FINAL REPORT

A Study of the Salt-Water Intrusion Problem Between Salina, Kansas, and Solomon, Kansas, in the Smoky Hill River Valley - Addendum

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ABSTRACT

When the original report, "A Study of the Salt-Water Intrusion Problem Between Salina, Kansas, and Solomon, Kansas, in the Smoky Hill River Valley," was completed as originally planned, several additional points had come to light and needed additional research. This addendum addresses those points we felt most deserving of additional research.

The following points are with regard to the Wellington aquifer model. Improved valley wall definition did not significantly change the results of the original report. The volume reductions of salt-water leakage are still in the 20% range. Regional flow can capture about 50% of the fresh-water leakage induced by the relief wells in some cases. The result is that the water discharged in the natural discharge zone is considerably diluted. The net effect of the relief well system may be a reduction of 70-80% in the salt load discharged to the alluvium. However, studies of the time scale for the dilution to occur indicates that 50-150 years may elapse before most of the dilution effect is felt at the discharge area.

We have also considered several factors affecting chemical quality of the water pumped during a Wellington aquifer pump test. The fresh-water leakage induced by pumping could dilute the pumped water and lower the concentrations of various constituents. We have considered the time for water to move through the confining layer, leakage as a function of radial distance, travel time as a function of radial distance, and the effect of regional flow. The conclusion is that for the typical pumping test lasting only a few weeks no significant change in chemical quality should be observed.

The following comments are with regard to the effectiveness of a bank-side alluvial relief well system. First of all, we estimated the effect on a single rather small flood event. We found that pumping at or double the

estimated bedrock flux value would not prevent upconing after the flood peak; however, it did reduce the intrusion to the river considerably. Pumping at double the bedrock flux rate would cause the salt-water mound under the river to decay.

Similar results were found with a more detailed model that tried to take into account a series of flood events. The pumpage from the bank-side alluvial relief well system could not always prevent upconing following a sizeable flood event at pumpage rates equal to or double the estimated bedrock flux. However, the relief well system did lower the peaks in the chloride concentration considerably.

Lastly, a series of hypothetical management schemes were tested to try to control the chloride concentration. The net result was that, if concentrated brine could be withdrawn from the alluvium and placed in either a reservoir or the river at the appropriate time, the river chloride concentration could be maintained at or below 250 mg/l. However, there are several practical problems that would prevent the complete accomplishment of this feat.

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I. INTRODUCTION

When the original report, "A Study of the Salt-Water Intrusion Problem Between Salina, Kansas, and Solomon, Kansas, in the Smoky Hill River Valley," was completed as originally planned, several additional points had come to light and needed additional research. This addendum addresses those points we felt most deserving of additional research.

First of all, with regard to the Wellington aquifer simulation, we consider the effect of regional flow on the relief well system and the chemical quality changes that might occur in a typical pumping test. The regional flow may capture a significant portion of the fresh-water leakage induced by the relief well system. If this occurs, the water discharged will be considerably diluted even though the volume is not reduced dramatically. We would also like to know the time scale over which this dilution would occur. Typically, pumping tests in the Wellington aquifer have not shown a dramatic change in chemical quality. We shall consider the physical processes that could cause a change in chemical quality and estimate their effect.

Secondly, with regard to the Alluvial aquifer we wish to test the effectiveness of a bank-side alluvial relief well system. The alluvial wells will be screened near the bottom of the alluvium in the salt-water zone. We shall test the alluvial system on a single hypothetical flood event and a series of flood events that occurred between 1973 and 1977.

Lastly, assuming concentrated brine can be pumped from the base of the alluvium, we consider a series of hypothetical management schemes to control the chloride concentration in the river. The last scheme considers pumping the salt water either into the river or a holding reservoir, depending on the quality of the river water. If the scheme is to succeed, the reservoir must not continue to fill with salt water. Hopefully, the river flow will be such that the reservoir may be maintained less than full.

II. WELLINGTON AQUIFER

IMPROVED VALLEY BOUNDARIES

One of the improvements we decided to make on the Wellington aquifer model involved improved valley wall boundaries on the north and south of the Smoky Hill River Valley. These boundaries are shown in Figure A-1. It was felt that the valley wall boundaries should be described as accurately as possible to truly evaluate the effectiveness of the relief well system. The hydraulic conductivity of the confining bed was left unchanged from Figure II-9 of the original report. The transmissivity distribution that resulted from a series of calibration runs is shown in Figure A-2. We were able to match the historical water level within 1-2 feet.

All of the pumpage schemes evaluated in the original report were rerun using this improved model. The results of these runs are summarized in Table A-1. Table A-1 differs very little from Table II-3 of the original report. The conclusion is that better valley wall definition does not significantly change the model results. The percent volume reductions of salt-water leakage again are in the range of 20-30% for the better schemes.

EFFECT OF REGIONAL FLOW ON RELIEF WELL EFFICIENCY

The efficiencies of the various relief well schemes were reported in the original report and in the previous section as volume reductions of salt-water leakage. It was assumed that all the induced fresh-water leakage flowed to the wells and was pumped out. Calculations in the original report show that

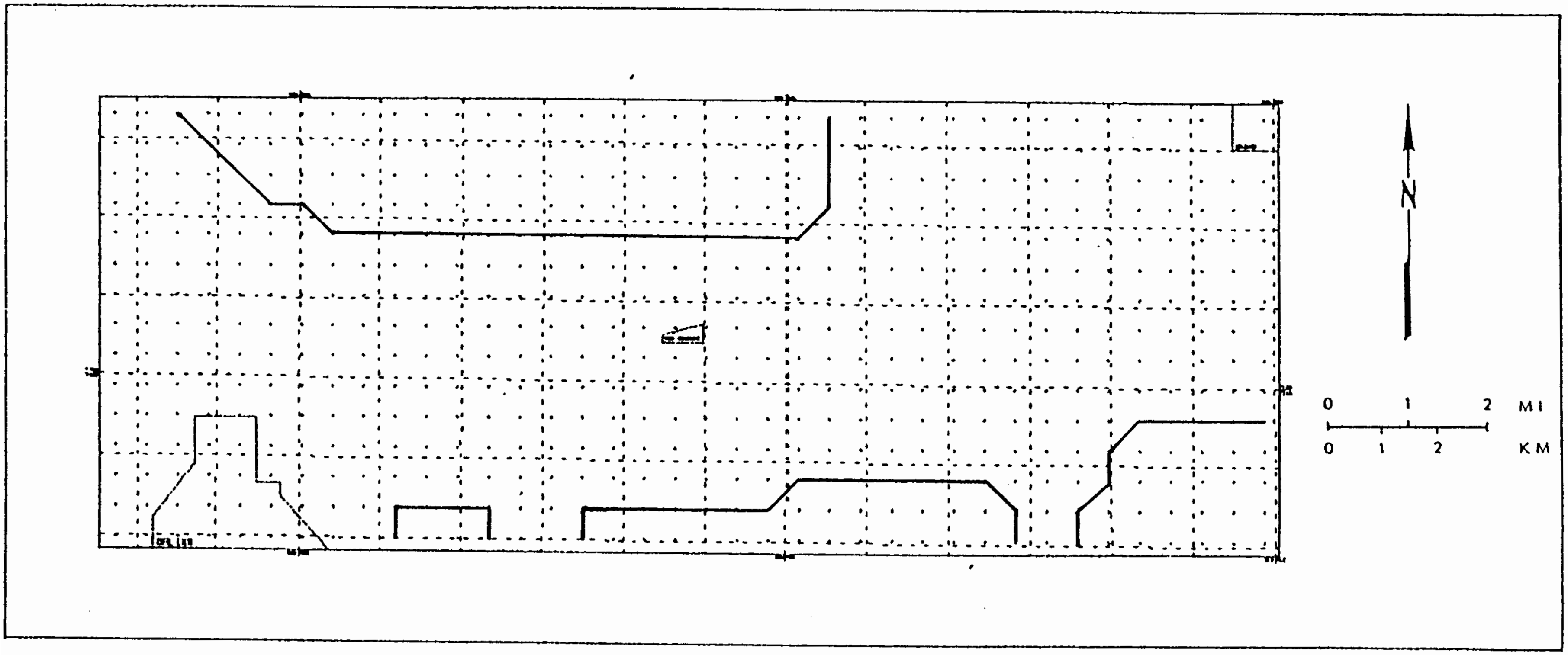


Figure A-1. Improved valley boundaries.

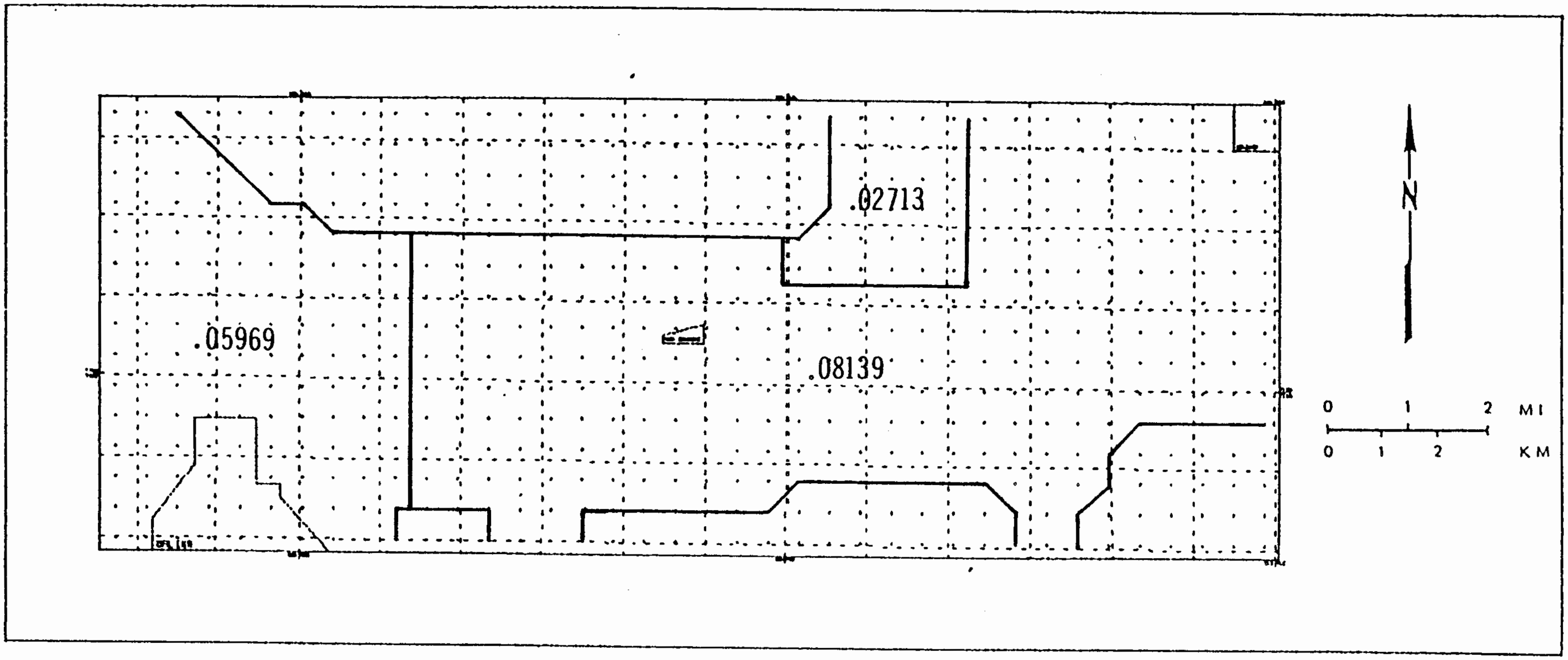


Figure A-2. Transmissivity distribution (ft^2/sec) for improved boundaries.

Table A-1. Summary of the simulation results for various pumpage schemes for the calibrated model with improved boundaries.

