UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

A SPECIAL PLANNING TECHNIQUE FOR STREAM-AQUIFER SYSTEMS

By
C. T. Jenkins and O. James Taylor

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WATER
RESOURCES
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ABSTRACT

The potential effects of water-management plans on stream-aquifer systems in several countries have been simulated using electric-analog or digital-computer models. Many of the electric-analog models require large amounts of hardware preparation for each problem to be solved and some become so bulky that they present serious space and access problems. Digital-computer models require no special hardware preparation but often they require so many repetitive solutions of equations that they result in calculations that are unduly unwieldy and expensive, even on the latest generation of computers. Further, the more detailed digital models require a vast amount of core storage, leaving insufficient storage for evaluation of the many possible schemes of water-management. A concept introduced in 1968 by the senior author of this report offers a solution to these problems. The concept is that the effects on streamflow of ground-water withdrawal or recharge (stress) at any point in such a system can be approximated using two classical equations and a value of time that reflects the integrated effect of the following: irregular impermeable boundaries; stream meanders; aquifer properties and their areal variations; distance of the point from the stream; and imperfect hydraulic connection between the stream and the aquifer. The value of time is called the stream depletion factor (*sdf*). Results of a relatively few tests on detailed models can be summarized on maps showing lines through points of equal *sdf*. Sensitivity analyses of models of two large stream-aquifer systems in the State of Colorado show that the *sdf* technique described in this report provides results within tolerable ranges of error. The *sdf* technique is extremely versatile, allowing water managers to choose the degree of detail that best suits their needs and available computational hardware. Simple arithmetic, using, for example, only a slide rule and charts or tables of dimensionless values, will be sufficient for many calculations. If a large digital computer is available, detailed description of the system and its stresses will require only a fraction of the core storage, leaving the greater part of the storage available for sophisticated analyses, such as optimization. Once these analyses have been made, the model then is ready to perform its principal task--prediction of streamflow and changes in ground-water storage. In the two systems

described in this report, direct diversion from the streams is the principal source of irrigation water, but it is supplemented by numerous wells. The streamflow depends largely on snowmelt. Estimates of both the amount and timing of runoff from snowmelt during the irrigation season are available on a monthly basis during the spring and early summer. These estimates become increasingly accurate as the season progresses, hence frequent changes of stress on the predictive model are necessary. The *sdf* technique is especially well suited to this purpose, because it is very easy to make such changes, resulting in more up-to-date estimates of the availability of streamflow and ground-water storage. These estimates can be made for any time and any location in the system.

INTRODUCTION

Since the dawn of civilization, irrigation has played a major role in the production of food and fiber in arid and semiarid regions. In the valley of the River Nile, the agricultural economy, which was the mainstay of the Kingdom of the Pharaohs, depended almost entirely on natural irrigation by yearly inundation of the flood plain. During dry years, the insufficient natural flooding was supplemented by water lifted from the stream by crude, but clever devices powered by man or by beasts. The remains of canal networks that diverted water from the Rivers Tigris and Euphrates attest to human efforts to bring water to the crops that were essential to their economy. Few of these early efforts included significant storage facilities, hence the well-being--or even survival--of their cultures was profoundly dependent on the vagaries of the rivers. As time passed, this dependence was lessened by use of surface storage--and water-management planning was born. Today, most irrigation systems rely heavily on surface storage to improve the year-to-year adequacy of water for irrigation. Water from irrigation wells sometimes is used as a supplement, but seldom has been fully incorporated in management plans.

Storage Facilities

In many instances, surface impoundments are costly to construct and have a limited period of usefulness because of loss of storage space due to siltation. Even during their useful life, some are very inefficient because of excessive losses from evaporation and the attendant concentration of salts, inundation of productive land, and trapping of nutrients.

In many places streams and extensive alluvial aquifers are hydraulically connected, forming stream-aquifer systems. Planned conjunctive use of streamflow, surface storage, and water in the associated ground-water reservoir offers an attractive improvement over complete reliance on streamflow and surface storage. The planning of conjunctive use of water diverted directly from the stream and ground water withdrawn by wells is considerably more difficult than planning for a surface stream-reservoir system, but the results may be very rewarding. To name a few possible rewards, evaporation losses, concentration of salts, and water-logging of soils can be reduced, and the choice of means of delivery of water to the plants can be widened. For example, center-pivot sprinkler systems, which are supplied by large-capacity wells, are becoming increasingly important in one of the irrigation systems discussed in this report, principally because of the low cost of operation, especially in terms of manpower required. Water-management plans that did not consider the effects of these wells will become more and more unreliable as the number of sprinklers increases.

