac{z_\ell - z}{z_\ell-z_\ell+1}\right) - 4\mu_\ell \frac{(z-z_\ell)(z-z_\ell+1)}{(z_\ell - z_\ell+1)^2}, \quad (28)$$

and μ is defined as

$$\mu(z) = \frac{2i\mu_\ell}{\pi}\left(\frac{z-1/2\ (z_\ell + z_\ell+1)}{z_\ell+1 - z_\ell}\right). \quad (29)$$

In equation 27, z_ℓ and $z_\ell+1$ are the endpoints of the line doublet. In equation 28, S_ℓ and $S_\ell+1$ are real numbers representing the strength of the doublet at endpoints z_ℓ and $z_\ell+1$, and μ_ℓ is the parabolic component of strength defined such that the strength at the midpoint between and z_ℓ and $z_\ell+1$ equals $1/2(S_\ell + S_\ell+1) + \mu_\ell$.

That the real part of equation 27, the potential, is indeed discontinuous across the line doublet, may be seen as follows. If $z = \delta$, where δ is on the line doublet, equation 28 is real, so that the potential, $\Phi_p(\delta)$, becomes

$$\Phi_p(\delta) = \frac{S(\delta)}{2\pi} \cdot \Theta, \quad (30)$$

where Θ is the imaginary part of the logarithm in equation 27,

$$\Theta = \arg\left(\frac{z_\ell+1-\delta}{z_\ell-\delta}\right). \quad (31)$$

The angle Θ is $+\pi$ if δ is selected on the upper side of the line doublet (see figure 10), and $-\pi$ if δ is on the lower side. Consequently the potential, $\Phi_p(\delta)$, in equation 30 jumps by an amount $S(\delta)$ when crossing the line doublet, whereby $S(\delta)$ varies parabolically over the line element.

It may be seen from equation 28 that $S(\delta)$ assumes the values S_ℓ, $1/2(S_\ell+S_\ell+1) + \mu_\ell$ and $S_\ell+1$ when δ is z_ℓ, $1/2(z_\ell+z_\ell+1)$ and $z_\ell+1$, respectively. The potential along each side of a line doublet is plotted in figure 10.

The doublet strength, $S(\delta)$, may be expressed in terms of $\Phi_o(\delta)$ by use of equation 26,

$$S(\delta) = \left(\frac{k_1 - k_o}{k_o}\right) \cdot \Phi_o(\delta). \quad (32)$$

The imaginary part of equation 27, the stream function $\Psi_p(z)$, is continuous everywhere, so that the discharge normal to the line doublet is continuous. Therefore, doublets that model the jump in potential across permeability discontinuities preserve continuity of flow across the boundary.

MODELING FRACTURE ZONES

Zones of concentrated rock fracturing are modeled as discrete zones of high average permeability. Line doublets are distributed end to end along the entire closed boundary of the fracture zone to account for the jump in potential that results from this discontinuity in aquifer permeability.

A fracture flow problem may involve more than one zone of high permeability, furthermore, wells may be located both inside and outside of these zones. Flow resulting from far field conditions is introduced by means of a uniform gradient of flow across the domain of interest.

The uniform flow rates and the well discharges are considered known, but the doublet strengths along discontinuities in permeability are not known in advance. Their values depend on the potential along the doublets as given by equation 32. Imposing the condition of equation 32 at a number of control points along the line doublet results in a set of equations for which the unknown strength parameters may be solved. Once the doublet strengths are determined, the potential in the aquifer can be evaluated as the sum of the potentials due to the uniform flow, all wells and all doublets.

Matrix Equations

Consider the flow domain depicted in figure 11, with permeability k_1 inside the region depicted and k_o outside. Figure 11 illustrates an idealized fracture zone flow problem in which intersecting zones of rock fracturing are modeled as a single high permeability region. A well is situated at the fracture zone intersection.

Fifty-eight line doublets are used to define the boundary of this high permeability fracture zone. Thus there are 58 unknown strengths, S_ℓ, defined at doublet endpoints, and 58 unknown parabolic strength parameters, μ_ℓ, defined at doublet midpoints. The condition of equation 32 is imposed on all doublet endpoints and midpoints, i.e., on all control points.

This leads to the following 58 equations for line doublet endpoints, δ_j, $(j = 1,2,\ldots 58)$

$$S_\ell \Lambda_{\ell j} + \mu_\ell \chi_{\ell j} + G_j + \Phi_o = \left(\frac{k_o}{k_1 - k_o}\right) S_j, \qquad (33)$$

$(\ell = 1,2,\ldots 58)$,

and the following 58 equations for the line doublet midpoints, δ_j, $(j = 59,60,\ldots 116)$,

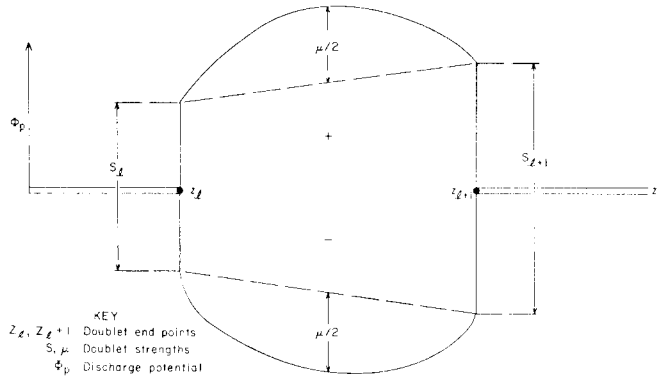

FIGURE 10. - Jump in potential at a line doublet.

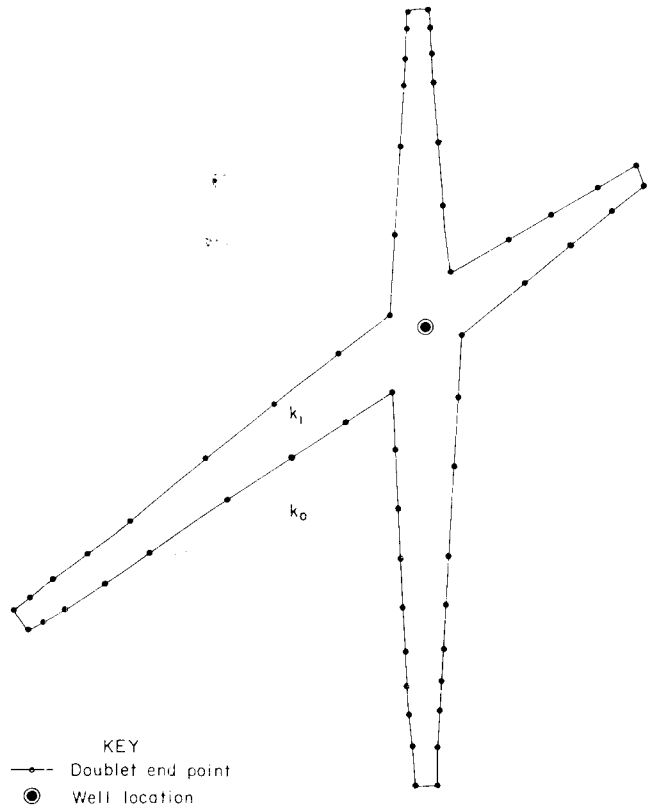

FIGURE 11. - Idealized fracture zone setting.

$$S_\ell \Lambda_{\ell j} + \mu_\ell \chi_{\ell j} + G_j + \Phi_o = \left(\frac{k_o}{k_1 - k_o}\right) \frac{S_{j-58} + S_{j-57}}{2} + \mu_{j-58}, \qquad (34)$$

$(\ell = 1,2,\ldots 58)$,

where $S_{59} = S_1$ and $\mu_{59} = \mu_1$.

The coefficient functions $\Lambda_{\ell j}$ and $\chi_{\ell j}$ are defined as

$$\Lambda_{\ell j} = \frac{1}{2\pi}\left[\left(\frac{z_{\ell+1}-\delta_j}{z_{\ell+1}-z_\ell}\right)\cdot \arg\left(\frac{z_{\ell+1}-\delta_j}{z_\ell-\delta_j}\right) - \left(\frac{z_{\ell+1}-\delta_j}{z_{\ell+1}-z_\ell}\right)\cdot \arg\left(\frac{z_\ell-\delta_j}{z_{\ell+1}-\delta_j}\right) \quad (\ell\neq j)\right] \tag{35}$$

and

$$\chi_{\ell j} = \frac{-2}{\pi}\left(\frac{(\delta_j-z_\ell)(\delta_j-z_{\ell+1})}{(z_\ell - z_{\ell+1})^2}\right)\cdot \arg\left(\frac{z_{\ell+1}-\delta_j}{z_\ell-\delta_j}\right). \tag{36}$$

Special care must be taken in calculating Λ_{jj} since the argument function in equation 35 contains a removable singularity. The expression for Λ_{jj} is

$$\Lambda_{jj} = \frac{1}{2\pi}\arg\left(\frac{z_{j+1}-\delta_j}{z_{j-1}-\delta_j}\right). \tag{37}$$

The function G_j contains all known contributions to the potential,

$$G_j = \mathrm{Re}\,[\Omega_w(\delta_j) + \Omega_f(\delta_j)], \tag{38}$$

where $\Omega_w(\delta_j)$ and $\Omega_f(\delta_j)$ are the complex potentials due to wells and uniform flow.

Equations of the form of equations 33 and 34 contain 116 unknown strength parameters, S_ℓ and μ_ℓ, and an unknown potential, Φ_o. Specifying the potential Φ^* at a point outside the domain of interest provides the additional equation

$$S_\ell\Lambda_{\ell j} + \mu_\ell\,\chi_{\ell j} + G_j + \Phi_o = \Phi^* \quad (j = 117), \tag{39}$$

necessary to solve for the unknown doublet parameters.

These 117 equations may be written in matrix form

$$a_{\ell j}\cdot x_\ell = y_j, \tag{40}$$

where $a_{\ell j}$ becomes, with equations 33 through 39,

$$\begin{aligned}
a_{\ell j} &= \Lambda_{\ell j} - \delta_{\ell j}\left(\frac{k_o}{k_1-k_o}\right) && \text{for } (\ell = 1,2,\ldots 58),\ (j = 1,2,\ldots 58),\\
a_{\ell j} &= \chi_{\ell j} && \text{for } (\ell = 59,60,\ldots 116),\ (j = 1,2,\ldots 58),\\
a_{\ell j} &= \Lambda_{\ell j} - \delta_{\ell j}\left(\frac{k_o}{k_1-k_o}\right) - \delta_{\ell,j+1}\left(\frac{k_o}{2(k_1-k_o)}\right) && \text{for } (\ell = 1,2,\ldots 58),\ (j = 59,60,\ldots 117),\\
a_{\ell j} &= \chi_{\ell j} - \delta_{\ell j}\left(\frac{k_o}{k_1-k_o}\right) && \text{for } (\ell = 59,60,\ldots 116),\ (j = 59,60,\ldots 117),
\end{aligned} \tag{41}$$

and

$$a_{\ell j} = 1 \qquad \text{for } (\ell = 117),\ (j = 1,2,\ldots 117),$$

and where $\delta_{\ell j}$ is the Kronecker delta

$$\delta_{\ell j} = 1 \text{ if } \ell = j \text{ and}$$

$$\delta_{\ell j} = 0 \text{ if } \ell \neq j. \qquad (42)$$

The vectors x_ℓ and y_j in equation 40 are given by

$$x_\ell = S_\ell \text{ for } (\ell = 1,2,\ldots 58),$$

$$x_\ell = \mu_{\ell-58} \text{ for } (\ell = 59,60,\ldots 116),$$

$$x_\ell = \Phi_o \text{ for } (\ell = 117), \qquad (43)$$

and

$$y_j = G_j \text{ for } (j = 1,2,\ldots 117). \qquad (44)$$

The solution vector, x_ℓ, is obtained in equation 40 by use of Gauss Jordan elimination (see reference 31).

Plotting Piezometric Head Contours

Once the solution vector is known, i.e., once S_ℓ and μ_ℓ are known, the potential at an arbitrary point z in the domain of interest is obtained from

$$\Phi(z) = \text{Re } [\Omega_p(z) + \Omega_w(z) + \Omega_f(z)] + \Phi_o, \qquad (45)$$

where $\Omega_p(z)$, $\Omega_w(z)$, and $\Omega_f(z)$ are the complex potentials, due respectively to all zones, all wells, and uniform flow.

Piezometric head contours are obtained by first calculating ϕ at a network of points, using equations 45 and 15. A cubic spline technique is used to generate contour plots (see reference 32).

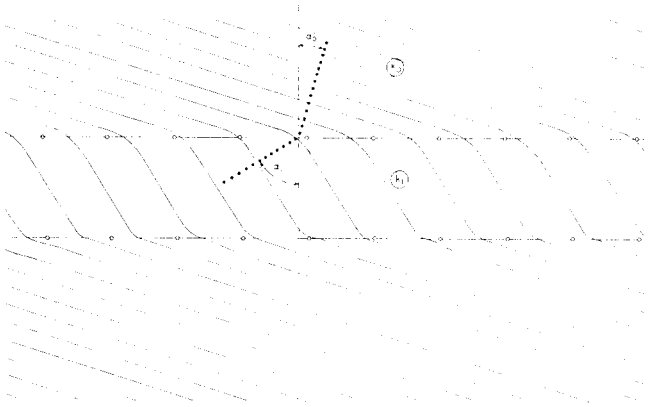

FIGURE 12. - Inhomogeneity in a strip.

Validation

Program DWATR has been validated by solving a problem of uniform confined flow in a homogeneous region of permeability, k_o, containing a homogeneous infinite strip of permeability, k_1. The exact solution to this problem is described in reference 33. At the boundary between k_o and k_1, the refraction of piezometric contours may be represented as

$$\frac{\tan \alpha_1}{\tan \alpha_o} = \frac{k_1}{k_o}, \qquad (46)$$

where α_o and α_1 are angles indicated in figure 12. The location of doublet endpoints on the boundary between k_o and k_1 are also indicated. In figure 12, $k_1/k_o = 5$, $\alpha_o = 17.5$, and $\alpha_1 = 57.5$. Thus the refraction of contour lines predicted by program DWATR appears to be correct.

PROGRAM DWATR

Program DWATR was developed using the semianalytic method just described. The program was written in Fortran 77 and run on a minicomputer with a 16-bit processor and 1.0 megabyte of internal memory. Virtual memory was used for runs involving more than 150 line doublets.

While streamlines are generated numerically using one of the two Newton-Raphson subroutines incorporated in DWATR, streamline plots (and contour maps) are generated by separate programs. Appendix A describes program modules and input-output (I-O) logical unit numbers.

Streamline data created by DWATR are output to disk I-O units 15 and 17. Contour data are output to I-O units 15 and 13. A significant portion of DWATR's

computation time involves calculating the exact strengths at line doublet control points. For computational efficiency these strengths are output to (and may be reinput from) logical unit 19.

DWATR input parameters and their formats are listed in appendix B. Appendix C is a source listing of the program.

A magnetic tape copy of DWATR, sample I-O data sets, and graphical support programs are all available from the Bureau's Twin Cities (MN) Research Center.

IDEALIZED FRACTURE ZONE SIMULATION

The idealized fracture zone setting depicted in figure 11 serves as the initial application of DWATR. Two intersecting fracture zones are modeled as a single high-permeability region. The ratio of permeabilities inside and outside the region is given by $k_1/k_o = 1{,}000$. A well is simulated at the center of the region. Uniform flow is also assumed to occur.

The boundary of the high-permeability region in this figure is composed of 58 line doublets. Doublet strengths are interpolated parabolically between endpoints leading to 116 strength parameters, to be calculated along the boundary.

The accuracy with which line doublets approximate the jump in potential at a permeability zone boundary depends, naturally, on how well a second order doublet approximation represents the actual strength distribution on the boundary. Therefore, selecting the number and spacing of line doublet endpoints is important to obtaining an accurate simulation of a particular flow problem. Too few line doublets along a boundary leads to significant errors of approximation in both Φ and Ψ near the zone boundary. Tracing streamline paths using Newton's method is especially difficult in this case.

In figure 11, doublets are concentrated at the ends of the fracture zone where the gradient in Φ is steepest. Since strength, S, is proportional to Φ at the permeability zone boundary, a concentration of doublet control points is often necessary along intervals of the boundary where equipotential lines are compressed together.

A piezometric surface is developed for the flow problem depicted in figure 11. In figure 13, drawdown of the piezometric surface in the vicinity of the well is clearly influenced by the high permeability fracture zone. The theoretical maximum discharge from this well is limited by the requirement that $\phi > 0$ at the well radius. Maximum discharge is increased by a factor of 2.65 as a result of the fracture zone setting.

APPROPRIATE APPLICATIONS FOR DWATR

The fracture valley settings for which DWATR is appropriate are those where the coal seam is overlain by a single aquifer unit. The aquifer is often confined by a shale layer beneath hilltops and unconfined beneath deeply incised stream valleys. Typically this shallow aquifer is intensely fractured beneath the valley bottom. Numerous fracture traces also cut across the valley bottom, and extend

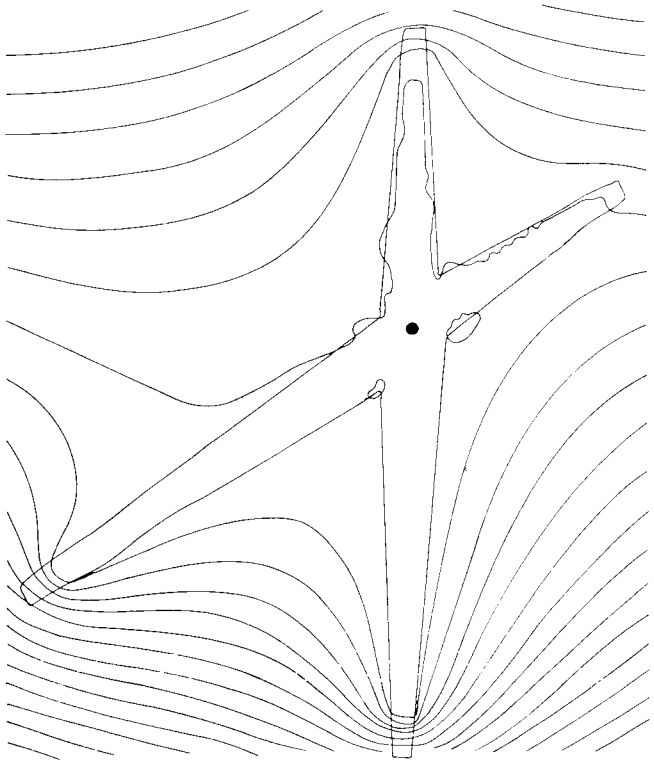

FIGURE 13. - Idealized fracture zone piezometric surface.

hundreds or thousands of feet into the adjacent hills.

Other hydrogeologic features encountered in mine dewatering problems include layered aquifer systems, concentrated surface infiltration to fracture zones, and drainage into nearby underground mine voids. Program DWATR is presently unable to handle these complexities.

These constraints on the application of this model imply that at this stage in its development the model can be used most effectively to aid in conceptual understanding of ground water flow associated with fracture zone well sitings, in addition to providing additional justification for focusing mine dewatering attention on preferred (high permeability) ground water flow paths, such as fracture zones.

Application of DWATR at the Sunshine Mine (West Virginia) dewatering test site was not undertaken until after the dewatering field work had been completed. It is suggested however that hydrology modeling and field dewatering activity be performed more or less concurrently. Conceptual understanding of a dewatering problem increases most when the problem is used in an experimental fashion to discern the relationship between various parameters and the sensitivity of the overall setting to manipulation of parameter values.

Program DWATR may supply an explanation for seemingly anomalous pump test results. It may be used to predict the impact of introducing new wells and it can suggest where additional field data (permeability measures, details of fracture zones, etc.) should be collected in order to fill gaps of understanding.

SUNSHINE MINE DEWATERING SITE

The Sunshine Mine is a small, underground room and pillar operation. The mine is located in the Monongahela River basin in northcentral West Virginia (fig. 14). Geologically it lies almost on the axis of the Kingwood syncline. The valley setting that overlies a portion of the Sunshine Mine workings is known locally as Crab Orchard Run (fig. 15). Most of the ground water inflow problems at the Sunshine Mine workings occurred in the vicinity of this valley.

The coal seam being mined is the Upper Freeport and the depth to coal beneath Crab Orchard Run averages 110 ft. The Upper Freeport coal is overlain by the Conemaugh Formation and underlain by the

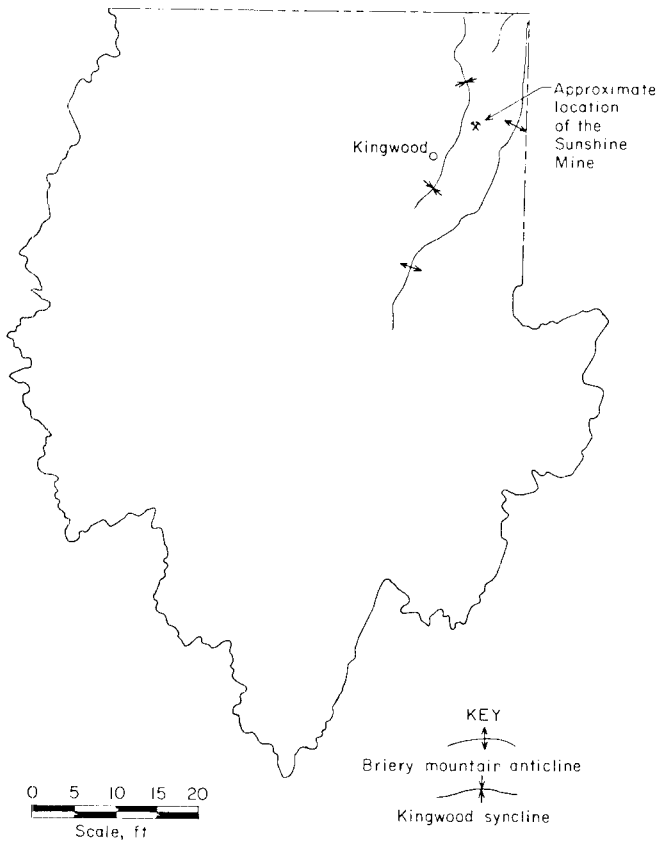

FIGURE 14. - Location of the Sunshine Mine dewatering test site in the Monongahela River basin of West Virginia (3).

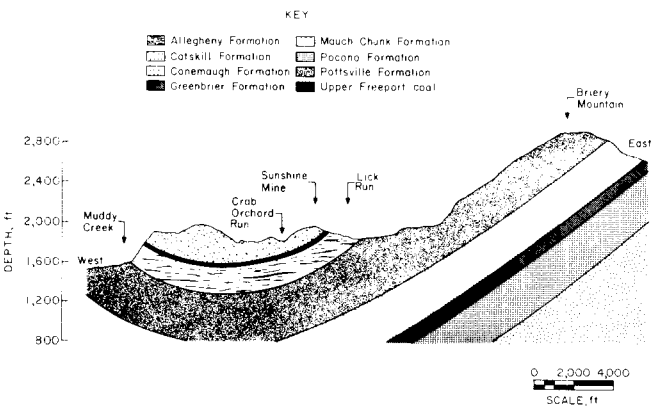

FIGURE 15. - Sunshine Mine location within the Kingwood syncline (3).

Allegheny Formation (3). The Briery Mountain anticline, elevated 1,000 ft above the bottom of Crab Orchard Run and approximately 3 miles east, is believed to be a regional source of recharge for deeper sandstone units below the coal seam, creating an underlying east to west gradient of flow in the Kingwood syncline.

A portion of the topographic map which includes Crab Orchard Run is reproduced in figure 16. Overlain on this map are the Sunshine Mine workings, the photolinear features (fracture traces) that are indicators of high-permeability fracture zones in underlying rock units (35), and the locations of 18 wells and piezometer holes constructed within Crab Orchard Run, as part of this investigation.

Most of the fracture traces are concentrated in the valley bottom, however, five well-defined zones that cut across the valley are also indicated in this figure. More detailed specifications for the wells and piezometer holes annotated on this figure appear in table 3.

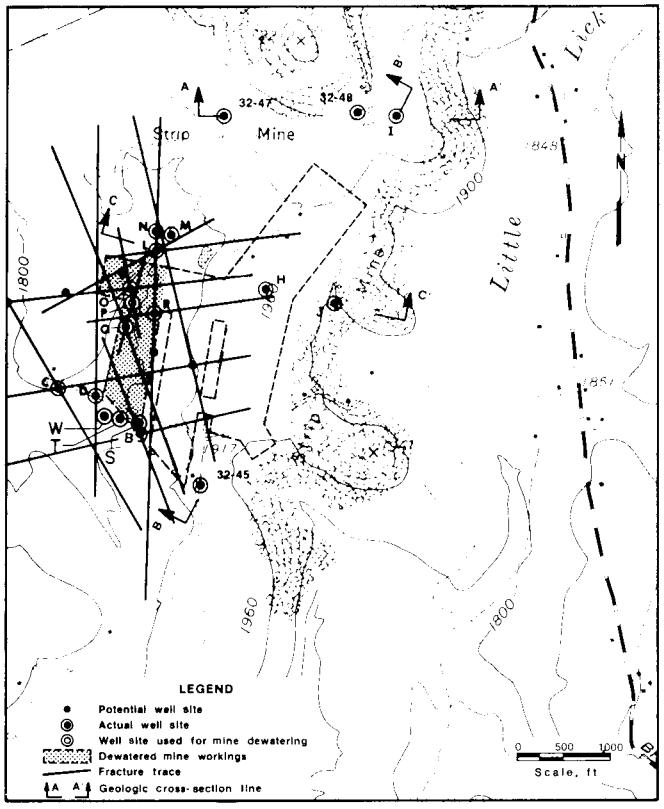

FIGURE 16. - Fracture traces and well locations in the vicinity of Crab Orchard Run (34).

Mining company records indicate that the strike of the coal seam is 40° west of north and the dip is to the southwest at 3.4° (6 pct). Geologic cross sections appearing in figures 17 through 19 were constructed from well and core hole data obtained in the vicinity of the mine. In addition to the Upper Freeport coal, these cross sections show the orientation and thickness of a shallow sandstone layer that lies above the coal seam. Figure 16 shows the location of these cross sections in plan view.

Wells labeled 32-45, 32-47, and 32-48 on figure 16 were core holes drilled earlier by the mining company. Water level measurements in these holes were not available.

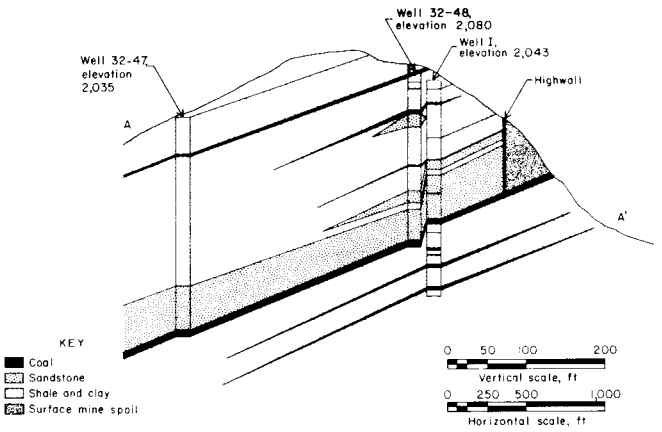

FIGURE 17. - Geologic cross section at AA'.

