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Abstract

The Kern Water Bank (KWB) is located in the Kern River alluvial fan at the southern end of the San Joaquin Valley, Kern County, California. In January and August 2000, shallow and deep monitoring wells were sampled at 10 or 13 locations, respectively. The samples were analyzed for chlorofluorocarbons (CFC-11 and CFC-12) and stable isotopes of water ($\delta^{18}O$ and δD). Results indicate that relatively young groundwater (<20 yrs) is found in northern and central areas in the shallower wells near where water is actively recharged. An intermediate dated (20 to 40 yrs) groundwater component is encountered in the deeper wells of the central areas of the KWB. The oldest waters (>40 yrs) are found in the southern and western areas and in the deep northern wells. The stable isotope composition varied significantly within the KWB and correlated neither with location or CFC age. It suggests a Sierra Nevada water source.

A numerical model of flow was developed using Visual Modflow™ Software. The model is composed of three layers (total thickness 226 m), representing the basic aquifer structure. Each layer is built on a 58 columns, 39 rows grid consisting of 1935 active and 327 inactive cells ranging in size from 0.16 to 0.65 km^2. The model is built with hydrogeological parameters compiled by the California Department of Water Resources, monitoring wells, production wells, and assumed boundary conditions. Other field data consisted of: (i) spring 1994 initial groundwater surface, (ii) KWB and Kern County Water Agency (1994-2000) artificial recharge rates, (iii) seven years of hydraulic heads records at 26 monitoring wells and (iv) pumping rates at productions wells. The calibrated model was run over a 7 years simulation period (1994-2000) in a transient mode, with twelve time steps for each stress period. The root mean squared error between simulated and measured hydraulic heads was calculated at 8 m. The best agreement between simulated and observed hydraulic heads was found in the deep wells located in the southern section of the KWB away from the active spreading ponds.

Key Words: Ground Water Banking; Tracers; Chlorofluorocarbons; Ground Water Modeling, Kern Water Bank.

1. INTRODUCTION

1.1 Background

Groundwater has been a primary source of potable water in arid regions for centuries. In the second half of the 20th century, the soaring demand for water placed unprecedented stress upon many aquifers throughout the world. One recent development in groundwater management aimed at augmenting water supplies has been Aquifer Storage and Recovery (ASR) projects. This practice, which is also known as groundwater banking, consists of recharging recycled waste water, surplus runoff, or aqueduct water into permeable aquifers and extracting the recharged at some later date. This artificial recharge process can take on various modes of hydrologic transfer to the aquifer such as: spreading water in ponds, using injection wells or improving infiltration from a river to the underlying aquifer. As a result, ASR has become an important method for the combined management of surface and ground water. ASR has also become an important method to control land subsidence caused by declining water levels, to control saline water intrusion in coastal or closed basins aquifers, to maintain baseflow in streams and to raise water levels to reduce the costs of groundwater pumping.

One of the largest ASR operations in the United States is taking place in Kern County, California (Figure 1). The Kern Water Bank (KWB) is located in the Kern River alluvial fan at the southern end of the San Joaquin Valley, California. It comprises about 78 km^2 of parcels owned by several local water entities and the State of California under the management of the Kern Water Bank Authority (KWBA), a consortium of private and public entities. The KWB was created with the purpose of reducing negative impacts generated by competing urban, agricultural, and environmental demands on the freshwater supply. Water banking helps reducing groundwater overdraft in the San Joaquin Valley and improves the flexibility and efficiency of managing the State Water Project (SWP) by providing storage south of the Sacramento-San Joaquin Delta. It has created a nexus for water management practices between the Kern County Water Agency (KCWA), the KWBA and other state water agencies.

1.2 Research objectives

The primary research objective of this study is to improve the current understanding of hydrologic flows within and adjacent to the Kern River alluvial fan. A field study of dissolved chlorofluorocarbons (CFC-11 and CFC-12) and stable isotopes of water ($\delta^{18}O$ and δD) was performed to achieve this goal. In conjunction with this field study, a previously released numerical model of regional groundwater flow for the Kern Water Bank and adjacent area was revised. This report discusses the degree of success in coupling direct, field determined aquifer parameters and properties, with an earlier designed numerical flow model.