Planning Difficulties

One of the major obstacles in planning conjunctive use of ground and surface water has been the intricacy of the calculations necessary to assess transient ground-water flow. The planner has been faced with two alternatives: (1) questionable oversimplification of the system that is necessary in order to use directly two classical equations that apply to transient ground-water flow (Theis, 1941; Conover, 1954; Glover and Balmer, 1954; Glover, 1960; Theis and Conover, 1963; Hantush, 1964, 1965); or (2) construction of electric-analog or digital-computer models. Such models have been constructed in several countries to simulate the potential effects of water-management plans on complex stream-aquifer systems. Many electric-analog models require large amounts of hardware, and lengthy preparation for each problem to be solved and some become so bulky that they present serious space and access problems. Digital-computer models require no special hardware preparation but often require so many repetitive solutions of equations that calculations are unduly expensive and unwieldy, even on the latest generation of computers. Further, the more detailed digital models require a vast amount of core storage, leaving insufficient storage for evaluating the many possible schemes of water management.

Need

The need, then, is for a planning technique that is simple, that can be adapted to a wide range of computational hardware, and is sufficiently accurate to meet the requirements of sophisticated systems analyses such as optimization, linear programing, and most important, to provide a tool to predict changes in streamflow and ground-water storage during an irrigation season. Information inputs for such a planning technique include estimates of the amount and timing of water that will enter the system, crop requirements, and legal constraints.

A most desirable feature of the predictive tool is ease in updating as estimates of the inputs become progressively more accurate. In the two systems discussed in this report, direct diversion from the streams is the principal source of irrigation water, but is supplemented by numerous wells. The streamflow depends largely on snowmelt during the spring and early summer. Estimates of both the amount and timing of snowmelt runoff during the irrigation season are made, beginning in March. As the season progresses, these estimates become increasingly accurate, hence frequent changes in programed recharge to or withdrawal from the aquifer (positive or negative aquifer stresses, see Moulder and Jenkins, 1969) on the predictive model are imperative. These changes can be made on a detailed digital model with relative ease, but, because of the nature of the necessary computational procedure, the time steps following the changes must be reduced to the very small values used initially in order to simulate the change accurately, thereby adding substantially to computer time.

Purpose

The purpose of this report is to describe a special planning technique that efficiently meets these needs. The technique has been developed for two large systems in Colorado; the irrigated valleys of the Arkansas and of the South Platte Rivers. The use of the technique is not confined to those two systems; it can be used in similar systems anywhere in the world. It is emphasized that the technique does not provide a means of calculating the distribution of head in the aquifer; the sole concern is calculating the interrelated changes in streamflow and aquifer storage. Discussion of the assumptions made, the mathematics, and the errors introduced are given by Jenkins (1968a, 1968b, 1970).

THE CONCEPT

The technique is based on the concept (Jenkins, 1968a) that the effects on streamflow of aquifer stresses can be approximated by use of the two classical equations and a system descriptor that has the dimension of time. The basis for the concept is the similarity in shape of (1) the response curves of effect on streamflow by a steady stress on a detailed model, reduced to a dimensionless basis, and (2) the dimensionless curves defined by the two equations. The equations are:

$$q/Q = \operatorname{erfc}\left(\frac{a}{\sqrt{4tT/S}}\right) \qquad (1)$$

and

$$\frac{v}{Qt} = 4i^2 \operatorname{erfc}\left(\frac{a}{\sqrt{4tT/S}}\right) \qquad (2)$$

for which:

v = the volumetric change in streamflow caused by an aquifer stress from the beginning of the stress [L^3],

t = the time since the aquifer stress began [T],

a = the distance from the point of stress to the stream [L],

q = the instantaneous rate of effect on streamflow caused by a stress on an aquifer hydraulically connected to the stream [L^3/T],

Q = the steady rate of aquifer stress [L^3/T],

T = the transmissivity of the aquifer [L^2/T],

S = the specific yield of the aquifer [dimensionless],

erfc = the complementary error function, and

i^2 erfc = the second repeated integral of the error function.

