Case Study of the Sheahan Wellfield Using $^3H/^3He$ Field Data to Determine Localized Leakage Areas

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Abstract: Source water protection zones are not easily determined for semiconfined aquifers with highly localized areas of leakage from overlying shallow aquifers. This research is a companion case study to a theoretical study detailing the inverse modeling of aquifer mixing zones using age-distribution models. Where the first study detailed the capabilities of inverse age-distribution modeling given various sets of environmental tracer data and prior information, this study demonstrates the successful application of the technique to a real-world problem with a robust conceptual model verified in the current literature. The case study presented here considers a hydrogeologic setting in the northern Mississippi Embayment where highly localized leakage features exist between a shallow alluvial aquifer and the Memphis aquifer. Geochemical analyses, environmental, and radiochemical tracers have been used to develop and verify a conceptual model of the flow system at the Sheahan Wellfield in Memphis, Tenn. This study used inverse age-distribution modeling of tritium and helium-3 at multiple wellheads to determine the most highly probable location of a near field leakage source that is impacting wellheads. The method was used to identify the most likely location of the leakage site, and to identify an area at most risk for wellhead management considerations.

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CE Database subject headings: Leakage; Aquifers; Tracers; Water quality; Mississippi River; Bays; Tennessee.

Introduction

When semiconfined aquifers are used as a drinking water source, it is important to understand the spatial recharge mechanisms. This is particularly true in the vicinity of production wells, so that potential avenues of contamination can be identified for the development of wellhead protection strategies. Semiconfined aquifers are more vulnerable to contamination than completely confined aquifers because breaches in confining layers allow hydraulic communication with overlying shallow aquifers. Shallow aquifers are more susceptible to anthropogenic contamination, due to their proximity to the surface, and can provide a mechanism for contamination of semiconfined aquifers should harmful constituents progress to the water table. Locating these leakage features is an arduous task given the types of observation data available. The use of environmental tracers to investigate the vulnerability of semiconfined groundwater systems is supported strongly in the literature (Maloszewski and Zuber 1983; USEPA 1993).

A technique has been developed combining an environmental tracer, prior knowledge of a system, and other hydrogeologic data with age distribution modeling to identify a source of recharge to a wellhead for wells screened within a semiconfined aquifer (Ivey et al. 2008). As the companion case study, this research provides the field data and analysis in support of the theoretical study. The theoretical background for this research will not be repeated in this paper, and readers are encouraged to review Ivey et al. (2008) for detailed information regarding the underlying principles. The objective of this study was to evaluate a conceptual model of the system using environmental tracers and age-distribution modeling in order to identify a localized leakage feature in an existing wellfield. This study was implemented using wellheads within the Sheahan Wellfield in Memphis, Tenn., where a robust conceptual model has been developed and verified in the literature with regard to leakage, degree of semiconfinement, and sources of recharge (Gentry et al. 2006, 2003; Larsen et al. 2003).

Regional Hydrogeology

Memphis is located in the south-central portion of Shelby County within west Tennessee, as shown in Fig. 1. The citizens of Memphis receive their water supply from the extensive Memphis aquifer. The Memphis aquifer is confined to a semiconfined sand aquifer which is part of a larger hydrogeologic feature known as the Mississippi Embayment, shown in Fig. 1. The Mississippi Embayment is a trough-shaped formation that is filled with over 914 m of unconsolidated sediments of sand, silt, clay, and minor amounts of lignite, with a base structure of Paleozoic rock. The Memphis area is located in the center of the northern Mississippi Embayment, which plunges southward along an axis approximating the Mississippi River.