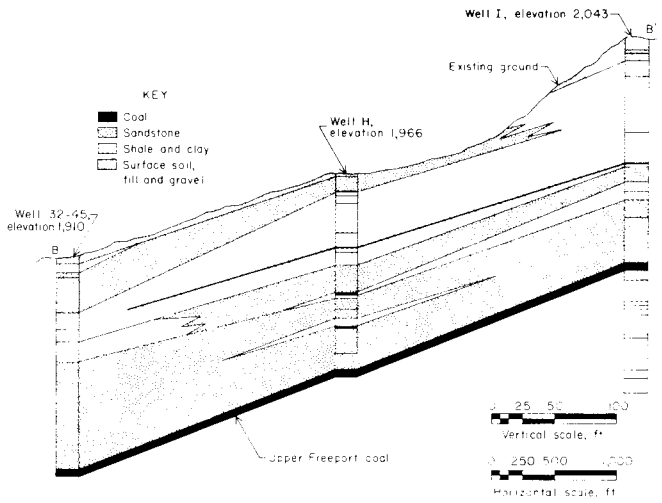

FIGURE 18. - Geologic cross section at BB'.

TABLE 3. - Crab Orchard Run well and aquifer data, feet

Well	Coordinates		Elevation[1]	Well depth	Casing length	Upper Freeport coal elevation	Static water level--		Shallow confined aquifer thickness	Fracture zone status
	x	y					Elevation	Above datum[2]		
B.....	50	-2,100	1,800	458	27	1,645	1,756.0	NAp	140	Int.
C.....	-1,750	-1,200	1,777	501	141	1,646	1,711.5	NAp	54	Int.
D.....	-850	-1,350	1,775	454	12	1,652	1,740.2	NAp	111	Single.
H.....	2,700	1,000	1,966	[3]140	8	[e]1,791	1,906.0	218.0	105	None.
I.....	5,300	4,800	2,043	275	174	1,869	1,893.0	NAp	70	Do.
L.....	200	1,800	1,807	314	120	1,708	1,724.0	NAp	99	Int.
M.....	800	2,200	1,811	82	8	[e]1,709	1,802.2	114.2	100	None.
N.....	200	2,200	1,816	200	119	1,714	1,762.9	NAp	102	Single.
O.....	-300	950	1,801	218	9	1,697	1,786.8	NAp	104	Int.
P.....	-250	750	1,795	216	9	1,694	1,786.9	NAp	101	Int.
Q[4].....	-300	200	1,788	[3]112	0	[3]1,688	1,781.5	93.5	100	Int.
R.....	250	500	1,791	220	28	1,698	1,766.0	NAp	93	Int.
S[4].....	100	-2,000	1,807	[3]160	0	1,651	1,760.0	72.0	NA	Single.
T[4].....	-350	-1,850	1,803	[3]140	0	1,648	1,734.2	46.2	NA	None.
W[4].....	-600	-1,750	1,783	[e3]140	0	[e]1,650	1,734.6	46.6	NA	Do.
32-45[5].	1,300	-3,150	1,910	173	0	1,773	NA	NA	90	Do.
32-47[5].	1,600	4,200	2,035	272	0	1,780	NA	NA	NA	Do.
32-48[5].	4,500	4,800	2,080	214	0	1,875	NA	NA	86	Do.

[e]Estimate. Int Intersection.
[1]Wellhead.
[2]1,688 ft (Upper Freeport coal elevation at well Q).
[3]Shallow aquifer hole.
[4]Piezometer hole.
[5]Core hole.

NOTE.--All measurements taken in June 1982.

ANALYSIS OF FIELD DATA

The fracture trace analysis indicated that a dense network of fracture zones exists beneath Crab Orchard Run. Ten wells were drilled in this valley, both on and off the fracture traces (see figure 16).

Pumping was performed in each of these wells to obtain a rough measure of a well's sustainable yield and its consequent value for dewatering, however, pump tests to obtain a quantitative measure of permeability involved only four wells, D, O, P, and Q. The results of pump tests performed on this site are summarized in table 4.

The pump test results clearly indicate that most of the ground water flowing to the wells drilled in Crab Orchard Run was coming from the shallow aquifer unit indicated in figures 17 through 19 (34). As can be seen in figure 19, this shallow sandstone unit ranges from 85 to 130 ft thick. It is unconfined in the valley and confined by an overlying shale layer beneath adjacent hills. Below this aquifer is the 36- to 44-in thick Upper Freeport coal seam, and below the seam is a 5- to 20-ft-thick fireclay layer. Subsequent modeling investigations and mine-aquifer dewatering activity will focus on this shallow sandstone unit.

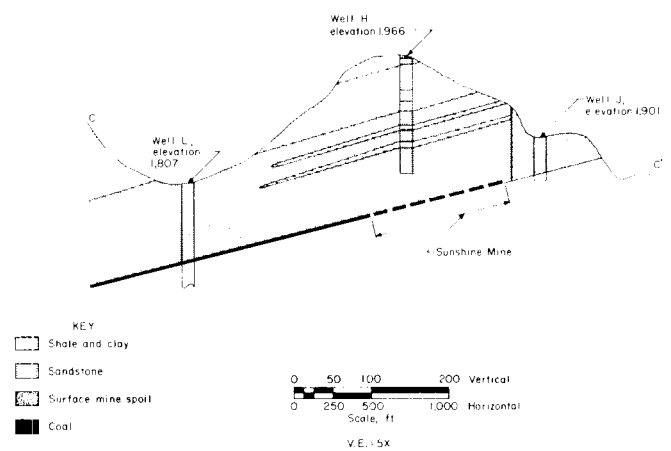

FIGURE 19. - Geologic cross section at CC'.

TABLE 4. - Summary of calculated values of transmissivity, permeability, and storativity from all pump tests (34)

Well		Section of rock	Method	Transmissivity, gpd/ft	Permeability		Storativity
Pumping	Observation				gpd/ft^2	m/h	
D	D	Entire hole.....	Specific capacity estimate, 1 h.	400	NAp	NAp	NAp
D	D	90 to 280 ft.....	Theis recovery method.	31.3	0.16	0.00027	NAp
D	D	75 to 90 ft.....	...do.....	1,193	79.5	.14	NAp
P	Q	Water table aquifer.	Time-drawdown in observation well; Theis fit.	15,916	NAp	NAp	0.008
P	Q	Water table aquifer. Same as above but for upper 32 ft dewatered.	Time-drawdown in observation well; Boulton delayed curve fit.	2.674	NAp	NAp	.001
P	P	Entire saturated hole.	Specific capacity estimate, 1 h.	37,000	NAp	NAp	NAp
P	P	...do.....	...do.....	10,000	NAp	NAp	NAp
O	O	18.58 to 218 ft...	...do.....	19,000	NAp	NAp	NAp
O	O	31.58 to 218 ft...	...do.....	1,300	7.05	.012	NAp
O	O	18.58 to 31.58 ft.	Specific capacity estimate and calculation.	17,700	1,475	2.5	NAp

D Single fracture sited. O,P Fracture intersection sited. Q Observation only.
NAp Not applicable.

A shallow ground water flow gradient probably runs from the hills just east and north of Crab Orchard Run southwest to the broader southern part of the valley.

The difference in head between wells H and Q (table 4) is used to estimate the rate of ground water flow in this shallow aquifer. With the low (intergranular) permeability values from pump tests at wells D and O (see table 4), uniform flow rates are estimated to range from 8.0 to 330.0 ft/yr (porosity is 0.1).

PARAMETERIZATION OF THE AQUIFER SETTING

For this simulation, the fracture influence on aquifer permeability is assumed to be uniformly distributed throughout the entire thickness of the shallow aquifer, within specified high-permeability zones.

The datum for this problem is the top of the Upper Freeport coal seam at well Q (elevation 1,688 ft). The coal and underlying shale layers form the bottom confining layer for the shallow aquifer.

High-permeability fracture zones are defined largely according to the valley outline of Crab Orchard Run. However fracture zones that cut across the valley are especially important, because of their orientation with respect to the direction of uniform flow. These fracture zones are individually identified and included within a high-permeability zone. Transverse fractures are assumed to extend for at least 1,000 ft beneath the adjacent hills and they are often the most clearly visible on stereopaired aerial photographs.

In order to accommodate a line doublet representation of fracture zones, and also to reduce the numerical computation associated with streamline tracing, the width of individually identified fracture zones is defined uniformly as 100 ft.

Permeability zones are superimposed on the fracture trace network of Crab Orchard Run, in figure 20. The zone having the highest permeability is designated k_2. This zone includes the central valley bottom and the individual transverse fracture zones. All those dewatering wells, that had a 24-h sustained yield exceeding 100 gpm were included within this zone (see figure 16).

Specifically, this includes a portion of the valley to the southwest in the vicinity of well C. Well C was the single most productive well drilled during this project, sustaining a 500- to 700-gpm discharge rate for over 8 h.

Well D, although it was barely able to sustain 20 gpm, is located within k_2, but very close to the boundary. Well D was a compromise location when it was discovered that the fracture intersection just north of it was inaccessible to drilling equipment.

Two other high-permeability regions were also defined, k_1 in the northern part of the valley in the vicinity of wells L, M, and N and k_3 in the southeastern area, near wells B and S. Although fracture zones were believed to be located in these areas of the valley, wells on these sites sustained yields of only 5 to 60 gpm. While this is significantly more than the 1- to 5-gpm yield of a typical domestic well in the area, it indicates that the fracture connection at these sites may be more limited than in the central part of the valley.

At the north end of the valley zone k_1 was defined so as to exclude well M, which was not fracture sited, and which maintained a static level that was 15 to 20 ft higher than other wells in the valley. Otherwise zone k_1 conformed to the valley contour. In the southwest, zone k_3 was defined in order that wells B and S could be included, but wells T and W excluded. The reason for this stems from the much higher static head in shallow well S over that of nearby shallow wells T and W (see table 3). This seems to indicate that natural ground water flow from the northeast is recharging the area around well S much more readily, perhaps via fractures. Static head in well S is nearly the same as that of well B, which is known to be sited on an intersection. Well S is also very near a north-south fracture trace.

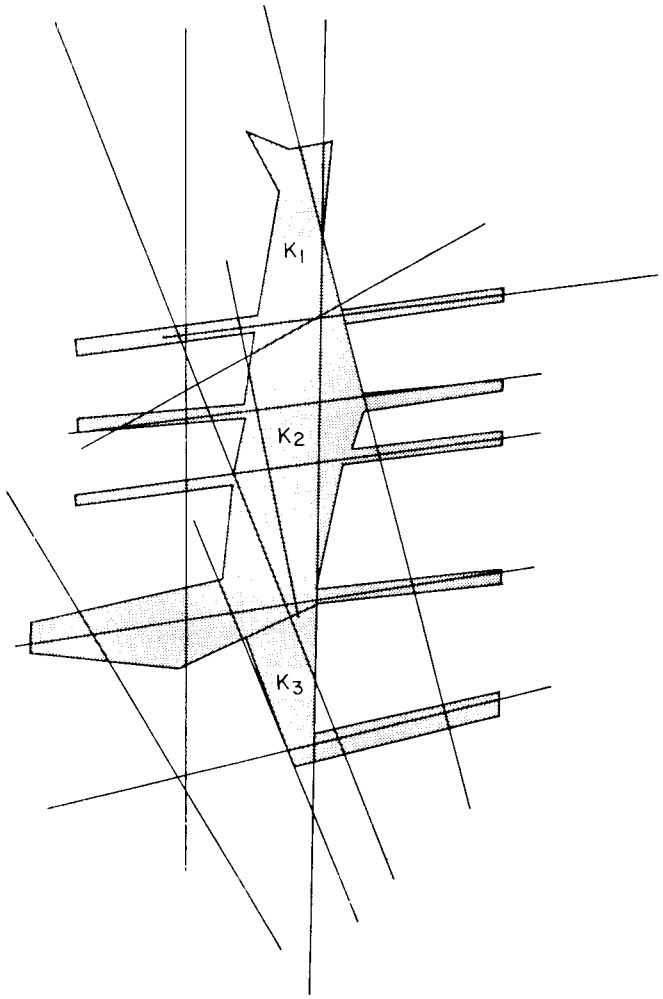

FIGURE 20. - Permeability zone representation of fracture traces near Crab Orchard Run.

Static Background Simulations

Static water level measurements at six shallow well locations in the vicinity of the mine (table 4) were used as criteria for judging the accuracy of a simulation of the shallow aquifer setting, prior to well pumping.

Initially, estimates of permeability used in this simulation were taken from pump test results (34). The surrounding unfractured aquifer, zone k, was assigned a permeability value obtained for the 32- to 218-ft interval of well O, an interval

that yielded little water during drilling and where little evidence of fracturing was encountered. Zone k_2 was assigned the high permeability value obtained in the 19- to 32-ft interval of well O. This narrow interval supplied most of the well discharge, and in addition, drill logs indicated broken rock at this depth.

All four permeabilities, in addition to the uniform flow rate and the far field boundary head, were then adjusted in order to best fit the available field measurements of static head in the shallow aquifer. After a number of trial and error runs, permeability values and a flow rate were selected that resulted in a reasonable approximation of static conditions observed in six shallow observation wells (see table 3). Table 5 describes these input values.

TABLE 5. - Static background parameter values, gallons per day per square foot

(Uniform flow = 141 ft/yr)

Zone	Pump test results	Range	Selected value
k_1.....	NA	10- 1,000	250.0
k_2.....	1,475.0	1,000-10,000	2,500
k_3.....	NA	10- 1,000	25.0
k.....	7.05	1- 10	2.5

NA Not available.

The permeability values selected for zones k_1 and k_3 were generally consistent with the results of well pump tests in these zones. Wells in zone k_2 sustained 4-h yields averaging between 300 and 400 gpm, wells L and N in zone k_1 were able to sustain 4-h discharge rates of less than 10 gpm, while well B in zone k_3 sustained a discharge rate of just over 60 gpm for 4 h following drilling.

A comparison of actual and simulated static head values at the six shallow well observation points appears in table 6. Head is measured in feet above the datum (datum = 1,688 ft).

The most difficult data point to fit in this simulation is the observed static head at well S. Field data present three pieces of information regarding the hydrologic setting of this well that are of interest. First (referring to table 3), the static head at well S is 26 ft higher than at neighboring wells T and W. Second, the head at S is 21 ft lower than at well Q. Third, S showed no measureable response to pumping from well D, while wells T and W responded with 25 ft or more of drawdown (34). As table 6 indicates, the distribution of head values among Q, S, and T in this simulation is only a fair match with the actual values. An interval of (low) permeability, k, between zones k_2 and k_3 might improve the simulated results by inducing a steeper gradient in head between wells Q and S.

TABLE 6. - Actual and simulated static heads; feet above the datum (1,688 ft)

Well	Actual	Simulated
H.....	218	215.0
M.....	115	115
Q[1].....	95	92
S[1].....	72	86
T[1].....	46	56
W[1].....	47	44

[1]A requirement of this simulation is that head be less than 100 ft everywhere in the valley where the aquifer is not confined by an overlying shale layer.

The simulated piezometric surface in the shallow aquifer beneath Crab Orchard Run, prior to dewatering well pumping appears in figure 21. In figure 21, head is measured in feet above the coal seam that is the bottom confining layer of this aquifer.

In general, uniform flow from the northwest results in a gradient in head that is steepest in the low-permeability, k, region surrounding the valley, as in the vicinity of wells H, W, and T.

The gradient is shallower in zone k_1 where the permeability is 10 times greater than k. Within k_2 and k_3, a very slight gradient is adequate to induce ground water flow at the rate of 141 ft/yr.

At the boundary between k_2 and the surrounding region of permeability k, the gradient is steepest at the tips of the

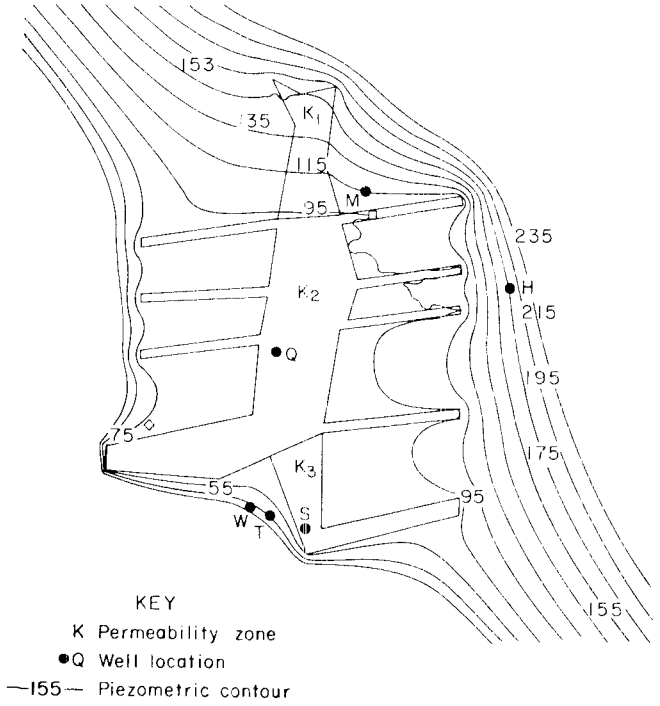

FIGURE 21. - Simulated piezometric surface beneath Crab Orchard Run.

transverse fracture zones, indicating that these fractures concentrate much of the natural ground water flow long before (and after) it has reached the valley bottom.

From a mining standpoint, this means that significant water inflow problems can occur long before mine development has reached beneath the valley bottom. The Sunshine Mine workings are approaching Crab Orchard Run from the east. Therefore, this simulation suggests that the first few mine entries should be aligned with one of the unfractured intervals between transverse fracture zones. This would prevent the mine from interfering prematurely with the dewatering action of wells that are operating in the valley bottom.

The average permeability of a fracture zone, its orientation with respect to the direction of natural ground water flow, and its location with respect to other fracture zones in the flow domain are all important in determining the extent to which uniform ground water flow is calculated by a particular zone. This in turn has implications for future siting of dewatering wells, since it is generally desirable to site wells within zones that are best able to concentrate the natural flow of ground water in the vicinity of the mine workings.

Simulation of Dewatering Well Operations

A pilot dewatering experiment was conducted at the Sunshine Mine for a 20-day interval in July 1982. The dewatering experiment involved pumping from wells P and R with daily drawdown measurements in P, R, O, and Q (fig. 16).

The effect of dewatering on ground water inflow to the Sunshine Mine workings is described in a later section. Concern here is with the effect of dewatering activity on the fractured aquifer setting of Crab Orchard Run and with the ability of DWATR to adequately simulate these effects.

Certain personnel and equipment constraints were imposed from the beginning on the pumping schedule at the Sunshine Mine. Personnel to operate the system and an electrical generator were available for no more than 4 h/d. Of necessity, therefore, the pumping schedule was intermittent. Although high-capacity pumps were available for maximum discharge during the 2.5 to 3 h that the pumps operated each day, by no means were the wells pumped at maximum 24-h capacity. From July 8 to 28, excepting July 18 and July 23, wells P and R were pumped simultaneously for 2.5 to 3 h/d. Pumps were set at 190 ft in P and 185 ft in R. Both wells were open to aquifers above and below the coal seam. Although the previous pump tests made it evident that the contribution of the lower aquifer to total well discharge was small.

From a modeling standpoint, it is important to know if steady state flow conditions were achieved at some time during this dewatering experiment. Further, since the pumping schedule was intermittent it is necessary to determine if the high intermittent pumping schedule can be approximated, for modeling purposes, as a much lower continuous pumping rate.

Figure 22, which shows the average (over 24 h) pumping rate and the maximum

daily drawdown in pumped wells P and R for each day of the dewatering experiment helps to answer these questions. Although discharge rates from P and R differ by a factor of 10, this figure clearly shows the effect of storage water being withdrawn during the first 2 to 3 days of pumping. Drawdown in well P stabilizes after 4 days of pumping, and in well R after only a single day of pump operation. The decline in pumping rate during the first few days is in response to the increasing depth to water in both well P and R.

Figure 22 shows that after the first 9 days of pumping (July 8-17), drawdown and pumping rates have stabilized in both wells. This drawdown-pumping rate equilibrium is disrupted, however, when pump operations are interrupted on the 18th and again on the 23d. The erratic drawdown and pumping behavior from the 18th onward appear to be the result of these pumping interruptions. Equilibrium appears to have been reestablished only during the last day or two of the experiment.

Figure 23 shows the drawdown response of observation wells O and Q as a result of pumping from P and R. Once again drawdown appears to stabilize after the first 9 days of pumping. Again this steady state condition is disturbed by pump shutdowns on the 18th and 23d of July. Equilibrium is reestablished before the end of the experiment, however.

Despite interruptions in the pumping schedule, steady state pumping rates and drawdown values, for use as input to a steady state dewatering simulation, can with some confidence be abstracted from this 21-day dewatering experiment. The steady-state parameter values in table 7 were abstracted from figures 22 and 23.

TABLE 7. - Steady state dewatering parameter values

Well	Pumping rate, gpm	Drawdown, ft
P.....	8.8-9.8	178.0
R.....	3.7-4.0	170.0
O.....	0	26.0
Q.....	0	14.5

They include the pumping rates selected for DWATR input, and observation well drawdown measurements for comparison of actual and simulated pumping results.

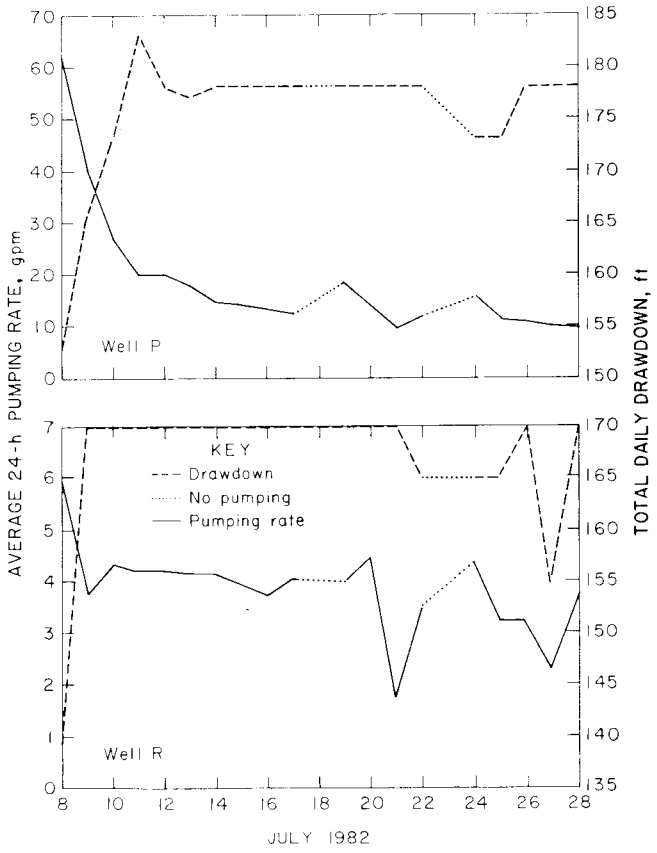

FIGURE 22. - Average pumping and total drawdown, wells P and R.

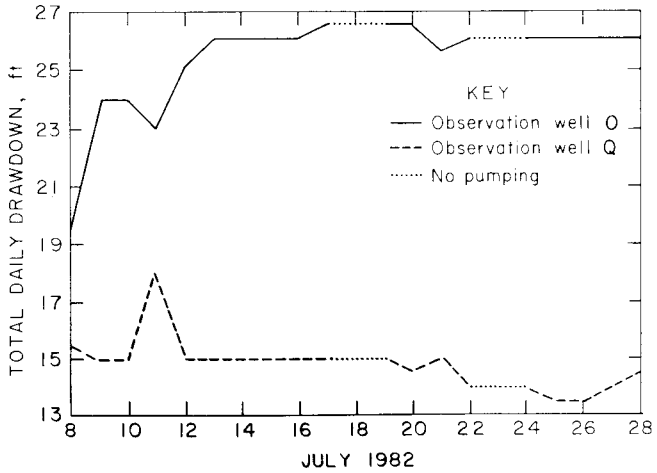

FIGURE 23. - Observation well drawdown (daily total).

Steady state pumping rates for wells P and R range between 8.8 to 9.8 gpm and 3.7 to 4.0 gpm respectively. The range of values reflects the slight downward trend in pumping rate, still apparent at the end of this dewatering experiment. The simulation of steady state dewatering effects is conducted using the minimum pumping rates as inputs.

The first test of this simulation involves a comparison of actual and predicted drawdown of two nearby observation wells. Table 8 summarizes the effect of pumping on observation wells O and Q. While there is close agreement between predicted and actual drawdown at well Q, the results at well O are less consistent. Here, the model has predicted 15 ft of drawdown while field measurements indicate 26 ft. This discrepancy is thought to be due in part at least, to the difference in depth of wells.

While well Q penetrates just the shallow aquifer, O, P, and R all extend more than 100 ft into the confined unit below the Upper Freeport coal seam (see table 4).

Pumping from wells R and P results in a cone of depression in both upper and lower aquifers. Well O, which is open to both upper and lower units, would certainly be affected by reduced head in the lower aquifer. Well Q, which is completed only in the shallow aquifer, would be affected only indirectly by reduced head in the lower aquifer. Thus pumping from wells P and R has a proportionally greater impact on the drawdown in well O than in well Q.

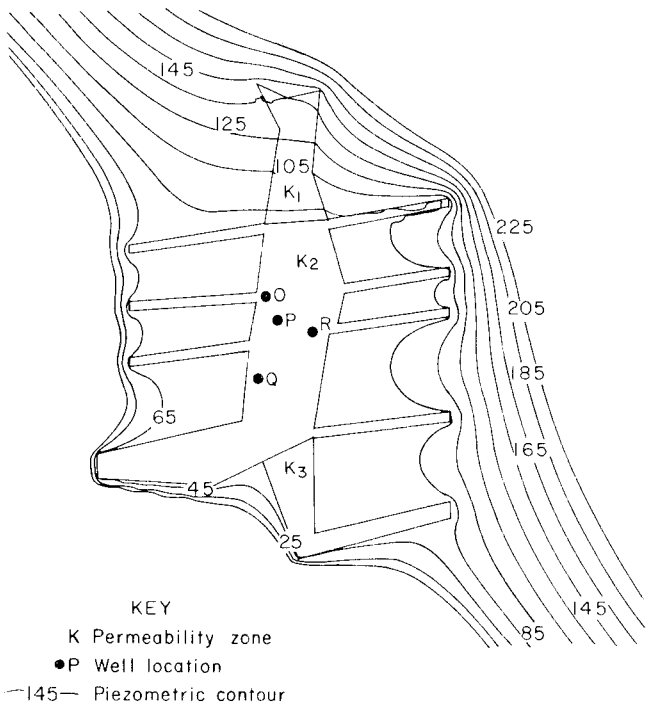

FIGURE 24. - Simulated piezometric surface due to dewatering well pumping.