The system descriptor, which is called the stream depletion factor (*sdf*), is defined as the time, measured from the beginning of a steady aquifer stress, during which the accumulated change in streamflow volume is 28 percent (an arbitrary value that has no special significance) of the accumulated volume of a steady stress. In the idealized system, which is a semi-infinite, homogeneous, isotropic aquifer fully penetrated by a straight, infinitely long stream, the *sdf* equals a^2S/T; in real systems, the *sdf* values are determined by simple tests at selected points on the model, and reflect the integrated effect of the following: irregular impermeable boundaries; stream meanders; aquifer properties and their areal variations; and distance of the point from the stream.

The results of a relatively few tests on the detailed model can be generalized on maps showing lines of equal *sdf* values (Jenkins, 1968b; Jenkins and Taylor, 1972), thus providing a succinct description of the hydraulics--the plumbing, so to speak--of the system. These maps provide even a nontechnical user with a suitable frame of reference. A part of one of the *sdf* maps for the Arkansas River valley is shown on figure 1.

COMPUTATIONS

The basic curves (fig. 2) and table 1 apply directly during periods of steady stress, and are graphical and tabular expressions of equations (1) and (2, expanded) rewritten using the term *sdf* for the term a^2S/T as:

$$q/Q = \text{erfc}\left(\sqrt{\frac{sdf}{4t}}\right) \tag{3}$$

and

$$\frac{v}{Qt} = \left(\frac{sdf}{2t} + 1\right)\text{erfc}\left(\sqrt{\frac{sdf}{4t}}\right) - \left(\sqrt{\frac{sdf}{4t}}\right)\frac{2}{\sqrt{\pi}}\exp\left(-\frac{sdf}{4t}\right) \tag{4}$$

The column headed $\frac{v}{Q\ sdf}$ in table 1 is convenient in calculations of effects on streamflow after the stress is stopped.

