UNITED STATES DEPARTMENT OF THE INTERIOR
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STREAM DEPLETION FACTORS, ARKANSAS RIVER VALLEY, SOUTHEASTERN COLORADO

A basis for evaluating plans for conjunctive use of ground and surface water

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Prepared in cooperation with the
COLORADO WATER CONSERVATION BOARD
and the
SOUTHEASTERN COLORADO WATER CONSERVANCY DISTRICT

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PREFACE

This report uses techniques explained in four papers that were prepared in cooperation with the Colorado Water Conservation Board and the Southeastern Colorado Water Conservancy District. Three of the papers (Jenkins, 1968a, 1968b; Moulder and Jenkins, 1969) were published in *Ground Water*, the journal of the Technical Division, National Water Well Association. The fourth (Jenkins, 1970) was published as a techniques manual of Water-Resources Investigations of the U.S. Geological Survey. Users of this report will find that the detailed discussions contained in the four papers mentioned above will be helpful.

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INTRODUCTION

The Arkansas River valley is a stream-aquifer system that consists of the Arkansas River and the associated valley-fill deposits. The hydrology, geology, and water-resources development in the valley have been described by Moore and Wood (1967). The history of delivery of irrigation water by canals indicates that the supply has been inadequate during some seasons and some years. The shortage can be reduced by carefully designed conjunctive use of ground and surface water. An analog model of the Arkansas River valley in Colorado was constructed to facilitate such designs (Moore and Wood, 1967).

The purpose of this report is to make hydrologic maps available to water managers and planners. The maps are useful for estimating the changes in streamflow caused by recharge to or withdrawal of ground water from the valley-fill aquifer between Pueblo, Colo. and the Kansas State line (fig. 1). Use of the maps (figs. 2-5) and a concept described will assist planners and managers in their task of providing timely delivery of water to the users, and in the administration of water laws.

Planned conjunctive use of ground water and surface water entails some degree of prediction, both of streamflow and changes in ground-water storage, which in turn requires analyses of the interaction between ground and surface water. Until recently, prediction of the interaction between ground and surface water depended almost entirely on two mathematical equations derived by several investigators (Theis, 1941; Conover, 1954; Glover and Balmer, 1954; Glover, 1960; Theis and Conover, 1963; Hantush, 1964, 1965). The equations are:

$$q/Q = \mathrm{erfc}\left(\frac{a}{\sqrt{4tT/S}}\right) = 1 - \mathrm{erf}\left(\frac{a}{\sqrt{4tT/S}}\right) \qquad \ldots\ldots\ldots\ldots \quad 1$$