The shallow aquifer piezometric surface, developed from this dewatering simulation, appears in figure 24. Pumping and observation wells are also annotated on this figure. Comparing this contour map with the one developed for the background simulation (fig. 21) reveals that the net effect of pumping from wells P and R is a head reduction of approximately 10 ft in zone k_2. Significant drawdown effects are more or less evenly distributed throughout all three permeability zones, although the effect of

TABLE 8. - Well P and R actual (34) and simulated pump test results and effects on observation wells O and Q

Observation well	Actual, June 25, 1982			Simulated	
	Static water level above datum,[1] ft	Maximum effect of 21 days of pumping (steady state flow)		Pumping rate, gpm	Total drawdown, ft
		Water level above datum,[1] ft	Total drawdown, ft		
Q.....	95.0	80.5	14.5	0	15.0
O.....	96.0	70.0	26.0	0	15.0
P.....	98.8	-79.2	178.0	8.8	NAp
R.....	78.0	-92.0	170.0	3.7	NAp

NAp Not applicable.
[1]1,688 ft (Upper Freeport coal elevation at well Q).

pumping on piezometric surface does not extend far beyond the boundaries of the zones.

Simulation of Alternate Dewatering Well Settings

The maximum dewatering potential of wells P and R is achieved by adjusting the pumping rate so that head at each well radius is zero in relation to the datum (pumps in P and R were set at 190 ft), giving discharge rates of 21 and 9 gpm, respectively.

The piezometric contour in figure 25 was generated using these maximum sustainable pumping rates. As this figure indicates, an additional 10-ft lowering of the piezometric surface beneath Crab Orchard Run could be expected from this maximum pumping rate.

Depending on the direction of future mine development, two other wells (B and C) drilled in Crab Orchard Run may have potential as dewatering sites. Although pumps were never installed in these wells, a simulation of the effects of pumping from wells B and C is included here, primarily to highlight the effect that well locations have on the piezometric surface in this high permeability setting.

Figure 26 is the piezometric surface resulting from this simulation. For comparison purposes, pumping rates selected for these wells are identical to those used to generate figure 25, i.e., C is pumped at 21 gpm, and B at 9 gpm.

As is evident from comparing figures 25 and 26, the location of dewatering wells within zones k_2 and k_3 (given the same pumping rate) has little effect on the resulting piezometric surface within the high permeability zone.

Although modest attempts were made in these simulations to mimic the field observations, by no means does this simulation represent an optimal parameter selection for this problem. Nor is it necessarily the intent of this investigation to generate a site-specific predictor of dewatering affects beneath Crab Orchard Run.

Modeling results are best used to provide insight into the hydrologic

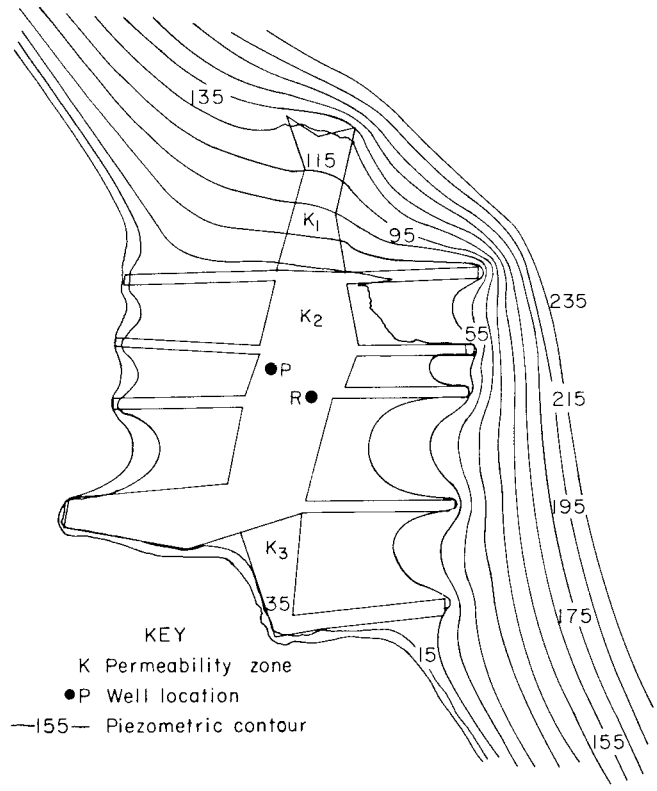

FIGURE 25. - Simulated piezometric surface resulting from maximum sustained pumping.

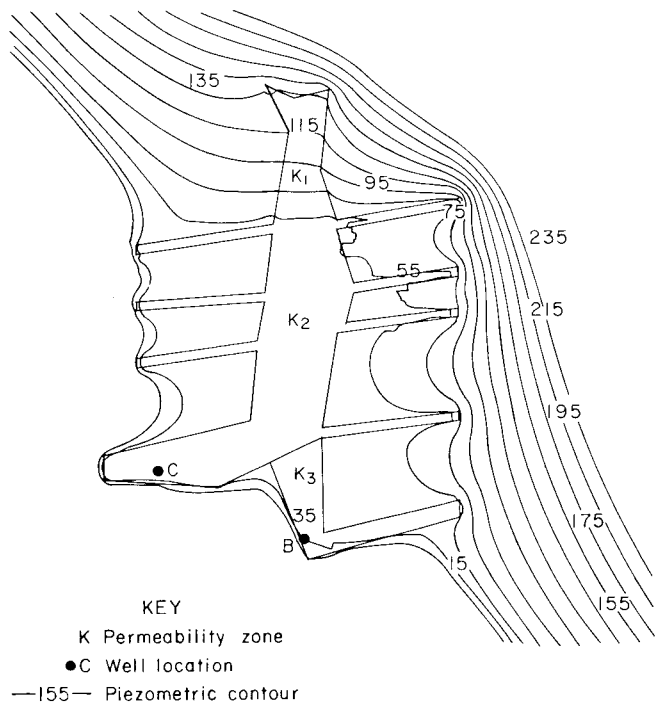

FIGURE 26. - Simulated piezometric surface resulting from sustained pumping of wells B and C.

behavior of high permeability valley settings and their response to dewatering activity. If a modeling investigation is conducted at the same time as the field activity, a good deal more trial and error manipulation of input parameters is justified in attempting to develop a more accurate simulation of the static fracture zone hydrologic setting. Such a model could then be used to guide exploratory drilling and pump testing in order to better define zones of high permeability in the valley.

The impact of dewatering well operations on inflow to the underground workings of the Sunshine Mine, as they advanced beneath Crab Orchard Run, has thus far not been considered. The mine inflow monitoring program and the in mine results of dewatering activity are presented in the following section.

SUNSHINE MINE DEWATERING FIELD TEST

The Sunshine Mine had a history of severe water problems which included not only high AMD (pH 3.0 to 3.5) treatment costs but also mine water interference with activity at the face. During the time of the dewatering project (October 1981 to August 1982) the mine had only recently opened, and was operating a five-entry development in a single active section. This wet section, which was more or less isolated from the other workings, was experiencing severe mine water interference with continuous miner operation and rubber-tired haulage vehicles. Mine water at the face was entering mainly through roof fractures and roof bolt holes. At the face, mine water was comparatively high quality, however, it became degraded as it was pumped from sump to sump and mixed with water coming from abandoned workings.

The Sunshine Mine workings, superimposed on a topographic map, were shown in figure 16. In that figure, the shaded portion of the workings represents the final development of the active section in this mine during the 9 months of active involvement with this project, January-September 1982.

FRACTURE TRACE ANALYSIS, WELL DRILLING AND DEVELOPMENT

Of the nine fracture-sited wells drilled during this project, three were located more or less on the periphery of future mine development (wells B, C, and D in figure 16). Although two of these wells were capable of sustaining very high yields, they were not used later in the actual mine dewatering operation, due to a change in mine development plans after the project had begun.

After siting, proposed dewatering wells were surveyed and located on the mine map in order to avoid projected haulageways and to ensure that well sites coincided with future pillar locations.

Eleven wells were drilled as part of this project (ten 6-in wells and one 10-in well). Six wells were drilled on fracture intersections. Two wells were sited on single fractures, and three others were nonfracture sitings. Well depths ranged from 82 to 501 ft (see table 3). An interpreted cross section running along Crab Orchard Run was developed from some of the drill logs and is presented in figure 27.

Initial well development (air surging) to remove drill cuttings wedged in cracks and fractures was inadequate at most drill sites. Consequently, before long-term pump tests could begin, a lengthy interval of remedial well development work was necessary.

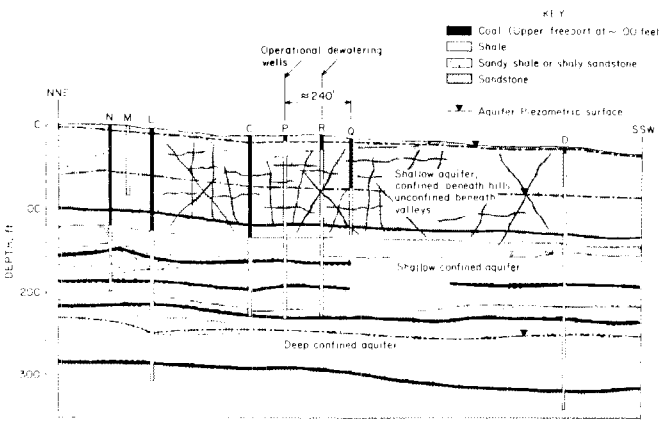

FIGURE 27. - Interpreted geologic cross section along Crab Orchard Run.

IN-MINE DEWATERING RESULTS

The in-mine assessment of dewatering efforts was by necessity limited to intermittent spot measurements of inflow to the wet section, made at various times during the course of the experiment. Inflow to the wet section exceeded 40,000 gpd prior to December 1981, while the section was being actively developed. Because of the high inflow rate and resulting production problems, this section was abandoned in December and all development work stopped. Pumping from this section continued, however.

Three measurements of wet section inflow were made during the period December 1981 to March 1982 prior to dewatering activity of any kind, drilling, pump testing, or scheduled pumping. These measurements indicated that inflow to the wet section had slowly declined after development work was stopped in December. By March, wet section discharge had declined to less than 21,000 gpd.

Well drilling and pump testing of wells L, M, N, O, P, Q, and R, began in mid-May and continued off and on until July 8. Shortly after wells L, M, and N were drilled in late May, the mine foreman reported an abrupt decline in infiltration, in the inactive section, particularly noticeable at point sources (roof bolt holes, etc.) in the mine. By mid-June, wells O, P, Q, and R had been drilled and tested; at this time the mine foreman reported that the water being discharged from the inactive section had decreased to approximately 1,000 to 2,000 gpd.

During June, two visits to the wet section were made to confirm that the previously wet section was now dry and that sump pumps set in the now inactive entries and capable of delivering 75 gpm were operating for only 10 to 20 min/d.

Because of the now apparently dry conditions, mining activity resumed in this section during the last week of June, accompanied by continued reports of dry workings as the entries advanced westward. Renewed mining activity had been underway for 2 weeks before scheduled pumping from dewatering wells P and R was able to begin on July 8.

During the 3 weeks of scheduled well pumping, from July 8 to 28, the apparent trend in mine infiltration was a gradual increase from the initial 1,000 to 2,000 gpd to approximately 6,000 gpd at the end of July. During the entire month, mine workings were expanding to the west beneath Crab Orchard Run.

At the end of July, mine development plans again changed. This time a concern over mine ventilation caused development to proceed in a southerly direction (see figure 16). The dewatering experiment was terminated shortly after this latest change in mine development plans occurred.

One final measurement in mid-August, 2 weeks after all dewatering activity had ceased, indicated that mine discharge from this section (the shaded area in figure 16) had climbed to 19,000 gpd. In early September, the mine foreman indicated that inflow was still increasing, however no further measurements were possible.

The area of mine development from which the underground sump collected mine drainage had expanded from 265,000 ft^2 at the start of the 21-day dewatering experiment to 540,000 ft^2 by the end of July. All of this development was in an intensively fractured valley setting.

The quality of water discharged from all dewatering wells was uniformly high (suitable for domestic use) throughout the course of pumping. After an initial flushing, the pH of dewatering well discharge stabilized at 6.5 to 6.8. Iron concentration stabilized at 2.0 to 3.0 mg/L. West Virginia Department of Natural Resources approval was obtained for temporary discharge of this water into a nearby stream without prior treatment. The receiving stream had a pH of 7.5 to 8.0 and total iron of 0.12 mg/L.

ANALYSIS

The Sunshine Mine workings were developed to within 300 ft of the valley bottom before being temporarily abandoned, so it seems unlikely that the piezometric head in the fracture zone beneath Crab Orchard Run was completely unaffected by

drainage into the mine. There is evidence to indicate however that the dewatering influence of the mine was quite limited. For instance, head measurements in the shallow wells of Crab Orchard Run indicated a stable or rising water table throughout April, May, and June. The water level in shallow well Q was less than 10 ft from the surface (see table 3).

Generally speaking, the time-dependent nature of mine inflow and the continuously expanding area of mine workings in active sections makes it difficult to measure the effectiveness of fracture zone dewatering from inside the mine. Before and after comparisons of mine inflow rates are tenuous since there are often a number of factors influencing the measured inflow rate that are difficult to isolate and measure, let alone control.

Measuring in-mine results of dewatering operations at the Sunshine Mine would have been far easier if wells had been developed, and pumping operations begun in January or February when the mine section was inactive, rather than waiting until July when this section had been reactivated and the mine void was once again expanding.

Considering that mine workings were advancing directly beneath the highly fractured valley setting of Crab Orchard Run during the entire month of July, outflow from this reactivated section remained at a comparatively low level, never exceeding 6,000 gpd during the entire 3-week interval in which scheduled pumping was taking place.

The limited number of in-mine measurements that were made during and after this 21-day experiment points to a significant increase in mine infiltration in early August, after pumping operations were terminated. However, it is not possible to completely isolate the effect of well dewatering from other variables that may have affected the mine inflow rate at this time. For instance, the direction of mine development also changed at about the same time that dewatering operations ended. The alignment of mine workings with the fracture valley setting may have contributed to the increase in mine infiltration during August.

CONCLUSIONS

This investigation has focused attention on fracture zones as an important element of both mine water problems and mine dewatering methods. A number of conclusions, generally having to do with fracture zone involvement in mine inflow, and with the design of mine dewatering operations are possible.

As the in-mine survey and fracture trace studies indicated, high permeability fracture zones ought to be the focus of mine dewatering activity, since they constitute preferred flow paths in the aquifer overlying underground workings. Ground water that is stored within the fracture zone network is water that will likely be released into newly developed and isolated mine workings.

As the flow simulation indicated, zones of fracture concentration are involved in minimizing the number of wells needed to dewater mine workings, since high pumping capacities are more likely when dewatering wells are sited within high permeability zones.

A savings in acid mine drainage treatment costs is possible, since ground water that is intercepted in the fracture zones, before it enters the mine workings, has not yet been degraded by contact with exposed pyritic material in the mine, or by mixing with acidic mine water coming from other workings.

Many of the advantages of fracture zone dewatering impact favorably on mine productivity, in the form of improved working conditions. All of which are most apparent when dewatering activity has reduced inflow to the active areas of mine development. The release of fracture zone storage water at the active face is closely associated with wet section mining conditions.

Ground water flow in fracture zone settings is often complex. Dewatering design activity must be preceded by a conceptual understanding of the various hydrogeologic conditions that influence the pattern of ground water flow in a specific mine-fracture zone setting.

The approach to fracture zone dewatering presented here is oriented toward localized, high inflow mine water problems that arise when mine development is in the vicinity of fracture zones or fracture valley topography. Typical mine water problems for which fracture zone dewatering may be an appropriate solution include, (1) wet sections where the alternatives to water inflow control are unacceptably low productivity or abandonment, perhaps giving up a sizable piece of coal reserve, (2) mine sections left inactive because of extreme water problems, in which renewed mining activity has once again become necessary (perhaps relatively short-term development for ventilation, water handling, haulage, etc.), or (3) initial entry development for a longwall panel, where the isolated nature of the entry leads to extreme water inflow problems.

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APPENDIX A.--DWATR PROGRAM MODULES

Routine	Purpose
	DRIVER CONTROL ROUTINES
DWATR.....	Input-output.
GRID.....	Calculate a grid of Ω values for input to a head contouring program.
SLINE.....	Generate a streamline pattern, by specifying streamline starting locations at wells or elsewhere in the flow region. Select streamline tracing method. Check for permeability zone crossing, normal streamline trace, and termination.
	FLOW PROBLEM COMPONENTS
OMA.....	Determine Ω, the additive solution from flow components, i.e. wells, permeability zones, uniform flow, far field boundary condition.
WELL.....	Determine Ω_w, the solution for the well component of flow. Account for branch cut singularities.
DIPOL.....	Determine Ω_p, the flow solution for discrete permeability zones. Linearly or parabolically interpolate doublet strengths between endpoints. Determine streamline entrance and exit from permeability zones.
	DOUBLET STRENGTH
STGTH.....	Determine line doublet strengths at endpoints subject to internal boundary condition involving permeabilities k_o and k_1. Generate n linear equations with n unknown double strengths.
MDPNT.....	Locate line doublet midpoints. Include these coordinates in the array of simultaneous strength equations for parabolic fit.
QUAD.....	Separate first and second order components of doublet strength at the doublet midpoint. Save the parabolic component.
GAUSS.....	Obtain a solution to a set of simultaneous linear equations using Gauss-Jordan (row reduction) procedure.
	STREAMLINE ITERATION
NEWRA.....	Determine z given Ω using Newton's method to iteratively find roots of nonlinear equation; compute error, check convergence on both Φ and Ψ.
NUMCA.....	Use a variation of Newton's method to trace streamlines, compute error, and check convergence on Ψ only.
	MINOR ROUTINES
DPCHK.....	Check current streamline location for proximity to dipole singularities. Restart streamlines after "stepping over" the singularity.
MXMN.....	Determine maximum and minimum values of z, Ω, and ϕ for plot and contour map program input.
PTOH.....	Convert potential to head. Account for continuous potential across confined and unconfined flow boundaries and continuous ϕ across permeability zone boundaries.
HTOP.....	Convert head to potential.
WELLR.....	Calculate an approach criterion for streamlines near well singularities.
INOUT.....	Determine if z is inside or outside the plot boundary.

DWATR INPUT-OUTPUT FILES

File name	Logical unit number
User input.....	10
Printer output.....	6
CRT output.....	1
Head and potential contour grid (disk).....	13
Plotting and contouring (disk).....	15
Streamline plotting (disk).	17
Doublet strengths (disk)...	19
Mass transport-streamline interface (disk).....	14

APPENDIX B.--INPUT VARIABLE DESCRIPTION

INPUT RECORD 1

Variable	Format	Description
IOPT....	I5	Input-output print option (1 or 0). If IOPT = 1, the program prints iterative streamline data. This option can be used as an aid in selecting proper error bounds, etc., for streamline convergence.
VOPT....	I5	Mass transport model interface option (1 or 0). If VOPT = 1, an interface file containing streamline data is generated on logical unit 14.
GOPT....	I5	Grid file option (1 or 0). If GOPT = 1, a grid of head and potential values is generated on logical unit 13 for later contour map construction.
XLO.....	F10.0	Rectangular window boundaries for grid and/or streamline generation, in feet.
YLO.....	F10.0	Do.
XHI.....	F10.0	Do.
YHI.....	F10.0	Do.
ZSPA....	F10.0	Grid interval on which potential and head values are generated, in feet (ignored if GOPT = 0).

Parameters on input records 1a, 1b, 1c, and 1d are passed to logical unit 14 for input to mass transport program. These four records should be included only if VOPT = 1.

INPUT RECORD 1a

Variable	Format	Description
D.....	E10.5	Molecular diffusion coefficient.
F.....	E10.5	Formation electrical resistivity.
PS.....	E10.5	Average formation particle diameter outside all permeability-porosity zones, in centimeters.
SIGMA...	E10.5	Inhomogeneity factor.
POROS...	E10.5	Porosity outside of all permeability-porosity zones, dimensionless proportion.
RHOS....	E10.5	Rock density outside all permeability-porosity zones, in grams per square centimeter.
ISKP....	15	Interval at which streamline nodes are output to LU 14. If ISKP = 1, all acceptable streamline nodes are output to LU 14. If ISKP = 2, every second node is output. If ISKP = 3, every third node is output, etc.
NZT.....	15	Number of permeability-porosity zones.

INPUT RECORD 1b

Variable	Format	Description
POR(i)..	8E10.5	Porosity inside permeability-porosity zone(i) (8 entries per line).

INPUT RECORD 1c

Variable	Format	Description
P(i)....	8E10.5	Average particle diameter inside permeability-porosity zone(i) (8 entries per line).

INPUT RECORD 1d

Variable	Format	Description
RHO(i)..	8E10.5	Rock density inside permeability-porosity zone(i) (8 entries per line).

INPUT RECORD 2

Variable	Format	Description
ZBND....	F10.0	Radius of far field, constant head boundary, with center at the origin, in feet.
RHD.....	F10.0	Far field constant head, in feet.

INPUT RECORD 3

Variable	Format	Description[1]
NWL.....	I5	Number of wells ($0 \leq NWL \leq 10$).
IFLO....	I5	Uniform ground water flow indicator (1 or 0). If IFLOW = 1, uniform flow exists.
MPT.....	I5	Number of streamline starting locations. A well, with multiple streamlines, is considered 1 starting location ($0 \leq MPT \leq 100$).
MXPTS...	I5	Maximum number of points per streamline ($MXPTS \leq 200$).
NZT.....	I5	$\lvert NZT \rvert$ is the number of discrete zones of differing permeability ($0 \leq \lvert NZT \rvert \leq 4$). If NZT > 0 doublet strengths are generated and written to a strength file, logical unit 19. If NZT < 0 doublet strengths are read from previously generated strength file, logical unit 19; parameters affecting flow are assumed to be identical to those used in generating the file. If NZT = 0 permeability is uniform throughout the flow domain.
STM.....	I5	Streamline tracing method. STM = 0, Newton-Raphson iterative convergence required on both Φ and Ψ. If STM = 1, unequal Φ intervals, and iterative convergence required on Ψ only.
DEC.....	F10.0	Interval between consecutive streamline points. If STM = 0, DEC is downgradient (+) or upgradient (-) interval in head (ϕ). If STM = 1, DEC is downgradient (+) or upgradient (-) interval in z.
PERM....	F10.0	Homogeneous aquifer permeability, outside all permeability zones, in gallons per day per square foot.
THICK...	F10.0	Aquifer thickness, in feet.
WRDS....	F10.0	Well radius, in feet.
AQ.....	A4	Aquifer type. AQ = CONA upper confining layer is present; AQ = UNCA if no upper confining layer is present.

[1]All parenthetic maximum and minimum values are dependent on array size in DWATR.

INPUT RECORD 4[1]

Variable	Format	Description
RERR[2]...	F10.0	Absolute error criteria for Φ convergence.
IERR....	F10.0	Absolute error criteria for Ψ convergence. (DWATR calculates a relative error criteria for Φ and Ψ.)
DPJP....	F10.0	The radius of a circle around each doublet singularity, wherein Newton's method is no longer used to calculate succeeding streamline points, in feet.

See footnotes at end of tabulation.

INPUT RECORD 4[1]--Continued

Variable	Format	Description
ITRMX...	I5	Maximum number of iterations permitted to achieve convergence criteria.
ALSTP...	F10.0	Minimum value for relaxation parameter α, where $0 < \alpha \leq 1$. If ALSTP < 0, α is assigned a fixed value of |ALSTP|.
LXDWN[2]..	I5	Number of diverging iterations before α is reduced.
LXUP[2]...	I5	Number of converging iterations before α is increased.

[1]If MPT = 0, omit this record. [2]This parameter is ignored if STM = 1.

MULTIPLE INPUT RECORD 5[1]

Variable	Format	Description
XSTRT...	F10.0	Center of a radial pattern of streamline starting points, in feet.
YSTRT...	F10.0	Do.
ANGL....	F10.0	Angular increment in a radial pattern of streamline starts, in degrees.
MLINE...	I5	Number of streamlines in the radial pattern, ($1 \leq$ MLINE ≤ 100).
RADS....	F10.0	Radius of a circle centered at (XSTRT, YSTRT), upon which MLINE streamline starting points are spaced, at equal intervals.
NUMBR...	I5	Starting point identification number.

[1]Number of records of this type must equal MPT, if MPT = 0, omit this record.

MULTIPLE INPUT RECORD 6[1]

Variable	Format	Description
XWL.....	F10.0	Coordinate location of a well, in feet.
YWL.....	F10.0	Do.
Q.....	F10.0	Well pumping rate output (+), input (-) in gallons per minute.
NUMW....	I5	Well identification number.

[1]Number of records of this type must = NWL, if NWL = 0, omit this record.

MULTIPLE INPUT RECORD 7[1]

Variable	Format	Description
ZONE1...	F10.0	Permeability zone identification number.
ZONE2...	F10.0	Permeability inside this zone in gallons per day per square foot.
ZONE3...	F10.0	Number of sides on this polygonal zone boundary. The zone boundary is entered in counterclockwise rotation if ZONE3>0, and in clockwise rotation if ZONE3<0 (see input record 8).
ZONE4...	F10.0	Permeability outside the zone (nested zones are permitted), in gallons per day per square foot.
ZONE5...	F10.0	Identification number of the zone outside this permeability zone. If ZONE5 = 0 outside permeability is homogeneous.

[1]Number of records of this type must equal NZT. Each input record 7 is followed immediately by the appropriate number of input records of type 8.

MULTIPLE INPUT RECORD 8[1]

Variable	Format	Description
DPOLEX..	F10.0	Coordinates (x,y) on the boundary of a permeability zone identified by ZONE5. Coordinates must be entered in a *counter*clockwise rotation.[2] Intervening straight line segments form the zone boundary. The last coordinate entered is assumed connected to the first via a straight line. Straight line segments *must not* intersect.
DPOLEY..	F10.0	

[1]Type 8 input records outline a single zone and follow immediately the input record 7 which identifies the permeability zone. Successive combinations of input record 7 and input record 8 designate additional zones. If NZT = 0, input record 7 and input record 8 are omitted.

[2]Concentric permeability zones are permitted, however successive *interior* zone boundaries must be entered in clockwise, then counterclockwise, then clockwise, etc., rotations. Direction of rotation is indicated by input record 7, ZONE3.

INPUT RECORD 9[1]

Variable	Format	Description
ANGL1...	F10.0	Direction of the uniform flow vector. $0 \leq$ ANGL1 ≤ 360 (respect to positive x axis).
VEL1....	F10.0	Ground water flux in feet per year (velocity = flux/porosity).

[1]If IFLOW = 0 omit this record.

