APPLICATION OF CARBON-14 GROUND-WATER AGES IN CALIBRATING A FLOW MODEL OF THE TUCSON BASIN AQUIFER, ARIZONA

by

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ABSTRACT

In the absence of pure piston flow, the carbon-14 ages of ground-water can be related to ground-water residence times only in the context of a flow model. To do this, a three-dimensional digital computer model of a portion of the Tucson Basin Aquifer was constructed using the theory of finite-state mixing cell models. The model was calibrated against the spatial distribution of adjusted carbon-14 ground-water ages, and once a reasonable fit was obtained, the ground-water residence times were calculated. The model also provides a first approximation to three-dimensional flow in the aquifer as well as an estimate of the long-term average annual recharge to the aquifer.

INTRODUCTION

This paper applies the theory of finite-state mixing cell models or FSMs (Simpson and Duckstein, 1975; Campana, 1975) to construct and calibrate a flow model of a portion of the alluvial Tucson Basin Aquifer of southern Arizona. The FSM is calibrated against the steady-state distribution of adjusted carbon-14 decay ages (Wallick, 1973). It is not necessary to assume that flow in the aquifer is of the pure piston variety; within a given cell, the FSM can simulate either perfect mixing (the simple mixing cell or SMC) or some regime between perfect mixing and pure piston flow (the modified mixing cell or MMC). In a given FSM, each mixing cell must use the same mixing rule, either SMC or MMC.

The principle behind FSM theory consists of subdividing a hydrologic system into mixing cells. This subdivision is based upon hydrologic and other information. The individual mixing cells can be of any desired size, and can be arranged in one-, two-, or three-dimensional networks. In the case of mass transport, which is considered in this paper, an estimate of the flow distribution in the system must be made, as well as inputs to and outputs from the system. The model is then iterated, and during each iteration, a simple mass balance is applied to each cell in order to simulate the movement of mass throughout the system. Each iteration corresponds to a length of time. The FSM is calibrated by adjusting the various parameters of the FSM until the modeler is satisfied with the agreement between the real-world data and the simulation results.

HYDROGEOLOGY OF THE TUCSON BASIN

The Tucson Basin is an elongated structural valley of about 2600 km^2 filled with unconsolidated alluvial deposits and older semi-consolidated and consolidated alluvial sediments (Davidson, 1973). The average thickness of the basin fill is about 1000 meters, with a maximum thickness of perhaps 3700 meters (Wallick, 1973, p. 30). The deposits include the Pantano Formation and Tinaja beds of Tertiary age and the Fort Lowell Formation of Quaternary age.

The aquifer in the Tucson Basin is essentially a single unconfined aquifer, although it is partially confined at some of the present depths of development (Davidson, 1973). Transmissivities in the aquifer range from about 12 m^2/day to 6200 m^2/day (Anderson, 1972) although in most places they are less than 620 m^2/day. Recharge to the aquifer comes primarily from two sources: infiltration from ephemeral streams during flow events and mountain front recharge. The total recharge is about equally divided between these two sources. In addition, the aquifer receives underflow across its southern and northern boundaries, and discharges underflow across its northwestern boundary (Davidson, 1973). The general direction of ground-water flow in the aquifer is from south to north.

THE TUCSON BASIN FSM

The study area is in the north-central part of the basin, in the general vicinity of the city of Tucson. The FSM of the area contains 26 mixing cells arranged in a three-dimensional cell network. Earlier models by the author attempted simulation using a two-dimensional network; however, it was essential to consider the three-dimensional flow of ground water in the study area in order to obtain a reasonable agreement between the observed and calculated decay ages. The FSM is composed of an upper and lower tier of cells.