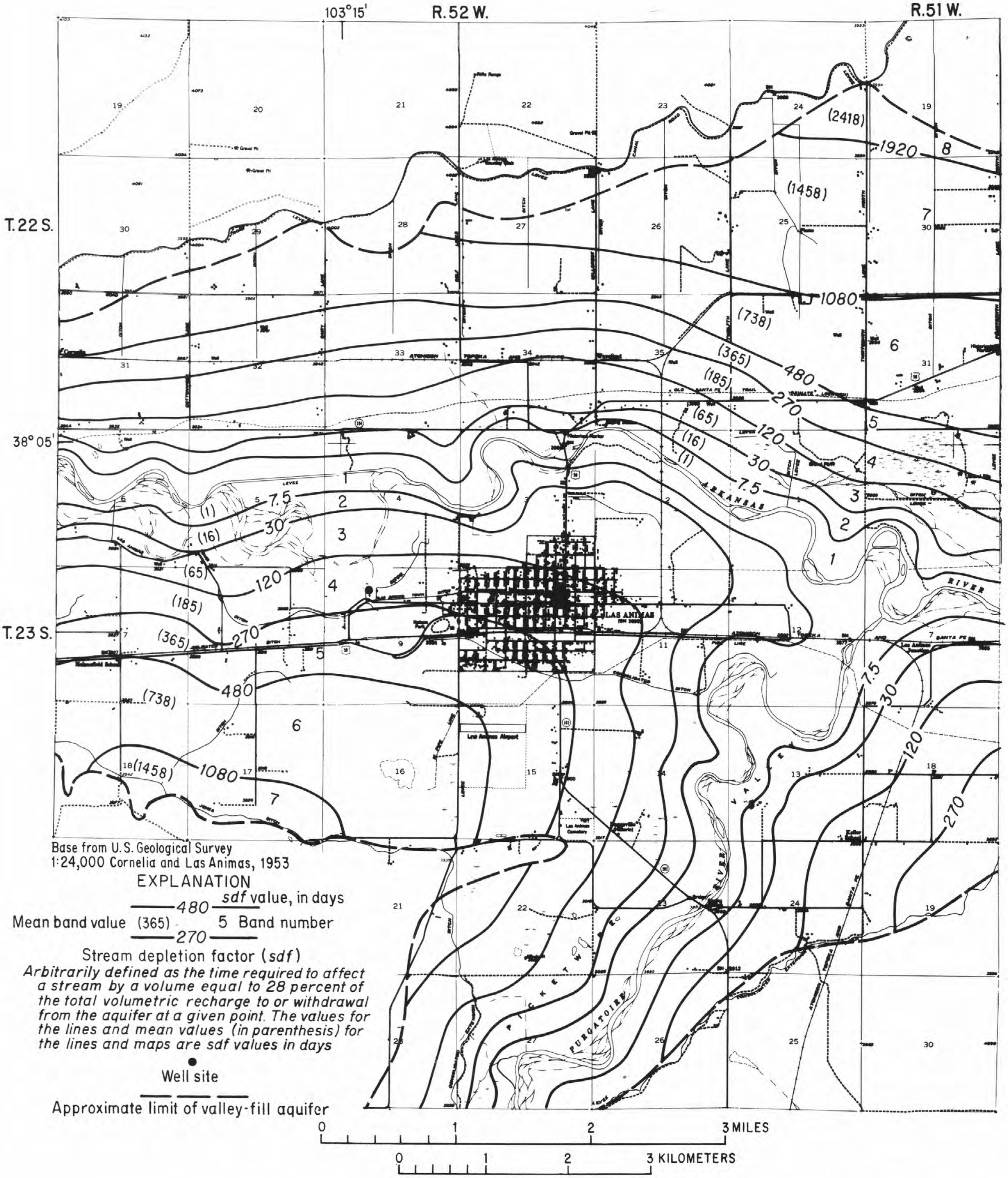

Figure 1.--Map of part of the Arkansas River valley, Colorado, showing lines of equal *sdf*.