Case	# of Wells	Well spacing (ft)	Pumpage per well (gal/min)	Maximum drawdown (ft)	Saltwater leakage (ft^3/sec)	Volume % Reduction	Freshwater leakage (ft^3/sec)	% Increase
I test 1	6	2000 NS	20	2-3	1.32	8.3	.54	35
I test 2	6	2000 NS	40	5-6	1.26	12.5	.75	88
I test 3	6	2000 NS	60	9-10	1.22	15.3	.99	148
I test 4	6	2000 NS	80	12-13	1.20	16.7	1.22	205
I test 5	6	2000 NS	100	15-16	1.17	18.7	1.47	268
II	20	2000 NS,EW	22.5	10-11	1.20	16.7	1.15	187
III	20	2000 NS 4000 EW	22.5	9-10	1.19	17.4	1.15	187
IV	206	2000 NS,EW	2.18	3-4	1.008	30.0	.911	128

Saltwater leakage without pumpage = 1.44 ft^3/sec

Freshwater leakage without pumpage = .40 ft^3/sec the percent reductions of concentrated brine are within a few percent of the volume reductions under this assumption. We decided that this assumption should be investigated more thoroughly. This section is a summary of our findings.

Discussion of Stagnation Point

It is well known that if we have a well pumping in a regional flow system there will be a groundwater divide outside of which no water flows to the well (Todd, 1980). This is shown as Figure A-3. In this figure, water is moving from right to left. Water inside the groundwater divide line moves to the well, while water outside moves with the regional flow and does not flow to the well. The point where the groundwater divide line crosses the x axis is called the stagnation point; the velocity of water at this point is zero because the competing forces of regional flow and flow to the well are equal and opposite at the stagnation point.

This presentation from Todd has been for a non-leaky confined aquifer. For a leaky aquifer such as the Wellington aquifer, part of the pumpage comes from regional flow and part comes from leakage. The fact that leakage supplies part of the pumpage means that the width of the area enclosed by the groundwater divide line will be narrower for a leaky aquifer. As shown in Figure A-3, the drawdown extends outside the groundwater divide line; therefore, leakage occurs outside the groundwater divide line. The question we must answer is: How much leakage occurs outside the groundwater divide line? As seen in Table A-1, the induced fresh-water leakage is near one cfs in several cases. This means that the induced fresh-water leakage is nearly the same as the brine flux in the Wellington aquifer. This could result in a significant dilution effect if a significant portion does not flow to the

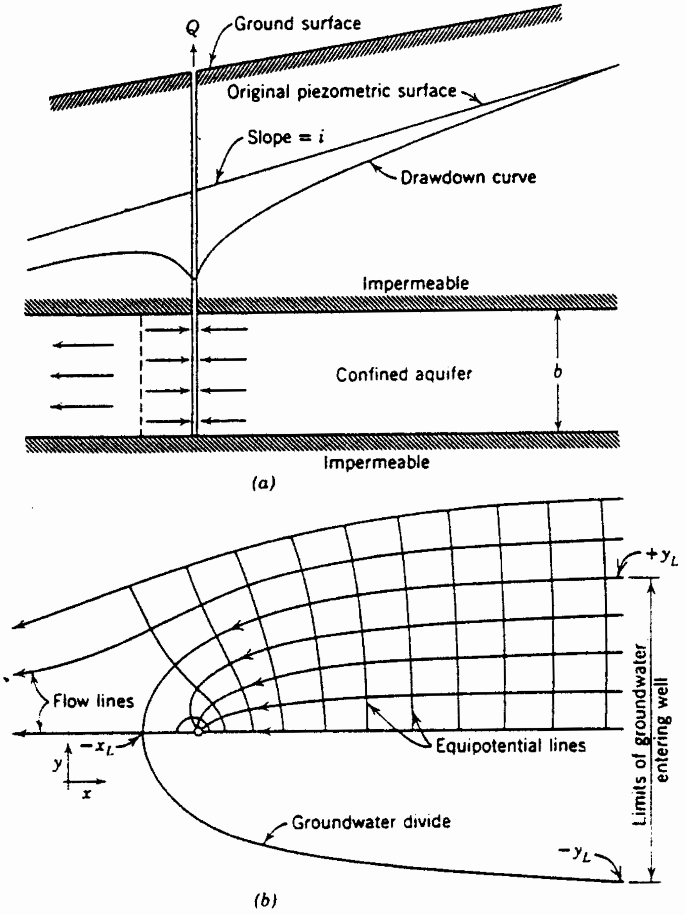


Figure A-3. A well pumping in a regional confined flow system (Todd, 1980).

well. Using some analytical solutions for the infinite leaky aquifer, we were able to predict a stagnation point about 1,500 feet downstream from a well pumping at 100 gpm with a regional flow typical of the Wellington aquifer. If the region of leakage extends significantly beyond 1,500 feet, that would imply a significant portion of the leakage does not flow to the well.

Model Results

In order to determine the position of the stagnation point and the amount of leakage going to the well, it was necessary to utilize the two-dimensional numerical model of the Wellington aquifer. Figure A-4 shows the pattern of natural leakage predicted with the head data input to the model. The light areas exhibit fresh-water leakage, while the cross-hatched areas exhibit salt-water leakage. Figure A-5 shows the steady-state leakage pattern for Case I-5, six wells pumping at 100 gpm. Notice that, except for the eastern part, we now have mostly fresh-water leakage over the model area. Also shown on Figure A-5 are the well locations and the stagnation line. The stagnation line was determined from the head values at each node. No water east of the stagnation line flows to the relief wells. Notice that a significant amount of fresh-water leakage occurs east of the stagnation line.

The fresh-water leakage west of the stagnation line <u>may</u> flow to the well and be pumped out. For Case I-5 shown in Figure A-5 there is .54 cfs of fresh-water leakage west of the stagnation line. If this figure is added to the concentrated brine flux of 1.04 cfs, we see that a total flux of water moving through the line of wells is 1.58 cfs. However, at 100 gpm, six wells only pump 1.34 cfs; therefore part of this total flux (.24 cfs) is not captured and moves east of the stagnation line to be further diluted by fresh-water leakage before reaching the natural discharge area.

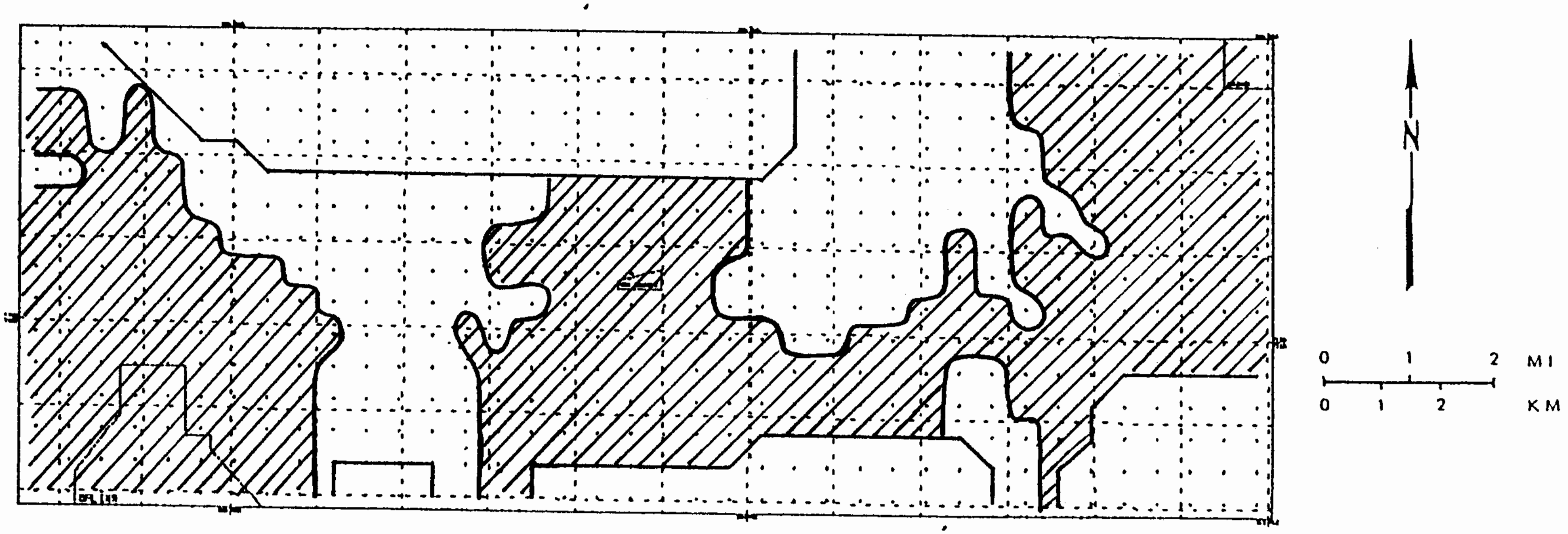


Figure A-4. Natural leakage system (areas of salt-water leakage are cross-hatched).

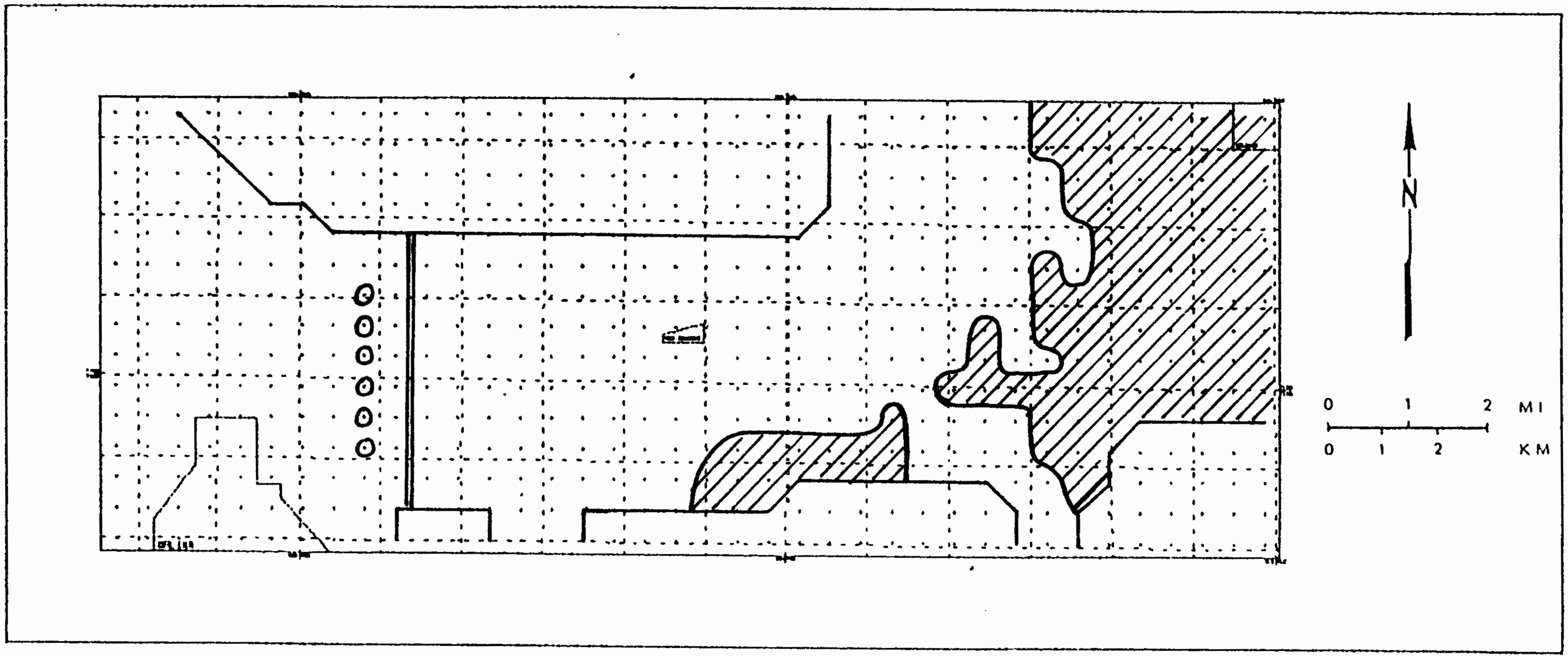


Figure A-5. Leakage pattern for six wells pumping at 100 gpm (⊙ well location, ‖ stagnation line, areas of salt-water leakage are cross-hatched).