The upper tier of cells consists of 17 cells (Figure 1), assigned the numbers 10 through 26. The locations of these cells were chosen primarily on the basis of the available C-14 decay age distribution and the hydrogeology of the area (Davidson, 1973). All the C-14 decay age data were taken from the cells in the upper tier, although not all the cells in this tier were represented by an observed C-14 decay age. The C-14 decay ages were calculated by Bennett (1965) and adjusted by Wallick (1973). The cells in the upper tier are assumed to represent the aquifer to a depth of 150 meters below the water table.

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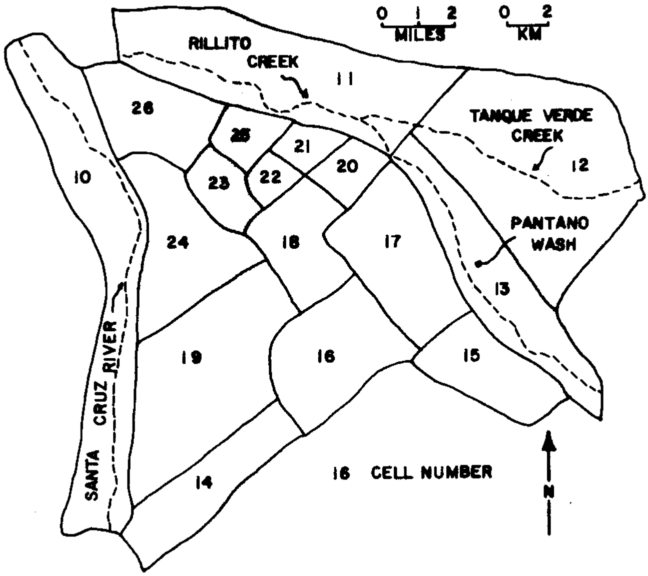

Figure 1. Upper tier of cells in the Tucson Basin FSM.

The lower tier consists of 9 cells, numbered 1 through 9 (Figure 2).

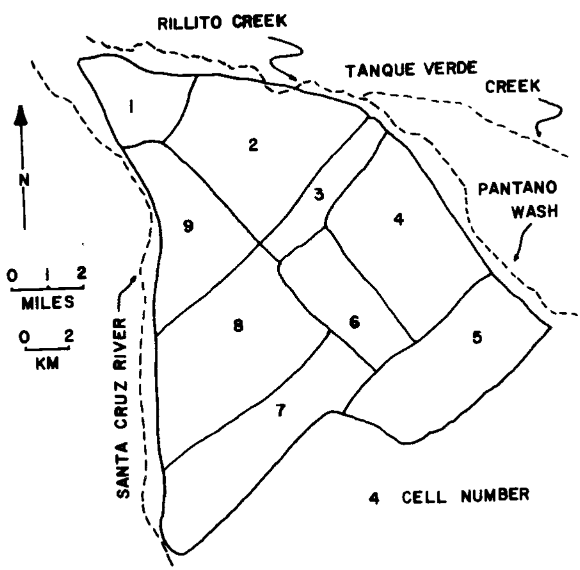

Figure 2. Lower tier of cells in the Tucson Basin FSM.

These cells represent the aquifer from 150 meters below the water table to 600 meters below it. The initial arrangement of the cells was based on the hydrogeology of the area, and subsequently modified during the calibration process.

Cell volume represents water volume, and is obtained by multiplying the total cell volume by an estimate of the cell porosity. During calibration, the cell volumes were adjusted and these adjustments amounted to changes in the porosities of the various cells. Table 1 lists the cells of the FSM, along with their final volumes (VOL), the volume of water flowing into each cell at each iteration (the boundary recharge volume or BRV), and the ratios BRV/VOL.

Table 1. VOL, BRV, and BRV/VOL for each cell in the Tucson Basin FSM.