1.3 Principles of dating water using CFCs

Chlorofluorocarbons (CFCs) are stable, synthetic, halogenated alkanes with no known natural sources. Their release into the atmosphere and their incorporation into the earth hydrologic cycle have been closely coupled with production rates. Hence, CFCs have been distributed globally and are found in most shallow groundwater. The tropospheric mixing ratios of both CFC-11 and CFC-12 increased nearly exponentially from about 1940 until the mid-1990s. Thereafter, they have remained relatively constant (Figure 2). The last 25 years of this record has been determined with direct measurements while prior to 1976, the tropospheric mixing ratios were estimated using production and release records (McCarthy et al., 1977; Cunnold et al., 1997).

The CFC dating method is based on the assumption that groundwater is in equilibrium with tropospheric air at the water table. Thus, the CFC clock begins at the time of recharge and the inferred groundwater apparent age refers to the amount of time a given water parcel has been isolated from the soil atmosphere.

According to Henry's law for solubility, the equilibrium concentration of a dissolved gas (C_I) is proportional to its partial pressure (p_I). It is expressed as:

$$C_I = K_H \cdot p_I \tag{1}$$

where, K_H is the Henry's law constan. K_H has been measured for CFC-11 and CFC-12 in pure and salty water (Warner and Weiss, 1985). The Henry's law constant is a function of temperature and salinity and the CFC partial pressure is a function of time (i.e., Figure 2) and elevation. As a general rule, most shallow groundwater is too dilute to require corrections for salinity.

The water temperature at the time of recharge is difficult to infer and is fundamental to using the CFC clock. For example, at equilibrium, the dissolved CFC-11 concentration at 5°C is more than double the CFC-11 concentration at 25°C (Warner and Weiss, 1985). Measurements of dissolved noble gases have indicated that in areas experiencing natural recharge through a soil zone, the recharge temperature is similar to mean annual air temperature (Stute et al., 1995). Thus, as a first approximation in this study, the average air temperature in Bakersfield (18.5°C) will be used.

Local CFC sources can modify the CFC apparent age. Near some urban areas, tropospheric mixing ratios have been determined to be enriched in CFCs relative to the background air composition (Oster et al., 1996; Ho et al., 1998; Wang et al., 1998). Additional, anthropogenic point sources such as industrial waste water and sewage effluent can contaminate surface and groundwater in CFC (Schultz et al., 1976; Clark et al., 1995). More recently, Plummer et al. (2000) have suggested that CFC contamination is associated with some agricultural practices. These potential sources of contamination would yield CFC apparent ages that are younger than the actual age or CFC concentrations greater than equilibrium values with the clean troposphere.

Recharge temperature at the water table is another obvious component that can modify CFC apparent ages. If the assumed air temperature is higher than the actual recharge temperature, the CFC inferred groundwater recharge year is more recent as less gas can dissolve into warmer water. In this case we might obtain a series of non-interpretable samples with higher field values than any modeled inferred concentrations.

Vadose zone processes can also modified CFC tracer ages. First, with rapid aqueous transport as is probably the case during artificial recharge operations in the Kern Water Bank, addition of excess air in the form of trapped bubbles will produce higher concentrations and younger CFC apparent ages. The excess air will increase CFC concentrations in the water above equilibrium values. Second, rapid flow through the Vadose zone or shallow water tables may lead to equilibration at temperatures other than the mean annual air temperature. Third, groundwater equilibrates with soil air and the CFC mixing ratio in soil air may be different from the troposphere (Cook and Solomon, 1995).

Once in the groundwater, CFCs behave conservatively under aerobic conditions. However, CFCs do degrade under anaerobic conditions (Lovley and Woodward, 1992; Oster et al, 1996). CFC-11 degrades about ten times faster than CFC-12, yielding differences in apparent ages (Oster et al., 1996). Other processes such as water mixing and hydrodynamic dispersion might also modify the CFC clocks.