We still cannot make a detailed calculation of the amount of salt water removed without a density dependent model. However, we can make approximate calculations based on reasonable assumptions. For example, if we assume the salt water and fresh water west of the stagnation line mix completely, then the amount of concentrated brine pumped is given by:

$$\left(\frac{1.34 \text{ cfs}}{1.58 \text{ cfs}}\right) \times 1.04 \text{ cfs} = .89 \text{ cfs}.$$

This represents 85% of the original 1.04 cfs of concentrated brine. On the other hand, if we do not assume complete mixing and, instead, assume all fresh-water leakage west of the stagnation line is pumped, then the amount of concentrated brine pumped is given by:

$$1.34 \text{ cfs} - .54 \text{ cfs} = .80 \text{ cfs}.$$

This represents 77% of the original 1.04 cfs of concentrated brine. So, we see that realistically the six well scheme pumping at 100 gpm should produce a 77-85% reduction of actual salt discharged to the alluvium. However, the volume of salt-polluted water discharged to the alluvium has only been reduced by near 20%. The salt concentration of the naturally discharged water has been considerably diluted by the fresh-water leakage.

Similar calculations, as made for Case I-5 in the preceding paragraph, have been made for various pumpage schemes considered in the original report. These are summarized in Table A-2. The efficiency ranges from about 20% to 85%. It appears that the six wells pumping at 100 gpm is the better choice of those considered.

Table A-2. Efficiency of various pumpage schemes in removing concentrated brine.

Case	# of Wells	Well Spacing (ft)	Pumpage per well (gpm)	Total Pumpage (cfs)	Fresh Flux West of Stag. Line (cfs)	Total Flux Past Wells (cfs)	Brine Pumped Assuming Comp. Mixing (cfs)	Brine Pumped Assuming All Col. 6 pumped (cfs)	Efficiency Range
I-1	6	2000 NS	20	.27	.04	1.08	.26	.22	21-25%
I-2	6	2000 NS	40	.53	.15	1.19	.46	.38	37-45%
I-3	6	2000 NS	60	.80	.26	1.30	.64	.54	52-62%
I-4	6	2000 NS	80	1.07	.37	1.41	.79	.70	67-76%
I-5	6	2000 NS	100	1.34	.54	1.58	.89	.80	77-85%
II	20	2000 NS,EW	22.5	1.00	.38	1.42	.73	.62	60-70%
III	20	2000 NS 4000 EW	22.5	1.00	.42	1.46	.71	.58	56-68%
						Add col. 6 and OSF	(col. 5/col.7) x OSF	(col. 5-col. 6)	

Original salt-water flux (OSF) = 1.04 cfs concentrated brine

TIME SCALE FOR STEADY STATE AND FRESH-WATER DILUTION

The preceding section indicates that a relief well system would be effective in producing a sizeable reduction in the total salt load discharged to the alluvial aquifer. The question not answered there is: How long does it take for the dilution effect to be felt? It is generally known that in a confined aquifer the head can redistribute itself much faster than the actual water molecules. Therefore, we should investigate both the time for a steady-state head distribution to occur due to the relief well system and the time for dilution to occur due to regional water flow.

Steady-State Head Distribution

All previous work on the Wellington aquifer model has been for steady-state simulations. In order to run a transient simulation and watch the model approach steady state, it is necessary to estimate the storage coefficient (S in equation I-1 of the original report, page 4). Data on the storage coefficient is scarce and probably somewhat inaccurate. It is known that relatively short term pumping tests may not give accurate values of storage coefficient. This can be seen from pumping test analyses given by Gillespie (1979) where he reports values ranging from .14 to 6×10^{-6}.

We have analyzed two sets of pumping test data in the original report. We used the leaky aquifer assumption and the data fit the curve quite well. We obtained two values for storage coefficient 4.5×10^{-3} and $.56 \times 10^{-3}$ (page 19 of the original report). Unfortunately, there is almost an order of magnitude difference in the two. We have run the two-dimensional numerical model for both values of storage coefficient for six wells pumping at 100 gpm (Case I-5). For S = .0045, the steady-state head distribution is attained in about 4.8 years. For S = .00056, the steady-state head distribution is attained in about .5 years. In general, the steady-state head distribution is attained at a time directly proportional to the storage coefficient. In other words, if the storage coefficient increases by a factor of 10, the time for reaching steady state also increases by a factor of 10. The values for S that we have used are probably pretty good average values; therefore, one can estimate the time to reach steady state as on the order of a few years.

Fresh-Water Dilution

The question of how long it will take for the full effect of the dilution to be felt in the discharge area is tough to answer since we do not have a model that will handle spatially varying density. However, we should be able to make pretty good estimates by considering the actual water velocity given by: (Darcy's Law)

$$V = -\frac{K}{n}\frac{\Delta h}{\Delta \ell} \tag{A-1}$$

where V is the actual water velocity, K is the hydraulic conductivity, n is the porosity, and $\frac{\Delta h}{\Delta \ell}$ is the hydraulic gradient. The hydraulic gradient down the Smoky Hill River Valley is about .00075 before the relief well system is turned on. After steady state has been reached with the six wells pumping at 100 gpm, the hydraulic gradient is about .00051. A reasonable value for the porosity is .20. To get the hydraulic conductivity K, we must divide the transmissivity by the thickness of the Wellington aquifer. Whittemore (1981, p. 65) estimates the thickness to be about 30 feet from disposal well data. The pump test analysis of the original report gave transmissivities of 1,310 ft^2/day and 3,412 ft^2/day. The calibration of the numerical models, described in the original report, indicated that transmissivity could range from .03 -

.095 ft^2/sec (2,600-8,200 ft^2/day). This is a fairly sizeable range of transmissivity. It is difficult to say which transmissivity is more accurate. Pump test values are point measurements whereas model calibration values are more regional in nature. Let us assume the larger value since this will allow the most rapid mixing and dilution. Thus, 8,200 ft^2/day/30 ft = 273 ft/day for the hydraulic conductivity. We can now estimate the water velocity from Darcy's Law:

$$V = \frac{(273\ \text{ft/day})}{(.2)} (.00051) = .70\ \text{ft/day} = 250\ \text{ft/yr}$$

It should be noted that a decrease in either the saturated thickness or the porosity results in a larger velocity. We have used reasonable values but better data would be desirable.

A crude way to calculate the variation of dilution with time is to calculate the time for the fresh-water leakage shown in Figure A-5 to move to the natural discharge area. The water movement is primarily west to east; thus, the leakage from any column of nodes arrives at the discharge area at a certain time dependent on the water velocity and the distance that column of nodes is from the discharge area. Using our average value of 250 ft/yr for water velocity, we can calculate the percent of leakage (or equivalently the percent of dilution) arriving at the discharge area at any time. Figure A-6 is a plot of dilution as a function of time, which shows that it will take about 160 years to get the full dilution effect at the discharge area. This is easy to see, since there is roughly 40,000 feet between the line of relief wells and the discharge area.

$$\frac{40{,}000\ \text{ft}}{250\ \text{ft/yr}} = 160\ \text{yrs}$$

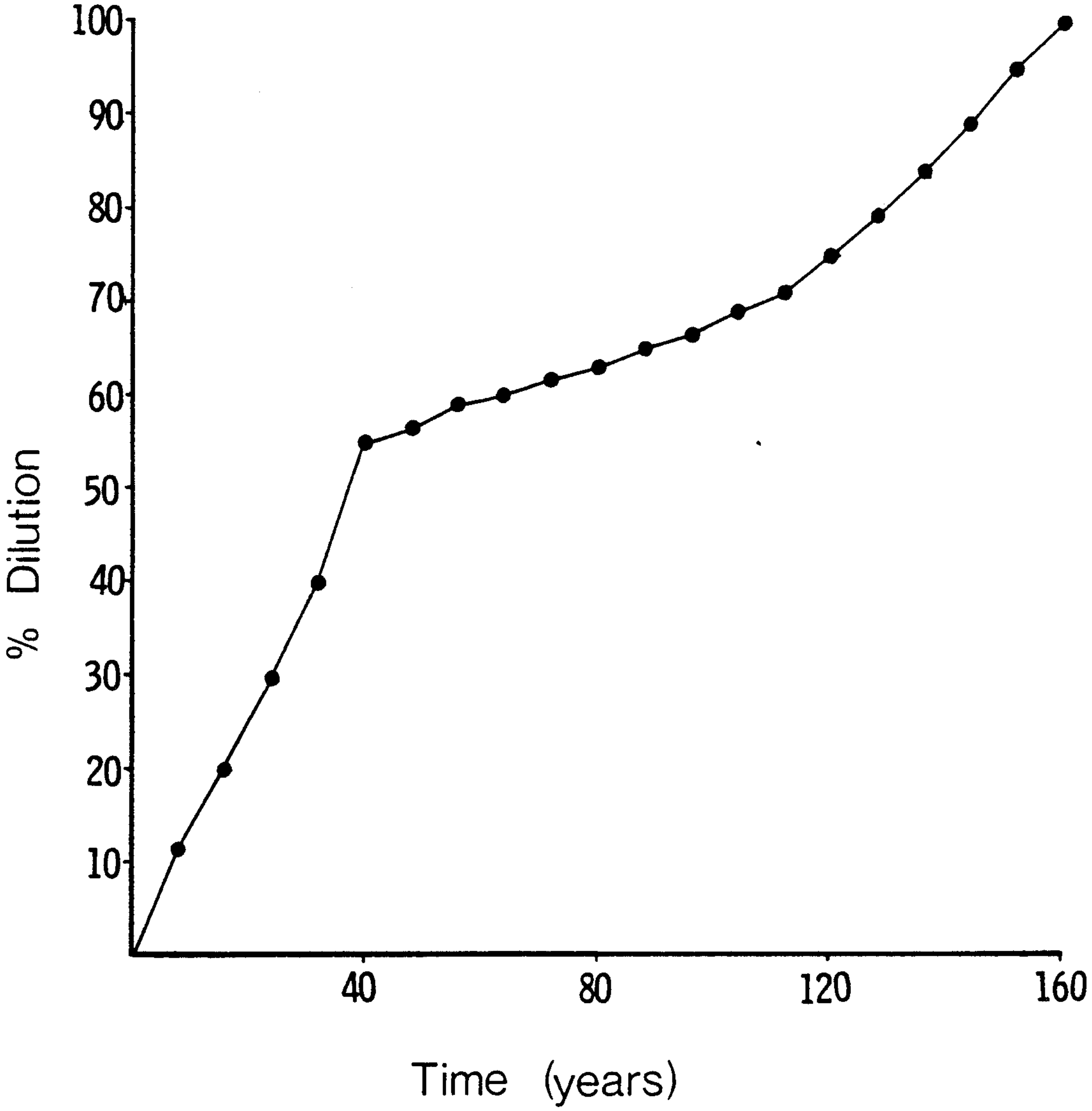


Figure A-6. Dilution as a function of time.

Figure A-6 indicates about 50% of the dilution effect should be felt in about 40 years. The dots represent our calculations and they do not fit on a nice smooth line because the leakage is not distributed uniformly. This is a crude calculation of dilution versus time and should not be taken too quantitatively. However, Figure A-6 should represent the gross features of dilution over time.

It is possible to reduce the time for dilution effects to be felt in the recharge area by moving the relief well system closer to the discharge area. However, the relief well system must be kept in an area where the confining layer is fairly impermeable to keep fresh-water leakage to a minimum.