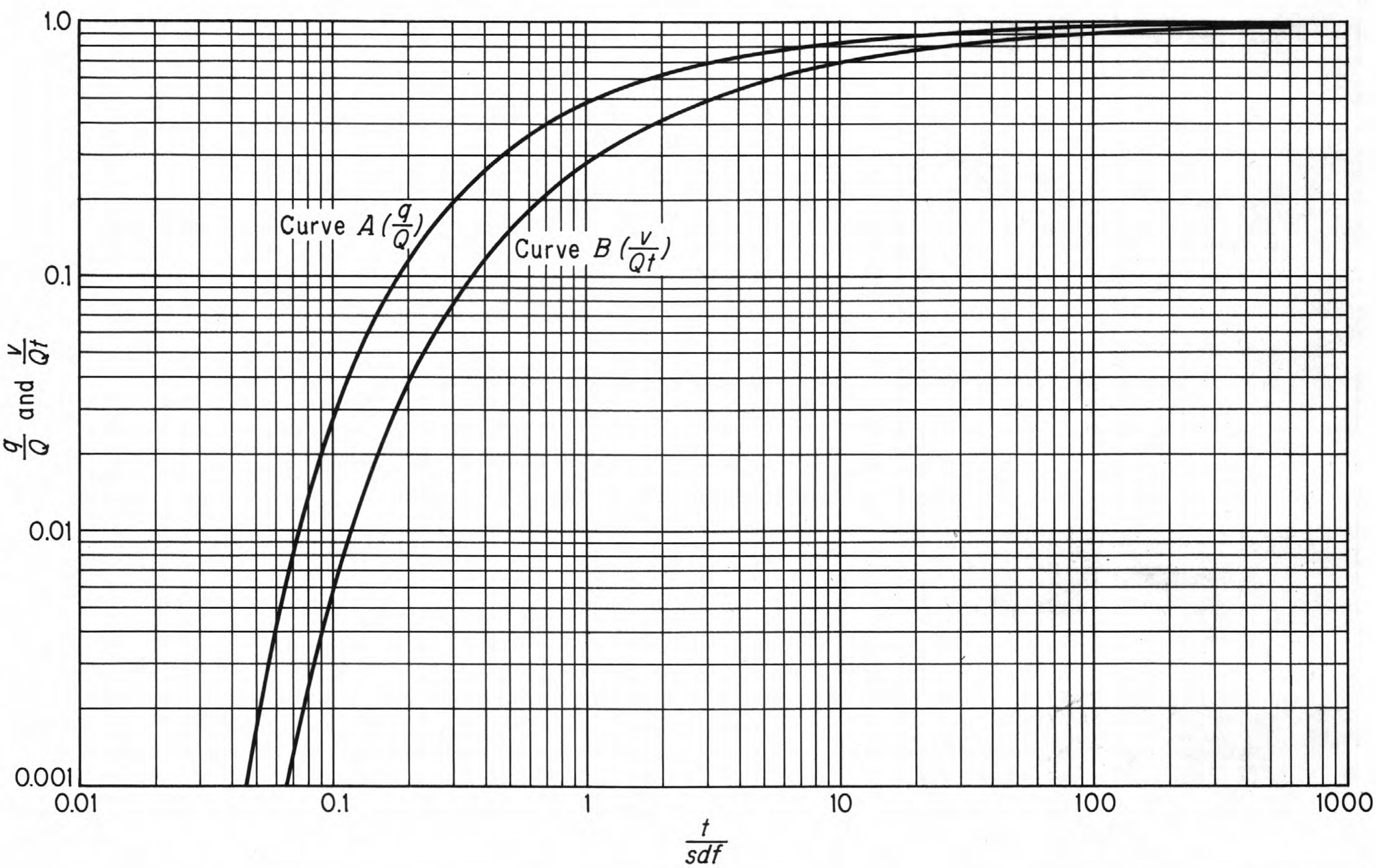

Figure 2.--Curves to determine rate and volume of effects on a stream caused by stresses on the aquifer.

Table 1.--Values of q/Q, $\frac{v}{Qt}$, and $\frac{v}{Q\ sdf}$ corresponding to selected values of t/sdf

$\frac{t}{sdf}$	q/Q	$\frac{v}{Qt}$	$\frac{v}{Qsdf}$
0	0	0	0
.07	.008	.001	.0001
.10	.025	.006	.0006
.15	.068	.019	.003
.20	.114	.037	.007
.25	.157	.057	.014
.30	.197	.077	.023
.35	.232	.097	.034
.40	.264	.115	.046
.45	.292	.134	.060
.50	.317	.151	.076
.55	.340	.167	.092
.60	.361	.182	.109
.65	.380	.197	.128
.70	.398	.211	.148
.75	.414	.224	.168
.80	.429	.236	.189
.85	.443	.248	.211
.90	.456	.259	.233
.95	.468	.270	.256
1.0	.480	.280	.280
1.1	.500	.299	.329
1.2	.519	.316	.379
1.3	.535	.333	.433
1.4	.550	.348	.487
1.5	.564	.362	.543
1.6	.576	.375	.600
1.7	.588	.387	.658
1.8	.598	.398	.716
1.9	.608	.409	.777
2.0	.617	.419	.838
2.2	.634	.438	.964
2.4	.648	.455	1.09
2.6	.661	.470	1.22
2.8	.673	.484	1.36
3.0	.683	.497	1.49
3.5	.705	.525	1.84
4.0	.724	.549	2.20
4.5	.739	.569	2.56
5.0	.752	.587	2.94
5.5	.763	.603	3.32
6.0	.773	.616	3.70
7	.789	.640	4.48
8	.803	.659	5.27
9	.814	.676	6.08
10	.823	.690	6.90
15	.855	.740	11.1
20	.874	.772	15.4
30	.897	.810	24.3
50	.920	.850	42.5
100	.944	.892	89.2
600	.977	.955	573

Residual Effects

Changes in streamflow due to a stress on the aquifer continue after the stress is stopped. These changes are called residual effects in this report. As time approaches infinity, the accumulated change in streamflow approaches the total accumulated volume of stress, and the rate of change in streamflow approaches zero. In a real system, the multitude of streamflow changes due to a multitude of aquifer stresses tend to mask out the effects of any single stress; however, the equations are linear, hence the principle of superposition applies. Thus, residual effects can be evaluated by assuming that the stress continues and that an imaginary stress equal in magnitude but opposite in sign begins at the time the stress in question is stopped. The curves in figures 3 and 4 show residual effects for five selected dimensionless stress-duration times. The duration of stress is indicated by t_p, and t_i indicates the time after stress ends.

Sample Computation

The *sdf* technique is extremely versatile, allowing water managers to choose the degree of detail that best suits their needs and available computational hardware. Simple arithmetic using only a slide rule and the dimensionless curves or tables would, for example, be sufficient for many calculations.

An example of such computations is: A municipal well is to be drilled at the location shown by the dot on figure 1. Downstream water use requires that the depletion of the stream be limited to no more than 10^5 cubic metres during the irrigation season, which commonly is about 200 days. The well will be pumped continuously during the irrigation season only. Winter recharge is ample to replenish ground-water storage depleted by pumping in the previous irrigation season, thus residual effects can be disregarded.