and

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

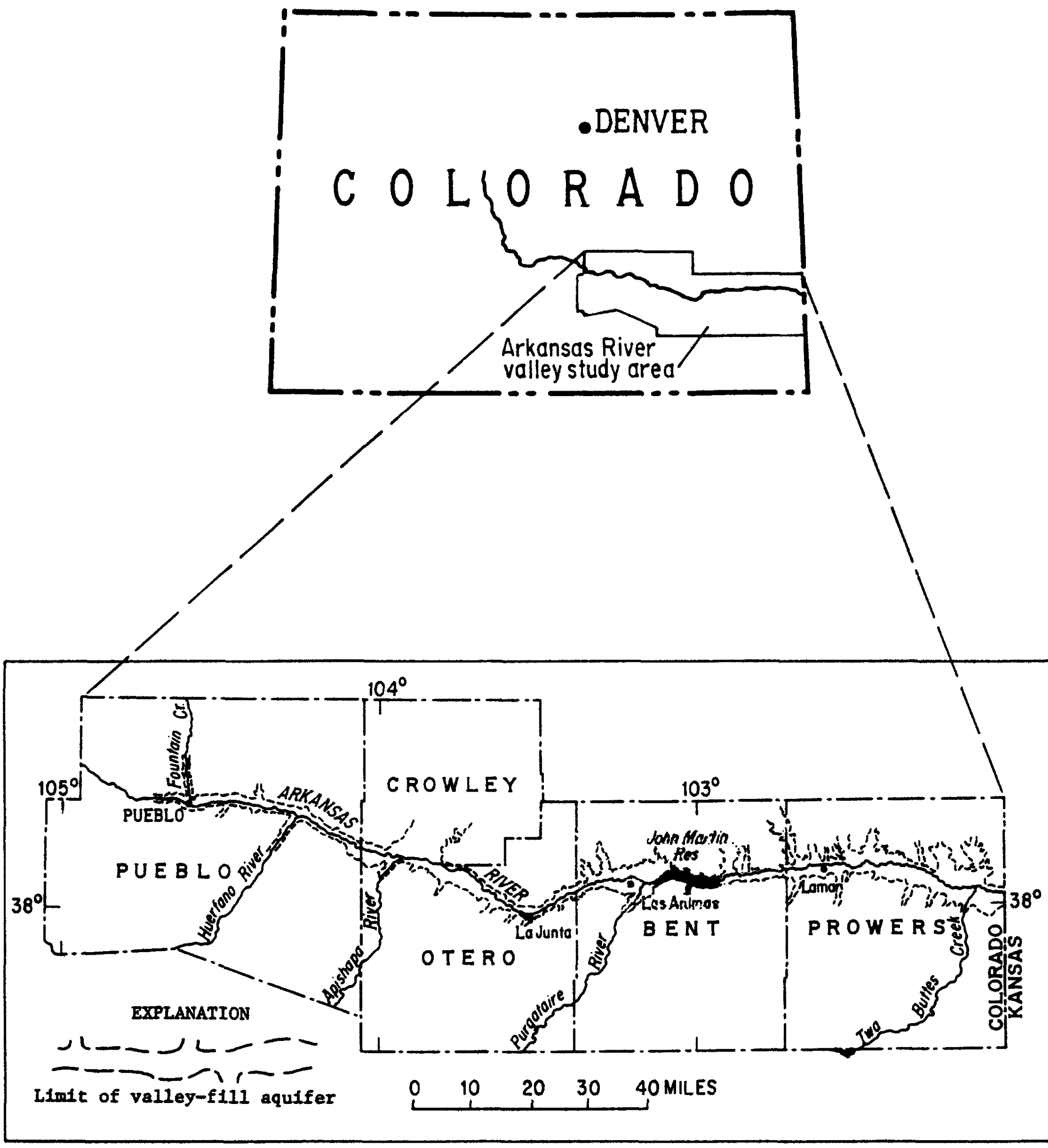

Figure 1.--Index map showing extent of valley-fill aquifer of Arkansas Valley in southeastern Colorado.

for which:

v = the volumetric change in streamflow caused by recharge to, or withdrawal of water from an aquifer during a specified time.

t = the elapsed time since recharge or discharge of water to or from an aquifer began.

a = the distance from the point of recharge or discharge of water to or from an aquifer to the stream.

q = the instantaneous rate of effect on streamflow caused by recharge to, or withdrawal from an aquifer hydraulically connected to the stream.

Q = the steady rate of recharge or discharge of water to or from an aquifer.

T = the transmissivity of the aquifer.

S = the specific yield of the aquifer.

erf = the error function.

erfc = the complementary error function.

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

Equation 1 is used to calculate the change in streamflow at time t caused by recharge to or withdrawal of water from an aquifer that is hydraulically connected to the stream. Equation 2 is used to calculate the volumetric effect on the stream caused by recharge to or withdrawal of water from an aquifer between times $t = 0$ and $t = t$. The equations can be used with any consistent units.

These equations *directly apply only to the idealized system*, which is a semi-infinite, homogeneous, isotropic aquifer *fully penetrated* by a *straight, infinitely long stream.* Real systems invariably are much more complex, generally to a degree that casts doubt on the validity of the results from equations 1 and 2. Analyses of real systems using models, either electric or digital, can account for heterogeneity and nonlinear boundaries. Even so, study of complex aquifer and stream systems requires an inordinate amount of manpower and computer time. However, results from a comparatively few simple tests on a model can be generalized for calculating the desired quantitative relation between streamflow and recharge tc or withdrawal from the aquifer, using a technique that employs a concept called the stream depletion factor.

STREAM DEPLETION FACTOR

The basic concept introduced by Jenkins (1968a, 1970) is that the effects on streamflow of ground-water withdrawal or recharge at any point in a stream-aquifer system can be approximated by equations 1 and 2 and a system descriptor which has the dimension of time. The descriptor, which Jenkins has called the stream depletion factor, or *sdf*, can be obtained by a test on a model. The *sdf* summarizes the effects of the hydraulic properties of the aquifer and the locations and types of boundaries. The *sdf* was arbitrarily chosen as the elapsed time over which streamflow volume is changed in the amount, 28 percent of the cumulative recharge or withdrawal volume. For example, if the *sdf* at a discharging well is 65 days, after 65 days of constant withdrawal the stream is depleted by a volume equal to 28 percent of the volume withdrawn from the well. The arbitrary use of 28 percent to define the *sdf* was designed to simplify calculations. In the measurement and use of the *sdf*, it is assumed that the hydraulic properties of the aquifer and the location of all boundaries remain constant and the stream and certain tributaries are hydraulically connected with the valley-fill aquifer. The *sdf* concept can be used to calculate curves or coefficients which describe both the rate or cumulative volume of streamflow change due to virtually any type of intermittent, variable, or constant recharge or discharge. The effect on streamflow is directly proportional to the rate of recharge or discharge, under the stated assumptions.

The simplification of the interrelation between ground water and surface water was done in the following steps:

1. Preparation of a simulation model of the stream-aquifer system.

2. Determination of the stream depletion factor at selected locations in the system, using the model.

3. Contouring of selected values of the stream depletion factor, which subdivides the system into bands which are approximately parallel to the stream, and possibly tributaries to the stream.