The time estimates given in this section depend most critically upon the porosity and the transmissivity. If the porosity is reduced to .02 the time is 16 years instead of 160 years. If the low value for transmissivity, 1310 ft^2/day, is used with a porosity of .2 the time is 1000 years instead of 160 years. Obviously, better data with regard to these parameters would be desirable.

FACTORS AFFECTING CHEMICAL QUALITY OF A PUMPING TEST

In several pumping tests that have been performed on the Wellington aquifer there is no definite change of water quality over the period of a few days or weeks. It is the purpose of this section to examine several factors that could affect chemical quality and to estimate the magnitude of their effect and the time scale of their action.

Time For Alluvial Water to Move Through the Confining Layer

The velocity of water movement through the confining layer is given by Darcy's law, equation A-1.

$$V = - \frac{K}{n} \frac{\Delta h}{\Delta \ell}$$

K is the hydraulic conductivity of the confining bed, n is the porosity of the confining bed, Δh is the head difference induced across the confining bed by the pumping test, and $\Delta \ell$ is the thickness of the confining bed. The hydraulic conductivity of the confining bed is not well known. Analysis on a shale core by the USGS gave a value of .39 - 1.4 x 10^{-8} ft/sec. The model calibration used 1 x 10^{-8} ft/sec in the tighter areas and 1 x 10^{-7} ft/sec in the discharge area. The pumping test analysis in the original report gave 2.1 x 10^{-4} - 1.6 x 10^{-6} ft/sec. It seems unlikely that K could be smaller than about 1 x 10^{-8} ft/sec or greater than about 2 x 10^{-4} ft/sec. These two numbers at least give us the extremes. For six wells pumping at 100 gpm the steady state drawdown (h) near the well is given as about 15 feet in Table A-1. Assume the porosity of the shale confining layer to be 20%. The thickness of the confining layer is variable as shown in Table II-1 of the original report; 30 feet might be a reasonable average. We can calculate the two extremes of water movement through the confining bed by using the two extremes of hydraulic conductivity.

$$V_{MAX} = \frac{(2x10^{-4} ft/sec)}{.2} \quad \frac{15 \text{ ft}}{30 \text{ ft}} = 5.0 \times 10^{-4} \text{ft/sec}$$

$$= 43 \text{ ft/day} = 1.6 \times 10^{4} \text{ ft/yr}$$

$$V_{MIN} = \frac{(1\times10^{-8}\,\mathrm{ft/sec})}{.2}\ \frac{15\ \mathrm{ft}}{30\ \mathrm{ft}} = 2.50 \times 10^{-8}\mathrm{ft/sec}$$

$$= .21 \times 10^{-2}\ \mathrm{ft/day} = .80\ \mathrm{ft/yr}$$

Since the calibrated numerical models in the original report use no values greater than 1×10^{-7} ft/sec for K, we assume this to be a reasonable value. This results in a velocity of 8 ft/yr through the confining layer. Therefore, it would take 3.8 years for a fresh-water molecule to move from the alluvium to the Wellington aquifer. Even increasing K to 1×10^{-6} ft/sec, it would require .38 years to traverse the confining bed. Thus, no fresh leakage would be observed in the normal pumping test if K is less than 1×10^{-6} ft/sec. However, if K is as large as 2×10^{-4} ft/sec then significant leakage could occur in the duration of a normal pumping test.

Leakage as a Function of Radial Distance

In a simple leaky aquifer system the steady-state condition is obtained when the pumpage is completely supplied by leakage. In the original report it is clear that the induced fresh-water leakage produced by various relief well schemes is comparable to the total pumpage. We would like to look at the leakage as a function of radial distance from the pumped well. To do this, we shall use the analytical solution for the simple leaky aquifer (Walton, 1970). The leakage from the well radius (r_w) to some distance (R) from the pumped well is given by

A-2 $$L = \frac{2\pi K}{m} \int_{r_w}^{R} r\, s\, dr$$

where K is the hydraulic conductivity of the confining layer, m is the thickness of the confining layer, and s is the drawdown computed from the leaky aquifer equation (Cobb, McElwee, and Butt, 1981).

In Figure A-7 we have plotted the leakage expressed as a precent of the pumpage as a function of the radial distance for a steady-state condition in a leaky aquifer with a single well pumping at 100 gpm. The data in Figure A-7 is for three values of Wellington aquifer transmissivity, 1,000 ft^2/day (.012 ft^2/sec), 3,000 ft^2/day (.035 ft^2/sec), and 6,000 ft^2/day (.069 ft^2/sec) and two values of hydraulic conductivity for the confining layer (K), .000864 ft/day (1×10^{-8} ft/sec) and .00864 ft/day (1×10^{-7} ft/sec). We have used 30 feet for m , the thickness of the confining layer. From equation A-2 we see that leakage is inversely proportional to m. Decreasing m increases the leakage and vice versa. We see that in general decreasing the transmissivity of the Wellington aquifer increases the leakage near the well and increasing K increases the leakage near the well. However, in Figure A-7 we see that less than 10% of the pumpage in the form of leakage occurs within 1,000 feet of the well and less than 25% occurs within 2,000 feet of the well. We see that we must go out at least 4,000 feet for the leakage to approach 50% of the pumpage.

Travel Time as a Function of Radial Distance

The leakage data in Figure A-7 is interesting but we cannot use it to predict the effect on the quality of water in a pump test until we know typical travel times through the Wellington aquifer for water at various

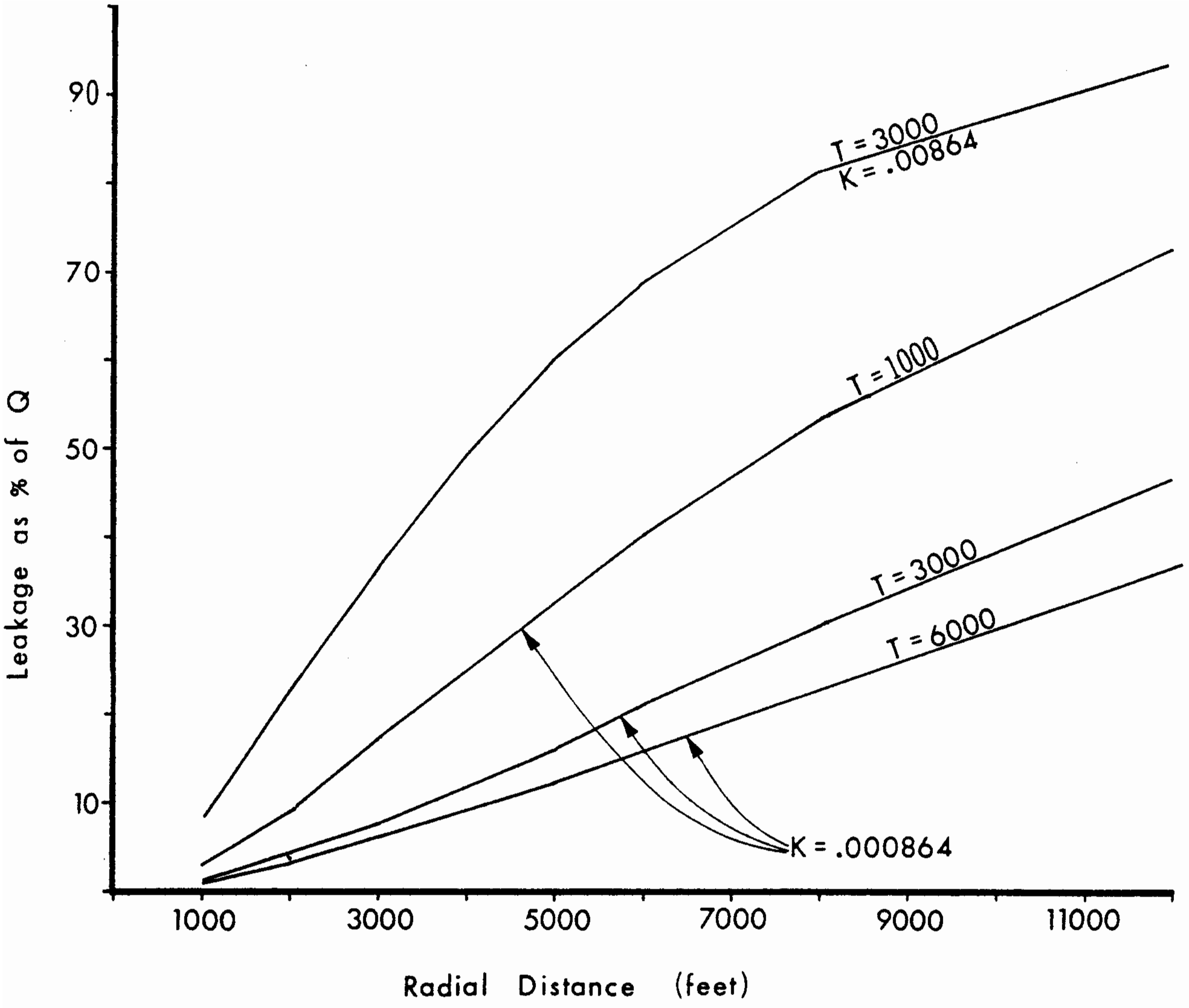


Figure A-7. Leakage (as % of pumpage Q) as a function of radial distance (units of T are ft^2/day and K are ft/day).

distances from the pumped well. The travel times can be computed from Darcy's Law (eq. A-1) if we know the hydraulic conductivity of the Wellington aquifer and if we can calculate the gradient $\Delta h/\Delta \ell$. The gradient may be calculated from the analytical solution for the leaky aquifer (Cobb, McElwe, and Butt, 1981). Figure A-8 shows the travel time for water to reach the well as a function of radial distance for various transmissivities for a single well pumping 100 gpm. The travel time is not a strong function of K, the hydraulic conductivity of the confining layer, so only curves for K = .000864 ft/day are shown. This is expected since K controls the travel time in the confining layer but not in the Wellington aquifer. We have assumed a Wellington porosity of 20%. The effect of regional flow has been included in Figure A-8. The regional flow will cause water upstream from the well to reach the well sooner than downstream water. However, it is clear from Figure A-8 that all the water from 1,000 feet away from the well cannot reach the well in less than 1.5 years. Looking at Figure A-7 again we see that less than 10% of the pumpage in the form of leakage occurs within 1,000 feet of the well. The conclusion is that it would probably take 1.5 years for the quality of the water in a pump test to change by 10%. Therefore, probably no significant change would be seen in a typical pump test. However, if the porosity of the Wellington aquifer is as low as .02 the time scale would be divided by 10. In that case, it would take .15 years for the quality to change by 10% in the above example.

