Estimating Net Drawdown Resulting from Episodic Withdrawals at Six Well Fields in the Coastal Plain Physiographic Province of Virginia

By Michael J. Focazio and Gary K. Speiran

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[Plates are in pocket]]

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
million gallon per day (Mgal/d)	0.04381	cubic meter per second

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929–a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929

Abbreviated water-quality units: Chemical concentration is given in milligrams per liter (mg/L).

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Abstract

This report presents the results of a study by the U.S. Geological Survey, in cooperation with the Hampton Roads Planning District Commission, to describe a method of estimating net drawdown resulting from episodic withdrawal of ground water in the Coastal Plain Physiographic Province of Virginia. The ground-water-flow system of the Virginia Coastal Plain consists of areally extensive and interconnected **aquifers**[1]. Large, regionally coalescing **cones of depression** that are caused by large withdrawals of water are found in these aquifers. Local ground-water systems are affected by regional pumping, because of the interactions within the system of aquifers. Accordingly, these local systems are affected by regional ground-water flow and by **spatial** and **temporal** differences in withdrawals by various users.

A geographic-information system was used to refine a regional ground-water-flow model around selected withdrawal centers. A method was developed in which **drawdown** maps that were simulated by the regional ground-water-flow model and the **principle of superposition** could be used to estimate drawdown at local sites. This method allows for the effects of **episodic withdrawal** and many withdrawal centers or wells to be estimated. Simulated-drawdown maps were created for six localities in the Coastal Plain Physiographic Province of Virginia.

Drawdowns were simulated for periods of 3, 6, 9, and 12 months for six centers of withdrawal that are owned and operated by the Cities of Chesapeake, Newport News, Norfolk, Portsmouth, Suffolk, and Virginia Beach, Virginia. The withdrawal rates remained constant for the specific time periods and represent maximum rates. Drawdown maps for the Brightseat-upper Potomac aquifer were made for each locality to apply this method.

INTRODUCTION

Large industrial and municipal withdrawals of water from the areally extensive and interconnected aquifers in the Coastal Plain Physiographic Province of Virginia have resulted in declines in water levels throughout major parts of this regional hydrologic system. These declines have created large, regionally coalescing cones of depression throughout much of the system; thus, withdrawals can cumulatively affect water levels in the wells of users throughout the area.

Large municipal withdrawals of water from the Coastal Plain aquifers of Virginia supplement surface-water supplies during drought; consequently, much of the withdrawal is episodic. Withdrawal schedules, when wells are pumped continuously and at constant rates, are unpredictable and can vary from several months to several years. Periods of pumping are typically interrupted by extended periods of no withdrawal.

Water-level declines because of episodic municipal withdrawals can affect water users near such withdrawals. Water-level declines in many areas can result from the combined effects of withdrawals by more than one municipality, because well fields are closely spaced, and during

[1]Terms defined in the glossary are in bold print where first used in this report.

droughts, several municipalities may pump water concurrently. Because of concerns about the effects of their withdrawals on local users, who are primarily domestic and small industrial users, municipalities in southeastern Virginia needed a readily available, simple, and reliable method to determine water-level declines caused by withdrawals from their supply wells.

Accurate simulation of future water-level declines because of withdrawal from this system is difficult, because rates of withdrawal change temporally and spatially and cannot be predicted. Different techniques, such as numerical ground-water-flow models and analytical methods, were used in previous studies to evaluate water-level declines for known pumping rates and schedules. It is impractical, however, to simulate all possibilities of future episodic withdrawal schemes even with the use of sophisticated ground-water-flow models. It is also impractical for each ground-water user to simulate the effects of their withdrawals with a ground-water-flow model during and after each episodic withdrawal and **recovery** cycle. The method presented here reduces the need for repeated simulations of drawdown by each user and allows users to quickly estimate drawdowns caused by their withdrawals at various times. This is particularly useful when withdrawal by other users also causes drawdown in an area. The U.S. Geological Survey (USGS), in cooperation with the Hampton Roads Planning District Commission, has developed a method and the associated hydrologic information from which net drawdowns caused by episodic withdrawals can be estimated.

Purpose and Scope

This report presents a method and hydrologic information needed to estimate water-level declines from individual, episodic withdrawals of ground water at each of six well fields in the Coastal Plain of southeastern Virginia. Regional ground-water flow-model simulations were used to estimate water-level declines caused by individual users for fixed periods of constant pumping. Water-level declines for selected periods of sequential withdrawal and recovery can be determined throughout the study area by applying the principle of superposition to information obtained from a series of maps that were made for each withdrawal center. Maps show drawdown in the Brightseat-upper Potomac aquifer at several times, as simulated by the regional ground-water-flow model of the Coastal Plain of Virginia (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Focazio, 1990; Harsh and Laczniak, 1990).

Study Area

The Coastal Plain Physiographic Province of Virginia (fig. 1) is underlain by a layered system of hydraulically interconnected aquifers and confining units (fig. 2). The regional system of aquifers, from youngest to oldest (shallowest to deepest), are Columbia, Yorktown-Eastover, St. Marys-Choptank, Chickahominy-Piney Point, Aquia, Virginia Beach, Brightseat-upper Potomac, middle Potomac, and lower Potomac aquifers.

The natural regional flow of ground water is from the **Fall Line** toward coastal areas. Local flow is from topographic highs toward major river valleys. Most natural recharge to the confined aquifers is in upland areas between river valleys in a narrow band near the Fall Line; natural discharge is to major river valleys and coastal waters (Harsh and Laczniak, 1990). Large withdrawals of ground water in the Coastal Plain have altered the natural flow patterns. Withdrawals have lowered water levels and changed directions of ground-water flow.

Previous Studies

The **depositional environments** of the sediments and geohydrologic framework of the aquifer system were described in detail by Meng and Harsh (1988). Hamilton and Larson (1988) and Laczniak and Meng (1988) refined the framework in southeastern Virginia and the York-James peninsula, respectively.

Digital ground-water-flow models were constructed to simulate ground-water flow in this complex hydrologic system, in which large withdrawals can create regional cones of depression and possible **well interferences** (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Harsh and Laczniak, 1990). These models have been combined into a single regional model (Focazio, 1990). Input and output information are stored and manipulated by use of a geographic information system (GIS) (Focazio and Samsel, 1993).

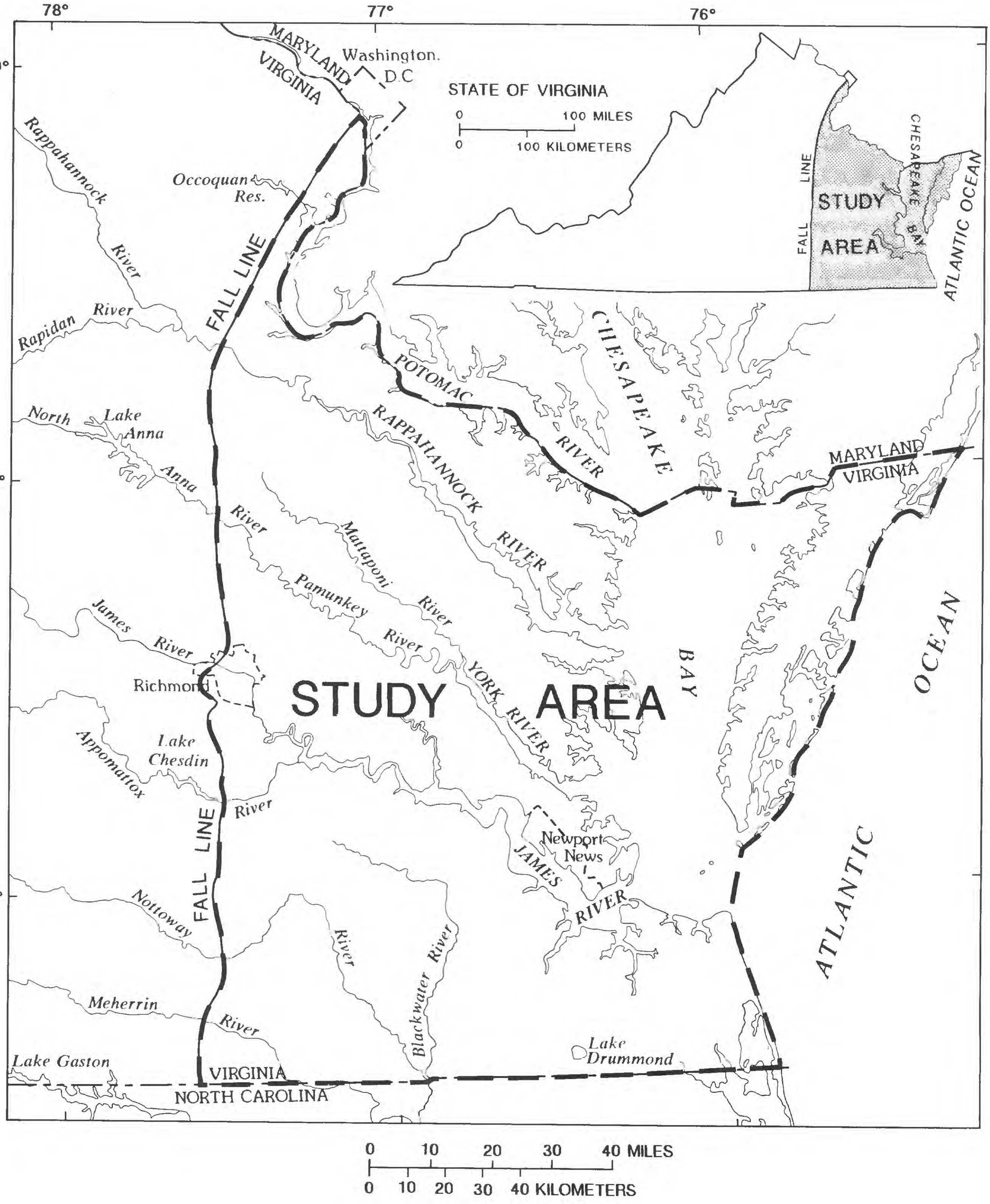


Figure 1. Location of study area.