Cell number	VOL (km^3)	BRV (km^3)	BRV/VOL (%)
1	1.23	.0019	.15
2	3.05	.0013	.04
3	.95	.0004	.04
4	2.47	.0013	.05
5	2.73	.0010	.04
6	1.23	.0005	.04
7	2.71	.0005	.02
8	2.65	.0003	.01
9	1.85	.0002	.01
10	1.48	.0086	.58
11	1.87	.0197	1.05
12	2.00	.0113	.57
13	1.36	.0175	1.29
14	.93	.0008	.09
15	1.05	.0123	1.17
16	1.42	.0025	.18
17	1.36	.0073	.54
18	.80	.0014	.18
19	2.10	.0015	.07
20	.23	.0069	3.00
21	.12	.0126	10.50
22	.12	.0111	9.25
23	.30	.0234	7.80
24	1.42	.0015	.11
25	.22	.0120	5.45
26	.99	.0269	2.72

The flow distribution within the model was initially assigned using the geohydrologic maps contained in Davidson (1973) and Anderson (1972). These maps were less useful in assigning flow distributions among the cells in the lower tier and between the upper and lower tiers. Data pertaining to the vertical movement of water and flow at great depths are limited. Davidson (1973) contains some information on the vertical movement of water in the aquifer, and this was useful in assigning an initial flow distribution between the two tiers. The initial flow distribution within the lower tier to some extent mirrored the distribution within the upper tier, except for the fact that the total amount of flow within the lower tier during a given iteration is much less than the total flow within the upper tier. In any event, the final flow distribution for the entire FSM was determined by the calibration process.

The initial estimate of average annual recharge to the model was determined from Davidson (1973). Most of the recharge consisted of infiltration from the Santa Cruz River, Rillito and Tanque Verde Creeks, and Pantano Wash and mountain front recharge from the mountains to the north and east of the study area. The average annual recharge to the area was one of the parameters adjusted during the calibration of the FSM. No effort was made to account for artificial withdrawals of water from the aquifer. Although pumpage in the area has been great over the past few decades, the time span covered by the model is large compared to the time of pumpage. Discharge from the aquifer in the study area represents natural discharge of ground water. In addition, no changes in the volumetric storage in the aquifer were allowed; during any iteration, the aquifer discharged as much water as it received from recharge areas, and the amount of recharge remained constant from iteration to iteration.

OPERATION AND RESULTS

The Tucson Basin FSM was iterated on an annual basis until each cell in the FSM reached a steady-state concentration of C-14. These steady-state concentrations were then converted to decay ages

($T_{1/2}$ = 5568 years) and compared with Wallick's (1973) adjusted C-14 decay ages. Model runs were made until a satisfactory agreement was obtained between the observed and calculated decay ages. Once this agreement was obtained, the mean ages (residence times) of the water were calculated. Calibration was accomplished using the SMC mixing rule; however, once the best agreement was obtained, the FSM was run once more using the MMC mixing rule. Mean ages were calculated for the MMC rule as well. The simulation results are given in Table 2, which also contains information on approximately how long it took each cell to acquire a steady-state concentration of C-14.

Table 2. Observed decay ages and simulation results for the Tucson Basin FSM.

Cell Number	Observed decay age[a] (years)	Calculated decay age (years)		Mean age of water (years)		Approximate time to reach steady state (years)
		SMC	MMC	SMC	MMC	
1	-	2336	2335	3018	3017	38000
2	-	2588	2587	3253	3252	42000
3	-	4163	4162	5166	5165	36000
4	-	2463	2462	2895	2894	32000
5	-	2516	2515	2897	2896	26000
6	-	5263	5263	6346	6345	37000
7	-	6109	6109	7879	7878	42000
8	-	8918	8917	13255	13254	50000
9	-	8538	8537	14358	14357	50000
10	-	171	170	172	171	2000
11	0	95	95	96	95	2000
12	-	175	175	177	176	3000
13	-	191	190	193	192	3000
14	1848	1759	1758	2258	2257	33000
15	161	276	275	278	277	3000
16	-	1333	1332	1668	1667	39000
17	1281	1035	1034	1282	1281	42000
18	3018	3131	3130	4090	4089	42000
19	3598,3680	3379	3378	4834	4833	42000
20	639	854	853	1078	1077	30000
21	0	296	295	362	361	25000
22	0	421	420	523	522	26000
23	0	367	366	471	470	37000
24	4176	4208	4207	6201	6200	45000
25	0	179	178	202	201	21000
26	1841	635	634	900	899	40000

[a]Raw decay age obtained by Bennett (1965) and adjusted by Wallick (1973). Adjusted age given.