Effect of Regional Flow

As mentioned in the previous section, regional flow may decrease the travel time for upstream leakage to reach the pumping well. However, not only will some downstream leakage be retarded, some will be lost completely. From

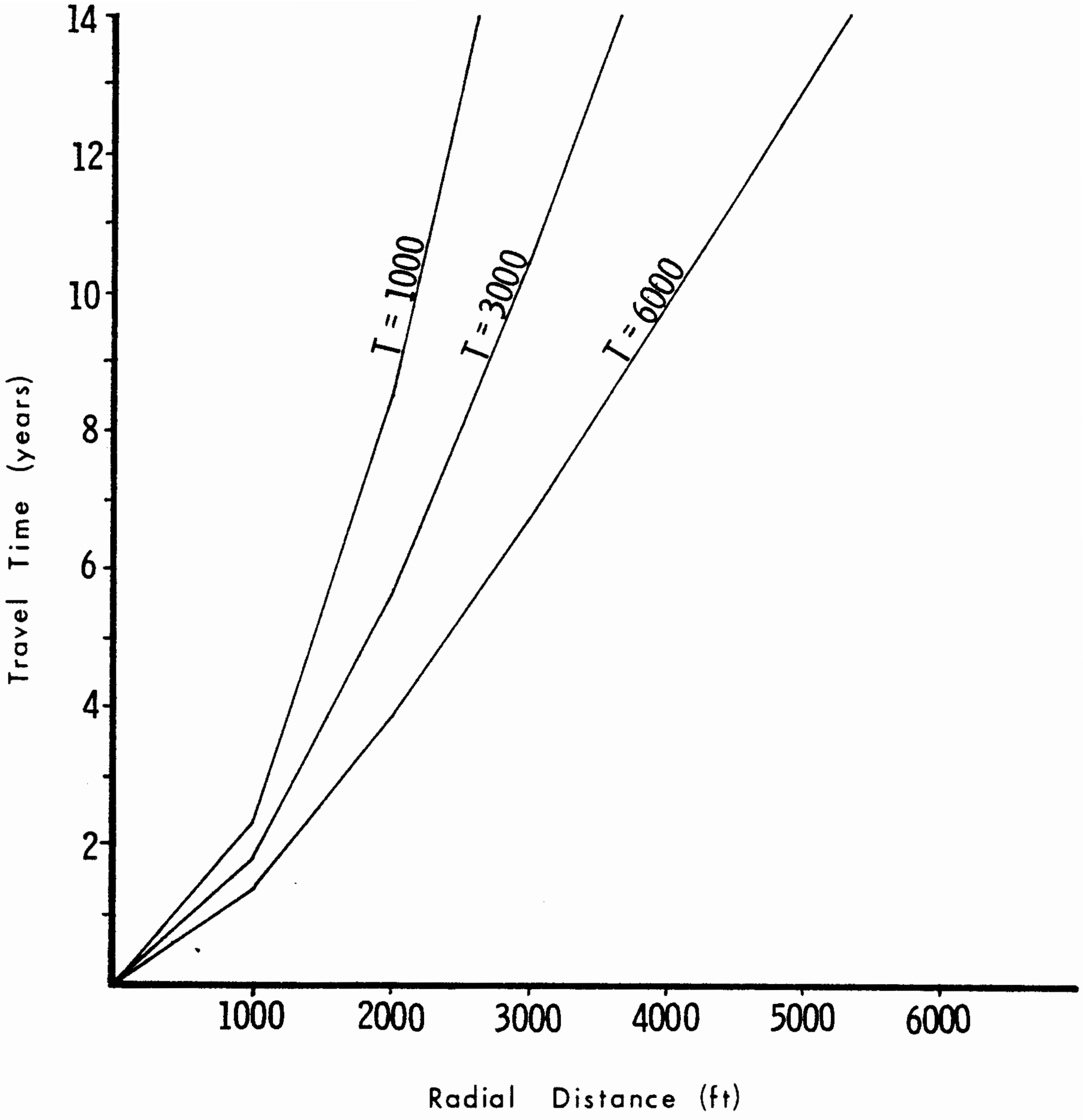


Figure A-8. Travel time for water to reach the well as a function of radial distance (units of T are ft^2/day).

earlier work in this report, it is clear that as much as 50% of the leakage may be lost to regional flow. this would further decrease the amount of fresh water leakage available to change the chemical quality of water in a pump test.

SUMMARY

We have addressed several additional points not covered in the original report on the Wellington aquifer. Improved valley wall definition did not significantly change the results of the original report. The volume reductions of salt-water leakage are still in the 20% range. Regional flow can capture about 50% of the fresh-water leakage induced by the relief wells in some cases. The result is that the water discharged in the natural discharge zone is considerably diluted. The net effect of the relief well system may be a reduction of 70-80% in the salt load discharged to the alluvium. However, studies of the time scale for the dilution to occur indicates that 50-150 years may elapse before most of the dilution effect is felt at the discharge area.

We have also considered several factors affecting chemical quality of the water pumped during a pump test. The fresh-water leakage induced by pumping could dilute the pumped water and lower the concentrations of various constituents. We have considered the time for water to move through the confining layer, leakage as a function of radial distance, travel time as a function of radial distance, and the effect of regional flow. The conclusion is that for the typical pumping test lasting only a few weeks no significant change in chemical quality should be observed.

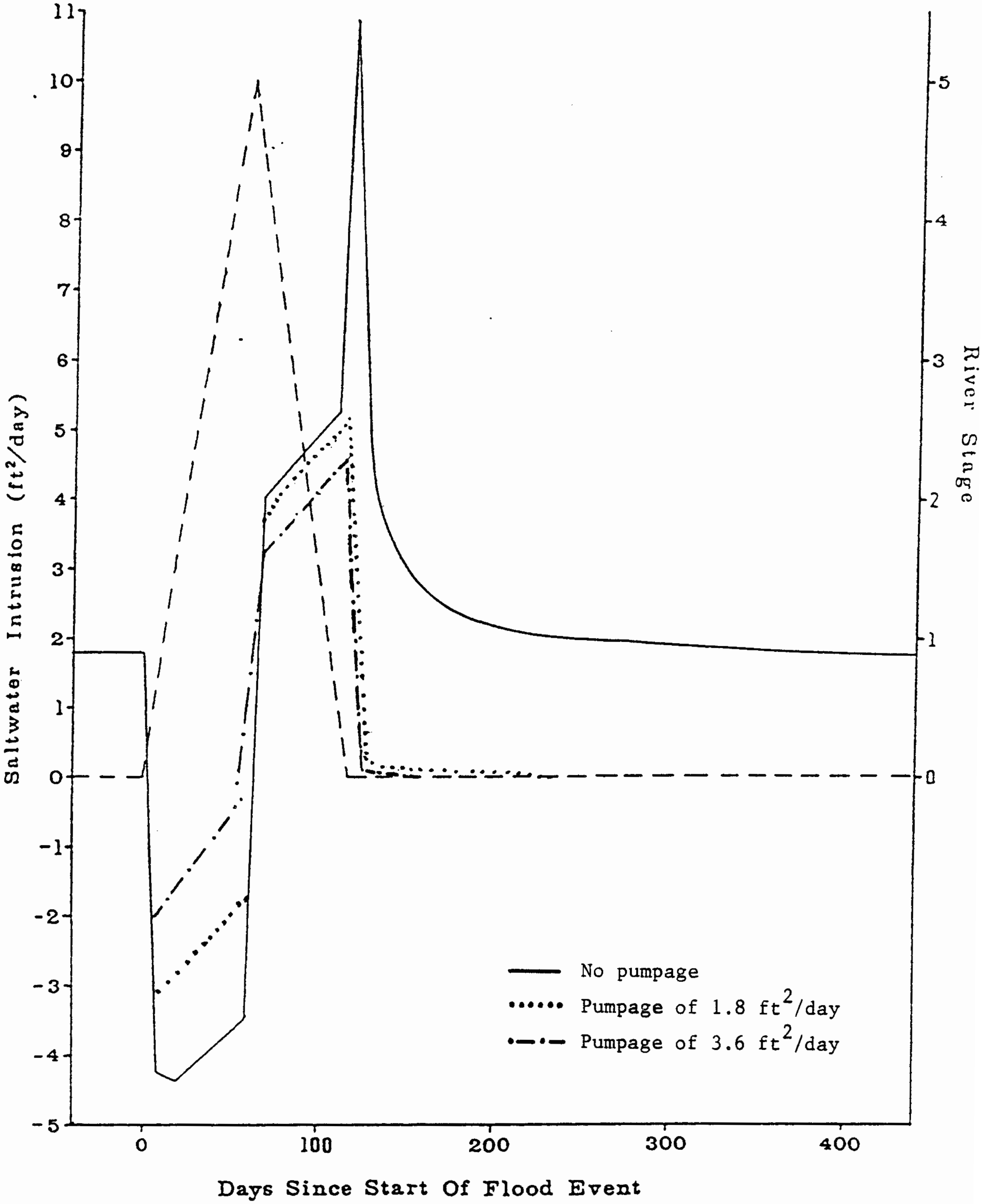
The results of this study seem to depend most critically upon two parameters: the hydraulic conductivity of the confining layer and the porosity of the Wellington aquifer. We have assumed that in the region of the relief well system the hydraulic conductivity of the confining bed is approximately 1 x 10^{-8} ft/sec. If it is significantly greater than this the results of this study could be modified considerably. We have assumed a porosity of 20% for the Wellington aquifer when calculating velocities using equation A-1, Darcy's Law. If the porosity is in fact 2%, then the time scales for Figures A-6 and A-8 should be divided by 10 since there is a direct relation of travel time to porosity. In our opinion, additional field effort should be expended to tie these two parameters down before definite decisions are made. Additional data on the storage coefficient and transmissivity of the Wellington aquifer would also be very valuable.

III. ALLUVIAL AQUIFER

EFFECT OF ALLUVIAL PUMPING ON THE UPCONING DUE TO A SINGLE FLOOD EVENT

The first thing we investigated was an alluvial well screened near the bottom of the alluvium in the salt-water zone under or near the river. We modeled this well as pumping at 1.8 ft^3/day per foot of river channel. (This is the assumed flux of salt water from the Wellington aquifer as calculated in the original report on page 58.) This model was then subjected to the same 5-foot flood event shown in Figure III-11 of the original report. We found that the flux of salt water into the river after the flood event was cut markedly as shown in Figure A-9 by the dotted line. The results of the original report with no salt-water pumping are shown as the solid curve in Figure A-9 for comparison. We found that pumping at the same rate as salt water was being added from the Wellington reduced the influx to the river but that the salt-water mound under the river remained stationary.

Figure A-9. Effect of salt-water pumping on the intrusion.



We decided to investigate the effect of doubling the pumpage rate of the salt-water well to 3.6 ft^2/day. The response of this model to the flood event is shown as the dot-dash curve in Figure A-9. The additional pumpage has reduced the salt-water flux to the river some, but not dramatically. However, after the passing of the flood event, the salt-water mound under the river decays slowly. This result is not too surprising since we know that, in order to reduce the amount of salt water in the alluvium, we must pump at a rate greater than the influx.

MODELING CHLORIDE CONCENTRATION AT ENTERPRISE

Having looked at a single flood event, we decided to try to model a series of flood events in the Smoky Hill River from 1973 to 1977 to predict the chloride concentration in the river at Enterprise. In order to do this, it was necessary to digitize several additional pieces of data. First of all, we needed the gage height and the flow of the Smoky Hill River at New Cambria along with the chloride concentration. The Solomon River is the other major drainage in this area; so we needed the flow and chloride concentration at Niles. We neglected other minor streams in the area. This data was obtained and digitized as <u>monthly averages</u>. This data was used with the cross-sectional model to try and predict the chloride concentration at Enterprise. The cross-sectional model would predict a fresh-water flux and salt-water flux for the reach between New Cambria and Solomon. When combined with the previously mentioned data, we can predict chloride concentration at Enterprise assuming nothing dramatic occurs between Solomon and Enterprise.

Model Calibration

There are many parameters one could manipulate to try to match the chloride concentration at Enterprise. We will assume that our cross-sectional model is already fairly well calibrated with respect to flow as described in the original report. The parameters we chose to vary were height of groundwater rise in 1973, length of river contributing salt water, and concentration of salt water entering the stream. It is clear from data presented by Gillespie and Hargadine (1980) that groundwater levels in the river valley were raised on the order of 15 feet by the flood event in mid-1973. We tried values of 10, 15, and 20 feet to see the effect on model results. Since we are using a cross-sectional model, we must assume that every length of river acts like this hypothetical cross-section. In fact, river conditions may change somewhat between New Cambria and Solomon. Some reaches may not be contributing salt water to the river. The other parameter which we have choosen to vary is concentration of salt water entering the river. With the sharp interface model, it is not possible to describe in detail the mixing of the fresh and salt water. However, it seems clear that by the time the salt water enters the river it may have been diluted considerably by fresh water. Decreasing the length of river contributing salt water by $1/2$ or decreasing the concentration of the salt water by $1/2$ give the same results. Therefore, it is not really possible to separate these two effects on the basis of observed chloride concentration.