APPENDIX C.--DWATR SOURCE LISTING

```
&WATR4 T=00004 IS ON CR00030 USING 00347 BLKS R=0000

0001  FTN7X
0002          BLOCK DATA  DATX
0003  C
0004  C
0005  C
0006          COMMON / CNST / I, PI
0007          COMMON / INPT / IOPT, NZNE, ITER, DPJP, IOMEG
0008          COMMON / ZARG / ARGPO, DODF
0009          COMMON / PJMP / JUMP, MU
0010          COMMON / POLE / ZONE, DPOLE
0011          COMMON / ONED / IFLO, ANGLi, UNFM
0012          COMMON / ZON / LOCZ
0013          COMMON / WELLD / ZBND, RPHI, Q, ZWL, STRT, WRAD, WRDS, NPT, NWL,
0014         1   NUMS, NUMW
0015          COMMON / ERRS / RERR, IERR, ITRMX, ALSTP, LXDWN, LXUP
0016          COMMON / CHEM / D, F, P, SIGMA, POR, RHO, ISKP
0017          COMMON / AQF / THICK, AQ, FL, BND
0018          COMMON / LINE / NLINE, STM, DEC, MXPTS
0019          COMMON / IO / LU, PL, GL, AL, JL, IL, TL
0020  C
0021  C
0022          DIMENSION   STRT (100), ZWL (30), Q (30), WRAD (30),
0023         1   NUMS (100, 2), NUMW (30), DPOLE (300), ZONE (4, 7), BND (4),
0024         2   NLINE (100), ARGPO(600), JUMP(300), MU(300), POR (4), P (4),
0025         3   RHO (4)
0026  C
0027          REAL  IERR, JUMP, MU, IOMEG
0028  C
0029          INTEGER  PL, GL, AL, STM, TL
0030  C
0031          COMPLEX  ZWL, I, STRT, BND, DPOLE, DODF, FACT1, FACT2, FACT3,
0032         1 FACT4, CLG
0033  C
0034          END
0035  C
0036  C
0037  C-------------------------------------------------------------------
0038  C-------------------------------------------------------------------
0039  C
0040  C                     BUREAU OF MINES HYDROLOGY MODEL
0041  C
0042  C                                1984
0043  C
0044  C       (AN APPROXIMATE ANALYTIC MODEL FOR STEADY STATE,2-DIMENSIONAL,
0045  C       GROUNDWATER FLOW PROBLEMS INVOLVING WELLS AND UNIFORM FLOW IN
0046  C       AN AQUIFER WITH REGIONS OF INHOMOGENEOUS PERMEABILITY.)
0047  C
0048  C-------------------------------------------------------------------
0049  C-------------------------------------------------------------------
0050  C
0051  C
0052  $EMA/SIZE/,/VECT/
0053          PROGRAM  DEWAR
0054  C
0055  C    THIS PROGRAM USES A 2 DIMENSIONAL, ANALYTIC ELEMENT APPROACH TO
0056  C    CALCULATE AQUIFER HEAD AND STREAMFLOW LINES RESULTING FROM WELL
0057  C    PUMPING AND UNIFORM FLOW IN A SATURATED AQUIFER CONTAINING DISCRETE
0058  C    ZONES OF DIFFERING PERMEABILITY.  THE SOLUTION DERIVED IS CONTINUOUS
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0059  C    ACROSS CONFINED/UNCONFINED FLOW BOUNDARIES.
0060  C
0061  C     ALL UNITS ARE U.S.  THE DATUM FOR MEASUREMENT OF HEAD IS THE
0062  C     BOTTOM CONFINING LAYER OF THE AQUIFER.
0063  C
0064  C
0065  C
0066            COMMON / SIZE / COEF, CHEM
0067            COMMON / VECT / CNST
0068            COMMON / CNST / I, PI
0069            COMMON / INPT / IOPT, NZNE, ITER, DPJP, IOMEG
0070            COMMON / ZARG / ARGPO, DODF
0071            COMMON / POLE / ZONE, DPOLE
0072            COMMON / PJMP / JUMP, MU
0073            COMMON / ONED / IFLO, ANGLI, UNFM
0074            COMMON / ZON / LOCZ
0075            COMMON / WELLD / ZBND, RPHI, Q, ZWL, STRT, WRAD, WRDS, NPT, NWL,
0076           1   NUMS, NUMW
0077            COMMON / ERRS / RERR, IERR, ITRMX, ALSTP, LXDWN, LXUP
0078            COMMON / IO / LU, PL, GL, AL, JL, IL, TL
0079            COMMON / CHEM / D, F, P, SIGMA, POR, RHO, ISKP
0080            COMMON / AQF / THICK, AQ, FL, BND
0081            COMMON / LINE / NLINE, STM, DEC, MXPTS
0082  C
0083  C
0084            DIMENSION  ARGPO (600), BND (4), CHEM (500, 17), CNST
0085           1   (300), COEF (300, 300), DPOLE (300), HDMN (3), HDMX (3),
0086           2   JUMP (300), MU (300), NLINE (100), NUMS (100, 2), NUMW
0087           3   (30), Q (30), STRT (100), WRAD (30), ZONE (4, 7), ZWL (30),
0088           4   ALTR (100), POR (4), P (4), RHO (4)
0089  C
0090            CHARACTER*4 AQ,AQFR(3)
0091            COMPLEX   BND, CDM, DODF, DODZ, DPOLE, DTRM, FLXVC, I, OMCON,
0092           1   OMDEC, OMEGA, OMPRT, OMST, STRT, VELVC, WLTRM, ZWL, Z, FACT1,
0093           2   FACT2, FACT3, FACT4, CLG
0094            INTEGER   AL, GL, GOPT, PL, STM, VOPT, TL
0095            REAL      IERR, JUMP, MU, IOMEG
0096  C
0097            DATA   AQFR (2), AQFR (3) / 'CONF','INED' /
0098  C
0099  C       INITIALIZATION.
0100  C
0101  C       PRINTER OUTPUT ON LOGICAL UNIT 6.
0102            LU = 6
0103  C
0104  C       STREAMLINE PLOT OUTPUT ON LOGICAL UNIT 17
0105            PL = 17
0106  C
0107  C       CONTOUR GRID OUTPUT ON LOGICAL UNIT 13.
0108            GL = 13
0109  C
0110  C       AUX. PLOT FILE CONTAINING PLOT SIZE,NO. WELLS,ZONES,COORDS.
0111  C       AND NO. STREAMLINES ON LOGICAL UNIT 15.
0112  C
0113            AL = 15
0114  C
0115  C       DOUBLET STRENGTH DATA SAVED ON LOGICAL UNIT 19.
0116            JL = 19
0117  C
0118  C       MASS TRANSPORT INTERFACE ON LOGICAL UNIT 14.
```

```
0119  C
0120        TL = 14
0121  C
0122        PI = 3.141592654
0123        I = (0.0, 1.0)
0124        REWIND 10
0125  C
0126  C
0127  C-----------------------------------------------------------------------
0128  C       READ PRINT OPTIONS CHEMICAL AND GRID OPTIONS AND PLOT SIZE.
0129        READ (10, 10) IOPT, VOPT, GOPT, XLO, YLO, XHI, YHI, ZSPA
0130  C-----------------------------------------------------------------------
0131  C
0132  C
0133  C***********************************************************************
0134  C       READ CHEM INTERFACE PARAMETERS.
0135  C
0136        IF (VOPT .EQ. 0) GO TO 1000
0137        READ (10, 20) D, F, PS, SIGMA, POROS, RHOS, ISKP, NZT
0138        IF (NZT .GT. 0)  READ (10, 25) (POR (IZNE), IZNE = 1, NZT)
0139        IF (NZT .GT. 0)  READ (10, 25) (P (IZNE), IZNE = 1, NZT)
0140        IF (NZT .GT. 0)  READ (10, 25) (RHO (IZNE), IZNE = 1, NZT)
0141  C***********************************************************************
0142  C
0143  C
0144   1000  CONTINUE
0145  C
0146  C-----------------------------------------------------------------------
0147  C       READ FAR FIELD HEAD BOUNDARY CONDITION.
0148        READ (10, 30) ZBND, RHD
0149  C-----------------------------------------------------------------------
0150  C
0151  C
0152  C       A NEGATIVE WELL RADIUS (WRDS) WILL INVOKE THE OPTIONAL WELL
0153  C       APPROACH CRITERIA I.E. HEAD(Z) .LT. HEAD(WELL RADIUS).
0154  C
0155  C
0156  C-----------------------------------------------------------------------
0157  C       READ NO.WELLS,STREAMLINES,UNIFORM FLOW,MAX.PTS.,NO.PERM.ZONES,
0158  C       STREAM.TRAC.METH.,DEC IN HEAD,BACKGRND.PERM.,AQ.THICK.,WELL RAD.,
0159  C       AQ.TYPE
0160        READ (10, 40) NWL, IFLO, MPT, MXPTS, NZT, STM, DEC, PERM, THICK,
0161       1    WRDS, AQ
0162  C-----------------------------------------------------------------------
0163  C
0164  C       REWIND ALL DATA FILES
0165  C
0166        IF (MPT .GT. 0) REWIND PL
0167        IF (MPT .GT. 0 .OR. GOPT .GT. 0) REWIND AL
0168        IF (NZT .NE. 0) REWIND JL
0169        IF (GOPT .GT. 0) REWIND GL
0170        IF (VOPT .GT. 0) REWIND TL
0171  C
0172  C       SPECIFY PLOT BOUNDARIES.
0173  C
0174        BND (1) = CMPLX (XLO, YLO)
0175        BND (2) = CMPLX (XHI, YLO)
0176        BND (3) = CMPLX (XHI, YHI)
0177        BND (4) = CMPLX (XLO, YHI)
0178  C
```

```
0179          XMID = (XHI + XLO) / 2
0180          YMID = (YHI + YLO) / 2
0181          XSID = XHI - XLO
0182          YSID = YHI - YLO
0183    C
0184          NZPLS = IABS (NZT)
0185          NZNE = NZPLS + 1
0186    C
0187    C     IF NO STREAMLINES SKIP INPUT.
0188    C
0189          IF (MPT .EQ. 0) GO TO 1030
0190    C
0191    C
0192    C     MIN. WELL RADIUS AT SINGULARITIES.
0193    C
0194          IF (WRDS .LT. .0001) WRDS = .0001
0195    C
0196    C
0197    C-----------------------------------------------------------------------
0198    C     READ ERROR CRITERIA FOR ITERATIVE METHS, MAX. ITERATION, LOW. ALP
0199    C     BOUND, LOWER AND UPPER RELAX. CRITERIA.
0200    C
0201    C     THE Z SPACING METHOD REQUIRES ONLY (IERR) ENTRY, OTHER
0202    C     PARAMETERS ARE IGNORED.
0203    C
0204          READ (10, 50) RERR, IERR, DPJP, ITRMX, ALSTP, LXDWN, LXUP,
0205         1 IRALT
0206    C-----------------------------------------------------------------------
0207    C     DEVELOP RADIAL STREAMLINE PATTERN AROUND EACH INJECTION WELL
0208    C     IF (RADS) = WELL RADIUS.
0209          NPT = 0
0210    C
0211            DO 1020  IPT = 1, MPT
0212    C     (NLINE) STREAMLINE STARTING POINTS ARE LOCATED ON A CIRCLE
0213    C     CENTERED AT (XSTRT,YSTRT) WITH RADIUS (RADS).
0214    C
0215    C
0216    C-----------------------------------------------------------------------
0217    C     READ STREAMLINE STARTING POINTS, ANGLE, NO. LINES, RADIUS, PT.NO.
0218            READ (10, 60) XSTRT, YSTRT, ANGL, MLINE, RADS, NUMBR
0219    C-----------------------------------------------------------------------
0220    C
0221    C
0222            IF (RADS .LT. .001)  RADS = .001
0223            ANGL = ANGL * PI / 180.
0224    C
0225              DO 1010  ILINE = 1, MLINE
0226              THETA = ILINE * ANGL
0227              NPT = NPT + 1
0228              NLINE (NPT) = MLINE
0229              STRT (NPT) = CMPLX (XSTRT + RADS * COS (THETA), YSTRT + RADS
0230         1    * SIN (THETA))
0231              NUMS (NPT, 1) = NUMBR
0232              ALTR (NPT) = IERR
0233     1010     CONTINUE
0234    C
0235     1020   CONTINUE
0236    C
0237          IF (IRALT .LE. 0)  GO TO 1027
0238            DO 1025 IRA = 1, IRALT
```

```
0239  C-----------------------------------------------------------------------
0240  C         AS AN ALTERNATIVE, SPECIFY A N-R CONVERGENCE CRITERIA ON PSI
0241  C         FOR INDIVIDUAL STREAMLINES.  THIS IS USEFUL FOR PROBLEMS
0242  C         WHERE SOME LINES ARE COMPRESSED CLOSE TOGETHER
0243  C         (STRONGER CRITERIA) AND SOME ARE SPACED FAR APART
0244  C         (WEAKER CRITERIA).
0245            READ (10, 15) IPT, ALTR (IPT)
0246  C-----------------------------------------------------------------------
0247   1025     CONTINUE
0248   1027   CONTINUE
0249
0250  C
0251   1030   CONTINUE
0252  C
0253          IF (NWL .LE. 0) GO TO 1050
0254            DO 1040  IWL = 1, NWL
0255  C
0256  C
0257  C-----------------------------------------------------------------------
0258  C       READ WELL LOCATION, PUMPING RATE AND WELL NO.
0259            READ (10, 70) ZWL (IWL), Q (IWL), NUMW (IWL)
0260  C-----------------------------------------------------------------------
0261  C
0262  C
0263   1040     CONTINUE
0264  C
0265   1050   CONTINUE
0266  C
0267  C       INPUT DOUBLET PARAMETERS.
0268  C
0269  C       MAXIMUM 5 ZONES, 10 DIPOLES(SIDES) PER ZONE.
0270  C       ZONE(I,1) = ZONE NUMBER,(I).
0271  C       ZONE(I,2) = PERM. INSIDE ZONE(I).
0272  C       ZONE(I,3) = NUMBER OF SIDES ON THE ZONE(I) POLYGON.
0273  C                   IF > 0 COUNTER-CLOCKWISE ROTATION
0274  C                   IF < 0 CLOCKWISE ROTATION
0275  C       ZONE(I,4) = ZONE(I,4) = PERM. OUTSIDE ZONE.
0276  C       ZONE(I,5) = OUTSIDE ZONE NUMBER (I)
0277  C       ZONE(I,6) = CUMULATIVE ZONE INDEX (START)
0278  C       ZONE(I,7) = CUMULATIVE ZONE INDEX (END)
0279  C
0280  C       DPOLE(I) = COMPLEX COORDINATE X+IY OF LINE DIPOLE ENDPOINTS.
0281  C                  I = PERMEABLILITY ZONE NUMBER (ZONE(I,1)).
0282  C                  J = LINE DIPOLE (ENDPOINT) NUMBER.
0283  C
0284  C       A CLOSED POLYGONAL BOUNDARY IS GENERATED ACCORDING TO THE
0285  C       SEQUENCE IN WHICH ENDPOINTS ARE READ IN.  THE CLOSING BOUNDARY
0286  C       IS OBTAINED BY CONNECTING DPOLE(1) WITH DPOLE(N).
0287  C       (N) DIPOLE ENDPOINTS FORMING A CLOSED POLYGON ARE ENTERED IN
0288  C       COUNTER CLOCKWISE ROTATION IF THEY FORM AN OUTER-MOST ZONE
0289  C       BOUNDARY. SUCCESSIVE INTERIOR ZONE BOUNDARIES ARE ENTERED IN
0290  C       CLOCKWISE, THEN COUNTERCLOCKWISE, THEN CLOCKWISE ETC. ROTATION.
0291  C
0292          IF (NZT .EQ. 0) GO TO 1070
0293  C
0294            DO 1060 IZNE = 1, NZPLS
0295  C
0296  C-----------------------------------------------------------------------
0297  C       READ PERM. ZONE PARAMETERS.
0298          READ (10, 80) (ZONE (IZNE, L), L = 1, 5)
```

```
0299  C-----------------------------------------------------------------------
0300  C
0301  C       DEFAULT OUTSIDE PERM IS BACKGROUND.
0302            IF (ZONE (IZNE, 5) .LE. 0.0) ZONE (IZNE, 4) = PERM
0303            IF (ZONE (IZNE, 5) .LE. 0.0) ZONE (IZNE, 5) = NZNE
0304  C
0305  C         DETERMINE ZONE BOUNDARY INDICIES.
0306  C
0307            IF (IZNE .GT. 1)  GO TO 1065
0308            ZONE (IZNE, 6) = 1.
0309            ZONE (IZNE, 7) = ABS (ZONE (IZNE, 3))
0310            GO TO 1075
0311   1065     ZONE (IZNE, 6) = ZONE (IZNE-1, 6) + ABS (ZONE (IZNE-1, 3))
0312            ZONE (IZNE, 7) = ZONE (IZNE-1, 7) + ABS (ZONE (IZNE, 3))
0313   1075     CONTINUE
0314  C
0315            NPOL1 = ZONE (IZNE, 6)
0316            NPOL2 = ZONE (IZNE, 7)
0317  C
0318  C
0319  C-----------------------------------------------------------------------
0320  C       READ ZONE BOUNDARYS.
0321            READ (10, 30) (DPOLE (IPOL), IPOL = NPOL1, NPOL2)
0322  C-----------------------------------------------------------------------
0323  C
0324  C
0325  C-----------------------------------------------------------------------
0326  C       READ DOUBLET STRENGTHS FROM PREVIOUS I-D-E-N-T-I-C-A-L RUN.
0327  C
0328            IF (NZT .LT. 0) READ (JL, 90) (JUMP (IPOL), MU (IPOL),
0329       1     IPOL = NPOL1, NPOL2)
0330  C-----------------------------------------------------------------------
0331  C
0332  C
0333   1060     CONTINUE
0334  C
0335  C       IF NO PERM. ZONES.
0336  C
0337   1070   ZONE (NZNE, 1) = NZNE
0338          ZONE (NZNE, 2) = PERM
0339          ZONE (NZNE, 4) = PERM
0340          POR (NZNE) = POROS
0341          P (NZNE) = PS
0342          RHO (NZNE) = RHOS
0343          LOCZ = NZNE
0344  C
0345  C
0346  C-----------------------------------------------------------------------
0347  C       READ ONE DIMENSIONAL FLOW DIRECTION AND AND FLUX.
0348  C       FLUX = VELOCITY * POROSITY.
0349          IF (IFLO .GT. 0)  READ (10, 30) ANGL1, FLUX
0350  C-----------------------------------------------------------------------
0351  C
0352  C
0353  C       ECHO AQUIFER TYPE AND OTHER INPUT PARAMETERS.
0354  C
0355  C       AQFR(1) = '    '
0356          IF (AQ .EQ.'CONA') AQFR (1) = '    '
0357          IF (AQ .EQ.'UNCA') AQFR (1) = '  UN'
0358          WRITE (LU, 110) (AQFR (L), L = 1, 3), THICK, ZBND, RHO, DEC,
```

```
0359        1   RERR, IERR, XMID, YMID, XSID, YSID
0360  C
0361  C
0362          WRITE (LU, 120) (AQFR (L), L = 1, 3), PERM
0363  C
0364          IF (NZT .EQ. 0) GO TO 1090
0365  C
0366            DO 1080  IZNE = 1, NZPLS
0367            WRITE (LU, 130) ZONE (IZNE, 2), ZONE (IZNE, 1)
0368            NPOL1 = ZONE (IZNE, 6)
0369            NPOL2 = ZONE (IZNE, 7)
0370            WRITE (LU, 140) (DPOLE (IPOL), IPOL = NPOL1, NPOL2)
0371   1080     CONTINUE
0372   1090   CONTINUE
0373  C
0374          IF (IFLO .LE. 0) GO TO 1100
0375          WRITE (LU, 150) FLUX, ANGL1
0376  C
0377  C
0378  C
0379   1100   CONTINUE
0380          IF (NZT .LT. 0) WRITE (LU, 160)
0381  C
0382  C
0383          IF (NWL .LE. 0) GO TO 1110
0384          WRITE (LU, 170)
0385          WRITE (LU, 180) (NUMW (IWL), ZWL (IWL), Q (IWL), IWL = 1, NWL)
0386  C
0387  C
0388  C
0389  C
0390   1110   CONTINUE
0391  C
0392  C       DEFAULT BOUNDARIES.
0393          IF (ZLIM .EQ. 0.0) ZLIM = ZBND
0394  C
0395  C       EXTRINSIC PERM AND 1-D FLOW CONVERTED TO (FT./HR.).
0396  C
0397          PERM = PERM * 3600.0 / 646315.0
0398          FLUX = FLUX / 365.0 / 24.0
0399            DO 1120  IZNE = 1, NZNE
0400            ZONE (IZNE, 2) = ZONE (IZNE, 2) * 3600.0 / 646315.0
0401            ZONE (IZNE, 4) = ZONE (IZNE, 4) * 3600.0 / 646315.0
0402   1120     CONTINUE
0403  C
0404  C       ONE-D. FLOW CONVERTED TO RADIANS,ESTABLISH 1-D BOUNDARY HEAD.
0405          ANGL1 = ANGL1 * 2.0 * PI / 360.
0406          UNFM = THICK * FLUX
0407  C
0408  C       PUMPING RATE CONVERTED TO (CU.FT./HR.)
0409  C
0410            DO 1130  IWL = 1, NWL
0411   1130     Q (IWL) = Q (IWL) / 7.4805 * 60.0
0412  C
0413  C       DETERMINE BOUNDARY PHI.
0414  C
0415          CALL HTOP (RPHI, RHO, PERM, THICK)
0416  C
0417  C       CALL DIPOLE STRENGTH ROUTINES
0418          LP = 2
```

```
0419  C
0420  C       LINEAR INTERPOLATION.
0421            IF (NZT .GT. 0 .AND. LP .LT. 2) CALL STGTH (IHD, RPHI, LP)
0422  C
0423  C       LINEAR AND SECOND ORDER INTERPOLATION
0424            IF (NZT .GT. 0 .AND. LP .GE. 2) CALL MDPNT (NZNE, IHD, RPHI, LP)
0425  C
0426  C
0427  C       IF NZT .LT. 0 STRENGTHS WERE OBTAINED FROM A PREVIOUS RUN.
0428  C
0429            NZT = NZPLS
0430  C
0431  C
0432  C       GENERATE A STREAMLINE PATTERN.
0433  C
0434            IF (MPT .NE. 0) CALL SLINE (HDMN, HDMX, VOPT, IFLAG, ICT1, ALTR)
0435  C
0436  C       GENERATE A GRID OF HEAD VALUES FOR CONTOURING.
0437  C
0438            IF (GOPT .NE. 0) CALL GRID (ZSPA, HDMN, HDMX, IFLAG, ICT2)
0439  C
0440            IF (GOPT .EQ. 0 .AND. MPT .EQ. 0) GO TO 1170
0441  C
0442  C       WRITE TO AUXILIARY PLOTTING FILE.
0443  C
0444            WRITE (AL, 190) XLO, YLO, XHI, YHI, ZSPA
0445            WRITE (AL, 200) NWL, NZT
0446            IF (NWL .LE. 0) GO TO 1145
0447  C
0448              DO 1140  IWL = 1, NWL
0449              WRITE (AL, 210) IWL, ZWL (IWL)
0450   1140       CONTINUE
0451  C
0452   1145   IF (NZT .LE. 0) GO TO 1165
0453            NTOT = ZONE (NZT, 7)
0454  C
0455            WRITE (AL, 210) NTOT
0456  C
0457              DO 1160  IZNE = 1, NZT
0458              NPOL = ABS (ZONE (IZNE, 3))
0459              NPOL1 = ZONE (IZNE, 6)
0460              NPOL2 = ZONE (IZNE, 7)
0461              WRITE (AL, 210) NPOL
0462  C
0463                DO 1160  IPOL = NPOL1, NPOL2
0464                WRITE (AL, 210) IZNE, DPOLE (IPOL)
0465   1160         CONTINUE
0466  C
0467   1165   CONTINUE
0468            WRITE (AL, 190) (HDMX (IH), IH = 1, 3)
0469            WRITE (AL, 190) (HDMN (IH), IH = 1, 3)
0470            WRITE (AL, 200) ICT1, ICT2
0471  C
0472   1170   CONTINUE
0473  C
0474  C
0475  C
0476       10   FORMAT ( 3I5, 5F10.0 )
0477       15   FORMAT (I5, F10.0)
0478       20   FORMAT ( 6E10.5, 2I5 )
```

```
0479      25  FORMAT (8E10.5)
0480      30  FORMAT ( 2F10.0 )
0481      40  FORMAT ( 6I5, 4F10.0, A4 )
0482      50  FORMAT ( 3F10.0, I5, F10.0, 3I5 )
0483      60  FORMAT ( 3F10.0, I5, F10.0, I5)
0484      70  FORMAT ( 3F10.0, I5 )
0485      80  FORMAT ( 5F10.0 )
0486      90  FORMAT ( 2E15.9 )
0487     110  FORMAT ( ////1X, 3A4, " AQUIFER THICKNESS ",F10.2, " (FEET)",/
0488        1    1X, "BOUNDARY COND. (RADIUS)",F10.2, " (FEET)"/1X,
0489        2    "BOUNDARY COND. (HEAD)"F10.2," (FEET)"/1X,"DECREMENT IN HEAD"
0490        3    ,F10.5, /1X, "ERROR CRITERIA: (PHI)" E10.5, " (PSI) "
0491        4    E10.5, /1X, "EVALUATION BOUNDARY (CTR.", F8.2, 1X, F8.2,
0492        5    ", SIDES", F10.2, " BY", F10.2, ")(FEET)")
0493     120  FORMAT ( //1X, 3A4, 1X, " AQUIFER PERMEABILITY",//1X,
0494        1    10H(BOUNDARY), F10.4, 1X, 11H(GL/DY/FT2) // )
0495     130  FORMAT(1X,"PERM. INSIDE ", F10.4, 1X,11H(GL/DY/FT2) //1X,
0496        1 "ZONE",1X,F5.0,5X,23HBOUNDARY COORDS. (FEET) ,5X,
0497        2 23HBOUNDARY COORDS. (FEET) ,/25X, 5H(X,Y) ,23X, 5H(X,Y) )
0498     140  FORMAT ( 15X, 2F10.2 , 8X, 2F10.2 )
0499     150  FORMAT ( //1X, 18HUNIFORM (1-D) FLUX, 1X, F10.5, 1X, 7HFT./YR.,
0500        1    1X, 14HAT AN ANGLE OF, F5.1, 1X, 8HDEGREES. )
0501     160  FORMAT ( //1X, 41H(DOUBLET STRENGTHS INPUT FROM A PREVIOUS ,
0502        1    15HIDENTICAL RUN.) )
0503     170  FORMAT ( //// 19X 32HWELL LOCATIONS AND PUMPING RATES//1X,
0504        1    8HWELL NO., 5X, 7HX-COORD  6X, 7HY-COORD , 2X, "PUMPING RATE (",
0505        2    "GAL/MIN)", 3X, 8HZONE NO. / )
0506     180  FORMAT ( /1X, I4, 5X, F10.2, 3X, F10.2, 3X, F10.2 )
0507     190  FORMAT ( 5E15.7 )
0508     200  FORMAT ( 2I4 )
0509     210  FORMAT ( I4, 2E15.7 )
0510  C
0511           END
0512  C
0513  C     .....................................................................
0514  C
0515           SUBROUTINE  GRID (ZSPA, HDMN, HDMX, IFLAG, ICT)
0516  C
0517  C       CALCULATE A GRID OF OMEGA VALUES FOR HEAD CONTOUR MAPPING.
0518  C
0519  C
0520           COMMON / CNST / I, PI
0521           COMMON / INPT / IOPT, NZNE, ITER, DPJP, IOMEG
0522           COMMON / POLE / ZONE, DPOLE
0523           COMMON / ZON / LOCZ
0524           COMMON / WELLD / ZBND, RPHI, Q, ZWL, STRT, WRAD, WRDS, NPT, NWL,
0525        1    NUMS, NUMW
0526           COMMON / IO / LU, PL, GL, AL, JL, IL, TL
0527           COMMON / AQF / THICK, AQ, FL, BND
0528  C
0529  C
0530           DIMENSION BND (4), DPOLE (300), HDMN (3), HDMX (3), NUMS (100,
0531        1    2), NUMW (30), Q (30), STRT (100), WRAD (30), ZHD (4), ZONE (4,
0532        2    7), ZWL (30)
0533  C
0534           REAL    IOMEG
0535  C
0536           INTEGER    AL, GL, PL, TL
0537  C
0538           COMPLEX    BND, DODZ, DPOLE, I, OMCON, OMDEC, OMEGA, OMPRT, STRT,
```

```
0539        1   ZSTR, ZWL, Z, D2ODZ
0540  C
0541            ICT = 0
0542  C
0543  C       ESTABLISH GRID BOUNDARIES.
0544            IXEND = REAL (BND (2) - BND (4)) / ZSPA
0545            IYEND = AIMAG (BND (4) - BND (2)) / ZSPA
0546            ZSTR = BND (4)
0547  C
0548            NZT = NZNE - 1
0549            IHD = 1
0550  C
0551  C       BEGIN COLUMN AND ROW LOOPS.
0552  C
0553              DO 1040  IY = 1, IYEND
0554  C
0555                DO 1030  IX = 1, IXEND
0556  C
0557  C       FIND EACH Z.
0558  C
0559                Z = ZSTR + CMPLX ((IX - 1) * ZSPA, - (IY - 1) * ZSPA)
0560  C
0561  C       OMIT Z VALUES TOO NEAR SINGULARITIES.
0562  C
0563                IF (NZT .LE. 0) GO TO 1005
0564  C
0565                  DO 1000  IZNE = 1, NZT
0566                  NPOL1 = ZONE (IZNE, 6)
0567                  NPOL2 = ZONE (IZNE, 7)
0568  C
0569                    DO 1000  IPOL = NPOL1, NPOL2
0570                    IF (CABS (Z - DPOLE (IPOL)) .GT. .50) GO TO 1000
0571                    HD = - 99.0
0572                    OMEGA = ( - 99.0, - 99.0)
0573                    GO TO 1020
0574   1000             CONTINUE
0575  C
0576   1005       CONTINUE
0577  C
0578                IF (NWL .LE. 0) GO TO 1015
0579  C
0580                  DO 1010  IWL = 1, NWL
0581                  IF (CABS (Z - ZWL (IWL)) .GT. .50) GO TO 1010
0582                  HD = - 99.0
0583                  OMEGA = ( - 99.0, - 99.0)
0584                  GO TO 1020
0585   1010           CONTINUE
0586  C
0587   1015       CONTINUE
0588  C
0589  C
0590                ICT = ICT + 1
0591  C
0592  C       CALCULATE OMEGA(Z).
0593  C
0594                CALL OMA (Z, OMCON, OMEGA, DODZ, D2ODZ, IFLAG, IHD, NZNE)
0595                ROMEG = REAL (OMEGA)
0596  C
0597  C       CALCULATE HEAD.
0598                CALL PTOH (ROMEG, HD, ZONE (LOCZ, 2))
```

```
0599  C
0600              ZHD (1) = HD
0601              ZHD (2) = REAL (Z)
0602              ZHD (3) = AIMAG (Z)
0603  C
0604  C       FIND MIN. AND MAX. VALUES FOR PLOTTING LATER.
0605  C
0606              CALL MXMN (ZHD, HDMN, HDMX, ICT)
0607  C
0608  C
0609  C       WRITE TO GRID FILE
0610  C
0611   1020       WRITE (GL, 10) IX, IY, Z, HD, OMEGA
0612  C       PRINT STATUS ON DISPLAY TERMINAL.
0613               WRITE (1, 20) IX, IY
0614   1030       CONTINUE
0615             WRITE (1, 30) IY
0616   1040     CONTINUE
0617  C
0618          IZERO = 0
0619          WRITE (GL, 10) IZERO
0620  C
0621          RETURN
0622  C
0623  C
0624  C
0625     10   FORMAT ( 2I4, 5E15.7 )
0626     20   FORMAT ( 'GRID ROW AND COLUMN...', 2I5 )
0627     30   FORMAT ( 'GRID COLUMN COMPLETED...', I5 )
0628  C
0629          END
0630  C
0631  C      .....................................................................
0632  C
0633          SUBROUTINE  SLINE (HDMN, HDMX, VOPT, IFLAG, ICT, ALTR)
0634  C
0635  C       CALCULATE A STREAMLINE PATTERN USING ONE OF TWO ITERATIVE METHODS
0636  C
0637  C
0638          COMMON / CNST / I, PI
0639          COMMON / INPT / IOPT, NZNE, ITER, DPJP, IOMEG
0640          COMMON / POLE / ZONE, DPOLE
0641          COMMON / ZON / LOCZ
0642          COMMON / WELLD / ZBND, RPHI, Q, ZWL, STRT, WRAD, WRDS, NPT, NWL,
0643         1   NUMS, NUMW
0644          COMMON / ERRS / RERR, IERR, ITRMX, ALSTP, LXDWN, LXUP
0645          COMMON / IO / LU, PL, GL, AL, JL, IL, TL
0646          COMMON / CHEM / D, F, P, SIGMA, POR, RHO, ISKP
0647          COMMON / AQF / THICK, AQ, FL, BND
0648          COMMON / LINE / NLINE, STM, DEC, MXPTS
0649  C
0650  C
0651          DIMENSION BND (4), DPOLE (300), HDMN (3), HDMX (3), HEAD (4,
0652         1   200), NLINE (100), NUMS (100, 2), NUMW (30), Q (30), STRT
0653         2   (100), WRAD (30), ZONE (4, 7), ZWL (30), ALTR (100), POR (4),
0654         3   P (4), RHO (4)
0655
0656  C
0657          COMPLEX   BND, CDM, DODZ, DPOLE, FLXVC, I, OMCON, OMDEC, OMEGA,
0658         1   OMPRT, OMST, STRT, VELVC, ZWL, Z, D2ODZ
```

```
0659          INTEGER   AL, GL, PL, STM, VOPT, TL
0660          REAL      IERR, IOMEG
0661    C
0662          DATA    POND, ZERO / 4HPOND, 4HZERO /
0663    C
0664    C     BEGIN STREAMLINE DEVELOPMENT
0665    C
0666    C     PRINT HEADERS.
0667          WRITE (LU, 10)
0668    C
0669          IF (STM .EQ. 1) WRITE (LU, 20)
0670          IF (STM .EQ. 0) WRITE (LU, 30)
0671    C
0672          ICT = 0
0673          ICTM = 0
0674    C
0675    C     BEGIN EACH STREAMLINE HERE.
0676    C
0677            DO 1100  IPT = 1, NPT
0678            ICT = ICT + 1
0679            ICTM = ICTM + 1
0680            IHD = 1
0681            IHDM = 1
0682            ITER = 0
0683            Z = STRT (IPT)
0684    C
0685    C     CALCULATE STARTING HEAD.
0686            CALL OMA (Z, OMCON, OMEGA, DODZ, D2ODZ, IFLAG, IHD, NZNE)
0687    C
0688            OMST = OMCON
0689    C
0690    C     CALCULATE RELATIVE ERROR CRITERIA FOR IM(OMEGA).
0691            IF (IPT .EQ. 1) RELE = ABS (AIMAG (OMCON))
0692            IERR = ALTR (IPT) * RELE
0693    C
0694            HEAD (2, IHD) = REAL (Z)
0695            HEAD (3, IHD) = AIMAG (Z)
0696            ROMEG = REAL (OMEGA)
0697            IOMEG = AIMAG (OMEGA)
0698    C
0699            CALL PTOH (ROMEG, HEAD (1, IHD), ZONE (LOCZ, 2))
0700    C
0701            CALL MXMN (HEAD (1, IHD), HDMN, HDMX, ICT)
0702    C
0703    C     TERMINATE STREAMLINE IF PONDING OR ZERO HEAD.
0704            IF (FL .EQ. POND) GO TO 1090
0705    C
0706    C     CHEMICAL INTERFACE OPTION.
0707            IF (VOPT .EQ. 0) GO TO 1000
0708            MINUS = - 1
0709            CALL STMVL (HEAD (1, IHD), OMEGA, Z, DODZ, D2ODZ, ICTM, IHDM,
0710         1  IPT, MINUS, ZONE (LOCZ, 2))
0711     1000   CONTINUE
0712    C
0713            HEAD (4, IHD) = IPT
0714    C
0715    C     WRITE TO PLOTTING FILE.
0716            WRITE (PL, 70) (HEAD (IH, IHD), IH = 1, 4)
0717    C
0718    C     PRINTER OUTPUT
```

```
0719            WRITE (LU,40)
0720            WRITE (LU,50)
0721            WRITE (LU,60)
0722            WRITE (LU, 80) IPT, IHD, OMEGA, DODZ, HEAD (1, IHD)
0723            WRITE (LU,51)
0724            WRITE (LU,61)
0725            WRITE (LU, 81) (HEAD (IH, IHD), IH = 2,3), FL, ITER, LOCZ
0726  C
0727  C       BEGIN LOOP FOR SUCCESSIVE STREAMLINE POINTS.
0728  C
0729   1010     IHD = IHD + 1
0730            IHDM = IHDM + 1
0731            ITER = 0
0732            LOCO = LOCZ
0733  C
0734  C       CHECK STREAMLINE APPROACH TO WELLS, STOP IF WITHIN
0735  C       WELL RADIUS.
0736  C
0737            IF (IFLAG .LE. 0) GO TO 1020
0738            IF (CABS (Z - ZWL (IFLAG)) .GE. ABS (WRDS)) GO TO 1020
0739            IF (DEC * Q (IFLAG) .GT. 0) GO TO 1050
0740  C
0741   1020     CONTINUE
0742  C
0743  C
0744  C       SELECT STREAMLINE TRACING METHOD,NEWTONS METHOD WITH CONVERGENCE
0745  C       ON BOTH PHI AND PSI OR ON PSI ALONE.
0746  C
0747  C       (1).  ALLOW PHI INTERVAL BETWEEN STREAMLINE POINTS TO VARY.
0748  C             ITERATE ON PSI ONLY.
0749  C
0750            IF (STM .EQ. 1) CALL NUMCA (DEC, DODZ, D2ODZ, Z, OMCON, OMEGA,
0751           1   IFLAG, IHD)
0752  C
0753  C
0754            IF (STM .NE. 0) GO TO 1030
0755  C
0756  C       (2).   FIX THE PHI INTERVAL, ITERATE ON BOTH PHI AND PSI.
0757  C
0758  C       MAINTAIN A CONTINUOUS OMEGA VARIABLE FOR NEWTON ITERATION AND
0759  C       COMPUTING CONVENIENCE.
0760  C       CONTINUOUS OMEGA (OMCON OR OMDEC).
0761  C
0762            HD = HEAD (1, 1) - (IHD - 1) * DEC
0763            IF (HD .LE. 0.0)  GO TO 1075
0764            CALL HTOP (ROMEG, HD, ZONE (NZNE, 2), THICK)
0765            OMDEC = CMPLX (ROMEG, AIMAG (OMST))
0766  C
0767            CALL NEWRA (OMDEC, DODZ, D2ODZ, Z, OMCON, OMEGA, IFLAG, IHD)
0768  C
0769  C
0770   1030     CONTINUE
0771  C
0772  C       CHECK TO SEE IF PERM. ZONE BOUNDARY WAS CROSSED.
0773  C
0774            IF (LOCO .NE. LOCZ) WRITE (LU, 90) LOCO, LOCZ
0775  C
0776            ROMEG = REAL (OMEGA)
0777            CALL PTOH (ROMEG, HEAD (1, IHD), ZONE (LOCZ, 2))
0778  C
```

```
0779  C       CHECK FOR PONDING OR ZERO HEAD.
0780            IF (FL .EQ. POND) GO TO 1090
0781            IF (FL .EQ. ZERO .AND. STM .EQ. 0)  GO TO 1090
0782  C
0783  C       HEAD(1,I) = HYDRAULIC HEAD (FT.)
0784  C       HEAD(2,I) = X-COORD. (FT.)
0785  C       HEAD(3,I) = Y-COORD. (FT.)
0786  C       HEAD(4,I) = STREAMLINE NUMBER.
0787  C
0788            HEAD (2, IHD) = REAL (Z)
0789            HEAD (3, IHD) = AIMAG (Z)
0790            HEAD (4, IHD) = IPT
0791  C
0792            CALL MXMN (HEAD (1, IHD), HDMN, HDMX, ICT)
0793  C
0794  C
0795  C       WRITE TO PLOTTING FILE, BUT FIRST LABEL BACKTRACKING
0796  C       STREAMLINE POINTS.
0797  C
0798            IF (IHD .EQ. 2)  HGRAD = HEAD (1, 1)
0799            IBACK = 1
0800            IF (DEC .GT. 0)  GO TO 1045
0801            IF (HEAD (1, IHD) .LE. HGRAD)  GO TO 1047
0802            IF (IFLAG .EQ. -2)  GO TO 1048
0803            HGRAD = HEAD (1, IHD)
0804   1048     IBACK = 0
0805            GO TO 1047
0806  C
0807   1045     IF (HEAD (1, IHD) .GE. HGRAD)  GO TO 1047
0808            IF (IFLAG .EQ. -2) GO TO 1049
0809            HGRAD = HEAD (1, IHD)
0810   1049     IBACK = 0
0811   1047     CONTINUE
0812  C
0813            WRITE (LU,40)
0814            WRITE (PL, 70) (HEAD (IH, IHD), IH = 1, 4), IFLAG, IBACK
0815            WRITE (LU,50)
0816            WRITE (LU,60)
0817            WRITE (LU, 80) IPT, IHD, OMEGA, DODZ, HEAD (1, IHD)
0818            WRITE (LU,51)
0819            WRITE (LU,61)
0820            WRITE (LU, 81) (HEAD (IH, IHD), IH = 2,3), FL, ITER, LOCZ
0821  C
0822            ICT = ICT + 1
0823            ICTM = ICTM + 1
0824  C
0825  C       CALCULATE STREAMLINE VELOCITY AND FLUX FOR KINETIC CHEMICAL
0826  C       MODEL INTERFACE.
0827  C
0828            IF (VOPT .EQ. 0) GO TO 1040
0829            IF (IHD .EQ. 1) GO TO 1041
0830            IF (MOD(IHD, ISKP) .NE. 0) GO TO 1042
0831   1041     IF (IFLAG .EQ. -2 .OR. IBACK .EQ. 1)  GO TO 1042
0832  C
0833            CALL STMVL (HEAD (1, IHD), OMEGA, Z, DODZ, D2ODZ, ICTM, IHDM,
0834         1  IPT, MINUS, ZONE (LOCZ, 2))
0835  C
0836            GO TO 1040
0837   1042     ICTM = ICTM - 1
0838            IHDM = IHDM - 1
```

```
0839   1040    CONTINUE
0840   C
0841   C       CHECK FOR ABNORMAL STREAMLINE TRACE.
0842   C
0843             IF (IFLAG .GE. 0) GO TO 1060
0844   C
0845   C       STAGNANT STREAMLINE
0846   C
0847             IF (IFLAG .EQ. - 1) WRITE (LU, 100) IPT
0848             IF (IFLAG .EQ. - 1) GO TO 1090
0849   C
0850   C       MAXIMUM ITERATIONS WITHOUT CONVERGENCE
0851   C
0852             IF (IFLAG .EQ. - 2) WRITE (LU, 110) IPT
0853             IF (IFLAG .EQ. - 2)  GO TO 1060
0854   C
0855   C       DIPOLE ENDPOINT IN THE STREAMLINE PATH.
0856   C
0857             IF (IFLAG .EQ. - 4) WRITE (LU, 170) IPT
0858             IF (IFLAG .EQ. - 4) GO TO 1090
0859   C
0860   C
0861   C       STREAMLINE AT WELL.
0862   C
0863    1050    HEAD (1, IHD) = - 999999.99
0864            HEAD (2, IHD) = REAL (ZWL (IFLAG))
0865            HEAD (3, IHD) = AIMAG (ZWL (IFLAG))
0866            HEAD (4, IHD) = IPT
0867            NUMS (IPT, 2) = NUMW (IFLAG)
0868            ICT = ICT + 1
0869   C
0870   C       WRITE TO PLOTTING FILE.
0871   C
0872            WRITE (PL, 70) (HEAD (IH, IHD), IH = 1, 4)
0873            WRITE (LU, 120) IHD, (HEAD (IH, IHD), IH = 1, 4)
0874            GO TO 1100
0875    1060    CONTINUE
0876   C
0877   C       CHECK PLOT BOUNDARIES.
0878   C
0879            CALL INOUT (BND, Z, IT)
0880            IF (IT .NE. 0) GO TO 1070
0881            WRITE (LU, 130) IPT
0882            GO TO 1090
0883   C
0884   C         ZERO HEAD
0885   C
0886    1075    WRITE (LU,180) IPT
0887            GO TO 1090
0888    1070    CONTINUE
0889   C
0890   C       MAX. STREAMLINE POINTS.
0891   C
0892            IF (IHD .LT. MXPTS) GO TO 1010
0893            WRITE (LU, 140) IPT
0894    1090    NUMS (IPT, 2) = - 7
0895    1100    CONTINUE
0896   C
0897    1110  CONTINUE
0898   C
```