Interpolation between the 120- and 270-day *sdf* lines gives an *sdf* value of 213 days at the proposed well site.

What is the maximum allowable rate of continuous pumping?

Given: sdf = 213 days
t = 200 days
$v = 10^5$ m^3
t/sdf = 0.94

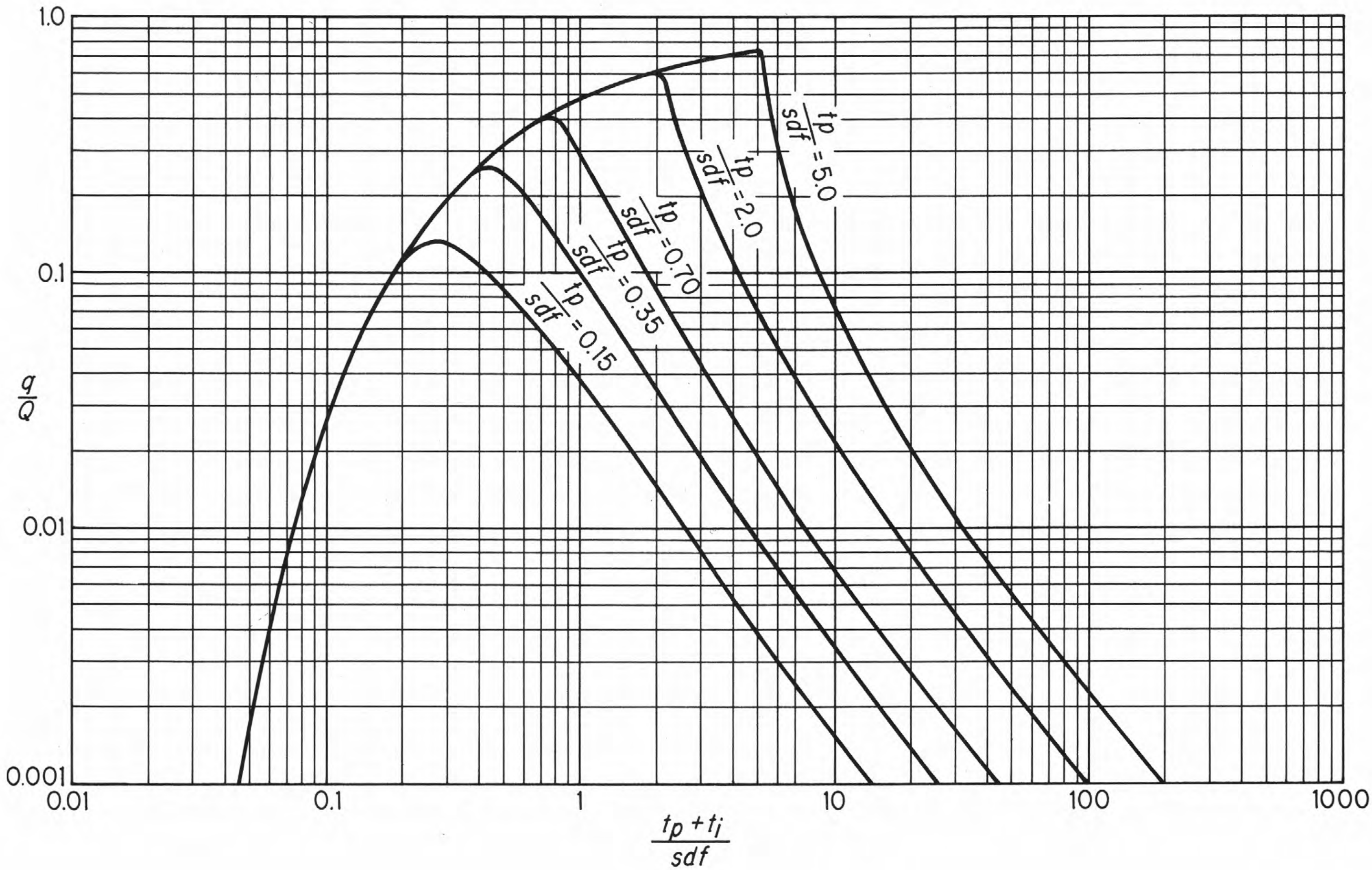

Figure 3.--Curves to determine rate of effect on streamflow during and after stress on the aquifer.