1.4 Description of the study area

Groundwater banking on the KWB property dates back to the early 1970's, when Tenneco West Inc. performed limited recharge in the northwestern portion of the KWB area (CDWR, 1990). The Kern County Water Agency began banking water in 1980 on an 11 km^2 recharge site located east of the KWB (Figure 1). When Tenneco offered for sale 186 km^2 along the Kern River in 1986, the Department of Water Resources (CDWR, 1987) explored the potential of using the property for artificial groundwater recharge. After conducting environmental impact studies and negotiations, the California Department of Water Resources (CDWR) purchased 78 km^2 in 1988. Following successful recharge operations by the state agency, the land was transferred in 1994 to the KWBA. Currently about 44 km^2 are used as spreading (recharge) ponds. The total property area is an irregular rectangle, 11 km (east-west) by 7 km (north-south). Between 1995 and 2000, a total of $1.13x10^9$ m^3 (916,000 acre-feet) of water has been recharged into the aquifer (Table 1). The system is designed to recover about $3x10^8$ m^3/year (240,000 acre-feet/year) and recharge about $5.5x10^8$ m^3/year (450,000 acre-feet/year) (Jonathan Parker, personal communication,2000).

The southern San Joaquin basin is bounded by the Tremblor ranges on the west, Sierra Nevada on the east, and the San Emigdio mountains to the south. The west side of the basin consists of a tightly folded anticlinorium which is sub-parallel to the San Andreas fault; the east side is a broad homocline that mimics the surface of the basement complex (Wilson, 1993). In the southern San Joaquin Valley, the strata can be subdivided into three distinct groups: Mesozoic basement rocks, late Mesozoic to Neogene marine rocks and Neogene to recent continental rocks and sediments. The Pliocene and younger shallow terrestrial sediments are present from approximately 1,250 m below the study area to the surface. Starting from the surface, three formations contain continental-derived sediments: the Kern River, the San Joaquin, and Tulare formations. Recent alluvial deposits overlie these formations.

The Kern River alluvial fan has a surface of about 2,850 km^2 (Hajas and Swanson, 1979) and contains the principal water bearing sediments of the aquifer. Sedimentary deposits in the Kern River alluvial fan are highly heterogeneous, with a predominance of sand and gravel deposited in channels and finer grained overbank deposits. Sediments in the Kern River alluvial fan are derived from weathered granodiorite of the Sierra Nevada Range which were transported into the field area by the Kern River. The KWB is located in the distal area of the Kern River alluvial fan and straddles the Kern River channel. This area contains lower energy deposits, such as clays from the Buena Vista lacustrine basin to the south and several laterally discontinuous clay and silt layers.

Today the Kern River rarely has surface flows that reach the Kern River alluvial fan area due to diversions to canals and storage in Lake Isabella. The Kern River originates in the southern Sierra Nevada (West of Lone Pine, California) and is the southernmost watershed on the western side of the Sierras. Flow in the lower section of the river is controlled at the Lake Isabella dam that was completed in 1957. Shortly thereafter, the ancestral Buena Vista Lake became agricultural land (Jonathan Parker, personal communication, 2000).

The KWB is part of the Tulare Lake Hydrologic Basin, a natural capture zone for waters draining from the Sierra Nevada to the east, the Tremblor Ranges to the west and the Tehachapi/Emigdio Mountains to the south. The surface topography across most of the study area is relatively flat lying with an average altitude of 93 m. The present climate is arid to semi-arid. The 59 years average precipitation is 158 mm/year (NCDC) and daily mean temperature ranges from slightly above freezing during the winter months to above 30° C in the summer season. The vegetation covering areas of the Kern River alluvial fan is mostly irrigated farmland (80%) with a minor amount of idle land (20%). All of the KWB area has reverted since the 1980's to idle land conditions. Common botanical species found are: *Aster spp., Salix spp., Bromus spp., Amaranthus spp.* The crops grown around the KWB in decreasing order of importance are cotton, alfalfa, pasture and sugar beets. A limited number of active oil wells exist today throughout the study area.