The Memphis aquifer is formed from fine to coarse-grained

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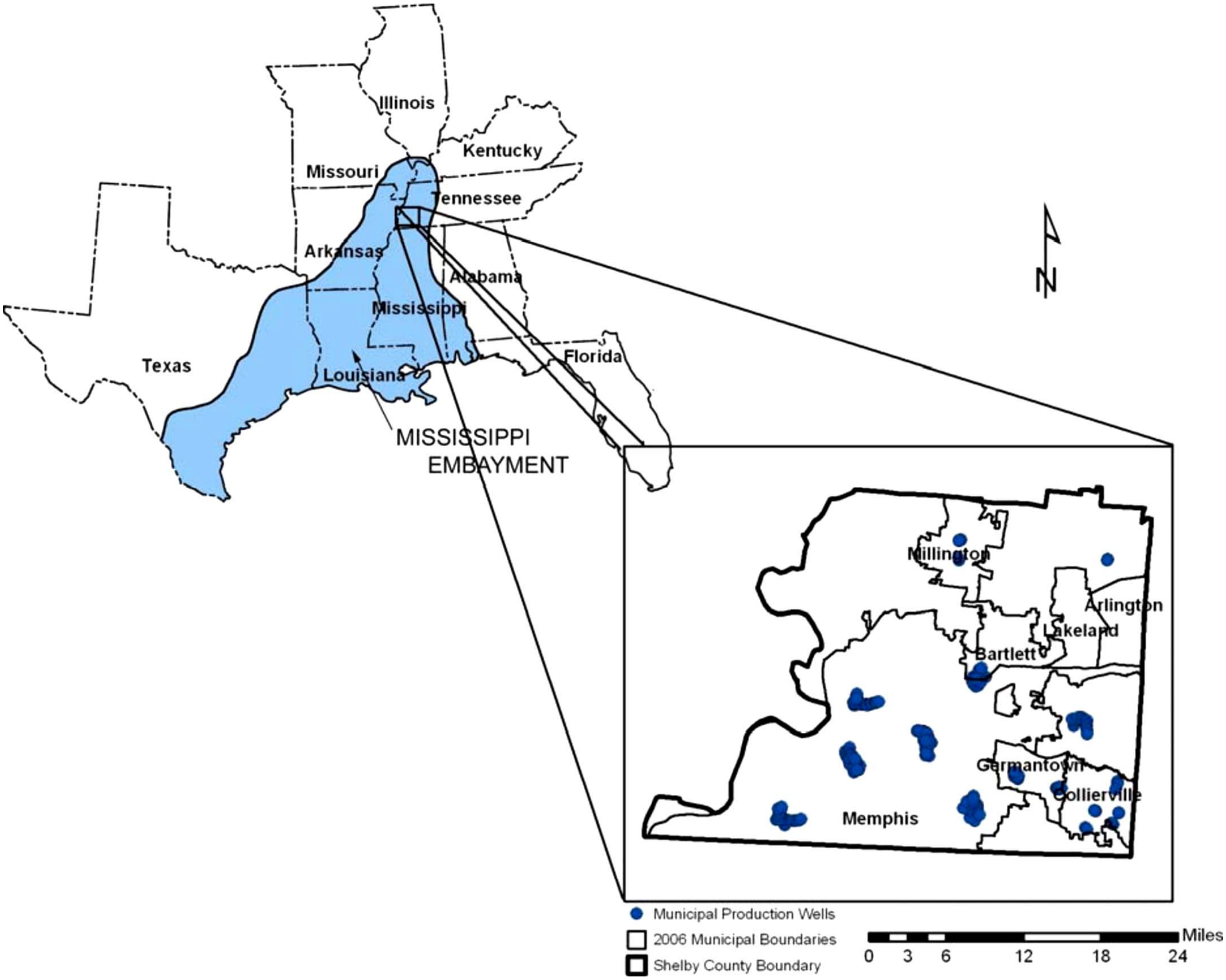

Fig. 1. Areal extent of Mississippi Embayment and location of Sheahan Wellfield in Memphis, Tenn.

sand with interspersed lenses of clay and small amounts of lignite (Brahana and Broshears 2001). The aquifer ranges in thickness from 122 to 274 m, generally increasing in thickness toward the southwestern portion of the county (Parks and Carmichael 1990). The Memphis aquifer is protected from the overlying shallow aquifer by a confining unit that consists of more than 61 m of clay in some areas (Parks 1990). It was previously thought that the confining unit was a continuous unit of nearly "impermeable" clay and thus the Memphis aquifer was not susceptible to vertical leakage (Wells 1933). However, today it is known that the clay beds vary in thickness from 61 to 1 m, and that the confining unit is absent in some locations (Parks 1990). Existing data indicate that heterogeneities and paleovalleys incised into the confining unit allow hydraulic communication between the underlying Memphis aquifer and the overlying shallow aquifer (Parks 1990; Larsen et al. 2002).

Additionally, geochemical models have been developed for specific areas within the county where it is known that shallow aquifer water is being introduced into the Memphis aquifer in the vicinity of confining unit breaches. These models indicate that between 6 and 32% shallow aquifer water is being received at affected wells within the Memphis aquifer (Larsen et al. 2003). The results of these models give some indication of the relative vulnerability of the Memphis aquifer, and of the significant role the shallow aquifer may play in its recharge. Further details regarding the regional hydrology are present in the literature and will not be presented here for brevity (Larsen et al. 2003; Gentry et al. 2006). Given the hydrologic data for the occurrence of highly localized aquitard leakage and the estimated contribution of water from the shallow aquifer, a methodology for determining wellhead protection zones that identifies areas of high vulnerability is needed.

Sheahan Wellfield

The Sheahan Wellfield is one of Memphis Light, Gas, and Water's ten production wellfields that provides the water supply to the consumers in the city of Memphis and some of the surrounding areas. The layout of the Sheahan Wellfield is shown in Fig. 2. The wellfield consists of 24 production wells screened in the Memphis aquifer at depths ranging from approximately 91 to 236 m below ground surface. The well screens are generally 24–30.5 m in

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Fig. 2. Layout of Sheahan Wellfield, Memphis, Tenn.

length, thus they are screened over very short intervals of the aquifer. Ground surface elevations in the Sheahan Wellfield range from approximately 82 to 93 m (NGVD 1929).

In 1965, leakage from the shallow aquifer to the Memphis aquifer was suspected just south of the Sheahan Wellfield due to a loss of water from Nonconnah Creek that was attributed to underflow (Nyman 1965). The creek was observed to be dry during fall months in this area, although upstream and downstream reaches still had measurable flow (Nyman 1965). An area to the immediate west of the Sheahan Wellfield (as shown in Fig. 2) has been identified as the probable location of a leakage window into the Memphis aquifer (Graham and Parks 1986; Parks 1990). Recent studies have provided chemical and isotopic evidence that the Memphis aquifer is receiving leakage from the overlying shallow aquifer in the vicinity of the Sheahan Wellfield and have established conceptual models for the behavior of the system (Graham and Parks 1986; Parks and Carmichael, 1990; Ivey 1997; Ivey et al. 2002; Larsen et al. 2002, 2003; Gentry et al. 2006).