Figure A-10 shows one of the better model runs as the dashed curve. The observed average monthly chloride concentration at Enterprise is shown as a solid curve. In general, the model results are below the observed values except in mid-1976. However, the general shape of the curve is very well represented. Therefore, one would expect that the model represents the major

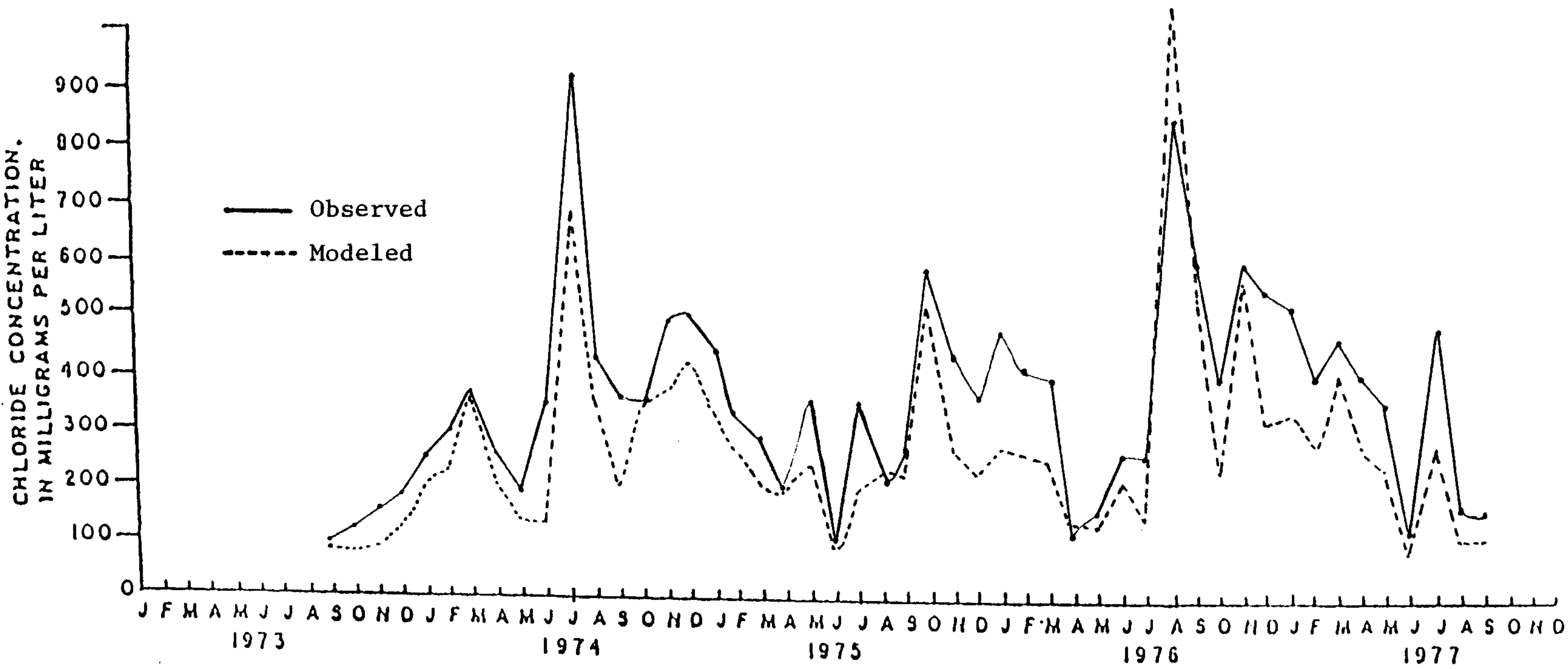


Figure A-10. Modeled and observed chloride concentration at Enterprise.

aspects of the real system. The model results in Figure A-10 were produced by assuming the groundwater levels were generally raised 15 feet by the flood in mid-1973. The model results also represent a situation where only one eighth of the river length between New Cambria and Solomon is contributing concentrated salt water or the entire length is contributing salt water with a concentration only one-eighth of the maximum value (22,500 mg/l). Other combinations such as one-half the river length contributing salt water at 45,000 mg/l are also possible.

The model outputs a monthly average value for salt-water flux to the river. These values have been averaged by year and are shown in Table A-3 along with data from Gillespie and Hargadine (1980). It is seen that the model results for salt-water flux are roughly twice as big as those observed. This suggests that half the river length might be contributing concentrated brine or the entire river length might be contributing salt water at a concentration of 90,000 mg/l. However, this does not fit with the factor of one-eighth found earlier. This is an inconsistency in the model that has not been resolved. If anything less than a factor of one-eighth is used, the chloride concentration peaks are much too large. However, this is a fairly crude model which seems to have the basic features of the real system tied up in it. Perhaps a more sophisticated model could resolve this inconsistency. Although the model is not perfect, it should be suitable for estimating the effect of alluvial pumpage of salt water.

No Salt-Water Flux Between New Cambria and Solomon

Using the model described earlier which seems to fit the observed chloride concentration at Enterprise fairly well, it is possible to isolate the effect of the reach between New Cambria and Solomon where it is felt most

Table A-3. Observed and modeled salt-water flux to the river.

Water Year	Brine Discharge (ft^3/s) Observed	Model	1/2 Model
1973	--	2.58	1.29
1974	1.77	3.40	1.70
1975	.56	.82	.41
1976	.42	.95	.48
1977	.31	.36	.18
Average	.77	1.62	.81

salt water reaches the river. The model was modified to ignore the salt-water flux in this reach and to calculate the expected chloride concentration at Enterprise. This data is shown as a dashed curve in Figure A-11 along with the observed values. Notice that the effect of shutting off the intrusion between New Cambria and Solomon has been to suppress the peaks. The chloride concentration curve is now much smoother. However, the chloride concentration still goes above the recommended 250 mg/l on occasion. The maximum chloride concentration is about 325 mg/l. Therefore, it appears that without reservoir augmentation at some low flows, it would not be possible to keep the river water at Enterprise under 250 mg/l by eliminating the salt-water intrusion between New Cambria and Solomon.

EFFECT OF PUMPING ON CHLORIDE CONCENTRATION AT ENTERPRISE

Earlier we simulated the effect of salt-water pumping from a bank-side relief well on a single small flood event. Using the same pumpage rate for salt water, 1.8 ft^2/day, we wish to see the effect on the model data shown in Figure A-10. In particular, we want to see how a succession of flood events reacts to the constant salt-water pumpage. Figure A-12 shows two model outputs. The dashed curve represents pumping salt water at one-eighth the concentrated value while the dotted curve represents pumping concentrated brine. The observed chloride concentration is shown as a solid curve. It is difficult to say whether the alluvial well could continue to pump concentrated brine for long time periods. A prototype well might be the only way to answer this question. At any rate, the real world result should be somewhere between the two cases considered here. Comparison of Figures A-12 and A-10 shows that the salt-water pumpage has considerably reduced the peaks of the chloride concentration curves. In fact the dotted curve is almost identical with

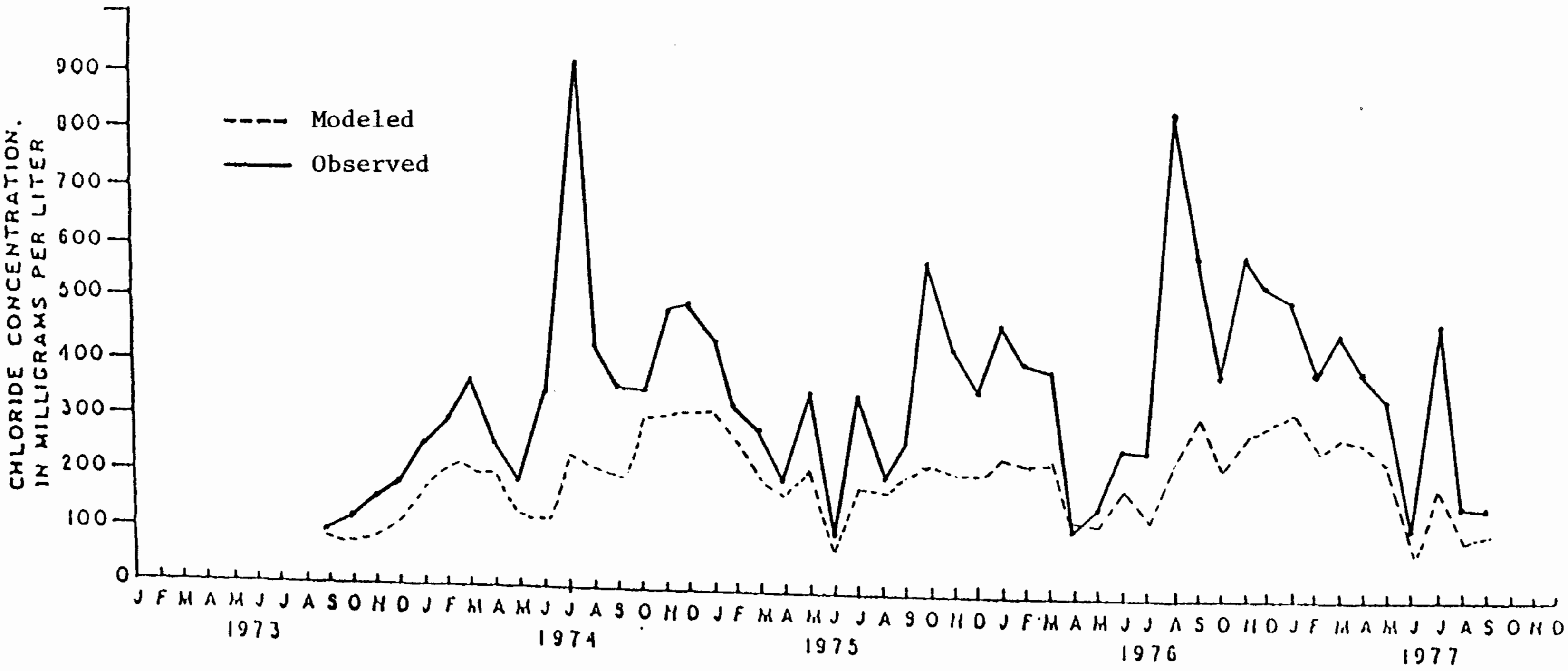


Figure A-11. Modeled chloride concentration at Enterprise without salt-water intrusion between New Cambria and Solomon.