Despite the poorly known stratigraphy at a small scale (< 500m), some general large scale features can be inferred. The typical aquifer hydrostratigraphy of KBW consists of an upper unconfined aquifer ranging in thickness between 60 and 90 m. The unconfined aquifer is separated from the middle aquifer by the low permeability discontinuous Corcoran clay. Throughout each layer, discontinuous clay/silt bodies act as aquitards to vertical flow. The monitoring well network installed in the KWB indicates that these aquitards cause semi-confined conditions in the deeper portions of the aquifer. This is demonstrated during the summer months when the deep and middle wells have lower groundwater elevation compared to the shallow wells (Swartz, 1995). The top of the middle aquifer is found at about mean sea level. The middle aquifer is underlain by a deep confined aquifer, which is typically initiated at depths exceeding 61 m below mean sea level. Wells tapping the deep aquifer have been drilled to a depth of 210 m (below ground level).

Many sources including irrigation water imported into the basin by Friant-Kern Canal, the California aqueduct, Kern River, and annual precipitation contribute to groundwater recharge. Historically the Kern River has been the primary source of natural recharge. However, due to low precipitation rates in the basin and the diversion of Kern River water away from the recharge area, most of the groundwater presently originates from the artificial recharge operations in the KWB and possibly from underground flow.

2. METHODOLOGY

2.1 Sample collection

Twenty and twenty-six nested monitoring wells (coupled shallow and deep wells, Table 2) in the KWB were sampled, respectively, in January and August 2000 (Figure 1). Water was retrieved with a diesel purge pump operated by the Kern County Water Agency at an average output of 189 L/min. The pump outlet was linked to a copper-tube sampling system. Samples were usually taken after five well volumes were pumped. General field data such as weather, air temperature, initial water level, draw down, and total water volume purged prior to sampling were recorded.

Conductivity and pH were monitored in the field using electronic probes. Dissolved oxygen concentrations were also determined in the field using a Chemet™. Stable isotope samples were collected in 60 ml glass bottles (January 2000 only). During the January sampling campaign, groundwater was collected in 100 ml glass syringes. This water was then transferred into boro-silicate glass ampoules and flame sealed in the field following the method of Busenburg and Plummer (1992). During August, about 10 ml of groundwater was collected in copper tubes sealed by stainless steel pinch-off clamps for CFC analysis. Extreme caution was taken during collection to ensure no ambient air was sealed in the copper tubes.

Sample isotope samples were analyzed in the laboratory of Dr. H. J. Spero at the University of California, Davis using a mass spectrometer. Oxygen and hydrogen isotopic values are reported using the standard delta notion and are referenced to Standard Mean Ocean Water (SMOW).

Chlorofluorocarbons were analyzed on a gas chromatograph using a Smethie et al (1988) designed purge and trap inlet system, within a week of collection. Briefly, CFC-11 and CFC-12 were stripped from the water samples with pure nitrogen gas. These compounds were then trapped on a short column containing Unibeads B at -70°C. The trap was then heated to >80°C and the gaseous CFCs flushed into a Shimadzu GC-14 eqipped w an Electron Capture Detector. CFC-11 and CFC-12 were separated on a Porasil C™ pre-column followed by a SP 2100™ main column. The detector response was calibrated with CFC standards calibrated to the SIO scale. The analytical detection limit for the copper tube samples was relatively high (0.15 pmol/l for both CFC-11 and CFC-12) due to the small volume of water collected.

In the summer 2000, Kern River water was sampled for water chemistry and CFCs at a location on the south side of the river, adjacent to the bike path between Highway 99 and the Golden State Freeway. The copper tubes were placed in about 20 cm of water and sealed with pinch-off clamps underwater after all air was flushed from the tubes.