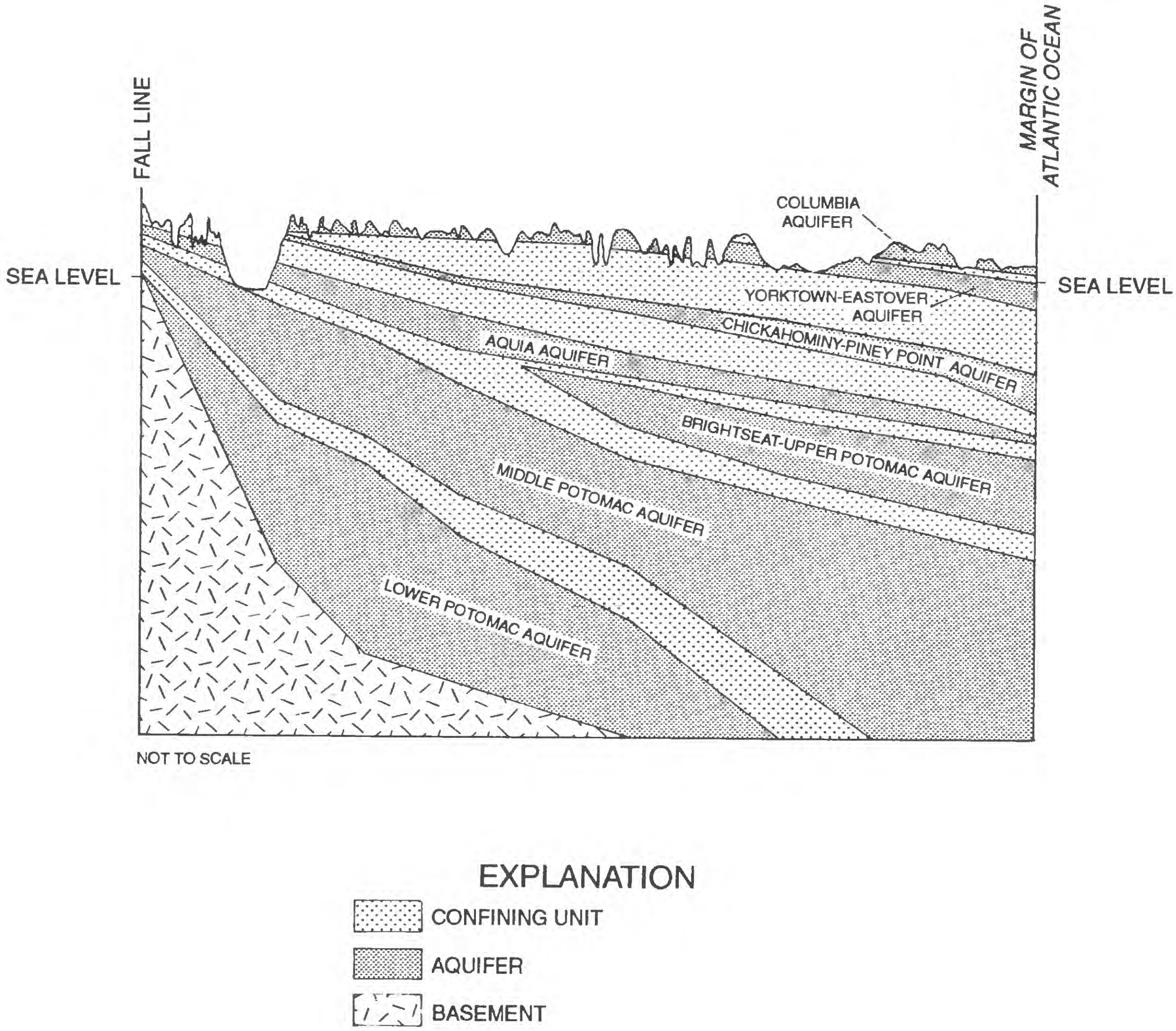


Figure 2. Diagrammatic geohydrologic section of eastward-thickening wedge of alternating aquifers and confining units. (Modified from Harsh and Laczniak, 1990.)

ESTIMATING NET DRAWDOWN

A method was developed for individual ground-water users to estimate water-level declines caused by withdrawals. The method combines results of simulations from the ground-water-flow model and the principle of superposition. Data for levels during extended periods of withdrawal at a constant rate and periods of no pumping can be combined. Maps of drawdown simulated with a ground-water-flow model can be used to assess the spatial distribution of water-level declines caused by continuous or episodic withdrawal by an individual user or groups of users. Accordingly, differences in water-level declines can be analyzed temporally and (or) spatially.

This study did not analyze the effects of withdrawals by all users in the area; only withdrawals for six users were simulated. Thus, declines greater than those calculated with this method might be observed in the field. Although some of this difference can result from inaccuracies in the simulations, much of the difference probably reflects the effects of other withdrawals.

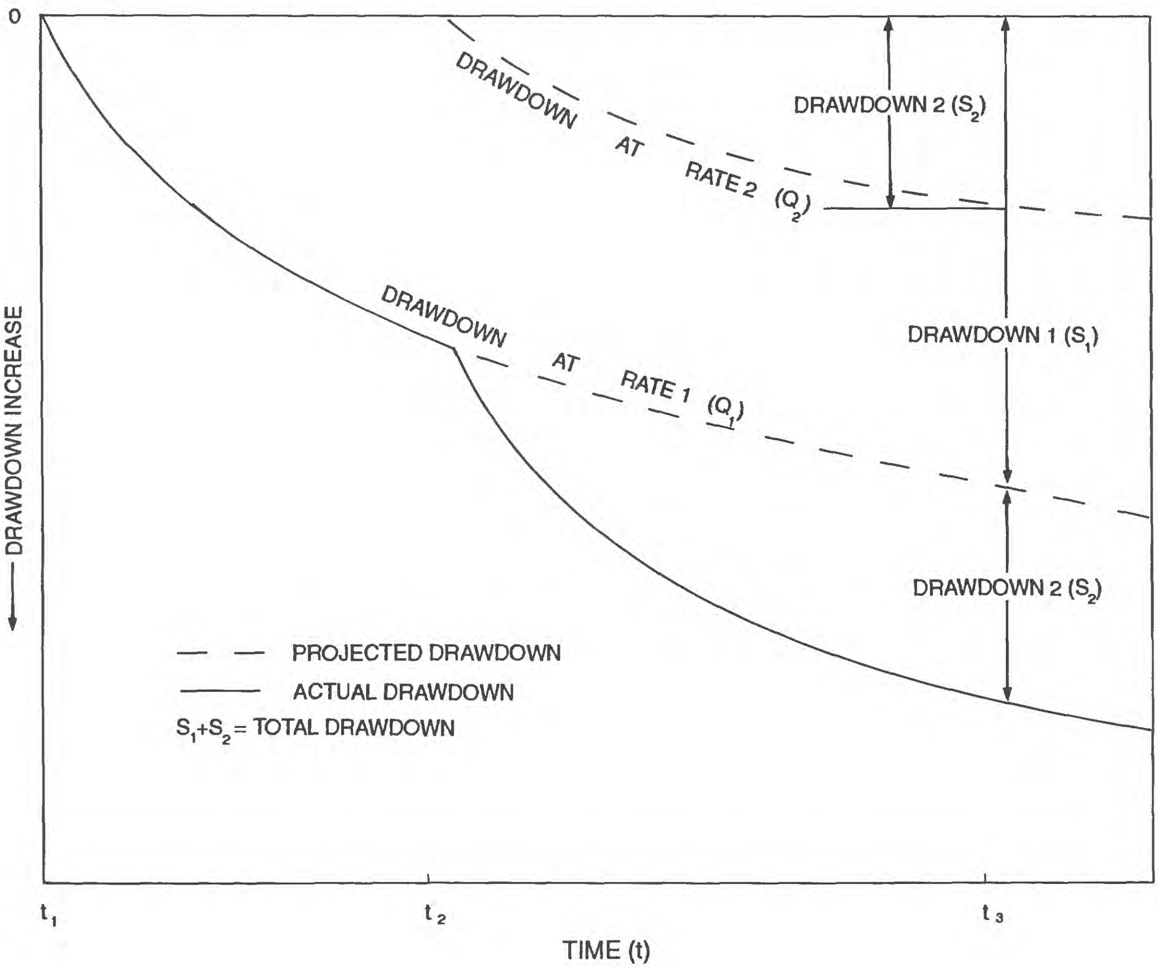


Figure 3. Superposition of drawdowns for two different withdrawal rates.

Principle of Superposition

The principle of superposition applies to **confined aquifer** systems in which ground-water flow can be expressed by linear differential equations (Reilly and others, 1987). The principle means, in its simplest form, that effects of multiple stresses (more than one withdrawal or recharge) are equivalent to the sum of the effects of the individual stresses (Reilly and others, 1987, p. 2).