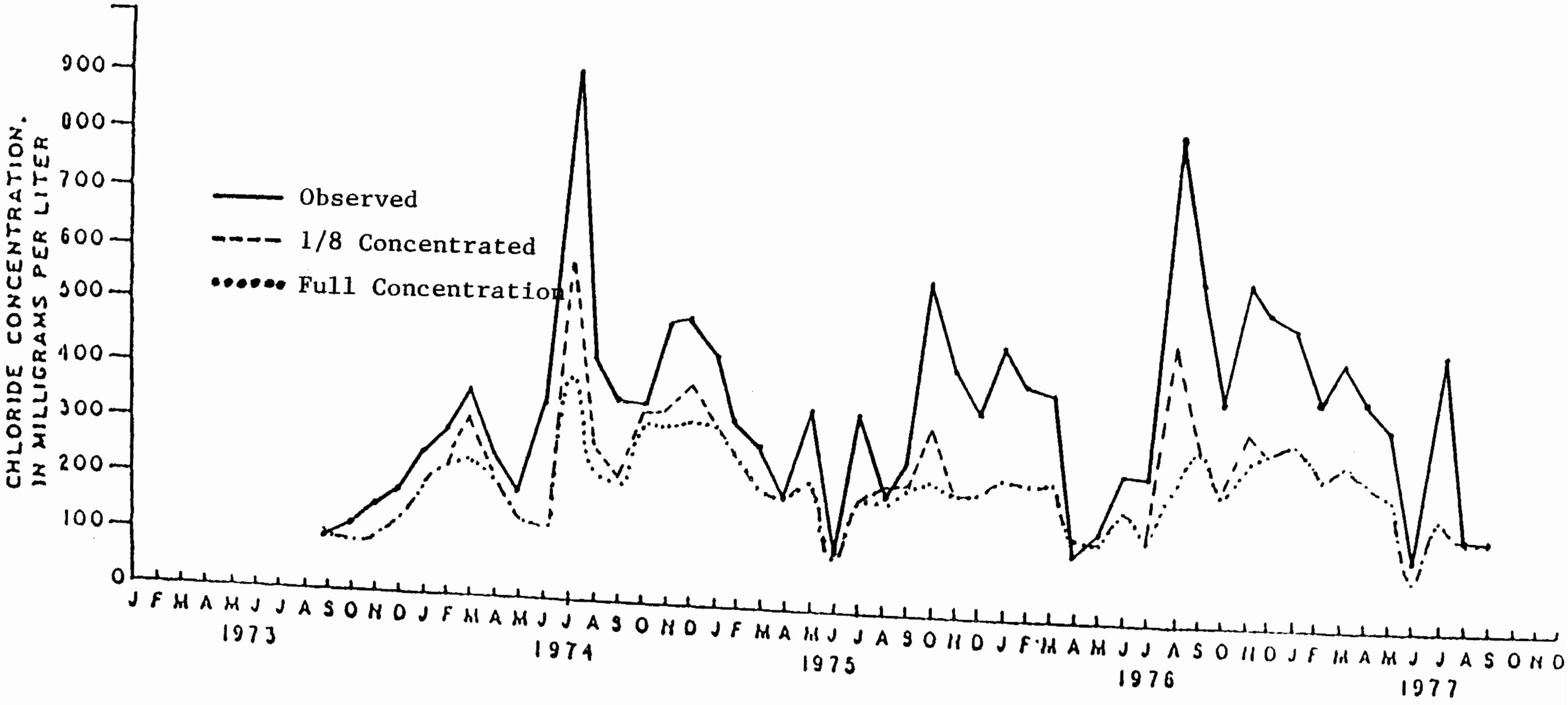


Figure A-12. Response of chloride concentration to salt-water pumping at 1.8 ft^2/day.

Figure A-11 except in mid-1974. However, the river water is still at a chloride concentration greater than 250 mg/l due to upconing some of the time. The maximum chloride concentration has been reduced to about 592 mg/l for the dashed curve and 398 mg/l for the dotted curve. The peak in the chloride concentration in mid-1974 is a strong one due to its reaction to the large flood events of 1973 and early 1974. Consequently, a relatively small amount of salt-water pumpage can not completely suppress it. On the other hand, the peak in mid-1976 seems to respond more favorably to the salt-water pumpage.

Figure A-13 shows as a dashed curve the model chloride response to doubling the salt-water pumpage (3.6 ft^2/day). Figure A-13 assumes pumping salt water at one-eighth the concentrated value. We have not shown the curve for pumping concentrated brine since it is almost identical with Figure A-11 which represents no intrusion to the river. Since we are pumping at a rate greater than the influx of salt water from the Wellington aquifer, the interface will decay slowly with time. As this happens, mixing of the salt and fresh water will become more important. The sharp interface model is not able to handle this situation. A variable density model would be needed to describe this situation.

Comparing Figures A-12 and A-13 we see that doubling the salt-water pumpage has again reduced the peaks in the chloride concentration. The maximum chloride concentration is about 400 mg/l for the dashed curve. Model results for pumping 3.6 ft^2/day of concentrated brine show the salt-water intrusion to be virtually eliminated. The real world situation should lie between these two results.

The results presented here suggest that the bank-side alluvial relief well scheme could be effective in reducing salt-water intrusion to the

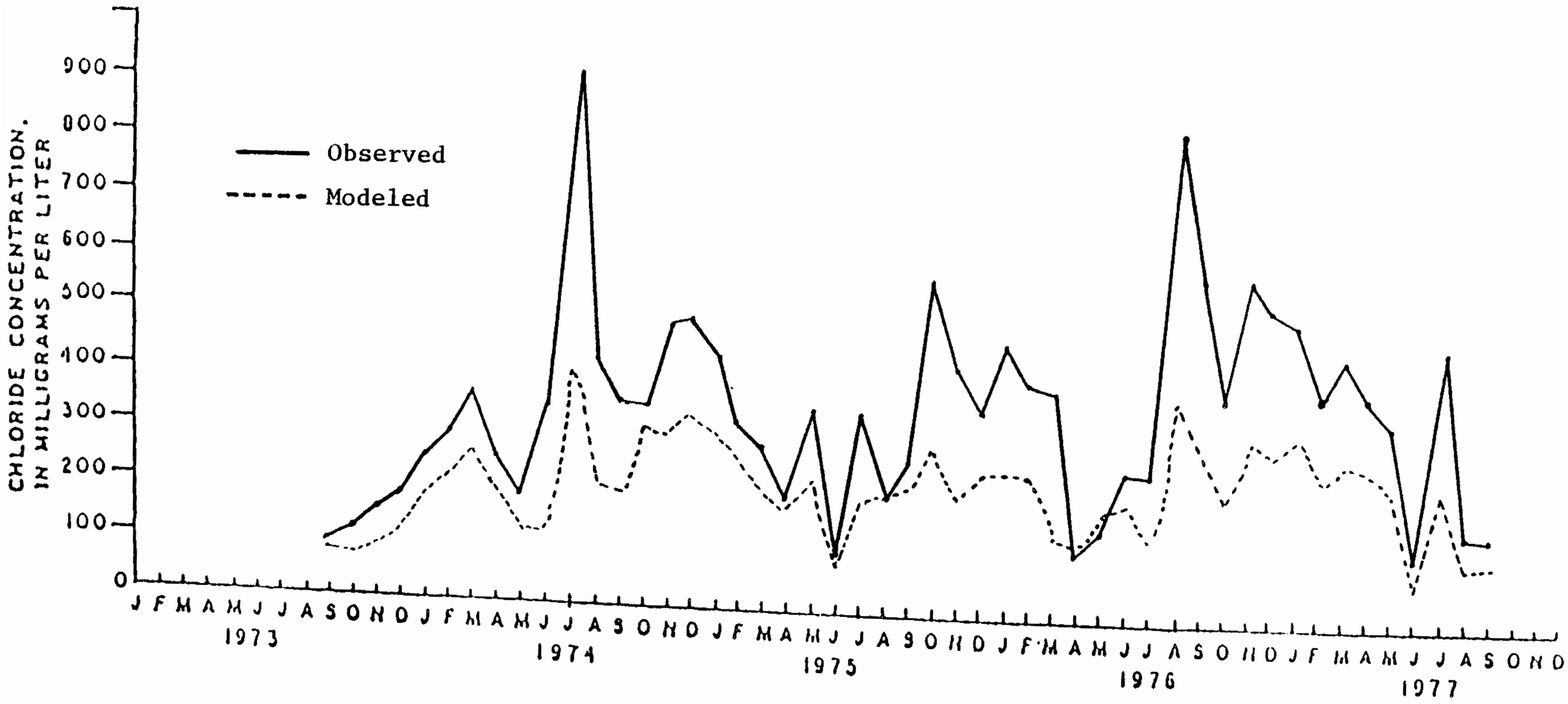


Figure A-13. Response of chloride concentration to salt-water pumping at 3.6 ft^2/day.

river. The degree of effectiveness depends on the concentration of salt water pumped. Obviously, the higher the concentration of the pumped water, the more effective the system. A prototype well could be the only way to determine the answer. A detailed site evaluation should be done if that is the course of action. However, Figure A-11 suggests that the river cannot be kept under 250 mg/l by eliminating the intrusion between New Cambria and Solomon. It is possible that the higher pumping rate over a number of years would lower the amount of salt water in the alluvium to a point where flood events would not induce substantial salt-water intrusion. This would be pushing the capabilities of the sharp interface models. A variable density model would be needed to give a definitive answer to this question.

HYPOTHETICAL MANAGEMENT OF CHLORIDE AT ENTERPRISE

From the above work, it seems that a relatively low rate of pumpage from a bank-side relief well will not always control the salt-water intrusion to the Smoky Hill River because the intrusion induced after a large flood event may be much larger than our pumping rate. The lower pumping rate of 1.8 ft^2/day over a seven-mile river section corresponds to .77 cfs, the average concentrated brine flux reported by Gillespie and Hargadine (1980) for 1973-1977. The previous chloride predictions were based on the model output which did not exactly match the observed values. Knowing the river discharge at Enterprise and the chloride concentration allows us to calculate the amount of concentrated brine being carried by the river. If we could extract .77 cfs of concentrated brine from the river, what would be the resulting concentration of the river water? The answer to this question is contained in Figure A-14. The solid curve shows the observed concentration and the dashed line shows the concentration after extraction. As we would expect from the model

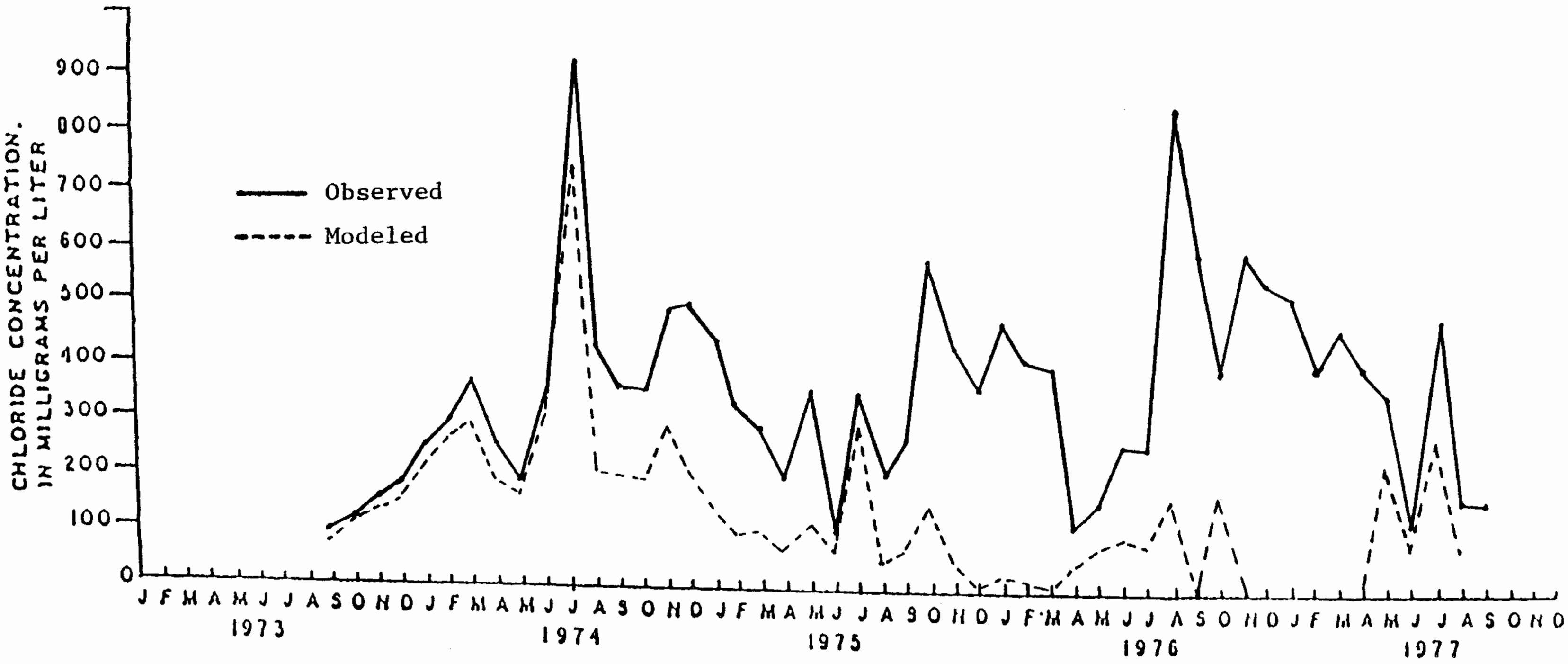


Figure A-14. Resulting chloride concentration at Enterprise after extraction of .77 cfs of concentrated brine.

results, the resulting concentration is greater than 250 mg/l sometimes. The maximum concentration is 748 mg/l. This confirms our model conclusion that pumping a constant relatively small amount of salt water will not always control the intrusion.