DISCUSSION

With the exception of cell 26, agreements between the observed and calculated decay ages are very good. The excellent agreement between the decay ages in cells 11, 15, 21, 22, 23, and 25 is not apparent until one considers that because of cumulative sampling, analytical and computational errors, any C-14 decay age of 500 years or less can be considered to be of age zero (Long, 1975). Wallick (1973) suspected that the zero observed decay ages in cells 21, 22, 23 and 25 indicated that the waters from which these samples were taken were recharged after 1954, and he suggested that the samples be analyzed for bomb tritium. The presence of bomb tritium in these samples would confirm the post-1954 recharge hypothesis. The poor agreement between the observed and calculated decay ages in cell 26 may indicate that there is more water flowing into this cell from cells 1 and 24 than is depicted by the FSM.

With the exception of cell 11, the calculated decay age in each cell is less than the mean age of the water, regardless of the mixing rule. This was expected, since each cell in the FSM is relatively well-mixed, even in the case of the MMC; only in the case of pure piston flow should the decay age equal the mean age (Simpson and Duckstein, 1975). In cell 11, the MMC mean age is identical to the MMC decay age, and in cells 10, 12, 13 and 15 the differences between the ages are slight. None of these cells exhibits pure piston flow; the fact that they are on or close to major recharge boundaries may account for the small differences between the ages.

INTERPRETATIONS OF THE TUCSON BASIN FSM

If one starts on the north, east or south sides of the FSM and moves toward the center of the model, there is a general tendency for the ages, both decay ages and mean ages, to increase. The age increases are logical, since the recharge areas are located primarily around the model periphery and the recharged water must travel farther to reach the center of the study area. This pattern of increasing ages is disrupted somewhat if one starts on the west side of the area at cell 10 (the aquifer immediately beneath the Santa Cruz River) and moves toward the center of the study area. The ages increase sharply in cells 19 and 24, then decrease slightly as one moves past these cells. In fact, the oldest ages in the upper tier of cells are found in cells 19 and 24. From this observation, one would suspect that the Santa Cruz River has not been effective in recharging the central part of the study area. Indeed, the FSM was programmed to minimize recharge from the Santa Cruz River to this part of the FSM; the rationale behind this minimization were the old observed decay ages in these cells and the ground-water contour maps of Anderson (1972, Plate 3) and Davidson (1973, Plate 1). These maps indicate that ground-water flow beneath the Santa Cruz River parallels the bed of this stream. Therefore, if one accepts the model as a valid representation of the system, then averaged over the lifetime of the model, about 50,000 years, the reach of the Santa Cruz River overlying cell 10 has not contributed a great amount of recharge to the interior regions of the study area. Unlike the Santa Cruz River, the model indicates that Rillito Creek, Tanque Verde Creek and Pantano Wash are reasonably effective in recharging the interior of the study area.

The model also provides some insight into the vertical movement of ground water in the study area. During each iteration (year), 0.0038 cubic kilometers of water moves from the lower tier to the upper tier, which is less than 8 percent of the total flow moving within the cell network during each year. The amount of water moving down from the upper tier of cells to the lower tier is approximately 0.0017 cubic kilometers per year, about 3 percent of the total. Although just 11 percent of the total flow is moving in the vertical plane (between the upper and lower tier) each year, this seemingly minor amount was quite critical for the good results of the model. The model also yielded an estimate of the long-term average annual recharge to the study area, approximately 0.05 cubic kilometers (40,000 acre-feet).