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0899  C       RESCALE LAST STREAMLINE FOR CHEM FILE AND TRANSFER CHEM. DATA
0900  C       TO OUTPUT DEVICE (LOGICAL UNIT 14).
0901  C
0902          IF (VOPT .EQ. 0) GO TO 1120
0903          MINUS = - 2
0904          ICTM = ICTM + 1
0905          CALL STMVL (DM, CDM, CDM, CDM, CDM, ICTM, IHDM, IPT, MINUS, DM)
0906   1120   CONTINUE
0907  C
0908          WRITE (LU, 150) ICT
0909          ENDSL = - 47.
0910          WRITE (PL, 160) ENDSL
0911  C
0912          RETURN
0913  C
0914  C
0915  C
0916      10  FORMAT ( ///,1X,80(1H*),/, 21X, 22HSTREAMLINE DEVELOPMENT   )
0917      20  FORMAT ( 21X, 23H(VARIABLE PHI INTERVAL), /// )
0918      30  FORMAT ( 21X, 20H(FIXED PHI INTERVAL), /// )
0919      40  FORMAT ( 1X, 80 ( 1H- ) )
0920      50  FORMAT ( /, 2X, 10HSTREAMLINE, 2X, 5HPOINT, 3X, 3HPHI, 10X,
0921        1   3HPSI, 5X, 11HD(PHI)/D(X), 2X, 11HD(PHI)/D(Y), 5X, 4HHEAD)
0922      51  FORMAT (/6X 7HX COORD, 4X, 7HY COORD, 2X, 11HCONF./UNCF., 2X,
0923        1   "N.R. ITER",1X, 4HZONE )
0924      60  FORMAT ( 6X, 3HNO., 6X, 3HNO., 25X, 11HD(PSI)/D(Y), 3X,
0925        1   12H-D(PSI)/D(X), 2X, 6H(FEET) )
0926      61  FORMAT ( 29X, 4HFLOW )
0927      70  FORMAT ( 4E15.5, 2I5 )
0928      80  FORMAT ( 2X, I5, 4X, I5, 4 (1X, E12.5), 1X, F10.2 )
0929      81  FORMAT ( 1X, F10.2, 1X, F10.2, 7X , A4, 3X, I5, 3X, I5)
0930      90  FORMAT ( 1X, 15HSTREAMLINE HAS , 17HCROSSED BOUNDARY
0931        1   15HFROM PERM. ZONE,I5, 13H TO PERM ZONE, I5, 1H. )
0932     100  FORMAT ( 1X, 10HSTREAMLINE, I5, 1X, 10HTERMINATED, 1X
0933        1   13HD(OMEGA)/D(Z) 1X 22HIS APPROXIMATELY ZERO.     )
0934     110  FORMAT ( 1X, 22H--WARNING-- STREAMLINE, I5, 1X, 9HFAILED TO, 1X,
0935        1   45HCONVERGE AT THIS POINT AFTER MAX. ITERATIONS. )
0936     120  FORMAT ( 8X, I5, 33X, F10.2, 1X, F10.2, 3X, F10.2, 2X, F10.2 )
0937     130  FORMAT ( 1X, 10HSTREAMLINE, I5, 24H TERMINATED AT BOUNDARY   )
0938     140  FORMAT ( 1X, 10HSTREAMLINE, I5, 29H TERMINATED AFTER MAX. NO. OF
0939        1   5HPTS./ / )
0940     150  FORMAT ( 1X, I5, 30H  RECORDS OF STREAMLINE OUTPUT )
0941     160  FORMAT ( 45X, E15.5 )
0942     170  FORMAT ( 1X, 10HSTREAMLINE, I5, 1X, 13HTERMINATED AT, 1X,
0943        1 18HDIPOLE SINGULARITY)
0944     180  FORMAT ( 1X, 10HSTREAMLINE, I5, 1X, 15HTERMINATED WITH, 1X
0945        1 10HZERO HEAD. )
0946  C
0947          END
0948  C
0949  C     .....................................................................
0950  C
0951          SUBROUTINE  OMA (Z, OMCON, OMEGA, DODZ, D2ODZ, MXWL, IHD, NZNE)
0952  C
0953  C       THIS ROUTINE DETERMINES THE ADDATIVE EFFECT OF ALL HYDROLOGIC
0954  C       COMPONENTS IN THE FLOW DOMAIN.
0955  C
0956  C
0957          COMMON / CNST / I, PI
0958          COMMON / ZARG / ARGPO, DODF
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```
0959          COMMON / WELLD / ZBND, RPHI, Q, ZWL, STRT, WRAD, WRDS, NPT, NWL,
0960         1   NUMS, NUMW
0961          COMMON / ONED / IFLO, ANGL1, UNFM
0962          COMMON / POLE / ZONE, DPOLE
0963          COMMON / ZON / LOCZ
0964          COMMON / IO / LU, PL, GL, AL, JL, IL, TL
0965    C
0966    C
0967          DIMENSION ARGPO (600), DPOLE (300), NUMS (100, 2), NUMW
0968         1   (30), Q (30), STRT (100), WRAD (30), ZONE (4, 7), ZWL (30)
0969    C
0970          COMPLEX   DODF, DODZ, DOLD, DOWL, DPOLE, I, OMCON, OMEGA, OMLD,
0971         1   OMWL, STRT, ZWL, Z, ONEFL, BND1, D2ODZ, D2WL, D2LD
0972          INTEGER   AL, GL, PL, TL
0973    C
0974          OMEGA = (0.0, 0.0)
0975          DODZ = (0.0, 0.0)
0976          D2ODZ = (0.0, 0.0)
0977    C
0978    C       DETERMINE WELL CONTRIBUTION TO OMEGA.
0979    C
0980          IF (NWL .LE. 0) GO TO 1000
0981          CALL WELL (Z, OMWL, DOWL, D2WL, MXWL, IHD)
0982          OMEGA = OMEGA + OMWL
0983          DODZ = DODZ + DOWL
0984          D2ODZ = D2ODZ + D2WL
0985     1000 CONTINUE
0986    C
0987    C
0988    C       ADD ONE DIMENSIONAL FLOW TO OMEGA AND DODZ SUBJECT TO BOUNDARY
0989    C       CONDITION THAT WHEN Z = ZBND*COS(ANGL)+ISIN(ANGL), OMEGA(1D)=0.
0990    C
0991          IF (IFLO .EQ. 0) GO TO 1010
0992          BND1 = ZBND * (COS (ANGL1) + I * SIN (ANGL1))
0993          ONEFL =   UNFM * (COS (ANGL1) - I * SIN (ANGL1)) * (Z - BND1)
0994          OMEGA = OMEGA + ONEFL
0995    C
0996          DODZ = DODZ + UNFM * (COS (ANGL1) - I * SIN (ANGL1))
0997    C
0998     1010 CONTINUE
0999    C
1000    C
1001    C       DETERMINE PERM. ZONE CONTRIBUTION TO OMEGA.
1002    C
1003          IF (NZNE .LE. 1) GO TO 1020
1004          CALL DIPOL (Z, OMLD, DOLD, D2LD, IHD, NZNE)
1005          OMEGA = OMEGA + OMLD + RPHI
1006          DODZ = DODZ + DOLD
1007          D2ODZ = D2ODZ + D2LD
1008    C
1009          OMCON = CMPLX (ZONE (NZNE, 2) / ZONE (LOCZ, 2) * REAL (OMEGA),
1010         1   AIMAG (OMEGA))
1011    C
1012          GO TO 1030
1013    C
1014    C       ADD BOUNDARY HEAD (POTENTIAL) IF NOT ALREADY DONE ABOVE.
1015    C
1016     1020 OMEGA = OMEGA + RPHI
1017          OMCON = OMEGA
1018     1030 CONTINUE
```