To understand the application of the principle of superposition, an understanding of drawdown and recovery responses in a confined aquifer is required. Withdrawal of ground water from a well results in water-level declines in the well and adjacent aquifer. When withdrawal begins, an area of drawdown in water levels develops around the well and expands with time until equilibrium is reached and water levels stop declining. Drawdowns are greatest at the well and decrease with distance from the well. At any observation well within the drawdown area, drawdown will begin after withdrawal begins. The time that drawdown begins at the observation well depends on several factors, including the distance between the observation well and the withdrawal well. Rates of change in drawdown in any affected well are greatest when drawdown begins in that well and decrease with time until equilibrium is reached.

For example, withdrawal from a well that begins at time t_0 and at a constant rate Q_1 affects water levels in an observation well after time t_1 and results in a drawdown s_1 at the observation well at time t_3 (fig. 3). With an incremental increase in withdrawal rate Q_2, water levels in the observation well are affected after time t_2. This incremental increase results in a drawdown s_2 at time t_3, and the total drawdown at time t_3 equals the sum of drawdowns (s_1+s_2) (fig. 3). The incremental withdrawal increase can be in the initial withdrawal well or in another withdrawal

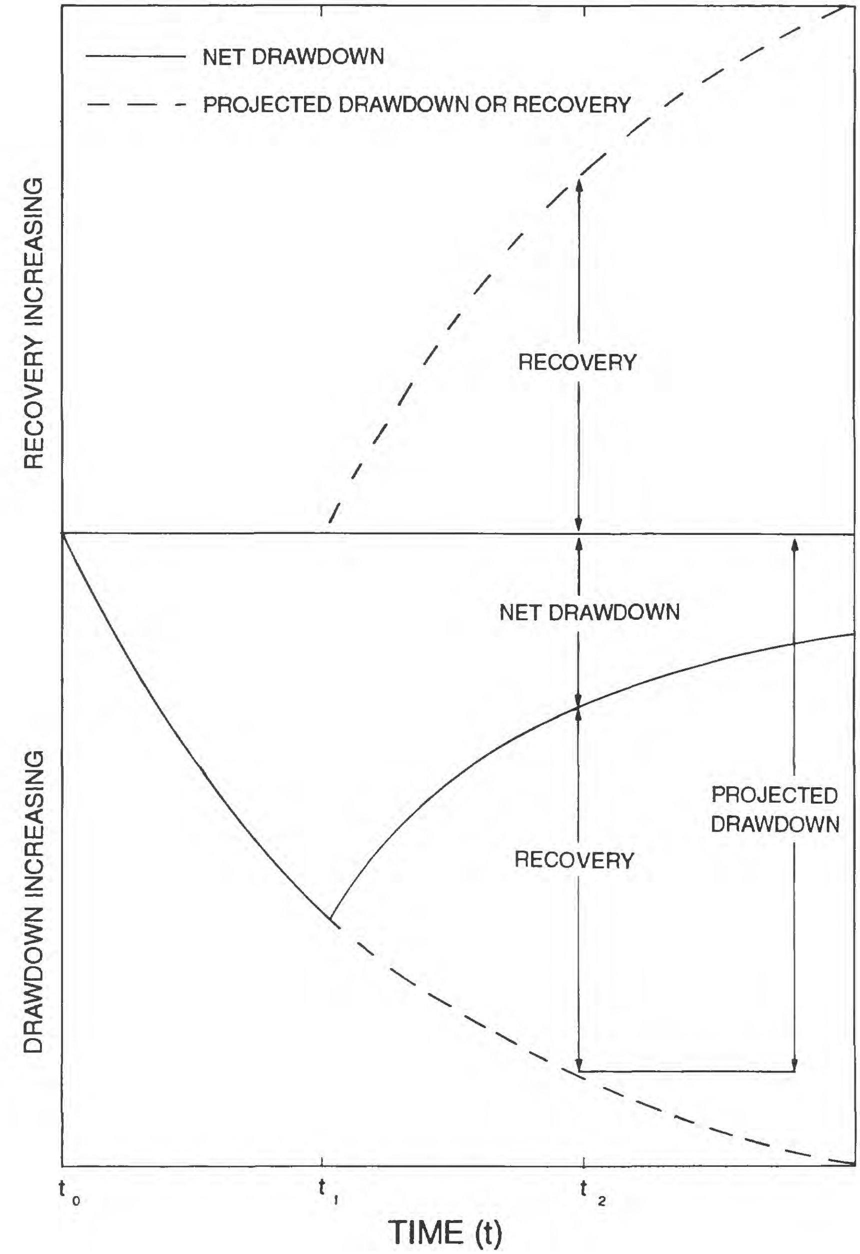


Figure 4. Superposition of recovery on projected drawdown to form a net drawdown.

well. This principle applies to an infinite number of stresses in a confined aquifer and can be extended for any period of time.

The principle of superposition similarly applies to withdrawal and recovery cycles for a pumped well (fig. 4). Withdrawal from a well that starts at time t_0 begins to draw water levels down in an observation well after time t_1. When the withdrawal ceases at time t_2, water levels begin to recover, producing a net drawdown that decreases with time. The net drawdown equals the drawdown projected as if the well continued to pump minus the recovery. The recovery is a mirror image of the projected drawdown offset in time by (t_2–t_1). The amount of drawdown decreases to zero at equilibrium.

The method can be extended for episodic withdrawal and recovery cycles. For example, effects of a withdrawal history where the pump was alternately turned on and off for 3 month periods over a 12-month period are shown in

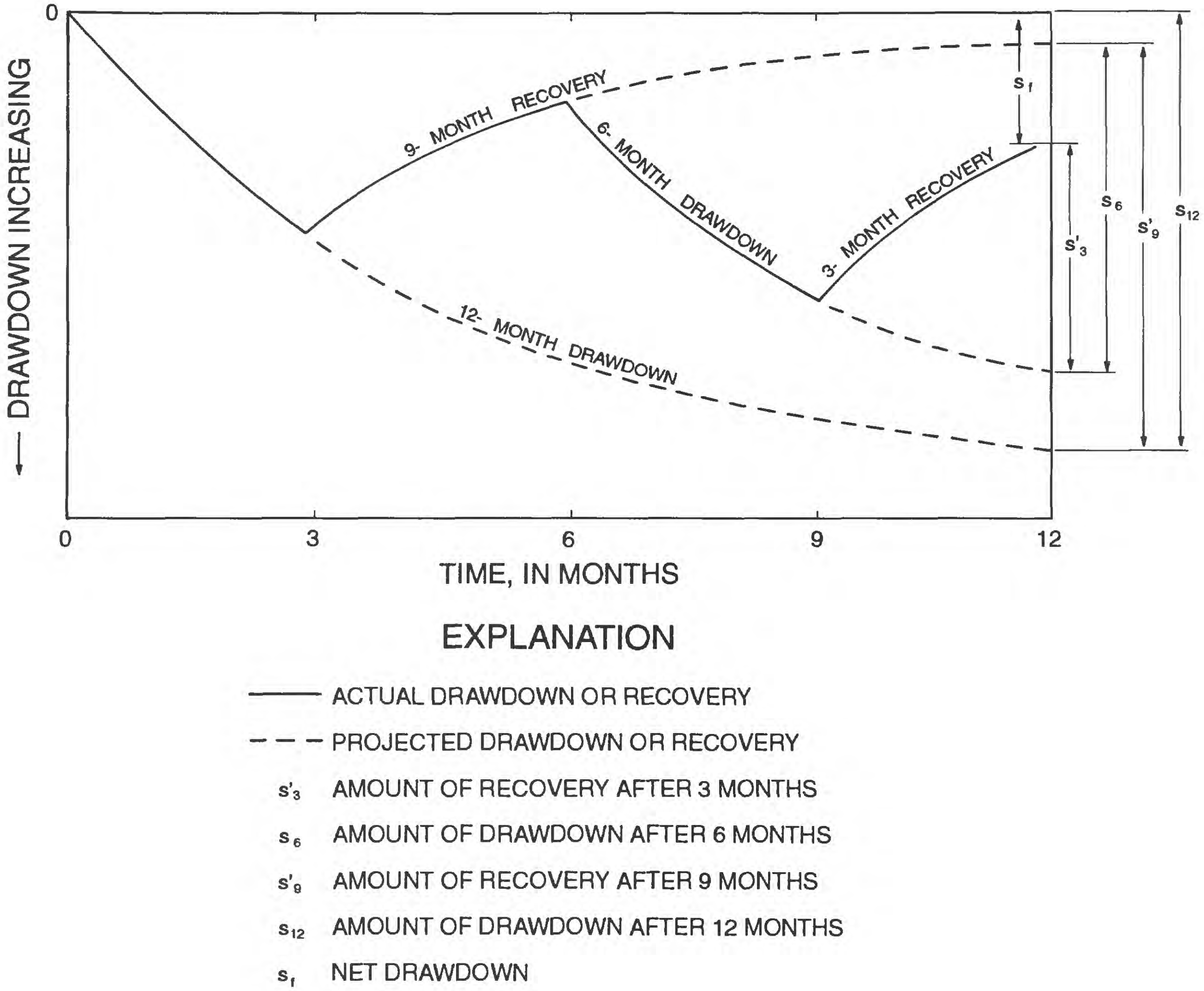


Figure 5. Superposition of cyclic drawdown and recovery.

figure 5. The net drawdown after 12-months is equal to the value of 12 months of drawdown s_{12}, minus the value of 9 months of recovery s'_9, plus the value of 6 months of drawdown s_6, minus the value of 3 months of recovery s'_3. This approach can be applied to any well in the system and is not limited to equal increments of time—3-month intervals are used here for simplicity.