ASSUMPTIONS

Numerous assumptions were made in the Tucson Basin FSM. The SMC mixing rule assumed that each year, the contents of each cell were completely mixed with any incoming material. Given the slow movement of ground water in the aquifer, this assumption is not very realistic. The MMC mixing rule is perhaps a better approximation of the mixing in the aquifer, although in most of the cells the MMC mixing rule approached the perfect mixing regime of the SMC. It was also assumed that the C-14 decay age distribution was a steady-state one, an assumption that appears to be reasonable. However, the major assumption of the Tucson Basin FSM is that the hydrologic conditions represented by the model have remained constant throughout the lifetime of the model, about 50,000 years. The hydrologic regime of the Tucson Basin has probably changed during the past 50,000 years. In fact, as recently as 90 years ago, the Santa Cruz River in the vicinity of Tucson was essentially a perennial stream (Hastings and Turner, 1965, p. 1). Smith (1910, p. 98) reported that in certain portions of the study area, springs existed and the aquifer discharged to streams. Yet despite the fact that the assumption of long-term hydrologic constancy is most likely invalid, the model seems to work reasonably well, perhaps because it may represent the "average" hydrologic regime of the past 50,000 years.

CONCLUDING REMARKS

The Tucson Basin FSM has not been validated; this can be done by collecting C-14 decay ages from those cells not represented by such ages. Sampling for bomb tritium and possibly chlorofluorocarbons might be useful in validating the model. With more data, a model using a finer cell network could be constructed.

Despite the fact that the model does not specifically include pumpage, its portrayal of three-dimensional flow in the study area should be useful in guiding future investigations into the nature of three-dimensional ground-water flow in the study area. The FSM might also be useful in constructing a three-dimensional hydraulic model. Such a hydraulic model might be based on a partial differential equation describing flow in the aquifer, since the FSM presented here is not a "true" hydraulic model. The mean ages of the waters in the various cells of the FSM could prove useful in predicting contaminant transport in the aquifer or in helping to calibrate a more rigorous mass transport model. All of the information yielded by the FSM should be of assistance in efficiently managing and exploiting the ground-water resources of the Tucson Basin, upon which the well-being of the inhabitants depends.

In a broader sense, the Tucson Basin FSM demonstrates that environmental tracers can be used to calibrate flow models of aquifers, and in doing so, can extract useful information on the hydrologic properties of the system. Environmental tracers are simply chemical species existing naturally in an environment. These tracers do not have to be radioactive, as are C-14 and tritium, but can be stable tracers such as oxygen-18 and deuterium. Nor must one deal with steady-state tracer distributions as was the case with the Tucson Basin FSM. Transient tracer distributions can be accomodated, and this has been demonstrated with a two-dimensional flow model of the Edwards Limestone of south-central Texas calibrated against the transient distribution of tritium (Campana, 1975). Finite-state mixing cell models should also be able to simulate contaminant movement in aquifers. In addition to aquifers, other hydrologic systems appear to be amenable to representation by FSMs.

Perhaps the most interesting aspect of finite-state modeling of environmental tracer distributions was illustrated by the climatological implications of the Tucson Basin FSM. Such FSMs should prove of some assistance in unraveling the paleoclimatology and paleohydrology of a particular region. Data for constructing and calibrating these models would be drawn not only from environmental tracer information but from historical climatic data as well as from disciplines such as dendroclimatology. This novel use of finite-state models remains totally unexplored, although the author believes it merits further investigation.

In conclusion, the Tucson Basin FSM provides hydrologists and water resources planners with useful information on a portion of the aquifer in the Tucson Basin. This information has an intrinsic value in managing the water resources of the area, although it can be used to design sampling programs or to construct other more sophisticated models. More importantly, the Tucson Basin FSM illustrates how FSMs can be used to extract more information from environmental tracer distributions than was previously possible.

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