4. Calculation of the average stream depletion factor of each band.

5. Generation of response curves for each band using the average stream depletion factor of the band and the solution of equation 2 obtained from a digital computer.

6. Selection of a time interval for use in subsequent simulations. Use of the digital computer and the principle of superposition to partition the response curves into response coefficients during each time interval due to unit recharge or discharge with a duration of one time interval.

7. Simulation of the effects of recharge and discharge during each time interval by multiplying rates of recharge or discharge in each band times the corresponding response coefficients. Superposition of results in time and space, where required.

The *sdf* was measured for 266 locations in the alluvial aquifer of the Arkansas Valley, shown on figures 2-5, using an electric analog model. The *sdf* values were contoured, and the resultant lines of constant *sdf* are presented on the maps, figures 2-5. Horse Creek, Adobe Creek, Apishapa River, Limestone Creek, and the Purgatoire River are tributary to the Arkansas River and are hydraulically connected to the valley-fill aquifer. Therefore the lines of constant *sdf* tend to parallel the above named tributaries and the Arkansas River. The maps were generalized by division into a maximum of 10 bands on each side of the river. The effect of recharge or withdrawal in any band can be calculated by using the average *sdf* value of the band, shown in parentheses on the maps. The generalization into bands allows rapid and simplified analysis of very complicated patterns of recharge and discharge (see Moulder and Jenkins, 1969). It is emphasized that the *sdf* concept cannot be used to calculate head distribution in the aquifer.

Hand calculations were simplified further by partitioning the volumetric effect on the river into monthly response by band. Monthly time intervals were used because of the normal availability of monthly hydrologic data. Table 1 shows a matrix of values that describes the volumetric effect on streamflow of aquifer recharge or withdrawal of 1 acre-foot for 1 month. The values were generated by a digital computer using the mean *sdf* value for each band and equation 2. The values must be multiplied by the actual recharge or withdrawal rate, and may be superimposed.

Example 1:

Estimate the approximate average rate of effect on the stream during June, assuming that wells in band 2 were pumped at 100 acre-feet per month in April.

-100 (0.0732) = 7.3 acre-feet per month depletion.

Example 2:

Estimate the approximate volume of return flow to the stream during June, July, and August, assuming that band 4 is recharged in June and July at 1,000 acre-feet per month.

Effect of June recharge = 1,000 (0.0239 + 0.1288 + 0.1159) = 269 acre-feet

Effect of July recharge = 1,000 (0.0239 + 0.1288) = 153 acre-feet

Total return = 422 acre-feet

Table 1.--*Coefficients*[1] *of volumetric change in streamflow caused by recharge to or withdrawal from the Arkansas River valley alluvial aquifer of 1 acre-foot per month for 1 month*

sdf Band	Months since recharge or withdrawal began											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.8113	0.1041	0.0196	0.0102	0.0065	0.0046	0.0035	0.0028	0.0023	0.0019	0.0016	0.0014
2	.4092	.2620	.0732	.0389	.0252	.0180	.0137	.0109	.0089	.0075	.0064	.0055
3	.1398	.2537	.1179	.0682	.0458	.0335	.0259	.0208	.0171	.0144	.0124	.0108
4	.0239	.1288	.1159	.0818	.0601	.0463	.0370	.0304	.0255	.0218	.0189	.0166
5	.0028	.0437	.0744	.0690	.0579	.0481	.0405	.0345	.0298	.0260	.0229	.0204
6	.0001	.0053	.0227	.0347	.0378	.0368	.0344	.0316	.0288	.0263	.0240	.0220
7	.0000	.0001	.0021	.0069	.0121	.0158	.0179	.0190	.0193	.0191	.0186	.0180
8	.0000	.0000	.0001	.0007	.0022	.0042	.0062	.0079	.0092	.0102	.0109	.0113
9	.0000	.0000	.0000	.0000	.0003	.0007	.0015	.0024	.0033	.0042	.0050	.0056
10	.0000	.0000	.0000	.0000	.0000	.0000	.0001	.0002	.0004	.0007	.0010	.0014

[1] Coefficients are dimensionless and may be used with any volumetric units.

Calculations can be made of the effects of a single well (Jenkins, 1968a, 1970) or for several wells that are not uniformly distributed over a band, by using the *sdf* of each well, which can be determined by interpolation (see Jenkins, 1968b).

CONCLUSIONS

By using the concept of the stream depletion factor in a stream-aquifer system, the valley-fill aquifer of the Arkansas River valley has been subdivided into bands based on the response of the stream to recharge to or withdrawal from the aquifer. The use of monthly response coefficients for each band and the principle of superposition facilitate the calculation of the approximate effects on streamflow of aquifer recharge and withdrawal, expressed as a rate or volume. The resulting quantitative description of the stream-aquifer interrelation should be extremely valuable in management studies designed to improve water delivery.

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