```
1019  C
1020  C
1021        RETURN
1022  C
1023  C
1024        END
1025  C
1026  C     ..................................................................
1027  C
1028        SUBROUTINE  WELL (Z, OMWL, DOWL, D2WL, MXWL, IHD)
1029  C
1030  C     THIS ROUTINE CALCULATES COMPLEX POTENTIAL (OMEGA) AT A
1031  C     GIVEN X,Y COORDINATE (Z), RESULTING FROM WELL PUMPING.
1032  C
1033  C
1034        COMMON / CNST / I, PI
1035        COMMON / ZON / LOCZ
1036        COMMON / WELLD / ZBND, RPHI, Q, ZWL, STRT, WRAD, WRDS, NPT, NWL,
1037       1   NUMS, NUMW
1038        COMMON / IO / LU, PL, GL, AL, JL, IL, TL
1039  C
1040  C
1041        DIMENSION IWIND (30), LSARG (30), NUMS (100, 2), NUMW (30), Q
1042       1   (30), STRT (100), WRAD (30), ZWL (30)
1043  C
1044        COMPLEX   CMLG, DOWL, DTRM, D1, D2, D3, I, OMWL, STRT, WLTRM,
1045       1   ZWL, Z, D2WL, D2TR
1046        INTEGER   AL, GL, PL, TL
1047        REAL      LSARG
1048  C
1049        OMWL = (0.0, 0.0)
1050        DOWL = (0.0, 0.0)
1051        D2WL = (0.0, 0.0)
1052        WLMX = 0.0
1053        MXWL = 0
1054  C
1055  C     LOOP FOR EACH WELL.
1056  C
1057          DO 1030  IWL = 1, NWL
1058  C
1059  C     DETERMINE THE ADDITIVE EFFECT OF EACH WELL ON THE POINT (Z).
1060  C
1061          QPI = Q (IWL) / (2.0 * PI)
1062          CMLG = CLOG ((Z - ZWL (IWL)) / ZBND)
1063  C
1064  C     ARBITRARILY, MAKE THE BRANCH CUT PARALLEL TO POS. X AXIS.
1065  C
1066          IF (AIMAG (CMLG) .LT. 0.0) CMLG = CMPLX (REAL (CMLG), AIMAG
1067       1   (CMLG) + 2.0 * PI)
1068          IF (IHD .NE. 1) GO TO 1000
1069          IWIND (IWL) = 0
1070          GO TO 1010
1071  C
1072  C     IF STREAMLINE CROSSES THE BRANCH CUT COUNTERCLOCKWISE THEN
1073  C     ADD 2PI FOR CONTINUITY OF ARG(Z).
1074  C
1075   1000   IF (LSARG (IWL) - AIMAG (CMLG) .GT. PI) IWIND (IWL) = IWIND
1076       1   (IWL) + 1
1077  C
1078  C     IF STREAMLINE CROSSES BRANCH CLOCKWISE, SUBTRACT 2PI.
```

```
1079  C
1080            IF (LSARG(IWL) - AIMAG(CMLG) .LT. - PI) IWIND(IWL) = IWIND
1081         1  (IWL) - 1
1082   1010     LSARG(IWL) = AIMAG(CMLG)
1083  C
1084  C       REVISE IM(OMEGA) ACCORDINGLY.
1085  C
1086            CMLG = CMPLX(REAL(CMLG), AIMAG(CMLG) + IWIND(IWL) * 2.0 *
1087         1  PI)
1088            WLTRM = QPI * CMLG
1089  C
1090  C         CHECK WELL APPROACH.
1091  C
1092            IF (CABS(Z - ZWL(IWL)) .LT. WRDS)  MXWL = IWL
1093   1020     CONTINUE
1094            OMWL = OMWL + WLTRM
1095  C
1096  C       CALCULATE D(OMEGA)/D(Z) FOR ITERATION SCHEME.  NOTE, WLTRM IS
1097  C       COMPLEX HERE BECAUSE INDIVIDUAL STREAMLINES ARE SPECIFIED.
1098  C
1099            DTRM = QPI / (Z - ZWL(IWL))
1100            D2TR = -QPI / (Z - ZWL(IWL)) ** 2
1101            DOWL = DOWL + DTRM
1102            D2WL = D2WL + D2TR
1103   1030     CONTINUE
1104  C
1105          RETURN
1106  C
1107  C
1108          END
1109  C
1110  C     ..................................................................
1111  C
1112          SUBROUTINE  NEWRA(DCDV, DERIV, D2ODZ, INDV, DEPV, DEPV2, IFLAG,
1113         1  IHD)
1114  C
1115  C       CALCULATE X AND Y(Z) GIVEN PHI AND PSI(OMEGA) USING NEWTONS
1116  C       METHOD TO ITERATIVELY FIND THE ROOTS OF A NON-LINEAR EQUATION.
1117  C       A RELAXATION PARAMETER(ALPHA) IS AUTOMATICALLY INCREASED OR
1118  C       DECREASED TO SPEED CONVERGENCE.
1119  C
1120  C       NEWTONS METHOD REQUIRING CONVERGENCE ON BOTH PHI AND PSI IS
1121  C       GENERALLY NOT PRACTICAL IF STREAMLINE PATHS ARE SHARPLY AFFECTED
1122  C       BY RADICAL DIFFERENCES IN PERMEABILITY.
1123  C       THIS ITERATIVE SCHEME IS INTENDED PRIMARILY FOR USE IN COUPLING
1124  C       THE HYDROLOGY OUTPUT WITH NUMERICAL MODELS OF MASS AND/OR
1125  C       CHEMICAL TRANSPORT ALONG STREAMLINES. (EG. INSITU LEACHING)
1126  C
1127          COMMON / CNST / I, PI
1128          COMMON / ZON / LOCZ
1129          COMMON / INPT / IOPT, NZNE, ITER, DPJP, IOMEG
1130          COMMON / ZARG / ARGPO, DODF
1131          COMMON / ONED / IFLO, ANGL1, UNFM
1132          COMMON / ERRS / RERR, IERR, ITRMX, ALSTP, LXDWN, LXUP
1133          COMMON / IO / LU, PL, GL, AL, JL, IL, TL
1134  C
1135  C
1136          DIMENSION ARGPO(600), LCIND(5)
1137  C
1138          COMPLEX   BESTD, BESTI, BESTV, BEST2, DCDV, DEPV2, DEPV, DEP1,
```

```
1139       1   DERIV, DIFF, DODF, INDV, I, LCIND, LSDIF, OLDER, OLDV, TINDV,
1140       2   D2ODZ
1141           INTEGER   AL, GL, PL, RELAX, TL
1142           REAL      IANG, IDIFF, IERR, IMNDF, IOMEG, MINER
1143   C
1144           IFLAG = 0
1145           ALPHA = 1.0
1146           RELAX = 0
1147           LAX = 0
1148           IF (IHD .EQ. 2) LCIND = INDV
1149   C
1150   C      PREVIOUS STREAMLINE POINT IS INITIAL ESTIMATE FOR NEXT POINT.
1151   C
1152           DEP1 = DEPV
1153           LSDIF = DEPV - DCDV
1154           SPAC = REAL (LSDIF)
1155           MINER = 9.0E9
1156   C
1157   C      CALCULATE RELATIVE ERROR FOR RE(OMEGA).
1158   C      UPDATE REAL ERROR CRITERIA AT EACH NODE.
1159   C
1160           RELR = ABS (RERR * REAL (DCDV))
1161   C
1162           IF (IOPT .EQ. 0) GO TO 990
1163           WRITE (LU,11)
1164           WRITE (LU,10) RELR, IERR
1165   C
1166   C      CHECK  FOR D(OMEGA)/D(Z) = 0.
1167     990   IF (CABS (DERIV) .LE. RERR) GO TO 1120
1168   C
1169    1000   CONTINUE
1170           ITER = ITER + 1
1171           OLDV = DEPV
1172           OLDER = DERIV
1173    1010   CONTINUE
1174   C
1175   C      CALCULATE A TENTATIVE NEW POINT (Z) ON THE STREAMLINE USING
1176   C      NEWTONS FORMULA AND PREVIOUS STREAMLINE POINT AS INITIAL GUESS.
1177   C
1178           TINDV = INDV - ALPHA * (OLDV - DCDV) / OLDER
1179   C
1180   C      CALCULATE OMEGA AT THIS TENTATIVE Z.
1181   C
1182           CALL OMA (TINDV, DEPV, DEPV2, DERIV, D2ODZ, IFLAG, IHD, NZNE)
1183   C
1184   C      CHECK PROXIMITY TO DIPOLE SINGULARITIES.
1185   C
1186           CALL DPCHK (TINDV, LCIND, OMCON, OMEGA, SPAC, IERR,
1187       1     IFLAG, ISING, IHD, IZ)
1188           IF (ISING .NE. 0) GO TO 1155
1189   C
1190   C      CALCULATE DIFFERENCE BETWEEN CALCULATED OMEGA AND DESIRED.
1191   C
1192           DIFF = DEPV - DCDV
1193           RDIFF = REAL (DIFF)
1194           IDIFF = AIMAG (DIFF)
1195   C
1196   C
1197           IF (IOPT .NE. 0) WRITE (LU, 20) TINDV, DIFF, ALPHA, RELAX, LAX
1198   C
```

```
1199  C       CHECK CONVERGENCE REQUIREMENT ON PHI AND PSI.
1200  C
1201   1020   IF (ABS (RDIFF) .LE. RELR .AND. ABS (IDIFF) .LE. IERR)
1202        1  GO TO 1115
1203           IF (ABS (RDIFF) .LT. RELR .OR. RDIFF * REAL (LSDIF) .GT. 0.0) GO
1204        1    TO 1030
1205  C
1206  C       ALTER RELAXATION PARAMETERS AS NEEDED.
1207  C
1208           RELAX = RELAX + 1
1209           LAX = 0
1210           GO TO 1040
1211   1030    LAX = LAX + 1
1212  C
1213   1040    IF (ABS (IDIFF) .LT. IERR .OR. IDIFF * AIMAG (LSDIF) .GT.
1214        1 0.0)  GO TO 1050
1215           RELAX = RELAX + 1
1216           LAX = 0
1217           GO TO 1060
1218   1050    LAX = LAX + 1
1219   1060    IF (RELAX .LE. LXDWN) GO TO 1070
1220           IF (ALPHA .LE. ALSTP) GO TO 1070
1221  C
1222  C       IF NEWTONS ITER. IS DIVERGING REDUCE ALPHA (RELAXATION PARAMETER)
1223  C       AND CHOOSE AN INTERIOR Z AS NEXT GUESS.  NOTE THAT ALPHA IS NOT
1224  C       AFFECTED BY PHI OR PSI DIVERGENCE WHILE THEY MEET THEIR
1225  C       INDIVIDUAL ERROR CRITERIA.
1226  C
1227           LAX = 0
1228           RELAX = 0
1229           ALPHA = ALPHA / 2.0
1230           GO TO 1080
1231  C
1232  C       COMPARE CALCULATED VALUE OF OMEGA TO DESIRED VALUE, IF CLOSE
1233  C       ENOUGH STOP ITERATING.
1234  C
1235   1070    IF (LAX .LT. LXUP) GO TO 1080
1236           IF (ALPHA .LT. 1.0) ALPHA = ALPHA * 2.0
1237           LAX = 0
1238           RELAX = 0
1239  C
1240   1080    INDV = TINDV
1241           LSDIF = DIFF
1242  C
1243  C       RETAIN THE BEST ESTIMATES IN CASE MAX. ITER. BOUND IS REACHED.
1244  C
1245           RELER = CABS (CMPLX (RDIFF / RELR, IDIFF / IERR))
1246           IF (RELER .GE. MINER) GO TO 1090
1247           MINER = RELER
1248           BESTI = TINDV
1249           BESTD = DEPV
1250           BESTV = DERIV
1251           BEST2 = DEPV2
1252           LOCB = LOCZ
1253   1090    CONTINUE
1254  C
1255  C       STOP IF MAX. ITERATION LIMIT IS EXCEEDED.
1256  C
1257           IF (ITER .GT. ITRMX) GO TO 1100
1258           GO TO 1000
```

```
1259   1100  WRITE (LU, 30)
1260  C
1261  C       BEST ESTIMATE BECOMES NEXT STREAMLINE POINT.  PRINT WARNING.
1262  C
1263          TINDV = BESTI
1264          DEPV = BESTD
1265          DERIV = BESTV
1266          DEPV2 = BEST2
1267          LOCZ = LOCB
1268          IFLAG = -2
1269          GO TO 1155
1270  C
1271  C       STREAMLINE POINT HAS BEEN FOUND.  SAVE THE LAST FIVE POINTS.
1272  C
1273   1115   IF (IZ .GT. 4)  GO TO 1140
1274          IZ = IZ + 1
1275          GO TO 1130
1276   1140     DO 1150 KZ = 1,4
1277   1150     LCIND (5 - KZ) = LCIND (6 - KZ)
1278   1130   LCIND (IZ) = TINDV
1279  C
1280   1155   INDV = TINDV
1281  C       DEPV = DCDV
1282  C
1283  C       CHECK FOR D(OMEGA)/D(Z) APPROX. EQUAL TO ZERO.
1284  C
1285          IF (CABS (DERIV) .LE. RERR) GO TO 1120
1286  C
1287          RETURN
1288  C
1289   1120   IFLAG = - 1
1290  C
1291          RETURN
1292  C
1293  C
1294  C
1295      10  FORMAT ( / 5X, 7HX-COORD , 5X, 7HY-COORD , 3X, 13HREAL CONVERG.
1296        1   4X, 12HIM. CONVERG. 2X, 5HALPHA, 2X, 5HRELAX, 2X, 7HRESTORE)
1297      11  FORMAT(/1X," REL. ERROR CRITERIA (REAL", F7.6," IM. ",F7.6,1H))
1298      20  FORMAT ( 2X, F10.2, 2X, F10.2, 2X, E12.5, 5X, E12.5, 3X, F5.3, 2
1299        1   (1X, I5) )
1300      30  FORMAT ( 8X, 43HNEWTON ITER. LIMIT EXCEEDED FOR THIS POINT. )
1301  C
1302          END
1303  C
1304  C     .....................................................................
1305  C     .....................................................................
1306  C
1307          SUBROUTINE  NUMCA (SPAC, DODZ, D2ODZ, Z, OMCON, OMEGA, IFLAG,
1308        1   IHD)
1309  C
1310  C       STREAMLINE TRACING USING NEWTONS METHOD, WITH CONVERGENCE
1311  C       REQUIRED OF PSI ALONE.  A RELAXATION PARAMETER IS INCLUDED
1312  C       TO SPEED CONVERGENCE.
1313  C       THIS ITERATIVE SCHEME GUARANTEES NEITHER EQUAL Z NOR EQUAL
1314  C       PHI SPACING OF STREAMLINE NODES.
1315  C
1316  C
1317          COMMON / INPT / IOPT, NZNE, ITER, DPJP, IOMEG
1318          COMMON / CNST / I, PI
```

```
      COMMON / ZON / LOCZ
      COMMON / ERRS / RERR, IERR, ITRMX, ALSTP, LXDWN, LXUP
      COMMON / IO / LU, PL, GL, AL, JL, IL, TL
C
C
      DIMENSION LCIND (5)
C
      COMPLEX   BESTC, BESTD, BESTO, BESTZ, CWZ, DODZ, I, LCIND, NEWZ,
     1   OMCON, OMEGA, WZ, WZ1, WZ2, Z1, Z2, Z
      INTEGER   AL, GL, PL, TL
      REAL      IERR, IMDIF, IOMEG, MINER
C
      MINER = 9.E9
      IFLAG = 0
      ALPHA = 1.0
C
      IF (IHD .NE. 2) GO TO 990
      IZ = 1
      LCIND (1) = Z
      ISING = 0
  990 CONTINUE
C
C     NEGATIVE ALSTP ALLOWS INITIAL ALPHA LESS THAN 1.
C     (USEFUL WHEN STREAMLINE CONVERGENCE IS DIFFICULT)
C
      IF (ALSTP .LT. 0.0)  ALPHA = ABS(ALSTP)
C
C
      IF (IOPT .EQ. 0) GO TO 991
      WRITE (LU,11) IERR
      WRITE (LU,10)
C     RELR = ABS(RERR * REAL(OMEGA))
C
C     OBTAIN ENDPOINT OF STREAMLINE TANGENT VECTOR OF LENGTH (SPAC).
C
  991 WZ = ( - 1.0, 0.0) * DODZ
      CWZ = CABS (WZ) / WZ
      NEWZ = Z + SPAC * CABS (WZ) / WZ
C     ITERATE ALONG THE EQUIPOTENTIAL PASSING THROUGH NEWZ TO
C     OBTAIN THE DESIRED PSI VALUE.
C
        DO 1030  ITER = 1, ITRMX
C
        CALL OMA (NEWZ, OMCON, OMEGA, DODZ, D2ODZ, IFLAG, IHD, NZNE)
C
C     CHECK STREAMLINE PROXIMITY TO DIPOLE ENDPOINT SINGULARITIES.
C
        CALL DPCHK (NEWZ, LCIND, OMCON, OMEGA, SPAC, IERR, IFLAG,
     1   ISING, IHD, IZ)
        IF (ISING .NE. 0) GO TO 1045
C
C     STREAMLINE POINT OK.
C
        WZ = ( - 1.0, 0.0) * DODZ
        IMDIF = IOMEG - AIMAG (OMEGA)
C
C     CHECK FOR CONVERGENCE ON PSI ONLY.
C
        AERR = ABS (IMDIF)
        IF (AERR .LT. IERR) GO TO 1035
```

```
1379  C
1380  C       CONVERGENCE NOT GOOD ENOUGH, FIND A NEW Z.
1381  C
1382            IF (IOPT .NE. 0) WRITE (LU, 20) NEWZ, IMDIF, ALPHA
1383  C
1384  C
1385  C       RETAIN BEST GUESS SO FAR.
1386  C
1387            IF (AERR .GE. MINER) GO TO 1000
1388            MINER = AERR
1389            BESTZ = NEWZ
1390            BESTO = OMEGA
1391            BESTD = DODZ
1392            BESTL = OMCON
1393            LOCB = LOCZ
1394  C
1395  C      ALTER RELAXATION PARAMETER AS NEEDED.
1396  C
1397   1000    CONTINUE
1398           IF (ITER .LE. 1) GO TO 1005
1399           Z2 = Z1
1400           Z2ER = Z1ER
1401           WZ2 = WZ1
1402   1005    Z1 = NEWZ
1403           Z1ER = IMDIF
1404           WZ1 = WZ
1405           IF (ITER  .LE. 1) GO TO 1010
1406           IF (Z1ER * Z2ER .GT. 0.0 .OR. ABS(Z2ER) .GT. ABS(Z1ER))
1407       1     GO TO 1010
1408           IF (ALPHA .LE. ABS(ALSTP))  GO TO 1010
1409           ALPHA = ALPHA / 2.0
1410           Z1 = Z2
1411           Z1ER = Z2ER
1412           WZ1 = WZ2
1413  C
1414  C        CALCULATE A NEW ESTIMATE OF Z.
1415  C
1416   1010    NEWZ = Z1 - ALPHA * I * Z1ER / WZ1
1417  C
1418   1030     CONTINUE
1419  C
1420  C       NEXT POINT NOT FOUND AFTER MAX. ITERATIONS.
1421  C       SO USE BEST EST. SO FAR.
1422  C
1423           NEWZ = BESTZ
1424           OMEGA = BESTO
1425           DODZ = BESTD
1426           OMCON = BESTC
1427           LOCZ = LOCB
1428           IFLAG = - 2
1429           GO TO 1045
1430  C
1431  C       NEXT POINT FOUND.  SAVE THE LAST FIVE STREAMLINE POINTS.
1432  C
1433   1035   IF (IZ .GT. 4) GO TO 1050
1434           IZ = IZ + 1
1435           GO TO 1040
1436  C
1437   1050     DO 1060 KZ = 1,4
1438   1060     LCIND (5 - KZ) = LCIND (6 - KZ)
```

```
C
 1040  LCIND (IZ) = NEWZ
 1045  Z = NEWZ
C
C       CHECK FOR MIN. DODZ
C
        IF (CABS (DODZ) .LE. RERR) IFLAG = - 1
C
        RETURN
C
C
C
   10  FORMAT ( / 5X, 7HX-COORD, 5X, 7HY-COORD, 3X, 15HPSI CONVERGENCE,
     1    5X, 5HRELAX )
   11  FORMAT (/1X, " REL. ERROR CRITERIA ON PSI ", F7.6 )
   20  FORMAT ( F10.2, 3X, F10.2, 5X, E12.6, 7X, F5.3,/)
C
        END
C
C     ..................................................................
C     ..................................................................
C
        SUBROUTINE  DPCHK (NEWZ, LCIND, OMCON, OMEGA, SPAC, IERR, IFLAG,
     1    ISING, IHD, IZ)
C
C       CHECK CURRENT STREAMLINE COORD. FOR PROXIMITY TO DIPOLE
C       SINGULARITIES.
C
C
        COMMON / ZON / LOCZ
        COMMON / INPT / IOPT, NZNE, ITER, DPJP, IOMEG
        COMMON / CNST / I, PI
        COMMON / POLE / ZONE, DPOLE
        COMMON / WELLD / ZBND, RPHI, Q, ZWL, STRT, WRAD, WRDS, NPT, NWL,
     1    NUMS, NUMW
        COMMON / LINE / NLINE, STM, DEC, MXPTS
        COMMON / IO / LU, PL, GL, AL, JL, IL, TL
C
C
        DIMENSION DPOLE (300), ZONE (4, 7), STRT (100), ZWL (30),
     1  Q (30), WRAD (30), NUMS (100, 2), NUMW (30), LCIND(5), NLINE(100)
C
        COMPLEX   DODZ, DPOLE, I, NEWZ, OMCON, OMEGA, Z, ZGSS2,
     1    ZGSS, ZWL, STRT, LCIND, D2ODZ
        INTEGER   AL, GL, PL, STM, TL
        REAL      IOMEG, IERR, IOM2, IOMM, IMDF
C
        NZT = NZNE - 1
C
C       CHECK ALL DIPOLE ENDPOINTS.
C
          DO 1000  IZNE = 1, NZT
          NPOL1 = ZONE (IZNE, 6)
          NPOL2 = ZONE (IZNE, 7)
C
            DO 1000  IPOL = NPOL1, NPOL2
            IF (CABS (NEWZ - DPOLE (IPOL)) .GT. DPJP)  GO TO 1000
C
C       A DIPOLE SINGULARITY IS IN THE PATH OF THIS STREAMLINE COORD.
C
```

```
1499              WRITE (LU, 10) NEWZ
1500   C
1501   C       ORIENT A CIRCLE AROUND THE DOUBLET ENDPOINT.  USE ONE OF THE
1502   C       LAST FIVE Z COORDS. TO DETERMINE THE RADIUS OF THE CIRCLE.
1503   C       PRIOR STREAMLINE POINTS ARE CHOSEN (INCREASING THE RADIUS
1504   C       OF THE CIRCLE) IF THE NEWTON ITERATION FAILS REPEATEDLY AT ONE
1505   C       DIPOLE SINGULARITY.
1506   C
1507          IF (IZ .LE. 0)  GO TO 1080
1508          Z = LCIND (IZ)
1509          IZ = IZ - 1
1510               ARGZ = AIMAG (CLOG (Z - DPOLE (IPOL)))
1511               IF (ARGZ .LT. 0)  ARGZ = ARGZ + 2.0 * PI
1512               RAD = CABS (Z - DPOLE (IPOL))
1513               IF (RAD .GT. 5.*DEC) GO TO 1080
1514   C
1515   C       CHECK FOR WELLS INSIDE THE DIPOLE CIRCLE.  IF THERE, CHECK
1516   C       STREAMLINES THAT TERMINATE AT THE WELL RADIUS.
1517   C
1518                 DO 1020 IWL = 1,NWL
1519                 WLRD = CABS (ZWL (IWL) - DPOLE (IPOL))
1520                 IF (WLRD .GE. RAD)  GO TO 1020
1521                 ZGSS = ZWL(IWL) + WRDS
1522                 CALL OMA (ZGSS, OMCON, OMEGA, DODZ, D2ODZ, MXWL, IHD, NZNE)
1523                 IOM2 = AIMAG (OMCON)
1524                 IOMM = AIMAG (OMCON) - Q (IWL)
1525                 IF ((IOMEG - IOM2) * (IOMEG - IOMM) .GT. 0.0) GO TO 1020
1526   C
1527   C       THE PSI VALUE IS FOUND AT A WELL RADIUS.
1528   C
1529                 IFLAG = IWL
1530                 GO TO 1060
1531    1020         CONTINUE
1532   C
1533   C       LOCATE A STARTING RIGHT BOUND ON THE CIRCLE.  STARTING ANGLE
1534   C       IS DETERMINED BY LAST Z + 1 DEGREE.
1535   C
1536               ANGL = ARGZ + PI / 180.0
1537               ZGSS2 = DPOLE (IPOL) + RAD * (COS (ANGL) + I * SIN (ANGL))
1538               CALL OMA (ZGSS2, OMCON, OMEGA, DODZ, D2ODZ, MXWL, IHD, NZNE)
1539               IOMM = AIMAG (OMEGA)
1540   C
1541   C       TRAVERSE THE PERIMETER OF THE CIRCLE IN 10 DEGREE (OR LESS)
1542   C       INCREMENTS, IN ORDER TO BOUND THE PSI VALUE.
1543   C
1544               IBND = 0
1545               TEN = PI / 18.
1546    1050       ANG2 = ANGL
1547               IF (ANG2 + TEN .GE. ARGZ + 2.0 * PI) TEN = PI / 180.
1548               IOM2 = IOMM
1549               IF (IBND .GT. 0) IBND = IBND + 1
1550   C
1551   C       IF PSI IS BOUNDED, HALVE THE LAST ANGLE INCREMENT AND
1552   C       CALCULATE A NEW PSI VALUE.
1553   C
1554    1030       ANGL = ANG2 + TEN / (2.0 ** IBND)
1555               IF (ANGL .GE. ARGZ + 2.0 * PI) GO TO 1080
1556               ZGSS = DPOLE (IPOL) + RAD * (COS(ANGL) + I * SIN (ANGL))
1557               CALL OMA (ZGSS, OMCON, OMEGA, DODZ, D2ODZ, MXWL, IHD, NZNE)
1558               IOMM = AIMAG (OMEGA)
```

```
1559  C
1560  C
1561  C           CHECK IF PSI IS BOUNDED.
1562  C
1563                IMDF = IOMEG - IOMM
1564                IF ((IOMEG - IOM2) * IMDF .GT. 0)  GO TO 1050
1565  C
1566  C       PSI HAS BEEN BOUNDED, CHECK ERROR IN PSI ESTIMATE.
1567  C
1568                IF (ABS (IMDF) .LE. IERR)  GO TO 1060
1569                IBND = IBND + 1
1570                IF (IBND .GT. 10)  GO TO 1090
1571                GO TO 1030
1572  C
1573  C       NEW Z HAS BEEN FOUND.
1574  C
1575   1060       NEWZ = ZGSS
1576                GO TO 1010
1577  C
1578  C       ONLY ONE PSI VALUE FOUND ON THE DIPOLE CIRCLE.  TERMINATE
1579  C       THE STREAMLINE.
1580  C
1581   1080       NEWZ = Z
1582                WRITE (LU, 20)
1583                IFLAG = -4
1584                GO TO 1010
1585  C
1586  C       UNABLE TO MEET SPECIFIED CONVERGENCE CRITERIA
1587  C
1588   1090       NEWZ = Z
1589                IFLAG = -2
1590  C
1591   1010       CONTINUE
1592                ISING = IPOL
1593  C
1594                RETURN
1595  C
1596   1000       CONTINUE
1597                ISING = 0
1598  C
1599           RETURN
1600  C
1601  C
1602  C
1603  C
1604      10   FORMAT ( 1X, 30HDIPOLE SINGULARITY ENCOUNTERED, 1X,
1605        1    29HIN STREAMLINE PATH AT COORDS., 2F9.2 )
1606      20   FORMAT ( 1X, 28HUNABLE TO LOCATE NEXT COORD.,1X,
1607        1    22HSTREAMLINE TERMINATES.)
1608  C
1609           END
1610  C
1611  C      ..................................................................
1612  C      ..................................................................
1613  C
1614           SUBROUTINE  MXMN (ZHD, HDMN, HDMX, ICT)
1615  C
1616  C       DETERMINE MAX AND MIN VALUES OF STREAMLINE COORDS AND HEAD.
1617  C
1618  C
```