A depression is present in the water table surface in the southern part of the Sheahan Wellfield. Because there is no pumping from the shallow aquifer, the depression in the water table is indicative of leakage to the underlying Memphis aquifer (Graham and Parks 1986). Additionally, a distorted temperature gradient exists in the Memphis aquifer in the southern portion of the wellfield. The distorted gradient was attributed to downward leakage from the overlying shallow aquifer, as the temperature was coolest at a greater depth than would typically be expected (Graham and Parks 1986). Recent shear wave data indicate an erosional feature in the confining unit in the south Sheahan area (Ground Water Institute 2001). Also, data from rotasonic drilling indicate a possible breach in the confining unit in the southern part of the wellfield (Gentry et al. 2006). A geologic cross section was developed from driller's and geophysical logs trending north-south through the Sheahan Wellfield (Larsen et al. 2002). The cross section showed that the confining unit is highly heterogeneous and contains several thick sand lenses.

In order to better characterize the localized leakage at the wellfield scale, samples from each well were collected in the fall of 1999 and again in the late spring/summer of 2000 for geochemical and environmental isotopic analyses. Tritium was detected in two-thirds of the water samples (Larsen et al. 2001). In general, the results showed that tritium concentration increased with decreasing depth (Ivey et al. 2002). From the isotope data, it was not possible to determine the spatial distribution of recharge. However, the results did suggest that the composition of water in the wells screened in the upper part of the Memphis aquifer is a binary mixture of shallow aquifer water (modern water) and unaffected deep Memphis aquifer water (submodern water) (Ivey et al. 2002).

From the initial tritium sampling in 1999–2000, five wells were selected from the Sheahan Wellfield and were sampled again in late 2000 (Ivey et al. 2002). These samples were analyzed for tritium and tritium/helium-3. The tritium/helium-3 analyses allowed the interpretation of apparent ages of the water samples

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from the five wells. The apparent age determined from an environmental tracer is defined as the time that has elapsed since the water was last in contact with the atmosphere. The apparent age representations are strongly coupled to the youngest water in the flow regime. The results indicated apparent ages ranging from 16 to 51 years (Ivey et al. 2002; Larsen et al. 2002). In general, the apparent age increased with increasing depth. The two samples screened in the uppermost part of the Memphis aquifer yielded ages of less than 20 years, indicating that a significant portion of modern recharge may be influencing these wells (Ivey et al. 2002; Larsen et al. 2002).

In addition to the relative age dating tools, geochemical analyses were performed on the water from the 1999 to 2000 sampling of the Sheahan Wellfield (Larsen et al. 2001). The geochemical properties of the Memphis aquifer are different from that of the shallow aquifer, which is comprised of fluvial terrace deposits and alluvial sand and gravel (Larsen et al. 2003). The Memphis aquifer in its unaffected (no modern water present) state has a low total dissolved solids (TDS) concentration, and is a calcium bicarbonate type (Brahana et al. 1987). The shallow aquifer, on the other hand, has a poorer water quality and a characteristically higher TDS concentration (Brahana et al. 1987). In the 1999–2000 geochemical analyses, the wells screened in the upper part of the aquifer which had the highest tritium values were comprised of a higher TDS, $Na-S-O_4-Cl$-rich water, whereas the wells screened in the lower part of the Memphis aquifer (corresponding to the wells with the lowest tritium values) were associated with a lower TDS, $Ca-Mg-HCO_3$-rich water (Larsen et al. 2001, 2003). Piper diagrams are available for further description of these geochemical analyses in Larsen et al. (2002).

Geochemical modeling was performed on the data available for the Sheahan Wellfield. One study used the geochemical code NETPATH (Plummer et al. 1994), and barium as a conservative tracer to identify a percentage of shallow water being received at well screens of affected wells (Ivey 1997). This study indicated that 8–14% shallow water was comprised of samples from certain wells within the Sheahan Wellfield. A more recent study using the geochemical data from the 1999 and 2000 sampling events predicted 6–32% shallow water comprising the samples from affected wells in Sheahan, based on the most reasonable models (Larsen et al. 2002, 2003). Thus, the Sheahan Wellfield was selected for this study because of the variety of information that exists to indicate that the Memphis aquifer is receiving a component of modern recharge in this area.

Methodology

The use of age distribution models in the identification of window features and the development of wellhead protection (WHP) areas for semiconfined aquifers with highly localized areas of leakage is absent from the literature. Although some studies have used the age-distribution models to assess relative vulnerability, the use of the models has not been extended to recharge feature identification and wellhead protection. The current research was intended to address the need for approaches to WHP area delineation for semiconfined aquifers that were less uncertain and could be calibrated. Additionally, the research is intended to expand upon the current body of research in the use of age-distribution models and environmental radioisotopes.