Results of Drawdown Simulations

Construction of the ground-water-flow model (also called the refined-grid model) started with a finite-difference grid of high resolution around the well fields. Information from the regional ground-water-flow model, such as the calibrated values of hydraulic properties, was input from the GIS into the refined-grid model (Focazio, 1990). This input maintained the regional characteristics of the properties and enabled a refined analysis near each well field. The fine grid provides increased resolution of drawdown simulations by assigning one well per grid cell of the model wherever possible, and by providing a greater grid-cell density around the wells than in other parts of the study area. The refined grid consists of 79 rows and 66 columns, and the grid cells range from 1.75 to 3.5 mi long (fig. 6). This model encompasses the same area as the regional model, with the original boundary conditions retained. The refined-grid model is a version of the regional model with a variably-spaced grid overlayed on the study area; therefore, it retains the same assumptions and limitations as the regional model (Harsh and Laczniak, 1990). Focazio and Speiran (1992) compared results of the refined-grid model and the regional model

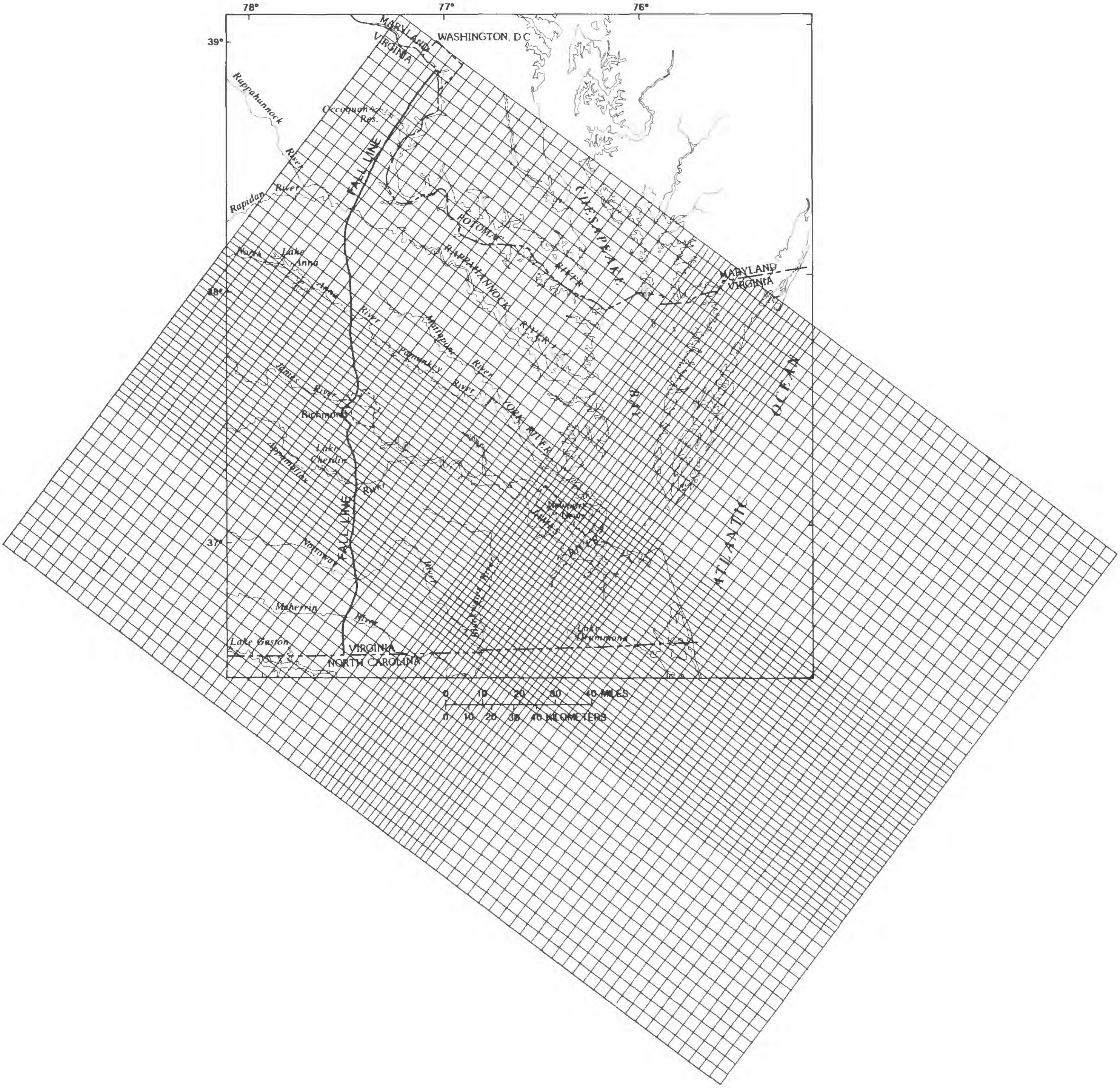


Figure 6. Locally refined finite-difference grid.

Table 1. Location of wells, withdrawal rates, and aquifers used for drawdown simulations
[Latitude and longitude are in degrees (°), minutes ('), and seconds (")]

Well number	Latitude (°, ', ")	Longitude (°, ', ")	Model		Withdrawal from Potomac aquifers (million gallons per day)		
			Row	Column	Lower	Middle	Upper
			Chesapeake				
1	364618	762741	44	32	0.00	2.10	0.90
2	364627	762737	44	32	.00	6.93	2.07
			Newport News				
1	372220	765027	25	43	.00	1.15	.00
2	372257	764835	25	44	.00	1.15	.00
3	372104	764835	25	42	.00	1.15	.00
4	372140	764834	25	43	.00	1.15	.00
5	372650	765404	23	44	.00	1.37	.00
6	372702	765220	23	44	.00	1.37	.00
7	372544	765503	23	43	.00	1.37	.00
8	372546	765331	23	43	.00	1.37	.00
			Norfolk				
1	364808	763752	39	29	.00	.70	3.24
2	355019	763805	38	30	.62	2.84	.43
3	364810	763921	38	29	.00	1.44	2.45
4	364838	763709	39	20	.00	1.75	2.13
5	364904	763305	41	31	.00	.41	3.63
6	364913	763152	41	32	.00	.48	3.55
			Portsmouth				
1	364345	763540	42	28	.00	2.90	.00
2	364330	763612	42	27	.00	2.26	.25
3	364452	763514	41	28	.00	3.99	.00
4	364347	763632	41	28	.00	2.01	.99
5	364318	763532	42	28	.00	1.47	1.53
			Suffolk				
1	365151	763433	39	33	.00	2.97	1.04
			Virginia Beach				
1	364840	763517	40	30	.00	4.04	.00
2	364727	763556	40	29	.00	4.04	.00
3	365232	764055	36	31	.00	3.99	.00
4	364812	764055	38	28	.00	3.99	.00
5	364556	765312	34	23	1.48	2.52	.00

and showed that results do not differ between the two types of discretizations. Thus, the refinement procedure does not alter interpretations of the regional hydrologic processes. Contour maps of simulated drawdown in the Brightseat-upper Potomac aquifer for different time intervals for each ground-water user were produced. Information from these maps can then be combined, by use of the principle of superposition, to create a history of drawdown and recovery in water levels at any location that result from withdrawal at each of the well fields.

The refined-grid model was used to simulate drawdown in the Brightseat-upper Potomac aquifer for 3, 6, 9, 12, 36, and 60 months from pumpage individually at the Chesapeake, Newport News, Norfolk, Portsmouth, Suffolk, and Virginia Beach well fields. Locations of wells, withdrawal rates, and aquifers pumped are listed in table 1. Withdrawal rates were supplied by the individual localities and remained constant during each period of simulation. Withdrawal rates for each individual well represent a maximum rate expected by the individual well owners. Although all wells within an individual well field might not be operating at the same time, the combined withdrawal from each locality's well field was simulated with these maximum rates. The drawdowns represent the combined effects of maximum withdrawal of all wells within a well field. The simulations thus represent one possible scenario that can be applied to assess the maximum drawdown from the individual well fields.

Simulation results indicate that drawdowns in the Brightseat-upper Potomac aquifer reached equilibrium within 12 months for withdrawal from the Chesapeake, Norfolk, and Virginia Beach well fields. Equilibrium was reached within 9 months for withdrawal from the Newport News, Portsmouth, and Suffolk well fields. Drawdown maps were only made for the time periods required to reach equilibrium. Drawdowns at 3, 6, 9, and 12 months for Chesapeake, Norfolk, and Virginia Beach withdrawals are shown in plates 2, 4, and 7, respectively. Drawdowns for 3, 6, and 9 months of withdrawal from the Newport News, Portsmouth, and Suffolk well fields are shown in plates 3, 5, and 6, respectively.

A grid that represents the locations of USGS 7.5-minute topographic maps overlays each of the drawdown maps. This grid will aid in locating points of interest on the maps. A separate map of the grid with quadrangle names is shown in plate 1.