```
      COMMON / IO / LU, PL, GL, AL, JL, IL, TL
C
C
      DIMENSION HDMN (3), HDMX (3), ZHD (4)
C
      INTEGER   AL, GL, PL, TL
      IF (ICT .GT. 1) GO TO 1010
C
        DO 1000  IH = 1, 3
        HDMX (IH) = - 9.E9
 1000   HDMN (IH) = 9.E9
C
 1010   DO 1020  IH = 1, 3
        IF (ZHD (IH) .LT. HDMN (IH)) HDMN (IH) = ZHD (IH)
        IF (ZHD (IH) .GT. HDMX (IH)) HDMX (IH) = ZHD (IH)
 1020   CONTINUE
C
      RETURN
C
C
      END
C
C     .....................................................................
C
C
      SUBROUTINE  PTOH (ROMEG, HD, PERM)
C
C     CONVERT POTENTIAL TO HEAD.  NOTE,THAT PHI IS CONTINUOUS ACROSS
C     CONFINED/UNCONFINED FLOW BOUNDARY.
C
C
      COMMON / IO / LU, PL, GL, AL, JL, IL, TL
      COMMON / AQF / THICK, AQ, FL, BND
C
C
      DIMENSION BND (4)
C
      CHARACTER*4 AQ
      COMPLEX   BND
      INTEGER   AL, GL, PL, TL
      REAL      KBND
C
      DATA    ZERO, POND, UNCF, CONF, CONA / 4HZERO, 4HPOND, 4HUNCF,
     1   4HCONF, 4HCONA /
C
      KBND = PERM * THICK ** 2
C
C     CHECK IF CONFINED OR UNCONFINED FLOW.
C
      IF (ROMEG .GE. KBND) GO TO 1010
      IF (ROMEG .GE. .5 * KBND) GO TO 1000
C
C     IF AQUIFER IS UNSATURATED, SET HEAD=0
C
      WRITE (LU, 10)
      FL = ZERO
      HD = 0.0
C
      RETURN
C
```

```
1679  C       IF FLOW IS UNCONFINED AT THIS POINT USE THIS EXPRESSION FOR HEAD.
1680  C
1681   1000   HD = ABS (SQRT (2.0 * ROMEG / PERM - THICK ** 2))
1682          FL = UNCF
1683  C
1684          RETURN
1685  C
1686  C       IF HEAD EXCEEDS AQUIFER THICKNESS, CHECK TO BE SURE THAT THE
1687  C       AQUIFER HAS AN UPPER CONFINING LAYER, IF NOT SURFACE PONDING
1688  C       EXISTS AND THIS SOLUTION BREAKS DOWN, TERMINATE STREAMLINE.
1689  C
1690   1010   IF (AQ .EQ. 'CONA') GO TO 1020
1691          FL = POND
1692          WRITE (LU, 20)
1693  C
1694          RETURN
1695  C
1696   1020   HD = ROMEG / (PERM * THICK)
1697          FL = CONF
1698  C
1699          RETURN
1700  C
1701  C
1702  C
1703      10  FORMAT ( 8X, 42HAQUIFER PUMPED TO ZERO HEAD AT THIS POINT.   )
1704      20  FORMAT ( 8X, 43HHEAD EXCEEDS UNCONFINED AQUIFER THICKNESS,
1705        1   23HSTREAMLINE TERMINATED. )
1706  C
1707          END
1708  C
1709  C     .....................................................................
1710  C
1711          SUBROUTINE  HTOP (PHI, HD, PERM, THICK)
1712  C
1713  C       CONVERT HEAD TO POTENTIAL.  NOTE, CHECK FOR CONFINED OR
1714  C       UNCONFINED FLOW.
1715  C
1716  C
1717          COMMON / IO / LU, PL, GL, AL, JL, IL, TL
1718  C
1719  C
1720  C       UNCONFINED FLOW.
1721  C
1722          INTEGER   AL, GL, PL, TL
1723          IF (HD .LE. THICK) PHI = .5 * PERM * (THICK ** 2 + HD ** 2)
1724  C
1725  C       CONFINED FLOW.
1726  C
1727          IF (HD .GT. THICK) PHI = PERM * THICK * HD
1728  C
1729          RETURN
1730  C
1731          END
1732  C
1733  C     .....................................................................
1734  C
1735          SUBROUTINE  INOUT (BND, Z, IT)
1736  C
1737  C       DETERMINE IF Z IS INSIDE OR OUTSIDE OF PLOT BOUNDARY.
1738  C
```

```
1739  C
1740          COMMON / IO / LU, PL, GL, AL, JL, IL, TL
1741  C
1742  C
1743          DIMENSION BND (4)
1744  C
1745          COMPLEX   BND, Z
1746          INTEGER   AL, GL, PL, TL
1747          IT = 0
1748          BIO = 0.0
1749  C
1750            DO 1000  IB = 1, 4
1751            IBP = IB + 1
1752            IF (IB .EQ. 4) IBP = 1
1753            BIO = BIO + AIMAG (CLOG ((Z - BND (IBP)) / (Z - BND (IB))))
1754   1000     CONTINUE
1755  C
1756          IT = BIO
1757  C
1758          RETURN
1759  C
1760  C
1761          END
1762  C
1763  C     ..................................................................
1764  C
1765          SUBROUTINE  DIPOL (Z, OMLD, DOLD, D2LD, IHD, NZNE)
1766  C
1767  C     THIS ROUTINE CALCULATES THE COMPLEX POTENTIAL RESULTING
1768  C     FROM ONE OR MORE LINE DIPOLES PLACED ON THE BOUNDARYS BETWEEN
1769  C     AQUIFER REGIONS HAVING DISCRETELY DIFFERENT PERMEABILITIES.
1770  C
1771  C     THE DIPOLE STRENGTH (S) IS THE LIMIT AS H GOES TO ZERO,
1772  C     AND Q GOES TO INFINITY OF Q*H, AT RATES
1773  C     SUCH THAT THE PRODUCT Q*H REMAINS CONSTANT. I.E. AS
1774  C     H GOES TO ZERO, Q GOES TO INFINITY AS 1/H.
1775  C
1776  C
1777  C
1778          COMMON / CNST / I, PI
1779          COMMON / ZARG / ARGPO, DODF
1780          COMMON / POLE / ZONE, DPOLE
1781          COMMON / PJMP / JUMP, MU
1782          COMMON / ZON / LOCZ
1783          COMMON / IO / LU, PL, GL, AL, JL, IL, TL
1784  C
1785  C
1786  C     CALCULATE OMEGA FOR ARBITRARY POINTS (Z), USING THE PREVIOUSLY
1787  C     CALCULATED DIPOLE STRENGTHS (S) AS ENTRIES IN THE COMPLEX
1788  C     POTENTIAL EXPRESSION.
1789  C
1790          DIMENSION ARGPO (600), DPOLE (300), JUMP (300),
1791         1   MU (300), OMDP (2), WIND (3), ZONE (4, 7)
1792  C
1793          COMPLEX   CLG, DODF, DOLD, DPARB, DPAR1, DPAR2, DPOLE, DPRFA,
1794         1   DPRFB, FACT1, FACT2, FACT3, FACT4, I, OMDP, OMLD, OMZN, OPREF,
1795         2   PARB, TERMP, TERM1, TERM2, TERM3, Z, D2LD, DPAR0, DPAR3, DPAR4
1796          INTEGER   AL, GL, OZNE, PLS, PLUS, PL, TL
1797          REAL      JUMP, MU
1798  C
```

```
1799          OMLD = (0.0, 0.0)
1800          DOLD = (0.0, 0.0)
1801          D2LD = (0.0, 0.0)
1802          NZT = NZNE - 1
1803    C
1804            DO 1010  IZNE = 1, NZT
1805            OMZN = (0.0, 0.0)
1806            WIND (IZNE) = 0.0
1807            NPOL1 = ZONE (IZNE, 6)
1808            NPOL2 = ZONE (IZNE, 7)
1809    C
1810              DO 1000  IPOL = NPOL1, NPOL2
1811              PLUS = IPOL + 1
1812              IF (IPOL .EQ. NPOL2) PLUS = NPOL1
1813              PLS = NPOL2 + IPOL
1814    C
1815    C       CALCULATE AND ASSEMBLE THE DOUBLET EXPRESSION.
1816    C
1817                FACT1 = Z - DPOLE (PLUS)
1818                FACT2 = DPOLE (PLUS) - DPOLE (IPOL)
1819                FACT3 = Z - DPOLE (IPOL)
1820                FACT4 = - FACT2
1821                TERM1 = FACT1 / FACT4
1822                TERM2 = FACT3 / FACT2
1823                TERM3 = FACT1 / FACT3
1824                TERMP = (Z - (DPOLE (PLUS) + DPOLE (IPOL)) / 2.0) / FACT2
1825                RCLG = REAL (CLOG (TERM3))
1826                ACLG = AIMAG (CLOG (TERM3))
1827    C
1828    C       TWO BRANCH CUTS ARE ASSOCIATED WITH EACH LINE DIPOLE,
1829    C       ONE AT EACH DIPOLE ENDPOINT.  BRANCH CUTS ARE SITUATED SO THAT
1830    C       THE BRANCH FROM ENDPOINT Z(J+1) OVERLIES THE LINE DIPOLE AND
1831    C       BRANCHES FROM BOTH Z(J+1) AND Z(J) OVERLAP AT THE RIGHT
1832    C       OF THE LINE DIPOLE.
1833    C
1834    C
1835    C       CALCULATE OMEGA PREFIX.
1836    C
1837                  OPREF = - I / (2.0 * PI) * (JUMP (IPOL) * TERM1 + JUMP
1838           1    (PLUS) * TERM2)
1839    C
1840    C       CALCULATE ANGLE MADE BY TENTATIVE Z AND ADJACENT BRANCH CUTS.
1841    C       POSITIVE ORIENTATION.
1842    C
1843                  ARGPO (IPOL) = AIMAG (CLOG ( - FACT3)) - AIMAG (CLOG
1844           1    (FACT2))
1845                  ARGPO (PLS) = AIMAG (CLOG ( - FACT1)) - AIMAG (CLOG
1846           1    (FACT2))
1847    C
1848                  IF (ARGPO (PLS) .LE. 0.0) ARGPO (PLS) = ARGPO
1849           1    (PLS) + 2.0 * PI
1850                  IF (ARGPO (IPOL) .LE. 0.0) ARGPO (IPOL) = ARGPO
1851           1    (IPOL) + 2.0 * PI
1852    C
1853    C       CALCULATE CONTINUOUS LINE DIPOLE (IPOL-PLS) ARGUMENT
1854    C       IN ZONE (IZNE).
1855    C
1856                CLG = CMPLX (RCLG, ARGPO (PLS) - ARGPO (IPOL))
1857    C
1858    C       DETERMINE IF PERM. ZONE BOUNDARY WAS CROSSED.
```

```
1859  C
1860  C     IF THE ANGLES MADE BY Z AND ZONE IZNE DOUBLET ENDPOINTS
1861  C     SUM TO 2PI THEN Z LIES WITHIN ZONE IZNE, IF THEY SUM TO 0
1862  C     Z LIES OUTSIDE.
1863  C
1864              WIND (IZNE) = WIND (IZNE) + AIMAG (CLG)
1865  C
1866  C     CALCULATE THE PARABOLIC COMPONENT OF DOUBLET STRENGTH.
1867  C     STRENGTH IS INTERPOLATED USING A PARABOLIC FIT, BETWEEN
1868  C     ENDPOINTS.  THE STRENGTH IS AN EXACT FIT AT THE MIDPOINT.
1869  C
1870              PARB = MU (IPOL) * ( - 2.0 * I / PI) * (TERM1 * TERM2 *
1871         1    CLG - TERMP)
1872  C
1873  C     ADD LINEAR AND SECOND ORDER TERMS.
1874  C
1875              OMDP (1) = OPREF * CLG + PARB
1876  C
1877  C     CUMULATIVE POTENTIAL FOR ONE ZONE.
1878  C
1879              OMZN = OMZN + OMDP (1)
1880  C
1881  C     CALCULATE D(OMEGA)/D(Z) FOR THE DIPOLE TERMS.
1882  C     D(OMEGA)/D(Z) IS CONTINUOUS EXCEPT AT BRANCH CROSSINGS.
1883  C
1884              DPRFA = I / (2.0 * PI) * (JUMP (IPOL) / FACT4 + JUMP
1885         1    (PLUS) / FACT2)
1886              DPRFB = FACT3 ** 2 - FACT1 ** 2
1887  C
1888              DPAR0 = FACT3 + FACT1
1889              DPAR1 = DPAR0 / FACT2 ** 2
1890              DPAR2 = FACT3 * FACT1
1891              DPARB = MU (IPOL) * (2.0 * I / PI)
1892              DPAR3 = FACT3 / FACT1
1893              DPAR4 = FACT4 / FACT1 ** 2
1894  C
1895              DOLD = DOLD + DPRFA * (CLG + DPRFB / DPAR2)
1896         1    + DPARB * (DPAR1 * CLG + 2.0 / FACT2)
1897  C
1898              D2LD = D2LD + DPRFA * (DPAR3 * DPAR4 +
1899         1    (2.0 * DPAR2 * FACT2 - DPRFB * DPAR0) / DPAR2 ** 2)
1900         2    + DPARB * (2.0 / (FACT2 ** 2) * CLG + DPAR1 * DPAR3 * DPAR4)
1901   1000       CONTINUE
1902  C
1903  C     CUMULATIVE POTENTIAL FOR ALL ZONES.
1904  C
1905  C     IWND = WIND(IZNE)
1906  C     IF (IWND .NE. 0)  OMZN = CMPLX(-REAL(OMZN),AIMAG(OMZN))
1907           OMLD = OMLD + OMZN
1908   1010    CONTINUE
1909  C
1910  C     DETERMINE THE PERM. ZONE LOCATION OF THE CURRENT (TENTATIVE) (Z).
1911  C     Z MAY LIE INSIDE A ZONE THAT IS ITSELF CONTAINED WITHIN ANOTHER
1912  C     ZONE.
1913  C
1914         LOCZ = NZNE
1915  C
1916           DO 1020  IZNE = 1, NZT
1917           IWND = WIND (IZNE)
1918           IF (IWND .EQ. 0) GO TO 1020
```

```
1919            OZNE = ZONE (IZNE, 5)
1920            WIND (OZNE) = 0.0
1921            LOCZ = IZNE
1922   1020     CONTINUE
1923  C
1924          RETURN
1925  C
1926  C
1927          END
1928  C
1929  C     ..................................................................
1930  C
1931  $EMA/SIZE/,/VECT/
1932          SUBROUTINE  STGTH (IHD, RPHI, LP)
1933  C
1934  C     THIS ROUTINE SOLVES (N) LINEAR EQUATIONS WITH (N) UNKNOWNS
1935  C     TO DETERMINE THE STRENGTH (DELTA PHI) OF (N) LINE DIPOLE
1936  C     ENDPOINTS FORMING THE BOUNDARY BETWEEN TWO OR MORE AQUIFER
1937  C     ZONES WITH DISCRETELY DIFFERENT PERMEABILITIES.
1938  C
1939  C
1940  C
1941          COMMON / SIZE / COEF, CHEM
1942          COMMON / VECT / CNST
1943          COMMON / POLE / ZONE, DPOLE
1944          COMMON / INPT / IOPT, NZNE, ITER, DPJP, IOMEG
1945          COMMON / PJMP / JUMP, MU
1946          COMMON / CNST / I, PI
1947          COMMON / ONED / IFLO, ANGL1, UNFM
1948          COMMON / ZON / LOCZ
1949          COMMON / IO / LU, PL, GL, AL, JL, IL, TL
1950  C
1951  C
1952          DIMENSION CHEM (500, 17), CNST (300), COEF (300, 300),
1953         1    DPOLE (300), JUMP (300), MU (300), ZONE (4, 7)
1954  C
1955          COMPLEX   CL, CLG, DODZ, DPOLE, FACT1, FACT2, FACT3, FACT4,
1956         1   FACT5, FACT6, I, OMCON, OMEGA, TERM1, TERM2, TERM3, TERM4,
1957         2   TERM5, Z, D2ODZ
1958          INTEGER   AL, ER, GL, PLUS, PL, TL
1959          REAL      JUMP, MU, IOMEG
1960  C
1961          ITER = 0
1962          ITFLG = 0
1963          WRITE (1, 40)
1964  C
1965            DO 1000  IPOL = 1, 300
1966  C
1967              DO 1000  JPOL = 1, 300
1968   1000       COEF (JPOL, IPOL) = 0.0
1969  C
1970  C     CALCULATE THE BOUNDARY CONDITION AT EVERY DIPOLE ENDPOINT.
1971  C     I.E. DIPOLE STRENGTH (S) = (K - K1)/K * PHI.  THIS CONDITION
1972  C     IS DEVELOPED FROM THE FUNCTION RELATING PHI AND HEAD AND
1973  C     FROM THE ASSERTION THAT AT THE ZONE BOUNDARY HEAD IS CONSTANT BUT
1974  C     PERM. CHANGES FROM K TO K1.
1975  C
1976          NZT = NZNE - 1
1977  C
1978            DO 1090  IZNE = 1, NZT
```

```
1979           NIPL1 = ZONE (IZNE, 6)
1980           NIPL2 = ZONE (IZNE, 7)
1981   C
1982   C      RATIO OF PERMS. INSIDE AND OUTSIDE.
1983   C
1984           PFUNC = ZONE (IZNE, 4) / (ZONE (IZNE, 2) - ZONE (IZNE, 4))
1985   C
1986   C     IF ZONE BOUNDARY IS ENTERED IN CLOCKWISE ROTATION, ORIENTATION
1987   C     IS REVERSED.
1988   C
1989           IF (ZONE (IZNE, 3) .LT. 0.0)
1990          1   PFUNC = -ZONE(IZNE, 2) / ZONE (IZNE, 4) * PFUNC
1991   C
1992   C      CALCULATE DIPOLE STRENGTH, LOOP ONCE FOR EACH DIPOLE.
1993   C
1994   C      DIPOLE STRENGTHS ARE DETERMINED BY SIMULTANEOUSLY SOLVING
1995   C      THE N REAL POTENTIAL EQUATIONS (ONE FOR EACH DIPOLE HENCE
1996   C      ONE FOR EACH S(J),J=1...N ),WITH THE ABOVE CONDITION.
1997   C
1998                DO 1080  IPOL = NIPL1, NIPL2
1999                MINUS = IPOL - 1
2000                IF (MINUS .LT. NIPL1)  MINUS = NIPL2
2001                PLUS = IPOL + 1
2002                IF (PLUS .GT. NIPL2) PLUS = NIPL1
2003   C
2004   C      THE POTENTIAL EXPRESSION FOR THE TWO DIPOLES IN
2005   C      PERMEABILITY ZONE (IZNE) AND ADJACENT TO
2006   C      (IPOL) INDIVIDUALLY CONTAIN TERMS WHICH BECOME INFINITE
2007   C      AS Z APPROACHES Z(J) (THE DIPOLE).  HOWEVER, COLLECTIVELY
2008   C      THESE TERMS CANCEL EACH OTHER, LEAVING A SINGLE FINITE
2009   C      LOG TERM WHICH IS HERE COMBINED WITH THE ZONE BOUNDARY COND.
2010   C
2011                FACT5 = DPOLE (IPOL) - DPOLE (PLUS)
2012                FACT6 = DPOLE (IPOL) - DPOLE (MINUS)
2013                TERM4 = FACT5 / FACT6
2014   C
2015   C      THE REAL PART OF THIS EXPRESSION INVOLVES AN ARGUMENT.
2016   C
2017                ARG = AIMAG (CLOG (TERM4))
2018   C
2019   C      ENSURE ARG HAS A SIGN OPPOSITE THAT OF OTHER INTERIOR ANGLES.
2020   C
2021                IF (ARG .GT. 0.0) ARG = ARG - 2.0 * PI
2022   C
2023                ARG4 = PFUNC - 1.0 / (2.0 * PI) * ARG
2024                IF (ABS (ARG4) .LE. 1.0E - 10) ARG4 = SIGN (1.0E - 10, ARG4)
2025   C
2026   C      BEGIN CALCULATING THE COEFFICIENTS FOR THE N SIMULTANEOUS
2027   C      EQUATIONS INVOLVING THE N UNKNOWN STRENGTHS (S).  THE
2028   C      DIAGONAL OF THIS MATRIX IS -1.
2029   C
2030   C
2031                COEF (IPOL, IPOL) = -1.0
2032   C
2033   C      INCLUDE IN REAL(OMEGA) THE CONTRIBUTION DUE TO A CONSTANT HEAD
2034   C      BOUNDARY, WELLS AND UNIFORM FLOW.
2035   C      NOTE THAT CNST INVOLVES Z(IPOL)
2036   C      OTHER OMEGA AND THE BOUNDARY PHI.
2037
2038   C
```

```
2039                NOPOL = 0
2040  C
2041                CALL OMA (DPOLE (IPOL), OMCON, OMEGA, DODZ, D2ODZ, MXWL, IHD,
2042         1    NOPOL)
2043  C
2044                CNST (IPOL) = - REAL (OMEGA) / ARG4
2045  C
2046  C       CALCULATE THE COEFFICIENTS OF THE DIPOLE STRENGTH MATRIX.
2047  C       INCLUDE ALL PERMEABILITY ZONES (ALL DIPOLES) IN THE MATRIX.
2048  C
2049                  DO 1070  JZNE = 1, NZT
2050                  NJPOL = ABS (ZONE (JZNE, 3))
2051                  NJPL1 = ZONE (JZNE, 6)
2052                  NJPL2 = ZONE (JZNE, 7)
2053                  IF (ZONE (IZNE, 1) .NE. ZONE (JZNE, 1)) GO TO 1030
2054                  NCT = NJPOL - 2
2055  C
2056  C       CALCULATE THE S MATRIX COEFFICIENTS FOR THOSE DIPOLES ON
2057  C       THE BOUNDARY OF PERMEABILITY ZONE (IZNE).
2058  C       LOOP N-2 TIMES SINCE TWO ADJACENT DIPOLES ARE OMITTED.
2059  C
2060                    DO 1020  JCT = 1, NCT
2061                    JPOL = JCT + IPOL
2062                    IF (JPOL .GT. NJPL2) JPOL = JPOL - NJPOL
2063                    MINUS = JPOL - 1
2064                    IF (MINUS .LT. NJPL1) MINUS = NJPL2
2065                    PLUS = JPOL + 1
2066                    IF (PLUS .GT. NJPL2) PLUS = NJPL1
2067  C
2068  C       CHECK FOR COINCIDENT DIPOLES WITHIN ZONE (IZNE),I.E. SLOTS.
2069  C
2070                    IF (DPOLE (IPOL) .EQ. DPOLE (PLUS)) GO TO 1020
2071                    IF (DPOLE (IPOL) .NE. DPOLE (JPOL)) GO TO 1010
2072                    FACT5 = DPOLE (JPOL) - DPOLE (PLUS)
2073                    FACT6 = DPOLE (JPOL) - DPOLE (MINUS)
2074                    TERM5 = FACT5 / FACT6
2075                    CLG = CLOG (TERM5)
2076  C
2077  C       COEF. OF STRENGTH FOR COINCIDENT ENDPOINT WITHIN ZONE (IZNE).
2078  C
2079                    COEF (JPOL, IPOL) = REAL ( - I / (2.0 * PI) * CLG)
2080         1    / ARG4
2081  C
2082                    GO TO 1020
2083   1010             FACT1 = DPOLE (IPOL) - DPOLE (PLUS)
2084                    FACT2 = DPOLE (JPOL) - DPOLE (PLUS)
2085                    FACT3 = DPOLE (IPOL) - DPOLE (JPOL)
2086                    FACT4 = - FACT2
2087                    TERM1 = FACT1 / FACT2
2088                    TERM2 = FACT3 / FACT4
2089                    TERM3 = FACT1 / FACT3
2090                    CLG = CLOG (TERM3)
2091  C
2092  C       COEFFICIENT OF STRENGTH S(J) FOR ENDPOINT(I) IN ZONE (IZNE).
2093  C
2094  C
2095                    COEF (JPOL, IPOL) = COEF (JPOL, IPOL) -
2096         1    REAL (I / (2.0 * PI) * TERM1 * CLG) / ARG4
2097  C
2098  C       COEFFICIENT OF STRENGTH S(J+1) FOR ENDPOINT (I) IN ZONE (IZNE).
```

```
2099  C
2100  C     NOTE THAT ALL COEF. ARE REAL SINCE DIPOLE CAUSES JUMP IN
2101  C     REAL(OMEGA).
2102  C
2103                  COEF (PLUS, IPOL) = COEF (PLUS, IPOL) -
2104        1    REAL (I / (2.0 * PI) * TERM2 * CLG) / ARG4
2105  C
2106   1020           CONTINUE
2107  C
2108                GO TO 1060
2109  C
2110  C     CALCULATE THE S MATRIX COEFFICIENTS FOR THOSE DIPOLES THAT ARE
2111  C     ON THE BOUNDARIES OF OTHER PERMEABILITY ZONES.
2112  C     (ALL DIPOLES MUST BE INCLUDED IN THE STRENGTH MATRIX).
2113  C
2114   1030           DO 1050  JPOL = NJPL1, NJPL2
2115                  MINUS = JPOL - 1
2116                  IF (MINUS .LT. NJPL1)  MINUS = NJPL2
2117                  PLUS = JPOL + 1
2118                  IF (PLUS .GT. NJPL2) PLUS = NJPL1
2119  C
2120  C     CHECK FOR COINCIDENT LINE DIPOLES IN OTHER ZONES
2121  C     OMIT INFINITE TERMS (SINCE THEY CANCEL EACH OTHER OUT)
2122  C     FROM CALCULATION OF STRENGTH COEFFICIENT.  THE FINITE PORTION
2123  C     IS CALCULATED HERE.
2124  C
2125                  IF (DPOLE (IPOL) .EQ. DPOLE(PLUS)) GO TO 1050
2126                  IF (DPOLE (IPOL) .NE. DPOLE (JPOL)) GO TO 1040
2127                  FACT5 = DPOLE (JPOL) - DPOLE(PLUS)
2128                  FACT6 = DPOLE (JPOL) - DPOLE (MINUS)
2129                  TERM5 = FACT5 / FACT6
2130                  CLG = CLOG (TERM5)
2131  C
2132  C     COEF. OF STRENGTH (S(J)) FOR CONINCIDENT ENDPOINT (I) IN ZONE
2133  C     (JZNE).  ONE TERM ONLY.
2134  C
2135  C
2136                  COEF (JPOL, IPOL) = REAL ( - I / (2.0 * PI) * CLG)
2137        1    / ARG4
2138                  GO TO 1050
2139  C
2140  C     DIPOLES NOT COINCIDENT.
2141   1040           FACT1 = DPOLE (IPOL) - DPOLE(PLUS)
2142                  FACT2 = DPOLE (JPOL) - DPOLE(PLUS)
2143                  FACT3 = DPOLE (IPOL) - DPOLE (JPOL)
2144                  FACT4 = - FACT2
2145                  TERM1 = FACT1 / FACT2
2146                  TERM2 = FACT3 / FACT4
2147                  TERM3 = FACT1 / FACT3
2148                  CLG = CLOG (TERM3)
2149  C
2150  C     COEF. OF STRENGTH S(J) FOR ENDPOINT I IN ZONE (JZNE).
2151  C
2152                  COEF (JPOL, IPOL) = COEF (JPOL, IPOL) -
2153        1    REAL (I / (2.0 * PI) * TERM1 * CLG) / ARG4
2154  C
2155  C     COEF. OF STRENGTH S(J+1) FOR ENDPOINT I IN ZONE (JZNE).
2156  C
2157                  COEF (PLUS ,IPOL) = COEF (PLUS, IPOL) -
2158        1    REAL (I / (2.0 * PI) * TERM2 * CLG) / ARG4
```