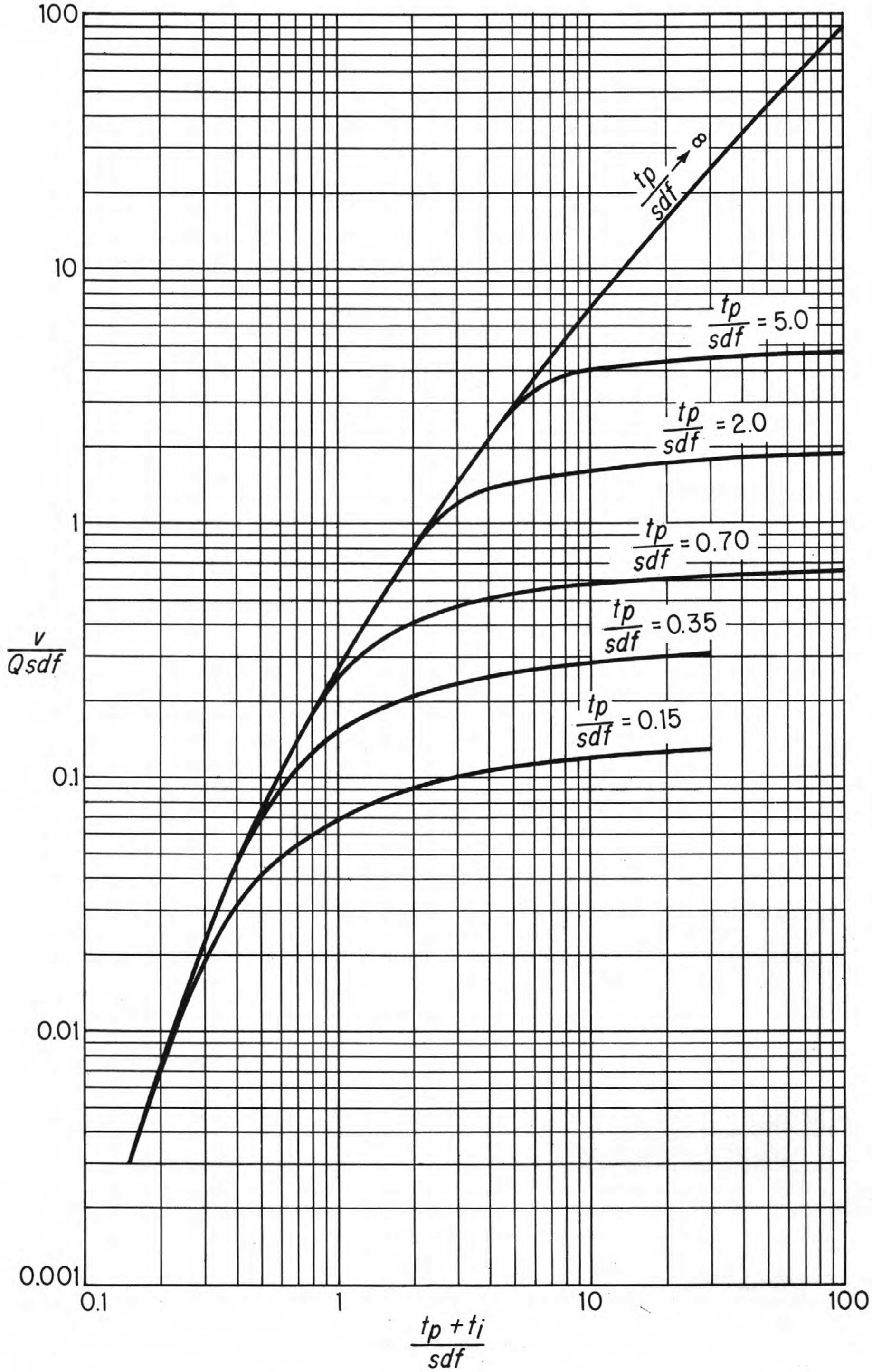

Figure 4.--Curves to determine cumulated effects on streamflow during and after aquifer stress.

From table 1, $v/Qt = 0.268 = \frac{10^5 \text{ m}^3}{Q \text{ (200 days)}}$

$$Q = \frac{10^5 \text{ m}^3}{(0.268)\ (200 \text{ days})} = \frac{10^5 \text{ m}^3}{53.6 \text{ days}} = \frac{1{,}870 \text{ m}^3}{\text{day}}$$

Jenkins (1968a, 1970) has shown many more examples of the solutions of problems that have to do with the conjunctive use of ground and surface water, using only simple arithmetic.