Regional water-level-decline data for the Chickahominy-Piney Point aquifer are of interest to the municipalities and also were analyzed. Results of this analysis indicate that drawdown in this aquifer was less than 10 ft in small areas near the wells for Newport News, Portsmouth, Suffolk, and Virginia Beach, and was approximately 20 ft in small areas near the Chesapeake and Norfolk well fields. Simulated withdrawals only were from the three Potomac aquifers underlying the Chickahominy-Piney Point aquifer; therefore, drawdown in the Chickahominy-Piney Point aquifer was caused by **leakage** to the underlying aquifers. The accuracy of the flow model decreases for the aquifers above the Potomac aquifers. The calibration of leakage through confining units in these overlying aquifers was limited (Hamilton and Larson, 1988; Laczniak and Meng, 1988; Harsh and Laczniak, 1990). The small simulated drawdown and limited accuracy of the model results for the Chickahominy-Piney Point aquifer thus make the results of marginal usage to this method. Consequently, drawdown maps are not presented for the Chickahominy-Piney Point aquifer.

Application of Principle of Superposition and Results of Drawdown Simulations

In determining net drawdown for a given location by using the principle of superposition, drawdown and recovery must be estimated for each pumping and recovery period in the cycle. Drawdown and recovery can be directly **interpolated** from drawdown contours on maps of simulated drawdown for the appropriate time periods, using a period of simulated continuous pumpage. Accurate visual interpolation can be difficult because of contour spacing and because drawdown varies logarithmically with distance in an aquifer with uniform water-transmitting properties; however, a graphical method of interpolation can be applied to reduce errors caused by interpolation directly from the maps.

The graphical method can be used for interpolation by constructing a curve of drawdown and the logarithm of distance with at least three values of drawdown. To construct this curve, the user must (1) draw a straight line on the map of simulated drawdown from the withdrawal center through and beyond the location of interest; (2) select those points where the straight line intersects drawdown-contour lines on the map; (3) determine the distance from the withdrawal center to the points at which the contours and drawn line intersect; (4) plot the distance on the logarithmic axis and the associated drawdown on the arithmetic axis on semilogarithmic graph paper; (5) determine the distance between the location of interest and the withdrawal center; and (6) plot this distance as a horizontal line on the graph. Once this has been completed, a straight line must be drawn that represents the line of best fit for the points on either side of the horizontal line. Ideally, the best-fit line passes through all points because drawdown varies logarithmically with distance; however, because the water transmitting characteristics of aquifers typically are not uniform, all points will not lie on the line. Thus, the most appropriate best-fit line is that line through the points closest to the location of interest. However, because of local variabilities in the hydrologic system and uncertainties inherent in digital-flow models, it may be useful to choose more points than those on either side of the location of interest to draw the best-fit line. Selection of points will require hydrologic judgement that is based on knowledge of the system. The intersection of the horizontal line and the best-fit line represents the drawdown (or recovery) at the location of interest for the specific time period. This procedure is repeated to obtain drawdown and recovery values for all periods needed for the analysis. Finally, by applying the principle of superposition to the values of drawdown and recovery obtained for the specific time periods at the location of interest, a cycle of drawdown and recovery can be analyzed.

The following discussion presents a step-by-step example of the graphical method of interpolation. The refined-grid model was used to simulate the drawdown at selected times through a 12-month period caused by a hypothetical user (user 1) with a constant withdrawal rate. The simulation included no other withdrawals throughout the simulation period (fig. 7). The hypothetical withdrawal schedule for user 1 is 3 months alternately of maximum withdrawal and no withdrawal for a total time period of 12 months. The net drawdown after 12 months at a locality of interest (location A, fig. 7) can be determined. The scale of the maps in figure 7 has been adjusted so that all four maps can fit on one page (for demonstration purposes only). Use of a scale, similar to that of plates 2-7, is necessary in minimizing error.

In order to estimate drawdown and recovery for the appropriate periods: (1) draw a straight line on each map through the withdrawal center and location A, that passes through all contour lines (fig. 7); (2) select these points where the straight line intersects drawdown-contour lines (points 1 through 5) on each map; (3) measure the distance of each point from the withdrawal center (approximately 10,500 ft for the 60-ft contour, point 1 on fig. 7); and (4) plot the distance on the logarithmic axis and the drawdown on the arithmetic axis on the semilogarithmic graph (fig. 8). The same procedure is followed for distance and drawdown at the 50-, 40-, 30-, and 20-ft contours (points 2, 3, 4, and 5 on fig. 7) and plotted as points 2, 3, 4, and 5 in figure 8. The fifth step is to determine the distance of the location of interest from the withdrawal center (fig. 7); step six is to plot this distance as a horizontal line. Once this is completed, draw a "best-fit" straight line through the points nearest the location of interest on the semilogarithmic graph. Note that points 4 and 5 are not on this straight line. This is probably caused by the spatial differences in the hydraulic properties of the aquifer in the model at such distances from the withdrawal center. Finally, the drawdown at location A is then found by identifying the drawdown where the best-fit line of the semilogarithmic plot (fig. 8) intersects the horizontal line for the distance of the location of interest from the withdrawal center. Thus, the drawdown is 45 ft at locality A after 3 months of withdrawal.

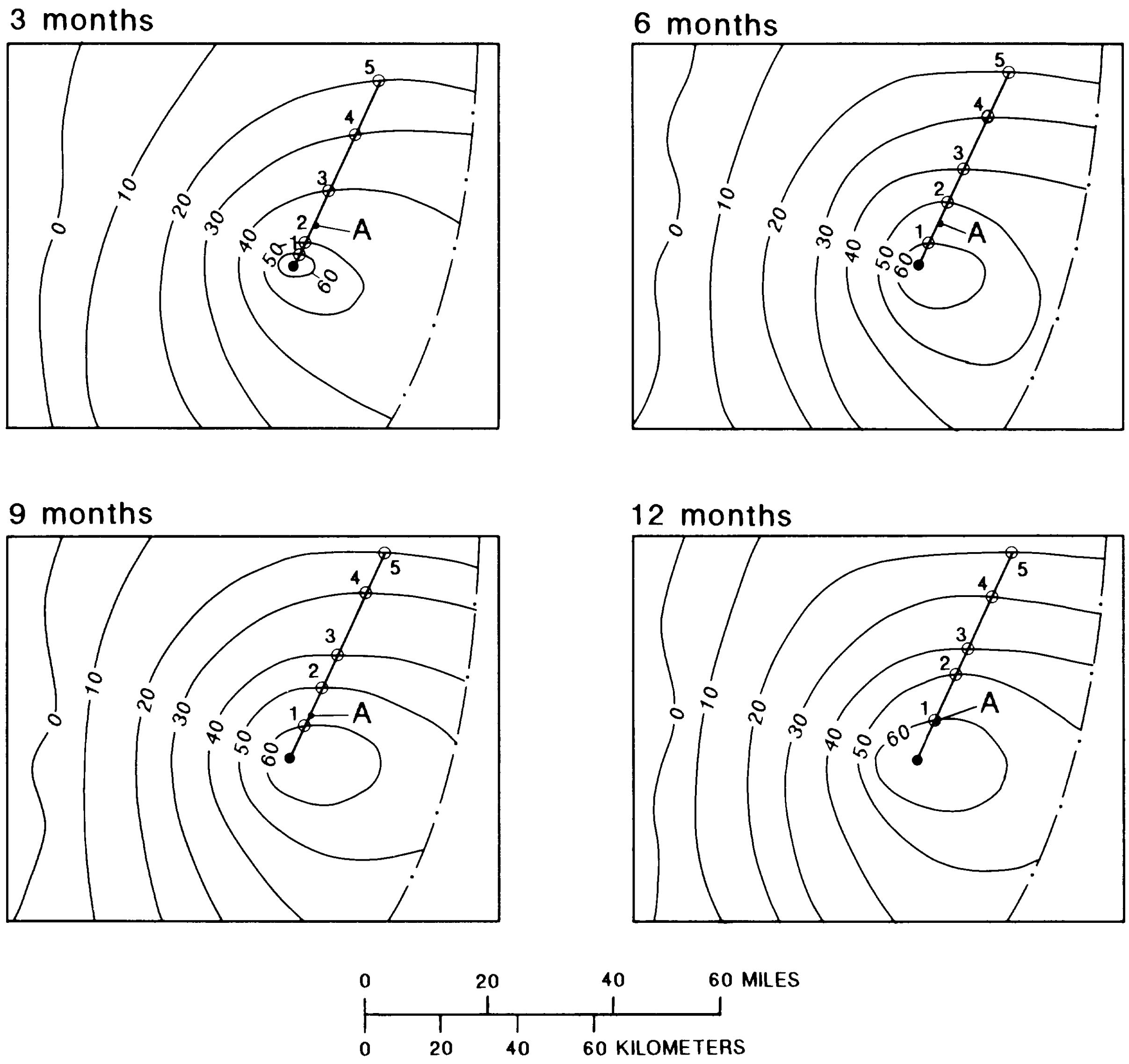
The same procedure was followed for the remaining three drawdown maps (fig. 7), for which the corresponding graphs were constructed (figs. 9, 10, and 11). The values of drawdown at locality A for the remaining time periods are determined as 55, 57, and 58 ft for 6, 9, and 12 months, respectively.