This research project involved the development of a new technique for locating likely sources of hydraulic communication between shallow and semiconfined aquifers, as presented in Ivey et al. (2008). An inverse age-distribution model was developed (Ivey et al. 2008), and the technique was applied to the Sheahan Wellfield site for Wells MLGW 78, 87, and 88, identified in bold text in Fig. 2, which were known to be near a localized leakage feature (Larsen et al. 2003; Gentry et al. 2006). These wells were also selected for modeling due to the known minimum data requirements from the theoretical model (Ivey et al. 2008). These wells were the only three for which sufficient tritium and tritium/helium-3 data were available. The exponential-piston model was selected as the age-distribution model appropriate for the Sheahan site based on the robust conceptual model developed through previous research (Graham and Parks 1986; Ivey 1997; Ivey et al. 2002; Larsen et al. 2002, 2003; Gentry et al. 2006). Fig. 3 shows the conceptual model for exponential-piston flow to a wellhead. The age distribution models developed for wellheads in the MLG&W Sheahan Wellfield were calibrated to existing environmental tracer data. Parameters estimated in the models were validated by comparison with additional hydrologic and geochemical data that were developed in previous studies (Parks 1990, Larsen et al. 2003).

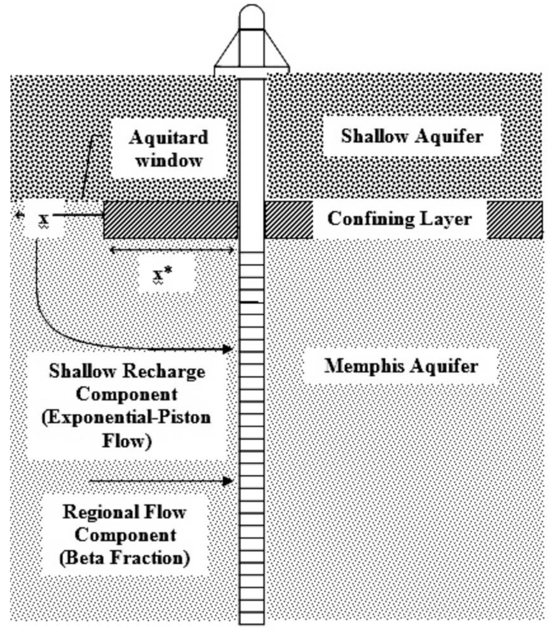

Fig. 3. Conceptual model of application of exponential piston model at wellhead

Tritium Input Function

The input function, C_{in}, is given by Maloszewski and Zuber (1996) and is expressed in Eq. (1)

$$C_{\text{in}} = \frac{[(\alpha\Sigma C_i P_i)_s + (\Sigma C_i P_i)_w]}{[(\alpha\Sigma P_i)_s + (\Sigma P_i)_w]} \quad (1)$$

where α=fraction of infiltration occurring in winter months that can be attributed to summer infiltration; C_i=monthly tritium concentration in precipitation; P_i=monthly precipitation amount; w=subscript representing winter months; and s=subscript representing summer months. Additional details on the tritium/helium-3 dating method can be found in Ivey et al. (2008). For

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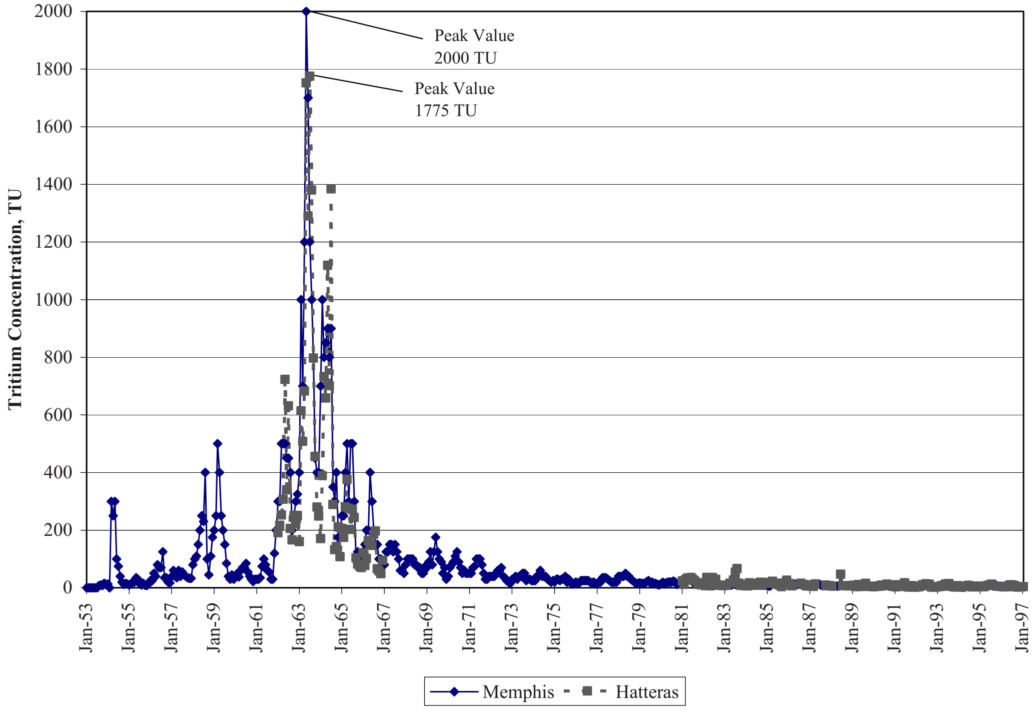