2.2 Numerical flow model design

The Visual Modflow™ Version 2.8.2.52 (Waterloo Hydrogeologic, 2001) finite-difference modeling software was used in this study. The model simulates flow in three dimensions. The three dimensional movement of groundwater of constant density through earth material may be described by the partial differential equation:

$$\frac{\delta}{\delta x}\cdot\left(K_{xx}\frac{\delta h}{\delta x}\right)+\frac{\delta}{\delta y}\cdot\left(K_{yy}\frac{\delta h}{\delta y}\right)+\frac{\delta}{\delta z}\cdot\left(K_{zz}\frac{\delta h}{\delta z}\right)\pm W=S_S\cdot\frac{\delta h}{\delta t} \qquad (2)$$

in which x, y, and z are cartesian coordinates aligned along the major axes of hydraulic conductivity K_{xx}, K_{yy}, K_{zz}; h is the hydraulic head (L); W is the volumetric flux per unit volume and represents sources (+) and or sinks (-) of water (t^{-1}); S_s is the specific storage of the porous material (L^{-1}) and t is the time variable. Equation (2) plus flow and/ or hydraulic head boundary and initial-head conditions constitute a mathematical model of ground-water flow. A solution of that equation is an algebraic expression of h as a function of (x,y,z,t) such that, when h is substituted into equation (2), the equation and its initial and boundary conditions are satisfied. A time varying hydraulic head distribution of this nature, characterizes the flow system, in that it measures both the energy of flow and the volume of water in storage. It can be used to calculate directions and rates of movements of groundwater flow. Except for very simple systems, analytical solutions of equation (2) are rarely possible. Thus, numerical methods must be employed to obtain approximate solutions. One such approach is the finite-difference method, wherein the continuous system described by equation (2) is replaced by a finite set of discrete points in space and time, and the partial derivatives are replaced by differences between functional values at these points. The process leads to a system of simultaneous finite difference equations whose solution yields values of hydraulic head in active grid cells at specified times (McDonald and Harbaugh, 1988).

The Strongly Implicit Procedure (SIP) algorithm was used to solve the finite-difference system of equations in all active cells of the finite-difference grid at all time steps. The SIP solver employed a maximum of 200 iterations and a hydraulic head- closure criterion of 3.05 mm (0.01 foot). Details of the SIP iterative algorithm coded in Visual Modflow™ are described in McDonald and Harbaugh (1988).

2.3 The Kern Water Bank Hydrogeological Model

The three-layer model was created based on an earlier model constructed by the California Department of Water Resources staff (White, 1993; Swartz, 1995). The total modeled area represents an area of 30 km by 22 km in an east-west and north-south directions. It ranges between 104 m (amsl) to 122 m below mean sea level. Due to the lack of detailed stratigraphic information, the aquifer layers do not represent exactly the geology of the area. However, they outline composite physical layers consistent with data from available triple-completion KWB monitoring wells (CDWR, 1992). The surface elevation of the first layer was determined from United States Geological Survey topographic maps. Changes in elevation in the study area range between 82 m (northwestern area) and 104 m amsl (central area of the model). The second layer is located between 0 and 61 m below mean sea level and the third layer spans between 61 and 122 m below mean sea level.

Each model layer is composed of 58 columns and 39 rows consisting of 1,935 active and 327 inactive cells that have surface areas between 0.16 and 0.65 km^2 (Figure 3). The inactive cells are located in the southwest corner of each model layer, representing the Elk Hills. With the exception of the Elk Hills that act as a barrier to groundwater flow to the west, there are no other significant faults or barriers to lateral movement of water within the study area (Swartz, 1995).

The uppermost layer of the model is unconfined. Layers 2 and 3 have identical hydrogeological properties in terms of specific storage and hydraulic conductivities and are semi-confined. Each block centered flow cell is individually parameterized using data obtained from White (1993) and Swartz (1995) reports. Hydrogeologic parameters (Table 3) were evaluated by the CDWR staff based on statistical analyses and established relationships between sediment type and hydrogeologic properties. Over 1,000 lithologic and electric logs from wells and borings drilled within the project area were collected and evaluated for reliability by a team of geologists from CDWR (White, 1993). Each evaluated log was geostatically mapped (White, 1993) on a Kern River alluvial fan Groundwater Model map, then two to three logs per section (2.6 km^2) were chosen to represent the geology of that section. The decision of which logs to accept was primarily based on obtaining proper well density followed by the category assigned to each log. Two lists of wells were compiled for further analysis: (1) wells representing shallow depths (ground surface to sea level), and (2) wells representing deep units (mean sea level to 122 m below mean sea level). The logs were then utilized to develop estimates of aquifer hydrogeological parameters.