Applying the principle of superposition, the final drawdown at locality A for the alternating cycle of withdrawal (3 months on, 3 months off, 3 months on, and 3 months off) equals the projected 12-month drawdown from the initial withdrawal (58 ft from fig. 11), minus the projected 9-month recovery from the initial recovery (57 ft from fig. 10), plus the projected 6-month drawdown from the second withdrawal period (55 ft from fig. 9), minus the 3-month recovery from the final recovery period (45 ft from fig. 8). Thus, the final drawdown equals 11 ft. The same calculation of net drawdown is made whether drawdown and recovery are determined by distance and drawdown curves, or by visual interpolation between contours on the maps. This method can be applied to a large number of ground-water users to determine the contribution of each user to the drawdown at particular locations.

Part of the observed drawdown at location A also can be caused by withdrawal by other ground-water users. For example, the drawdown map for user 2 after the same 12 months with a constant withdrawal rate (pumps on entire 12 months) is shown in figure 12. The drawdown at locality A from this user is 52 ft; total drawdown caused by user 1 and user 2 is 63 ft. Therefore, if all of the drawdown at locality A results from withdrawal by the two users, only 17 percent of the drawdown results from withdrawals by user 1 and the remaining drawdown (83 percent) results from withdrawals by user 2. Additional drawdown could be observed at locality A that result from withdrawals by other users that may not be identified.

Limitations and Assumptions of Estimation Technique

The method of net drawdown estimation is based on the assumption that no effects of **residual drawdown** are present at the particular withdrawal center of interest before the analysis begins. Consequently, the ground-water-flow system must be at equilibrium at the onset of withdrawal from that site. Water levels in aquifers in the Coastal Plain of Virginia, with the present (1992) withdrawal rates, reach equilibrium in a few months to 1 year; thus, the method is probably not limited by residual drawdown effects at any particular site when water has not been withdrawn from that site for more than 1 year. Equilibrium was reached within 9 months to 1 year at all of the



EXPLANATION

—— 20 —— LINE OF EQUAL DRAWDOWN--Interval 10 feet

———— DRAWN LINE USED FOR DISTANCE AND DRAWDOWN GRAPH

—— · —— ESTIMATED SEAWARD LIMIT OF AQUIFER--Less than 10,000 milligrams per liter chloride

● LOCATION OF PUMPED WELL

3○ POINT OF INTERSECTION OF LINE OF EQUAL DRAWDOWN AND DRAWN LINE

A LOCATION OF INTEREST IN ESTIMATING DRAWDOWN

Figure 7. Simulated drawdown after selected periods of continuous withdrawal by user 1.

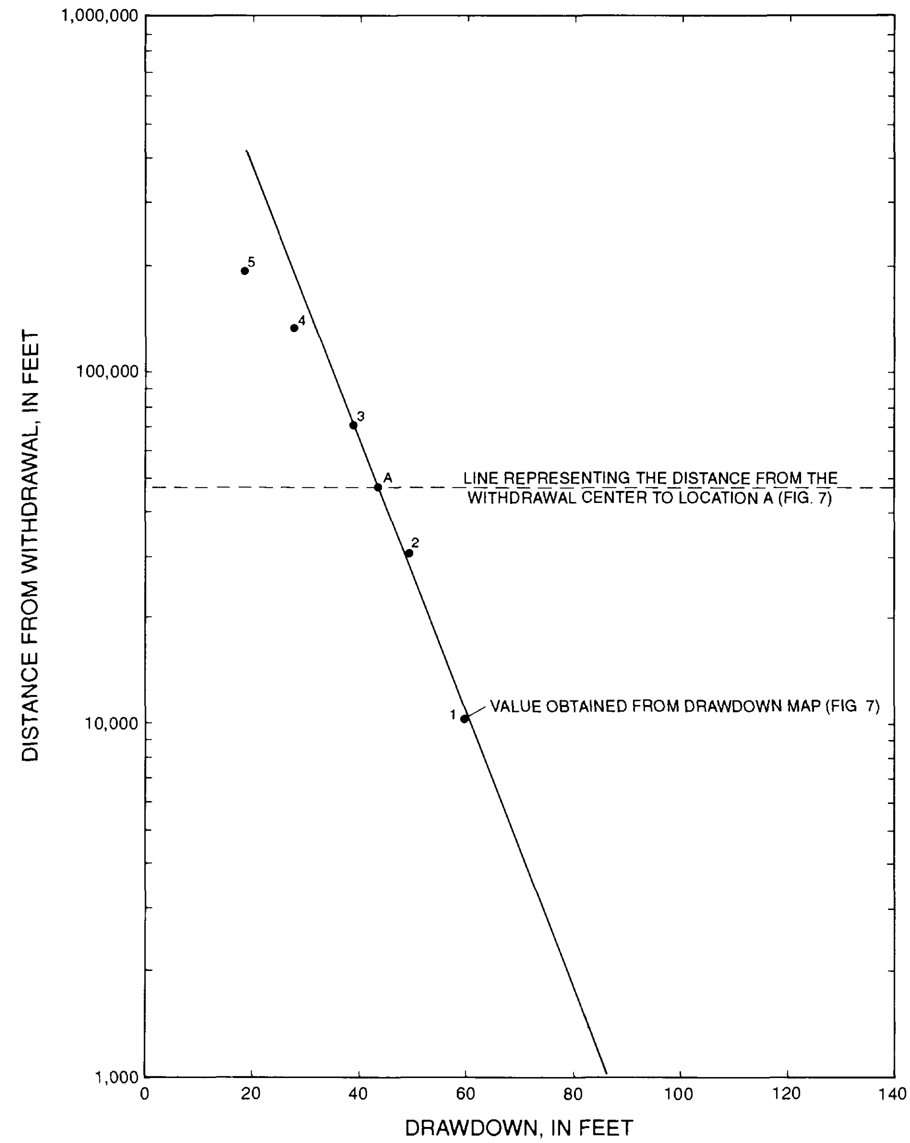


Figure 8. Straight-line semilogarithmic plot of distance and drawdown for 3 months.

localities and withdrawal rates that were simulated for this study. If, however, the method is applied during a recovery period, the drawdowns caused by a user will be overestimated.

The graphical method of interpolation is based on the assumption that distance and drawdown values plot as a straight line on semilogarithmic paper. This assumption can be limited if the water transmitting properties of the aquifer are not uniform. For example, the semilogarithmic graph of distance and drawdown for the 3-month period previously described (fig. 8) can produce errors in the drawdown estimate for location A if points 1 and 5 were used to draw the best-fit line. Points 4 and 5 may deviate from the best-fit line due to heterogeneities in water transmitting properties of the aquifer at large distances from the withdrawal center. These heterogeneities, and other factors, though requiring judgement in the graphical procedure, do in fact justify the use of the digital ground-water-flow model. A ground-water-flow model can represent heterogeneities on scales larger than a grid cell size

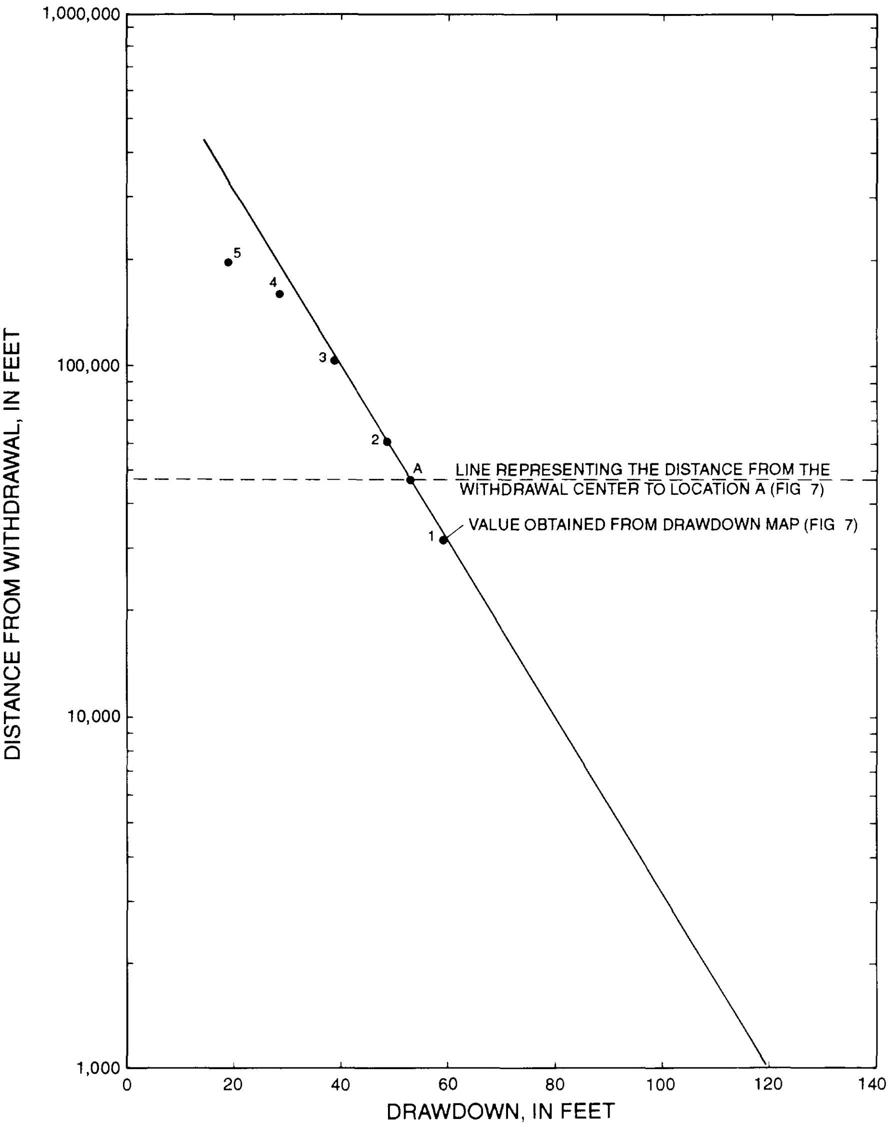


Figure 9. Straight-line semilogarithmic plot of distance and drawdown for 6 months.