Fig. 4. Tritium concentrations for Hatteras, N.C. (Source: IAEA 2001) and Memphis, Tenn. (Source: Cross 1989)

tritium, data for concentrations in precipitation are available for stations all over the world for periods before the advent of above ground nuclear weapons testing to the present, from the International Atomic Energy Agency (IAEA). The majority of records for tritium in precipitation began in the early 1960s, however data are available for many stations as early as the mid 1950s. When no data are available for the study area for C_i, data should be taken from the nearest IAEA station for which data are available, and through extrapolating correlations between other stations where gaps in data exist (Maloszewski and Zuber 1996, 2002). For the current research, a program developed by the United States Geological Survey (USGS) in conjunction with a study of tritium deposition across the continental United States was used to extrapolate monthly values of tritium for Memphis during the years 1953–1987 (Michel 1989; Cross 1989). The program extrapolated between stations with existing data to produce estimates of monthly tritium for a given latitude and longitude (Cross 1989).

For stations where gaps in data existed, tritium values were determined using the Ottawa Correlation (IAEA 2001). The Ottawa correlation used a least-squares regression to correlate data between IAEA stations across the Northern hemisphere with extensive data available for Ottawa, Canada. Stations generally had a correlation coefficient value of 0.9 or greater (Michel 1989). Michel (1989) identified a prevailing geographic gradient in tritium concentrations within the United States, with higher concentrations observed in the north and decreasing to the south, and extrapolated values for a given latitude and longitude based on its location relative to stations with available data.

For the years subsequent to 1987, data from Hatteras, N.C., were used to approximate the values for Memphis (IAEA 2001). Multiple cities were considered for use in this approximation; however, based on the available input records and the north-south gradient, data from Hatteras were selected to approximate values for the Memphis area. Hatteras (35.2°N, 75.6°W) lies on a latitude similar to Memphis (35.3°N, 90°W), and should adequately represent values for the Memphis area. IAEA data for Hatteras are shown with data estimated from Cross's program for Memphis in Fig. 4. The estimates during the 1950–1960 nationwide peak in atmospheric tritium concentration are the most important in development of the tritium input function. After the decline in atmospheric tritium values, any error in the estimate will not have much impact on the results of the effort to model tritium concentrations in groundwater (Maloszewski and Zuber 2002). Thus, any error associated with estimating tritium input concentrations for Memphis from Hatteras should be minimal.

Monthly precipitation data for Memphis were obtained through the National Climatic Data Center for a station at the Memphis International Airport. Monthly precipitation data were available from 1953 to the present. The alpha coefficient represents a fraction of infiltration occurring in winter months that can be attributed to summer infiltration due to vadose zone transport latency. Research has shown that for moderate climates, the value of α ranges from 0.4 to 0.8, and that the model results are significantly affected by changes in α only for systems having very rapid turnover times (Maloszewski and Zuber 2002). An alpha value of 0.5 was used for the Memphis area.

In addition to developing an estimate of the input function, it was necessary to lag the input function to account for groundwater travel time through the shallow aquifer before entering the Memphis aquifer through a probable leakage location. Different lag times were tested on the models of each of the three Sheahan wells to determine the most appropriate time shift to use. It was determined through simple Darcy velocity calculations that the youngest water in the shallow aquifer in the vicinity of the Sheahan Wellfield may be in the range of 4–17 years. This calculation was based on assuming that Nonconnah Creek is a source of recharge to the shallow aquifer. Simplifying assumptions were made using an average hydraulic gradient, a range of reported hydraulic conductivity values, and an average uniform saturated thickness. It is recognized that the assumptions required for the calculations may not necessarily represent the physical reality of

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the system; however, the values were used simply in a qualitative manner to assess the feasibility of the lag time determined subsequently through empirical testing using the application model. These calculations gave a feasibility range for testing the age distribution models developed for the Sheahan Wellfield to determine the most appropriate lag time for the system. The incorporation of a delay of the input function allowed the exponential-piston model to be developed with $t=0$ corresponding to an approximated entrance of recharge at the suspected window location.

Environmental Tracer Data and Sampling

Data used for this research include results for tritium and its decay product helium-3 measurements from previous sampling events and new tracer information collected specifically for this project. For detailed information about the tritium/helium-3 age dating method and its application in this research, please see Ivey et al. (2008). Apparent ages available for three wells (MLGW 78, 87, and 88), within the Sheahan Wellfield, indicate that they are receiving a component of modern recharge (Ivey et al. 2002; Larsen et al. 2002). These three wells were sampled again in the fall of 2002, along with two additional wells, and tritium/helium-3 analyses were obtained for all five wells. The two additional wells sampled in the fall 2002 sampling event were a Memphis aquifer production well (MLGW 99) and an adjacent shallow monitoring well (MLGW 99s). These wells were included in the fall 2002 sampling event due to previous research indicating a confining unit breach at MLGW 99 (Ground Water Institute 2001).