```
2159  C
2160   1050          CONTINUE
2161  C
2162   1060        CONTINUE
2163  C
2164   1070        CONTINUE
2165  C
2166   1080      CONTINUE
2167  C
2168   1090    CONTINUE
2169  C
2170  C      ISUM ROWS IN THE S MATRIX.
2171           ISUM = ZONE (NZT, 7)
2172  C
2173  C      SOLVE THE N LINEAR EQUATIONS INVOLVING N UNKNOWN DIPOLE
2174  C      STRENGTHS (S(J),J=1...N) USING GAUSSIAN ELIMINATION MATRIX SOLVER.
2175  C
2176          CALL GAUSS (ISUM, ER)
2177  C
2178  C      REPACK THE POTENTIAL JUMP FOR EACH DIPOLE.
2179  C
2180   1100  CONTINUE
2181  C
2182          WRITE (LU, 10)
2183  C
2184            DO 1130  IZNE = 1, NZT
2185            NIPL1 = ZONE (IZNE, 6)
2186            NIPL2 = ZONE (IZNE, 7)
2187  C
2188              DO 1120  IPOL = NIPL1, NIPL2
2189  C
2190              JUMP (IPOL) = CNST (IPOL)
2191  C           IF (IZNE .GE. 2) JUMP (IPOL) = - CNST (IPOL)
2192  C
2193              IMPOL = IPOL
2194              IF (LP .LE. 1) GO TO 1110
2195              IF (MOD (IPOL, 2) .EQ. 0) GO TO 1120
2196              IMPOL = (IPOL + 1) / 2
2197  C
2198  C      SAVE STRENGTH VALUES.
2199  C
2200   1110       WRITE (JL, 20) JUMP (IPOL)
2201  C
2202              WRITE (LU, 30) IZNE, IMPOL, DPOLE (IPOL), JUMP (IPOL)
2203   1120       CONTINUE
2204   1130     CONTINUE
2205  C
2206          RETURN
2207  C
2208  C
2209  C
2210      10  FORMAT ( /// 29X, 17HDOUBLET STRENGTHS, //, 32X, 11H(ENDPOINTS),
2211        1    //, 2X, 8HZONE NO., 3X, 11HDOUBLET NO., 9X, 12HCOORDS.(X,Y),
2212        2    9X, 17HJUMP IN POTENTIAL )
2213      20  FORMAT ( 2E15.9 )
2214      30  FORMAT ( 1X, I5, 7X, I5, 3X, 2E12.5, 7X, E15.7 )
2215      40  FORMAT ( 'SETTING UP DOUBLET STRENGTH MATRIX')
2216  C
2217          END
2218  C
```

```
2219  C     .....................................................................
2220  C
2221         SUBROUTINE  MDPNT (NZNE, IHD, RPHI, LP)
2222  C
2223  C     CALCULATE EXACT STRENGTH AT ENDPOINTS AND MIDPOINT
2224  C     OF EACH LINE DOUBLET BOUNDARY SEGMENT.
2225  C
2226         COMMON / IO / LU, PL, GL, AL, JL, IL, TL
2227         COMMON / POLE / ZONE, DPOLE
2228  C
2229  C
2230         DIMENSION DPOLE (300), ZONE (4, 7)
2231  C
2232         COMPLEX   DPOLE
2233         INTEGER   AL, GL, PL, TL
2234         NZT = NZNE - 1
2235  C
2236           DO 1020  IZNE = NZT, 1, -1
2237           NPOL1 = ZONE (IZNE, 6)
2238           NPOL2 = ZONE (IZNE, 7)
2239  C
2240  C     INSERT SPACE FOR MIDPOINT COORD.
2241  C
2242             DO 1000  IPOL = NPOL2, NPOL1, -1
2243   1000      DPOLE (2 * IPOL - 1) = DPOLE (IPOL)
2244  C
2245  C     INSERT MIDPOINT COORD.
2246  C
2247           ZONE (IZNE, 3) = ZONE (IZNE, 3) * 2
2248           ZONE (IZNE, 6) = ZONE (IZNE, 6) * 2.0 - 1.0
2249           ZONE (IZNE, 7) = ZONE (IZNE, 7) * 2.0
2250           MPOL1 = ZONE (IZNE, 6)
2251           MPOL2 = ZONE (IZNE, 7)
2252  C
2253             DO 1010  IPOL = MPOL1, MPOL2, 2
2254             IPLS1 = IPOL + 1
2255             IPLS2 = IPOL + 2
2256             IF (IPLS2 .GT. MPOL2) IPLS2 = MPOL1
2257             DPOLE (IPLS1) = (DPOLE (IPLS2) + DPOLE (IPOL)) / 2.0
2258   1010      CONTINUE
2259  C
2260  C
2261   1020    CONTINUE
2262  C
2263  C     CALCULATE SIMULTANEOUS EXACT STRENGTHS AT ENDPOINTS AND MIDPOINTS.
2264  C
2265         CALL STGTH (IHD, RPHI, LP)
2266  C
2267  C     SEPARATE NONLINEAR COMPONENTS.
2268  C
2269         IF (LP .GE. 2) CALL QUAD (NZT)
2270  C
2271         RETURN
2272  C
2273  C
2274         END
2275  C
2276  C     .....................................................................
2277  C
2278         SUBROUTINE  QUAD (NZT)
```

```
2279  C
2280  C      CALCULATE PARABOLIC COMPONENT OF DOUBLET STRENGTH AT EACH
2281  C      DOUBLET MIDPOINT.
2282  C
2283  C
2284           COMMON / POLE / ZONE, DPOLE
2285           COMMON / PJMP / JUMP, MU
2286           COMMON / IO / LU, PL, GL, AL, JL, IL, TL
2287  C
2288  C
2289           DIMENSION DPOLE (300), JUMP (300), MU (300), ZONE (4, 7)
2290  C
2291           COMPLEX   DPOLE
2292           INTEGER   AL, GL, PL, TL
2293           REAL      JUMP, MU
2294  C
2295           REWIND JL
2296  C
2297           WRITE (LU, 10)
2298  C
2299             DO 1020  IZNE = 1, NZT
2300  C
2301             MPOL1 = ZONE (IZNE, 6)
2302             MPOL2 = ZONE (IZNE, 7)
2303  C
2304               DO 1000  IPOL = MPOL1, MPOL2, 2
2305               IPLS = IPOL + 2
2306               IF (IPOL + 1 .EQ. MPOL2) IPLS = MPOL1
2307  C
2308  C      LINEARLY APPROXIMATED STRENGTH AT MIDPOINT.
2309  C
2310                 STMID = (JUMP (IPOL) + JUMP (IPLS)) / 2.0
2311  C
2312  C
2313  C      THE DISCREPANCY BETWEEN ACTUAL JUMP AND LINEARLY APPROXIMATED
2314  C      STRENGTH IS THE COMPONENT (MU) TO BE ADDED TO (S) AT THE
2315  C      MIDPOINT AND INTERPOLATED QUADRATICALLY BETWEEN THE ENDPOINTS.
2316  C
2317                 IMPOL = IPOL + 1
2318                 IM2 = IMPOL / 2
2319                 MU (IPOL) = JUMP (IMPOL) - STMID
2320  C
2321                 WRITE (LU, 30) IZNE, IM2, DPOLE (IM2), MU (IPOL)
2322   1000        CONTINUE
2323  C
2324   1020      CONTINUE
2325  C
2326             DO 1030  IZNE = 1, NZT
2327             ZONE (IZNE, 3) = ZONE (IZNE, 3) / 2.0
2328             ZONE (IZNE, 6) = (ZONE (IZNE, 6) + 1) / 2.0
2329             ZONE (IZNE, 7) = ZONE (IZNE, 7) / 2.0
2330  C
2331  C      RESTORE DIPOLE,AND STRENGTH ARRAYS.  SAVE STRENGTH VALUES.
2332  C
2333             NPOL1 = ZONE (IZNE, 6)
2334             NPOL2 = ZONE (IZNE, 7)
2335  C
2336               DO 1010  IPOL = NPOL1, NPOL2
2337               JUMP (IPOL) = JUMP (2 * IPOL - 1)
2338               MU (IPOL) = MU (2 * IPOL - 1)
```

```
2339              WRITE (JL, 20) JUMP (IPOL), MU (IPOL)
2340   1010       DPOLE (IPOL) = DPOLE (2 * IPOL - 1)
2341  C
2342   1030     CONTINUE
2343  C
2344  C
2345           RETURN
2346  C
2347  C
2348  C
2349      10   FORMAT ( ///, 31X, 11H(MIDPOINTS), //, 1X, 8HZONE NO., 3X,
2350        1    11HDOUBLET NO., 7X, 11HCOORDS(X,Y), 8X, 22HINCREMENT IN POTENTI
2351        2AL , /, 44X, 15H(PARABOLIC FIT) )
2352      20   FORMAT ( 2E15.9 )
2353      30   FORMAT ( 1X, I5, 7X, I5, 5X, 2E12.5, 5X, E12.5 )
2354  C
2355           END
2356  C
2357  C      ..................................................................
2358  C
2359  $EMA/SIZE/,/VECT/
2360           SUBROUTINE  GAUSS (MIN, ER)
2361  C
2362  C          OBTAIN A SOLUTION TO A SET OF SIMULTANEOUS LINEAR EQUATIONS
2363  C          OF THE FORM AX=B.
2364  C       DESCRIPTION OF PARAMETERS:
2365  C          I = ROW
2366  C          J = COLUMN
2367  C          COEF(I,J) = MATRIX OF COEFFICIENTS
2368  C          CNST(J)   = COLUMN OF CONSTANTS
2369  C                    = SOLUTION ARRAY
2370  C       METHOD:
2371  C          ROW REDUCTION USING THE GAUSS-JORDAN PROCEDURE
2372  C
2373  C
2374  C
2375           COMMON / SIZE / COEF, CHEM
2376           COMMON / VECT / CNST
2377           COMMON / IO / LU, PL, GL, AL, JL, IL, TL
2378  C
2379  C
2380           DIMENSION CHEM (500, 17), CNST (300), COEF (300, 300), COLI (300)
2381  C
2382           INTEGER   AL, ER, GL, PL, TL
2383           MINUS = MIN - 1
2384           TOL = 1.0E - 10
2385           ER = 0
2386           WRITE (1, 40)
2387  C
2388  C       PIVOTING IS NOT NECESSARY WITH THIS MATRIX SINCE THE DIAGONAL
2389  C       ELEMENT IS ALWAYS THE LARGEST IN THE ROW.
2390  C
2391             DO 1020  I = 1, MINUS
2392  C
2393               DO 1025  IROW = I, MIN
2394   1025        COLI (IROW) = COEF (IROW, I)
2395  C
2396  C       CHECK FOR SINGULAR MATRIX
2397  C
2398             IF (ABS (COLI (I)) .GT. TOL) GO TO 1000
```

```
2399            ER = 1
2400            WRITE (LU, 10)
2401            GO TO 1070
2402  C
2403  C      ELIMINATE VARIABLES
2404  C
2405   1000     JJ = I + 1
2406  C
2407               DO 1010  J = JJ, MIN
2408               CFIJ = COEF (I, J)
2409               CNST (J) = CNST (J) - CFIJ * CNST (I) / COLI (I)
2410  C
2411                 DO 1010  N = I, MIN
2412                 K = MIN - N + I
2413                 COEF (K, J) = COEF (K, J) - CFIJ * COLI (K) / COLI (I)
2414   1010          CONTINUE
2415  C
2416            WRITE (1, 20) I
2417   1020     CONTINUE
2418  C
2419  C      BACK SOLUTION
2420  C
2421            DO 1050  II = 1, MINUS
2422            I = MIN - II + 1
2423  C
2424               DO 1030  IROW = 1, I
2425   1030        COLI (IROW) = COEF (IROW, I)
2426  C
2427               DO 1040  JJ = 2, I
2428               J = I - JJ + 1
2429               CFIJ = COEF (I, J)
2430               CNST (J) = CNST (J) - CFIJ * CNST (I) / COLI (I)
2431  C
2432                 DO 1040  K = J, I
2433                 COEF (K, J) = COEF (K, J) - CFIJ * COLI (K) / COLI (I)
2434   1040          CONTINUE
2435  C
2436            WRITE (1, 30) I
2437   1050     CONTINUE
2438  C
2439  C      SOLVE FOR CNST
2440  C
2441            DO 1060  J = 1, MIN
2442   1060     CNST (J) = CNST (J) / COEF (J, J)
2443  C
2444   1070   RETURN
2445  C
2446  C
2447  C
2448      10   FORMAT ( //, 1X, 29HSINGULAR MATRIX - NO SOLUTION, / )
2449      20   FORMAT ( 'UPPER TRIANGULAR...IN COLUMN', I5 )
2450      30   FORMAT ( 'BACK SOLUTION...IN COLUMN', I5 )
2451      40   FORMAT ( 'BEGIN GAUSS ELIMINATION PROCEDURE')
2452  C
2453           END
2454  C
2455  C     ..................................................................
2456  $EMA/SIZE/,/VECT/
2457           SUBROUTINE  STMVL (HEAD, OMEGA, Z, DODZ, D2ODZ, ICT, IHD, IPT,
2458         1   MINUS, PERM)
```

```
2459  C
2460  C     FOR EACH POINT ON THE STREAMLINE
2461  C     THIS ROUTINE CALCULATES FLUID FLUX (SPECIFIC DISCHARGE),
2462  C     VELOCITY (VEL=FLUX/POROSITY) AND THEIR DERIVATIVES ANALYTICALLY
2463  C     FROM D(OMEGA)/D(Z) AND D2(OMEGA)/D2(Z) USING CAUCHY REIMANN
2464  C     CONDITIONS.  THESE VALUES ARE USED IN A CONVECTION
2465  C     DIFFUSION GEOCHEMICAL MODEL.
2466  C
2467  C
2468        COMMON / SIZE / COEF, CHEM
2469        COMMON / VECT / CNST
2470        COMMON / CNST / I, PI
2471        COMMON / WELLD / ZBND, RPHI, Q, ZWL, STRT, WRAD, WRDS, NPT, NWL,
2472       1   NUMS, NUMW
2473        COMMON / IO / LU, PL, GL, AL, JL, IL, TL
2474        COMMON / CHEM / D, F, P, SIGMA, POR, RHO, ISKP
2475        COMMON / AQF / THICK, AQ, FL, BND
2476        COMMON / LINE / NLINE, STM, DEC, MXPTS
2477        COMMON / ZON / LOCZ
2478  C
2479  C
2480        DIMENSION BND (4), CHEM (500,17), CNST (300), COEF (300, 300),
2481       1   NLINE (100), NUMS (100, 2), NUMW (30), Q (30), STRT (100), WRAD
2482       2   (30), ZWL (30), POR (4), P (4), RHO (4)
2483  C
2484        COMPLEX   BND, DODZ, DOD2, DVEL, D2ODZ, FLXVC, I, OMEGA, STRT,
2485       1   ZWL, Z
2486        INTEGER   AL, GL, PL, STM, TL
2487        REAL      KL, LASTL, MPERM
2488  C
2489        DATA    POND, ZERO, UNCF, CONF / 4HPOND, 4HZERO, 4HUNCF, 4HCONF /
2490  C
2491  C     INITIALIZATION.
2492  C
2493  C     MASS TRANSPORT INTERFACE FILE ON LU=14
2494  C
2495        MIN1 = - 1
2496        IF (MINUS .EQ. - 2) GO TO 1030
2497  C
2498  C     THE SECOND PARTIAL OF PHI WITH X AND Y IS GIVEN ANALYTICALLY.
2499  C     NOTE THAT RE(D2ODZ)=D2(PHI)/D2(X) AND IM(D2ODZ)=D2(PHI)/D(X)D(Y).
2500  C     D2(PHI)/D2(Y) IS FOUND FROM CAUCHY REIMANN CONDITIONS SINCE:
2501  C             D2(PHI)/D2(X) = -D2(PHI)/D2(Y) AND
2502  C             D2(PHI)/D(X)D(Y) = -D2(PHI)/D(Y)D(X).
2503  C     OR FROM THE CONSERVATION EQUATION SINCE:
2504  C             D2(PHI)/D2(X) + D2(PHI)/D2(Y) = 0.0
2505  C
2506        IF (FL .EQ. CONF) SATT = THICK
2507        IF (FL .EQ. UNCF) SATT = HEAD
2508        IF (FL .EQ. ZERO .OR. FL .EQ. POND) RETURN
2509  C
2510  C     PERMEABILITY CONVERTED FROM FT./HR.  TO CM./SEC.
2511  C
2512        MPERM = PERM * 30.48 / 3600.
2513  C
2514  C     SPECIFIC DISCHARGE AT A POINT IS OBTAINED BY DIVIDING D2ODZ BY
2515  C     THE SATURATED THICKNESS, (THICK) IN THE CONFINED CASE
2516  C     AND (HEAD) IN THE UNCONFINED CASE.  (HEAD) IS ALWAYS MEASURED IN
2517  C     FEET FROM THE BOTTOM CONFINING LAYER.
2518  C
```

```
2519  C       ALL CHEM ARRAY ENTRIES CONVERTED TO C.G.S. FOR USE IN
2520  C       KINETIC MODEL.
2521  C
2522  C           CHEM(ICT,1) = REAL(Z)
2523  C           CHEM(ICT,2) = IMAGINARY(Z)
2524  C           CHEM(ICT,3) = REAL FLUX VECTOR.
2525  C           CHEM(ICT,4) = IMAGINARY FLUX VECTOR.
2526  C           FLXVC = (X,Y) FLUX VECTOR.
2527  C           CHEM(ICT,5) = RESULTANT FLUX VECTOR.
2528  C           CHEM(ICT,6) =  HEAD AT EQUAL INTERVALS.
2529  C           VLXX = DERIVATIVE OF X VELOCITY VECTOR WITH X.
2530  C           VLYY = DERIVATIVE OF Y VELOCITY VECTOR WITH Y.
2531  C           VLXY = DERIVATIVE OF X VELOCITY  VECTOR WITH Y.
2532  C           CHEM(ICT,7) = DERIVATIVE OF X FLUX WITH X.
2533  C           CHEM(ICT,8) = DERIVATIVE OF Y FLUX WITH Y.
2534  C           CHEM(ICT,9) = DERIVATIVE OF X FLUX WITH Y.
2535  C           CHEM(ICT,10) = REAL(OMEGA) (EQUAL INTERVAL HEAD).
2536  C           CHEM(ICT,11) = IMAGINARY (OMEGA).
2537  C           KL = DISPERSION COEFFICIENT (FT**2/SEC.)
2538  C           CHEM(ICT,12) = RHO (ROCK DENSITY)
2539  C           CHEM(ICT,13) = CONVECTION COEFFICIENT (ALPHA)
2540  C           CHEM(ICT,14) = DISPERSION COEFFICIENT (BETA)
2541  C           CHEM(ICT,16) = NORMALIZED DELTA HEAD.
2542  C           CHEM(ICT,17) = POROSITY
2543  C           VL = VELOCITY(RESULTANT VECTOR).
2544  C
2545  C
2546            CHEM (ICT, 1) = REAL (Z) * 30.48
2547            CHEM (ICT, 2) = AIMAG (Z) * 30.48
2548            FLXVC = CMPLX (REAL (DODZ), - AIMAG (DODZ)) * 30.48 / SATT /
2549           1   3600.
2550            VL = CABS (FLXVC) / POR (LOCZ)
2551            KL = D / (F * POR (LOCZ)) + 0.5 * VL * SIGMA * P (LOCZ)
2552            CHEM (ICT, 3) = REAL (FLXVC)
2553            CHEM (ICT, 4) = AIMAG (FLXVC)
2554            CHEM (ICT, 5) = CABS (FLXVC)
2555            CHEM (ICT, 6) = HEAD * 30.48
2556            CHEM (ICT, 7) = REAL (D2ODZ) / SATT / 3600.
2557            VLXX = CHEM (ICT, 7) / POR (LOCZ)
2558            CHEM (ICT, 8) = - CHEM (ICT, 7)
2559            VLYY = - VLXX
2560            CHEM (ICT, 9) = - AIMAG (D2ODZ) / SATT / 3600.
2561            VLXY = CHEM (ICT, 9) / POR (LOCZ)
2562            CHEM (ICT, 10) = REAL (OMEGA) * 30.48 ** 3 / 3600.
2563            CHEM (ICT, 11) = AIMAG (OMEGA) * 30.48 ** 3 / 3600.
2564            CHEM (ICT, 15) = CHEM (ICT, 10)
2565            CHEM (ICT, 17) = POR (LOCZ)
2566            CHEM (ICT, 12) = RHO (LOCZ)
2567  C
2568  C       CALCULATE STREAMLINE CONVECTION AND DISPERSION TERM COEFFICIENTS
2569  C       FOR INPUT TO MASS TRANSPORT MODEL.
2570  C
2571            TERM1 = CHEM (ICT, 5) ** 2
2572            TERM2 = (2.0 * CHEM (ICT, 3) * CHEM (ICT, 4) / CHEM (ICT, 5) **
2573           1   2) * KL * CHEM (ICT, 9)
2574            TERM3 = KL * (CHEM (ICT, 3) ** 2 / CHEM (ICT, 5) ** 2 + 1.0) *
2575           1   CHEM (ICT, 7)
2576            TERM4 = KL * (CHEM (ICT, 4) ** 2 / CHEM (ICT, 5) ** 2 + 1.0) *
2577           1   CHEM (ICT, 8)
2578  C
```

```
C       ALPHA
C
        CHEM (ICT, 13) = (1 / MPERM) * (TERM1 - TERM2 - TERM3 - TERM4)
C
C       BETA
C
        CHEM (ICT, 14) = KL * ((CHEM (ICT, 5) ** 2) * (1 / MPERM) ** 2)
C
C       CREATE OUTPUT FILE FOR INPUT TO MASS TRANSPORT PROGRAM.
C
        IF (ICT .NE. 1) GO TO 1020
        WRITE (TL, 10) NWL
C
          DO 1010  KWL = 1, NWL
          WRITE (TL, 20) NUMW (KWL), ZWL (KWL)
 1010     CONTINUE
C
        WRITE (TL, 10) MINUS
        WRITE (TL, 20) NPT
 1020   CONTINUE
        IF (IHD .GT. 1) GO TO 1080
 1030   PHI1 = CHEM (ICT, 6)
        IF (ICT .EQ. 1) GO TO 1080
        LST = ICT - LASTH + 1
        KCT = ICT - 2
C
        WRITE (LU, 30) PHID
C
C       CALCULATE DISTANCE OF LAST POINT FROM PROD. WELL.
C
        LSTPT = IPT - 1
        IF (NUMS (LSTPT, 2) .GT. 0) GO TO 1040
        QLINE = - 10.0
        VN = - 10.0
        GO TO 1060
C
C       FOR EACH STREAMLINE CALCULATE INJECTION VOLUME, DISTANCE FROM
C       RECOVERY WELL, AND THE STREAMTUBE CROSSECTIONAL AREA AT THE
C       RECOVERY WELL.
C
 1040     DO 1050  KWL = 1, NWL
          QW = Q (KWL) / 3600.
          IF (NUMS (LSTPT, 1) .EQ. NUMW (KWL)) QLINE = ABS (QW / NLINE-
     1    (LSTPT)) * 30.48 ** 3
C
          IF (NUMS (LSTPT, 2) .NE. NUMW (KWL)) GO TO 1050
          QPROD = QW * 30.48 ** 3
          DIST = CABS (ZWL (KWL) - CMPLX (CHEM (KCT, 1), CHEM (KCT, 2)) /
     1    30.48)
 1050     CONTINUE
C
        VN = (QLINE / QPROD) * PI * SATT * DIST ** 2 * 30.48 ** 3
 1060   CONTINUE
C
C       RESCALE ALPHA AND BETA ACCORDING TO STREAMLINE LENGTH OF ONE.
C
        LAST1 = LASTH - 2
        CH16 = -1.0 - (CHEM (KCT, 6) - CHEM (LST-1, 6)) / PHID
        WRITE (TL, 50) LSTPT, LAST1, CHEM (KCT, 11), NUMS (LSTPT, 1),
     1    NUMS (LSTPT, 2), QLINE, VN, STM, CH16
```

```
C
          DO 1070  KPT = LST, KCT
          CHEM (KPT, 13) = CHEM (KPT, 13) / PHID
          CHEM (KPT, 14) = CHEM (KPT, 14) / (PHID ** 2)
          CHEM (KPT, 16) = (CHEM (KPT, 6) - CHEM (KPT - 1, 6)) / PHID
C
          WRITE (LU, 60) CHEM (KPT, 13), CHEM (KPT, 14), CHEM (KPT, 16),
     1    KPT
          WRITE (TL, 20) LSTPT, CHEM (KPT, 1), CHEM (KPT, 2), CHEM (KPT,
     1    10), CHEM (KPT, 13), CHEM (KPT, 14), CHEM (KPT, 16), CHEM (KPT,
     2    12), CHEM (KPT, 17)
 1070     CONTINUE
C
        WRITE (TL, 10) MINI
        IF (MINUS .EQ. - 2) WRITE (TL, 10) MINUS
 1080   PHID = PHI1 - CHEM (ICT, 6)
        LASTH = IHD
C
        RETURN
C
C
   10   FORMAT ( I4 )
   20   FORMAT ( I4, 8E15.5 )
   30   FORMAT ( // 1X, 21HSTREAMLINE POT. DIFF., E8.3, 11HCM.**3/SEC.,
     1    / 10X, 5HALPHA, 9X, 5HBETA , 9X, 14HHEAD DECREMENT, 5X,
     2    7HPT. NO.)
   50   FORMAT ( 2I4, E15.5, 2I4, 2E15.5, I4, E15.5)
   60   FORMAT ( 3X, E12.5, 5X, E12.5, 5X, E12.5, 5X, I5 )
C
        END
        END$
```

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