(1.75 to 3.5 mi for the refined-grid model). Other procedures, such as analytical methods, cannot account for the heterogeneities.

Other factors can affect the linearity of the distance-drawdown relation. Properties of the physical-system, such as the presence of impervious boundaries, as well as effects introduced by the flow model, also can cause the distance and drawdown to deviate from a straight line on semilogarithmic paper. Inaccuracies in the flow model because of lack of information far from the major pumping centers used for the original calibrations can be limiting. Inaccuracies in contour lines result from low spatial resolution of the model; inaccuracies also can result in deviations from a straight line on a semilogarithmic graph. Finally, energy loss due to well inefficiencies and all other limitations in the ground-water-flow model as described by Harsh and Laczniak (1990) apply to this study.

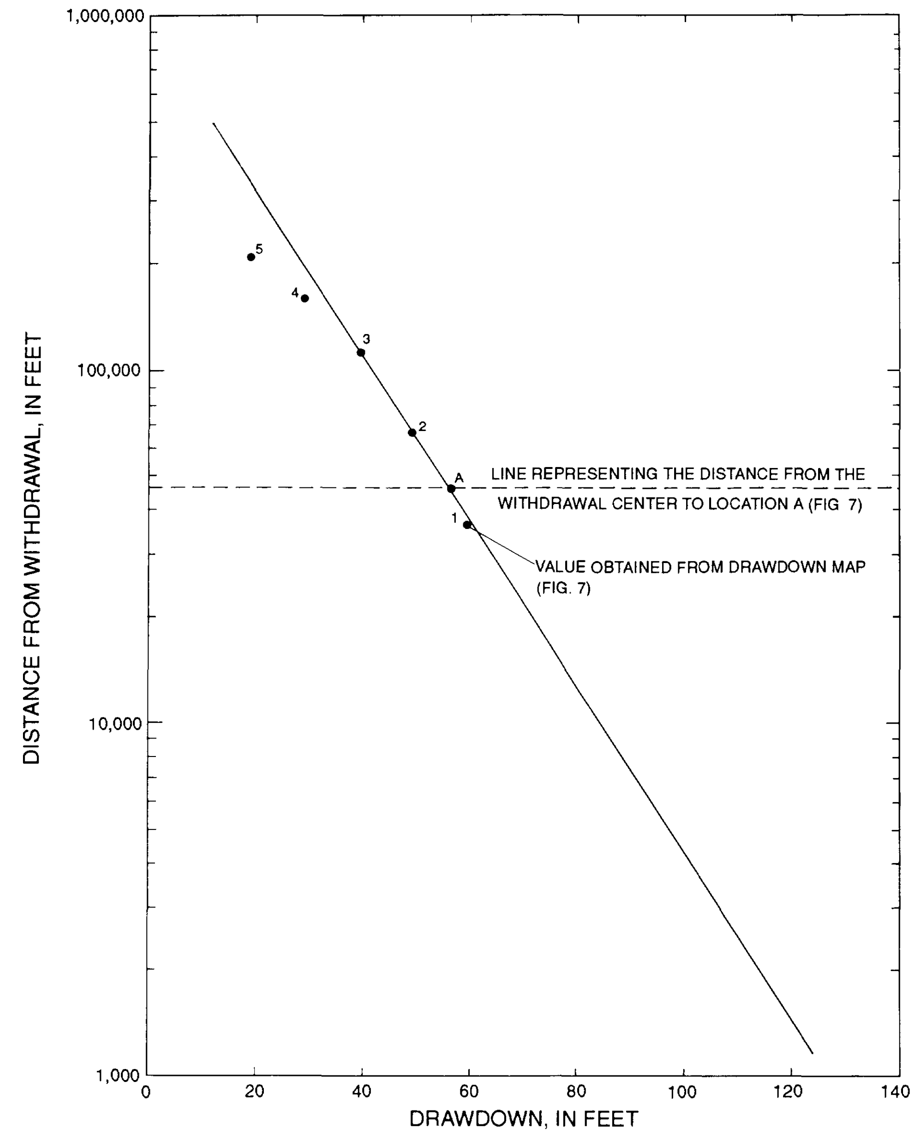


Figure 10. Straight-line semilogarithmic plot of distance and drawdown for 9 months.

The presence of coalescing drawdown cones caused by pumpage from wells in different grid cells can result in distance-drawdown lines (fig. 13) that differ as a function of flow direction. Distance and drawdown in two different directions from the center of withdrawal for the City of Norfolk after 1 year are shown in figure 13. The contours of drawdown used for this graph are shown in plate 4. Line 1 in figure 13 was constructed by plotting five points that began at the western withdrawal center (point A in pl. 4) and extended northward through five contours. Line 2 was constructed by plotting five points that began at the same location but extended eastward through five contours. Line 1 and 2 do not represent "lines of best fit" and are presented for illustrative purposes only. Line 2 shows a distinct difference in slope (point B in pl. 4). The interpolation scheme is not generally applicable where there are coalescing cones of depression due to simulation of multiple pumping centers. Where multiple pumping

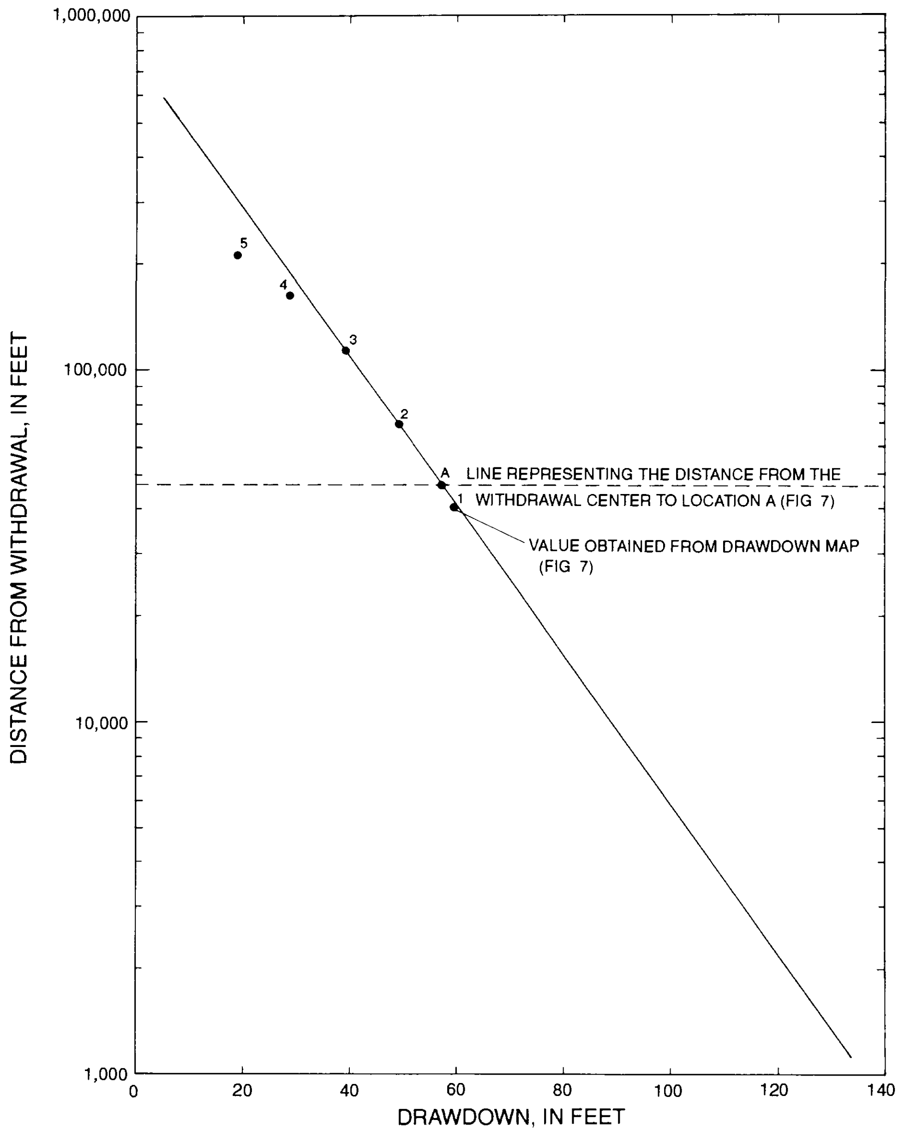
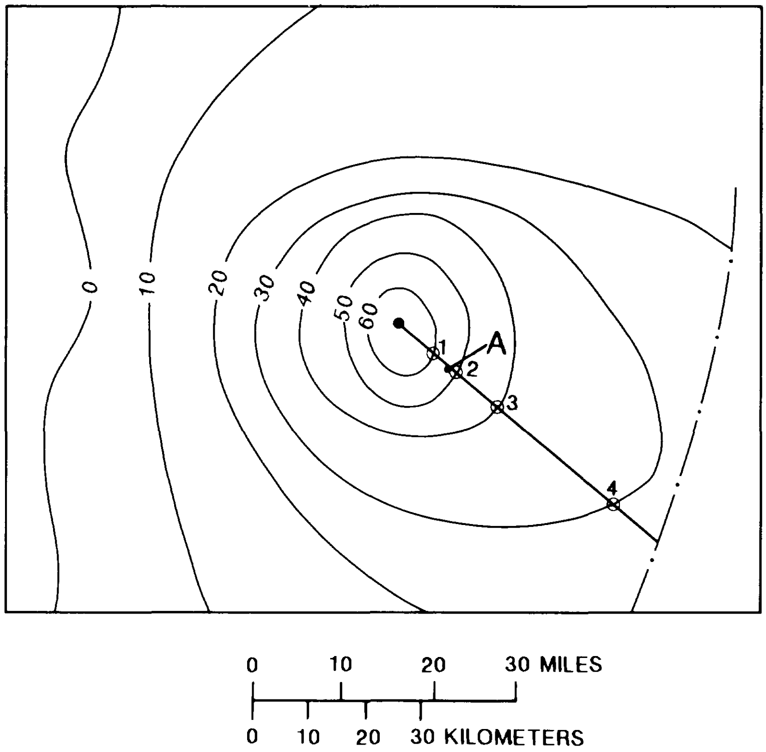