Helium-3 samples for the Memphis aquifer production wells were collected using watertight diffusion samplers consisting of copper tubes connected by a semipermeable diffusion membrane. This type of apparatus is typically used for such samples because it allows for the collection of the gases only, which reduces required laboratory preparation time. The samplers were deployed in flow-through cells that were attached to the well's sampling port through copper tubing. The pressure at the pumps was maintained near 345 kPa in order to avoid degassing of the water. The samples were allowed to equilibrate for 24 h prior to collection. Additionally, the production wells were allowed to run for a minimum of 12 h prior to sampling. The procedure for collection of helium-3 samples from the shallow monitoring well was similar to that for the production wells; however, diffusion samplers were lowered into the well rather than being placed in a flow-through cell, and were allowed to equilibrate for at least 2 days. Before deployment of the diffusion samplers, a minimum of three well volumes of water was pumped from the monitoring well.

Tritium samples were collected just before the diffusion samplers were deployed at the production or shallow monitoring wells. The samples were collected in 1-L amber glass bottles. Both the tritium and helium-3 samples from the Sheahan Wellfield were sent to the Noble Gas Laboratory at the University of Utah for tritium/helium-3 analysis. Tritium activity was determined by the helium in-growth method (Clarke et al. 1976; Bayer et al. 1989; Solomon and Cook 2000). The detection limit using this approach is 0.05 tritium units (TU). Helium isotopes were measured using a mass spectrometer, to a precision of approximately ±0.5%.

Results and Discussion

A lag time of 5 years was determined to provide the best model fit for all three wells. Times less than 5 years resulted in increasingly higher errors, as did times greater than 7 years. A shift of 5, 6, or 7 years yielded very similar results, however, the models using a lag time of 5 years had the best overall performance in terms of convergence. Thus, a 5 years shift in time was selected for use with the Sheahan well models. This caused a corresponding $t=0$ to occur at 1997, rather than 2002 for recharge entrance at a window location.

Table 1. Tritium and Helium-3 Observation Data for Selected Sheahan Wells

Well ID	Observation date	Tritium (TU)[a]	Helium-3 (TU)[a]
Well 87	1999-fall	2.76 ± 0.5	NA[b]
	2000-spring	1.63 ± 0.5	NA[b]
	2000-fall	2.30 ± 0.3	5.2
	2002-fall	1.38 ± 0.07	4.2
Well 88	1999-fall	1.09 ± 0.5	NA[b]
	2000-fall	1.30 ± 0.1	2.4
	2002-fall	1.00 ± 0.05	1.7
Well 78	1999-fall	0.99 ± 0.5	NA[b]
	2000-spring	0.82 ± 0.5	NA[b]
	2000-fall	0.29 ± 0.06	1.6

[a](TU) = tritium units.

[b]NA = not available.

All models were developed to estimate the values of x^*, the distance to the recharge source; x, the linear extent of the recharge feature; R, the recharge through the confining unit breach; and β, the percentage of submodern water contribution to the wellhead. For each model, prior information was only specified for β [derived from geochemical results (Larsen et al. 2003)]. Although prior information was not specifically given for the values of x and x^*, reasonable maximum and minimum values were entered into the model to limit the search space based on known hydrologic and geologic data.

The results achieved from the 2002 age dating for Sheahan Well 87 fit the dissolved gas models well, indicating there was not a significant amount of error resulting from sample collection or extraction. This provided an additional tritium and helium-3 value for use as a calibration target. The tritium and helium-3 data available for this well are shown in Table 1, along with the associated measurement error for each data point, where available. Well 87 had the highest error of the three calibrated models. This may be due to seasonal variation in tritium values. This well had the largest seasonal fluctuations apparent in the tritium observation data. The calibrated model closely approximated the helium-3 values; however, fairly large errors were present in the tritium estimates. However, in most cases, the model error was just slightly higher than the expected measurement error. A unique convergence was achieved, regardless of starting parameters. The model results are presented in Table 2, along with predicted values of x, x^*, R, and β.

The 2002 analyses for tritium/helium-3 also yielded good results for Sheahan Well 88. The exponential-piston model (EPM) for this well had the lowest error of the three calibrated models. Unique results were achieved for all four parameters. There were no data available for this well for the spring of 2000. The observation data available for this well are shown in Table 1. The results of the calibrated model are listed in Table 2, along with predicted parameter values.

The 2002 analyses for tritium/helium-3 did not yield acceptable results for Sheahan Well 78. Thus, 2002 values could not be

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Table 2. EPM Model Results for Selected Sheahan Wells

Well ID	Observation dates and selected model output	Measured value (TU)[a]	Simulated value (TU)[a]	Residual (TU)[a]
Well 87	Tritium-99	2.76	2.00	0.76
	Tritium-00 (spring)	1.63	1.92	−0.29
	Tritium-00 (fall)	2.30	1.88	0.42
	Tritium-02	1.38	1.81	−0.43
	Helium-00	5.2	5.11	0.09
	Helium-02	4.2	4.37	−0.17
	X	1,237 m	—	—
	*X**	442 m	—	—
	R	6.2 m	—	—
	β	0.78	—	—
	Horizontal velocity	0.30 m/day	—	—
	Mean transit time	15.5 years	—	—
Well 88	Tritum-99	1.09	1.06	0.03
	Tritium-00	1.30	1.03	0.27
	Tritium-02	1.00	1.14	−0.14
	Helium-00	2.4	2.19	0.21
	Helium-02	1.7	2.28	−0.58
	X	603 m	—	—
	*X**	457 m	—	—
	R	9.0 m/year	—	—
	β	0.87	—	—
	Horizontal velocity	0.21 m/day	—	—
	Mean transit time	13.7 years	—	—
Well 78	Tritum-99	0.99	0.61	0.38
	Tritium-00 (spring)	0.82	0.60	0.22
	Tritium-00 (fall)	0.29	0.59	0.30
	Helium-00	1.60	1.61	0.01
	X	1,186 m	—	—
	*X**	814–1,148 m	—	—
	R	7.9–8.8 m/year	—	—
	β	0.94	—	—
	Horizontal velocity	0.28 m/day	—	—
	Mean transit time	18.0 years	—	—