Complex Computations

The *sdf* concept is well adapted to the solution of problems involving an entire stream-aquifer system if a large-capacity digital computer is available. Moulder and Jenkins (1969) demonstrated a computational method that uses a "mean" value of *sdf* for each area (band) between lines of equal *sdf*. This method results in a compact description of the stream-aquifer system that has as much as two orders of magnitude fewer "computational nodes" than the number on the detailed model, drastically reducing the computer time and core storage needed to analyze the system. Computer time is further reduced by using terms (equations 3 and 4) that are furnished routines in many computer libraries rather than the simultaneous solution of many differential equations.

The compact model of the system occupies only a fraction of the core storage, leaving the greater part for optimization of management plans and other sophisticated analyses. Once these analyses have been made, the model then is ready to perform its principal task--prediction of streamflow and changes in ground-water storage for water-management purposes. Moulder and Jenkins (1969) have shown the results of manipulation of withdrawals from the ground-water reservoir to meet a downstream surface-water right, and have discussed, briefly, optimization of management plans.

REAL SYSTEMS

Detailed models were constructed for the two systems in Colorado; an electric-analog model of the Arkansas River valley and a digital model of the South Platte River valley. The results of 266 simple tests on the model of the 120,000 hectare Arkansas Valley, and 259 on the model of the 260,000 hectare South Platte Valley were sufficient to prepare the *sdf* maps of the two systems. Both detailed models used a finite difference approximation; about 30,000 nodes on the Arkansas Valley model, and the equivalent of about 60,000 nodes for the South Platte Valley model. The technique described reduced the number of "computational nodes" to fewer than 300 on the Arkansas Valley model (Jenkins and Taylor, 1972) and about 600 nodes on the South Platte Valley model (Hurr and others, 1972a, b, c, d, e, and f). Sensitivity analyses on the Arkansas Valley model showed that the loss in accuracy due to these reductions was minimal, very much less than the probable range in error in, for example, estimates of the amount and timing of snowmelt runoff.

The technique was used to simulate the historical operation of the hydrologic system in the Arkansas River valley (Taylor and Luckey, 1972). The simulation indicated an important constraint in water management. About 75 percent of precipitation and applied irrigation water is consumed and hence unavailable for reuse. The remaining 25 percent of applied water is recharged to the aquifer and returns to the stream or is intercepted by wells. The simulation of 5 years of historical data in monthly time intervals required only 20 seconds of computer time using an IBM 360/65 computer. The technique has been extended to water-management analyses of the entire hydrologic and irrigation system. Preliminary results indicate an integrated management plan for the stream-aquifer system would be the most beneficial. The extensive use of ground water during years of below normal runoff can increase the dependable supply and greatly increase the yield from irrigated land. Prediction runs are in progress and will be used to estimate the surface and ground water available to each water user. A predictable supply will allow the water users to plan the type of crop, labor force, and water delivery so as to reduce the number of years in which the yield from irrigated land is meager. The prediction runs simulated 24 months of prior operation and 12 months in the future. The 36-month simulations require only about 18 seconds of computer time.

Detailed models are not always necessary; a hydrologist who has prepared or assisted in the preparation of *sdf* maps from detailed models can produce an acceptable description of an unmodeled system, using intuitive reasoning, estimates of the hydraulic diffusivity of the aquifer, and consideration of its boundaries. For example, the junior author of this report has prepared such a description of a part of the valley of the Rio Aconcagua in Chile (Taylor, 1970).

The valley-fill aquifer of the Rio Aconcagua valley is thick but the hydraulic conductivity is small. A 24-month simulation was prepared to determine the effects of canal and well irrigation, consumptive use, and evapotranspiration from the shallow water table. The analysis showed that withdrawals from wells had a delayed effect on streamflow of several months due to the small transmissivity of the aquifer. The simulation required only 2 minutes of computer time using an IBM 365/40 computer.

SUMMARY AND CONCLUSION

In summary, a planning technique has been developed that facilitates the prediction of the hydrologic effects of water-management practices in stream-aquifer systems. The technique, based on equations for flow in porous media utilizes a stream-aquifer system descriptor called the stream depletion factor--*sdf*. The *sdf* technique is especially well suited to solving management problems that require prediction of streamflow and changes of ground-water storage.

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