Figure 11. Straight-line semilogarithmic plot of distance and drawdown for 12 months.

centers are simulated, direct visual interpolation between contours is the best method to use to estimate the drawdown at a locality of interest for a given time. The alternative is to separately simulate drawdowns caused by withdrawals from each center and apply the graphical technique.

The resolution of the flow model also limits the shortest distance from the withdrawal center that can be accurately depicted. For example, each grid cell within the model represents an area within which values for properties, such as water levels and aquifer transmissivity that have been averaged. Consequently, drawdowns on the order of a grid-cell distance (1.75 mi in the area of finest resolution) from the withdrawal center are averaged within that distance.

The graphical method can produce accurate estimates of drawdown, provided that the assumptions made by the method and the limitations of the method are recognized and considered. In many cases, visual interpolation can be sufficient.



EXPLANATION

—— 20 —— LINE OF EQUAL DRAWDOWN--Interval 10 feet

———— DRAWN LINE USED FOR DISTANCE AND DRAWDOWN GRAPH

—— · —— ESTIMATED SEAWARD LIMIT OF AQUIFER--Less than 10,000 milligrams per liter chloride

● LOCATION OF PUMPED WELL

3○ POINT OF INTERSECTION OF LINE OF EQUAL DRAWDOWN AND DRAWN LINE

A LOCATION OF INTEREST IN ESTIMATING DRAWDOWN

Figure 12. Simulated drawdown for 12 months of continuous withdrawal by user 2.

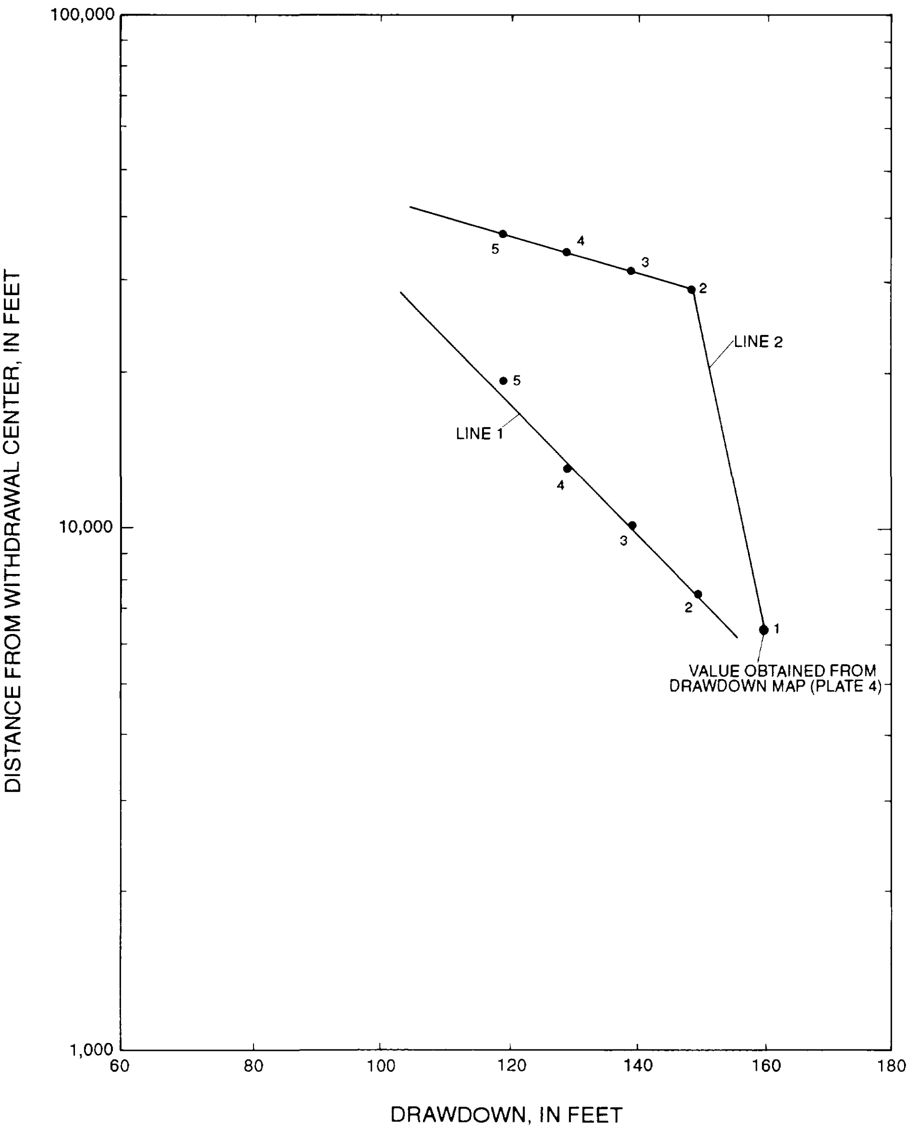


Figure 13. Straight-line semilogarithmic plot of distance and drawdown for 12 months for the City of Norfolk, Virginia.

SUMMARY

This report presents the results of a study by the U.S. Geological Survey, in cooperation with the Hampton Roads Planning District Commission, to describe a method of estimating net drawdown for episodic withdrawal of ground water in the Coastal Plain Physiographic Province of Virginia. The ground-water-flow system of the Coastal Plain Physiographic Province of Virginia consists of areally extensive and interconnected aquifers. Large, regionally coalescing cones of depression that are caused by large withdrawals of water are found in these aquifers. Local ground-water systems are affected by regional pumping, because of the interactions within the system of aquifers. Accordingly, these local systems are affected by regional ground-water flow and by spatial and temporal differences in withdrawals by various users.

A GIS was used to redesign a ground-water-flow model with a locally refined grid in the Virginia Coastal Plain. The output of the flow-model simulations was then

interfaced with the GIS to create drawdown maps for selected withdrawals and time intervals. Net drawdown for unscheduled, episodic withdrawal and recovery cycles can be estimated from these maps by application of the principle of superposition.

The method was applied to create drawdown maps in the Brightseat-upper Potomac aquifer for periods of 3, 6, 9, and 12 months for Chesapeake, Newport News, Norfolk, Portsmouth, Suffolk, and Virginia Beach, Virginia. Withdrawal rates were supplied by the individual localities and remained constant for each simulation period. The maps can be used to determine drawdowns caused by withdrawal at a specific well(s) at any given location for a range of withdrawal schedules by application of the principle of superposition. This provides an efficient method by which the individual local ground-water users can determine the amount of drawdown produced by their wells in a ground-water system that is a water source for multiple users and that is affected by regional-flow systems.

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(PAGE 21 FOLLOWS)

GLOSSARY

Aquifer. —A body of permeable and poorly permeable material that functions regionally as a water-yielding unit.

Cone of depression. —A depression of the potentiometric surface in the shape of an inverted cone that develops around a well which is being pumped.

Confined. —A modifier that describes a condition in which the potentiometric surface of ground water is above the top of the aquifer

Confined aquifer. —An aquifer bounded above and below by impermeable beds or by beds of distinctly lower permeability than that of the aquifer itself; an aquifer containing confined ground water.

Depositional environment. —The ambient conditions existing at the time sediments were deposited.

Drawdown. —The vertical distance that water level is lowered, or the reduction of pressure head because of the removal of water.

Episodic withdrawal.—Removal of water from a well on a noncontinuous basis.

Fall Line. —Imaginary physiographic feature that delineates the boundary between the Coastal Plain Physiographic Province and the Piedmont Physiographic Province.

Interpolated. —Estimation of an unknown value of a function between known values.

Leakage. —The flow of water from one hydrogeologic unit to another. The leakage may be through a semipervious confining layer.

Principle of superposition. —The effects of multiple stresses on a linear system are equivalent to the sum of the effects of the individual stresses.

Recovery. —The rise in water levels in a well following cessation of pumping the well.

Residual drawdown. —During a recovery period, the distance that the water level is found in a well to be below the initial (before pumping began) water level.

Spatial. —Relating to, occupying, or of the nature of space.

Temporal. —Of or relating to time.

Well interference. —Effects within an aquifer caused by interactions of wells that are pumped in proximity.