If we allowed variable salt-water pumping what would be the maximum amount to be extracted from the river to bring it down to 250 mg/l? This pumping rate is plotted in Figure A-15. It is over .77 cfs for only seven points. The maximum pumping rate is 2.76 cfs. However, we know from earlier work that we could not lower the chloride concentration to 250 mg/l by preventing all salt-water intrusion between New Cambria and Solomon. There is too much salt from other sources. Therefore, this exercise, although instructive, is not physically realizable.

An alternative salt-water pumpage scheme for managing the chloride concentration in the river would involve pumping into a reservoir when the river chloride concentration was greater than 250 mg/l and pumping directly into the river when the chloride concentration was below 250 mg/l. The salt water pumped into the river could come from a combination of reservoir salt water and alluvial salt water. The extraction rates (in terms of concentrated brine) to maintain the river at 250 mg/l are plotted in Figure A-16. The negative values represent pumpage from the alluvial aquifer into the storage reservoir when the river concentrations are greater than 250 mg/l. The positive values represent pumpage from the reservoir and alluvium into the river when its chloride concentration is less than 250 mg/l. Summing all the pumpage rates tells us whether the reservoir would gain or lose salt water over the period 1973-1977 if all pumpage into the river came from the reservoir. The sum is 13.0 cfs indicating that more salt water could have

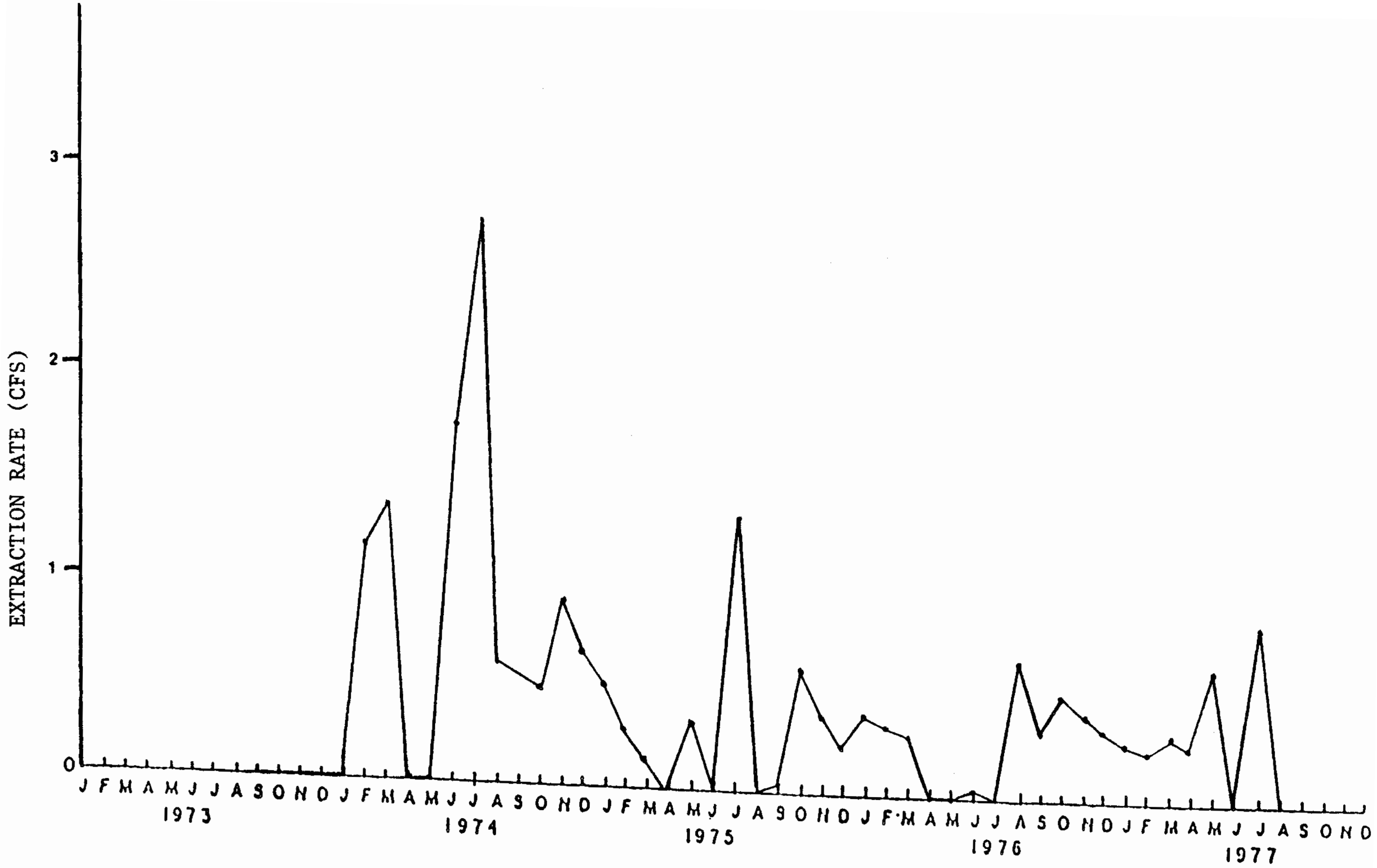


Figure A-15. Salt-water extraction rate to keep river water at or below 250 mg/1. Expressed in terms of concentrated brine.

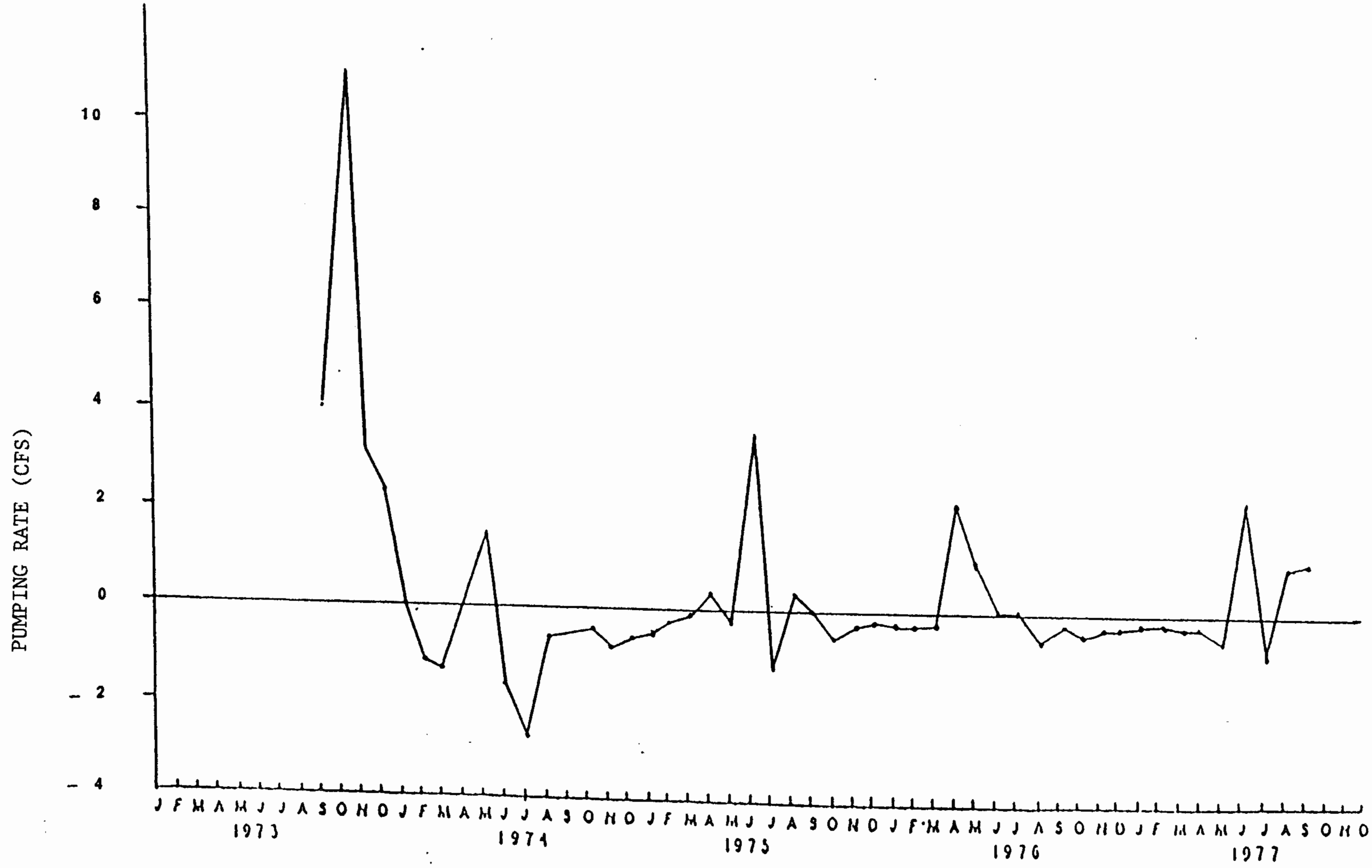


Figure A-16. Salt-water pumping rate to keep river water at 250 mg/l. Positive values indicate pumpage into the river. Negative values represent pumpage into a storage reservoir. Pumping rates are for concentrated brine.

been pumped from the alluvium. If concentrated brine could not be pumped, the extraction rates would need to be raised accordingly.

The above results seem to indicate that the chloride concentration could be maintained at or below 250 mg/l in the Smoky Hill River at Enterprise. However, a number of assumptions inherent in this idealistic calculation are probably not correct and would lead to deviations in the predicted results. First of all, there are other sources of salt water besides the reach from New Cambria to Solomon. Previous work indicates that a total alleviation of salt-water intrusion between New Cambria and Solomon would not always keep the chloride concentration below 250 mg/l. We have assumed that the bank-side alluvial relief wells screened near the bottom of the alluvium or maybe into the Wellington could continue to pump concentrated brine. This may not be true, mixing with fresher water may dilute the pumped water after some time. A detailed site specific investigation and a prototype well would probably be the only way to completely answer this question. Also, we have assumed an instantaneous response of the salt-water intrusion to the alluvial relief well pumping. In fact, there might be a lag of a few days. However, estimates from Darcy's Law would indicate that a response to alluvial relief well pumping should occur in less than a day.

SUMMARY

In this section of the report, we have tried to estimate the effect of a bank-side alluvial relief well system several ways. First of all, we estimated the effect on a single rather small flood event. We found that pumping at or double the estimated bedrock flux value would not completely prevent upconing after the flood event. However, pumping at double the bedrock flux rate would cause the salt-water mound under the river to decay.

Similar results were found with a more detailed model that tried to take into account a series of flood events. The pumpage from the bank-side alluvial relief well system could not always prevent upconing following a sizeable flood event at pumpage rates equal to or double the estimated bedrock flux. However, the relief well system did lower the peaks in the chloride concentration considerably. Lastly, a series of hypothetical management schemes were tested to try to control the chloride concentration. The net result was that, if concentrated brine could be withdrawn from the alluvium and placed in either a reservoir or the river at the appropriate time, the river chloride concentration could be maintained at or below 250 mg/l. However, there are several practical problems that would prevent the complete accomplishiment of this feat.

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Appendix I. Well location for various pumping schemes.

6 WELL LOCATION

I	J
7	9
8	9
9	9
10	9
11	9
12	9

20 WELL LOCATION -

SPACING -

2000 ft		4000 ft	
I	J	I	J
7	9	7	9
8	9	8	9
9	9	9	9
10	9	10	9
11	9	11	9
12	9	12	9
6	10	6	11
7	10	7	11
8	10	8	11
9	10	9	11
10	10	10	11
11	10	11	11
12	10	12	11
6	11	6	13
7	11	7	13
8	11	8	13
9	11	9	13
10	11	10	13
11	11	11	13
12	11	12	13