[a](TU) = tritium units.

used for model calibration. This resulted in a nonunique estimate of both x and R within the model runs. Even with the addition of prior information on x^*, there was still not enough information available to the model for a unique convergence. The estimates of x and β were within acceptable ranges upon convergence, varying by less than 6%. The observation data available for this well are shown in Table 1. The results of the calibrated model are listed in Table 2, along with predicted parameter values. A range of values is reported for the parameters x and R, since a unique calibration was not achieved.

The predicted regions of recharge for each well were analyzed to determine the most probable location of a recharge feature. The most probable location of a recharge feature is the area where all three predicted regions overlap. The extents were overlain on a map of the area to determine possible recharge sources, and whether or not the areas overlapped in the vicinity of the suspected window location west of the Sheahan Wellfield. The results are shown in Fig. 5. The area shown in bold outline is the location where all three model results overlap.

The residuals from calibrated models for the Sheahan Wellfield were higher than those from the test case presented in Ivey et al. (2008). The most likely cause of this is the uncertainty inherent in the approximated input function. For the test case, the input function was assumed to be known perfectly. Thus, very small errors resulted in the estimates of the tritium and helium-3 observations, and in the predicted values of x, x^*, β, and R. For real-world scenarios, the input function can only be approximated based upon annual average values. Additional sources of uncertainty that may contribute to the model errors are the variable nature of pumping at the wellfield, the fact that wells are not fully screened within the aquifer, and seasonal effects that cannot be accurately modeled. The resulting input function, however, is still appropriate for use in the technique and errors in the approximation due to this or any of the above mentioned sources of variability do not preclude a unique calibration provided enough tritium and helium-3 observation data are available.

The estimate of the lag time in the shallow aquifer is also a source of error in the technique. The ranges determined from Darcy calculations for the shallow aquifer assuming Nonconnah Creek as a recharge source, are made assuming that the simplifi-

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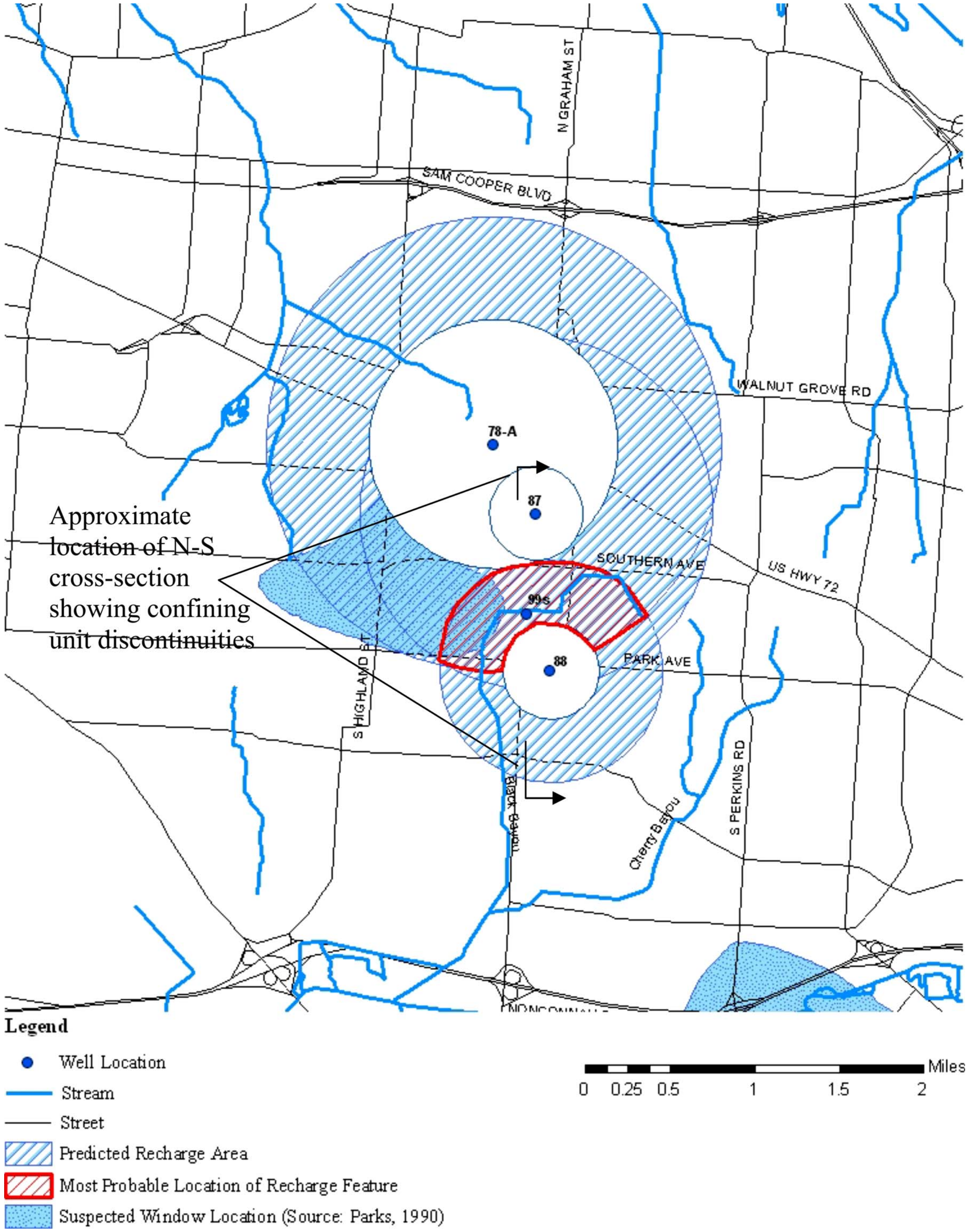