Specific yield (S_y) is a dimensionless variable that represents volume of gravity drained water per unit area of aquifer and per unit change in hydraulic head (Fetter, 2001). Each lithologic interval from the well logs was assigned a value of S_y based on the sediment type in that interval. A weighted average of S_y for 30.5 m feet intervals in each well was calculated. Each 30.5 m interval was subsequently averaged into intervals representing the KWB model layers.

Values of hydraulic conductivity K based on soil type were obtained from published correlation charts (Driscoll, 1986) using first-hand knowledge of the soils within the southern San Joaquin Valley. These estimated values of K were then plotted against values of S_y. A visually fitted line of these points was subsequently used to estimate all values for K based on the calculated values of S_y for each well. A second linear relationship was developed between S_y and K based on the premise that the maximum value of K used previously for fine sediments was not high enough to represent the coarse sediments within the basin. Laterally discontinuous clay/ silt bodies in the study area act as aquitards to vertical flow. The KWB database of monitoring-well hydrographs indicates that these aquitards cause semi-confined conditions in the middle portions of the aquifer. The depositional system is highly heterogeneous. Groundwater flow in the aquifer is considered anisotropic and assumed to be predominantly vertical.

The following parameters were imported from the CDWR Model (White 1993, Swartz 1995) with no modifications made in the first modeling phase: horizontal hydraulic conductivities (*x,y* axes), specific yield, grid geometry, layer configurations. In each modeled cell K_x and K_y are equal. $K_h=K_x=K_y$ values range between 0.15- 213 m/day. The vertical conductivity (z axis) was modified following import (Table 3). Vertical leakance (V_{cont}) maps (Swartz, 1995) were used to derive the vertical conductivity value (K_z). K_{z1} (vertical hydraulic conductivity in layer 1) was obtained by dividing V_{cont1} from the average thickness between two consecutive layers:

$$K_{z1} = 2 \cdot (\frac{V_{Cont1}}{b_1 + b_2}) \tag{3}$$

where b_1 and b_2 are the thickness of layers 1 and 2 in meters. *Kz* ranges respectively between 0.031 m/day (layer 1) and 0.024 - 0.0049 m /day layers 2 and 3 (Table 3). Specific yield ranges from 0.11 and 0.21 in the study area. Total porosity and effective porosity were set uniformly at 0.35 and 0.30 respectively in all layers. Specific storage values were not imported from the CDWR model. For the topmost unconfined layer specific storage was set equal to the specific yield. For the semi-confined aquifers (Layers 2 and 3) the specific storage value was optimized at 3.3×10^{-4} m^{-1}. The magnitude of this value was verified against storativity maps provided by Swartz (1995).

The 1999 Kern Water Bank Geographic Information System (GIS) database (Jonathan Parker, personal communication, KWBA, 2000) was used to locate the 14 artificial recharge ponds. The 1995-2000 KWB records were used to enter the artificial recharge rate in the model (Table 1). For 1994 only rain was inputted for recharge as no record exists in terms of artificial recharge for the KWB during that year. Recharge values were inputted in feet/day (1 foot/day≈0.3 m/day) and is defined as the sum of 10% of the yearly average precipitation and the KWB artificial recharge values (Table 1). Artificial recharge was not reduced by a 6% factor routinely applied by the KWB to account for losses during transfer, evaporation, and conduit seepage. An additional recharge pond located outside of the KWB boundary was added to the model layout and represents the 11 km^2 recharge facility managed by the KCWA. This recharge pond was used to input data representing KCWA spreading activities, Kern River loss and canal seepage as reported by the yearly agency report (Table 1). The model applied recharge to the highest active cell in each column. The rewetting cell function was not activated in the implemented Visual Modflow™ hydrogeological model.