Fig. 5. Extent of recharge window areas based upon exponential–piston model results at individual wellheads

cations necessary to perform the calculations (namely that the system can be approximated with an average hydraulic gradient and an average uniform saturated thickness) do not prevent a feasible range of travel times from being estimated. The estimates were calculated to determine whether or not the Nonconnah Creek system could be a feasible source of flux to the shallow aquifer to provide the recharge through the identified window feature. The identification of a possible recharge source to the shallow aquifer is of interest since the shallow aquifer in the vicinity of the Sheahan Wellfield has been desaturated, and a continuous source of water to the aquifer is required for it to contribute to the Memphis aquifer. The heterogeneity of the shallow aquifer system makes a definitive identification of its local recharge source difficult. It may be more probable that a paleochannel provides a rapid recharge path to the window feature estimated from this research, which would explain the apparent rapid flow through the shallow system (Larsen et al. 2002). Irrespective of the Darcy velocity calculations, the most reasonable fit of the Sheahan data was achieved by lagging the tritium input function. The lag time was assumed to be within a feasible range.

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Horizontal velocity and mean age estimates predicted from the Sheahan models correspond well to expected values, indicating that the errors inherent in approximating the real-world situation do not prevent reasonable results. Additionally, predicted recharge values from the Sheahan models fall within the range predicted by published numerical flow models from previous studies (Brahana and Broshears 2001; Gentry et al. 2003).

The estimate of the β parameter from geochemical codes is obtained using a single value for the tritium concentration for a wellhead. Averages for the geochemical parameters of the shallow aquifer are used in the model as well. Thus, the β parameter also provides a source of error in the technique. However, the large standard deviation applied to the β parameter ($\pm 20\%$) in prior information for the current models did not require strict convergence to the values obtained from the geochemical models.

In all three Sheahan well models, the only formal prior information provided was that for the percentage of submodern water (β). A fairly large standard deviation was given for β, as stated above, so that strict adherence to the prior information was not required for convergence. In the case of Wells 78 and 87, the calibrated models converged at the β values as indicated from the previous geochemical modeling results. The value for Well 88 was higher than that from the prior information; however, the close agreement between the geochemical modeling and the current research results indicates that the geochemical modeling results provide very reliable prior information for the estimation of the four parameters. Although prior information was not specified for x^*, the search space was constrained to reasonable values by supplying both a reasonable minimum and maximum in the model input.

One of the most important results from this method was the successful identification of the most probable location of a recharge source from actual field data. The results from the model runs for Sheahan Wells 78, 87, and 88 indicate a region most likely to contribute recharge from overlapping model results. The area identified previously in Fig. 5 incorporates part of the suspected window location determined by Parks (1990) and is consistent with recent studies of the area (Gentry et al. 2006). Gentry et al. (2006) provided a stratigraphic cross section of the area and included a natural gamma log from a shallow well in the vicinity, which indicated that a confining unit breach exists within the region identified in this research. The results of both the current research and that performed by Gentry et al. (2006) indicate that the vicinity of Well MLGW 99 is the most probable area of leakage.

Conclusions

The inverse age-distribution modeling is a useful tool for identifying localized leakage areas in an otherwise confined wellfield setting. The technique allowed identification of the most probable location of the leakage source, near MLGW 99, in the Sheahan Wellfield in Memphis, Tenn., and current results support information available from previous studies at the Sheahan Wellfield. The successful application of the model required the collection of both tritium and 3-helium samples from select wells in the vicinity of the leakage source. The inverse age-distribution model technique identified a common source of recharge to all three Sheahan wells investigated in this research, and estimated an average recharge rate through the window feature, R, of 6.2–8.8 m/year. The results of this research indicate that an area of vulnerability to a semiconfined aquifer can be identified using the proposed technique. This information can then be used to develop wellhead protection and management strategies in areas where confining unit breaches are known to exist.

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The following symbols are used in this paper:

C_i = monthly tritium concentration in precipitation;
C_{in} = tritium input function;
P_i = monthly precipitation amount;
R = recharge through confining unit breach;
s = subscript representing summer months;
w = subscript representing winter months;
x = linear extent of recharge;
x^* = distance to recharge source;
α = of infiltration occurring in winter months that can be attributed to summer infiltration; and
β = fraction of water that is tritium free.

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