Twenty-six monitoring wells with good records of hydraulic heads over the 1994-2000 periods were placed into the model grid. The hydraulic head observation point was discretized to the middle point of a screen. For one shallow well (25E 16LO1 #8), the screen mid-point was close to an aquifer boundary and therefore, the simulation output of this monitoring well was compared with the observed data. Eight active production wells (four within KWB boundary) were used in the model grid (Figure 3). Production wells on the KWB are approximately 210 m deep and have perforated intervals spanning between 46 m (amsl) to 107 m (below mean sea level) resulting in extraction from the three layers simultaneously. Active pumping was only recorded during 1994 and 1995 (KCWA, 1996, 1997). The total withdraw of groundwater from the KWB was $-66.4 \times 10^6 m^3$ (Table 1).

The elevation of the initial hydraulic heads (18 m to 79 m amsl) for the model runs were obtained from the Spring 1994 KCWA water level survey (Figure 4) (KCWA, 1997). The hydraulic head along the model boundaries for each layer was assumed to be constant. The model was run in a transient mode with 7 stress periods corresponding to the years of 1994-2000, twelve time steps were inputted for each yearly stress periods.

2.4 The Kern Water Bank Hydrogeological Model Calibration

Calibrations were run using field reported hydraulic head values combined with Visual Modlfow™ software features. The model was calibrated using the PEST™ (Nonlinear Parameter Estimation and Predictive Analysis) module available in Visual Modflow™. The non-linear Gauss-Marquardt-Levenberg optimization algorithm is used by PEST™. PEST™ adjusts model parameters and disturbances until the fit between model outputs and field observations is optimized (Waterloo Hydrogeologic, 2001). The module was ran to estimate: hydraulic conductivities (x, y, z axis), storage coefficients (S_s, S_y) and recharge values. The seven years hydraulic heads data for the 26 observation wells were used as an objective function. PEST™ minimizes the weighed sum of squared differences between model generated observation values and those measured in the field. This sum of weighted squared differences, computed from measurement discrepancies is defined as the objective function. For the non-linear KWB model, parameter estimation is an iterative process. At the onset of each iteration the relationship between model parameters and model generated observations is linearized by formulating it as a Taylor series. The derivatives of all observations with respect to all parameters is then calculated. This linear problem is then solved for a better parameter set and the new parameters are tested by running the model again. By comparing the changes in parameters to the improvement in the objective function PEST™ decides if another optimization iteration is needed.

3. RESULTS

3.1 KWB Wells Geochemistry

The stable isotopic composition of KWB groundwater varied between -10.5‰ and -13.7‰ for Δ ^{180} and -110‰ and -82‰ for δD and falls slightly below the Global Meteoric Water Line (GMWL) on a plot of δ^{18}O versus δD (Figure 5). The isotopic composition of the groundwater did not vary systematically with location, well depths, or CFC age (see below). KWB groundwater isotopic signature is comparable with the Emerald lake outflow water and is significantly heavier than the State Water Project water (Williams and Rodoni, 1997). Emerald Lake is located near the headwaters of the Kern River at an altitude of 2,800 m on the western slope of the Sierra Nevada (36°35'49"N, 118°40'29"W). The Emerald Lake data were provided by Dr. A. Leydecker (Donald A. Bren School of Envirnomental Science and Management, University of California, Santa Barbara). The slight shift below the Emerald Lake data may be caused by small amounts of evaporation that occurred during transit from the Sierras through Lake Isabella to the KWB.

Groundwater from the KWB can be geographically grouped by CFC apparent ages (Figure 6). Relatively young groundwater (< 20 yr) is found in the northern and central areas of the KWB in the shallowest wells. Since 1994, the KWBA routinely uses ponds located in this area for artificial recharge (Jonathan Parker, personal communication, KWBA, 2000). A less recent (20-40 yr) groundwater set is observed in the deep wells of the central areas and in southeastern shallow wells. Finally, the oldest ground waters (> 40 yr) are found in the deep wells away from the Kern River.

Agreement between the CFC-11 and CFC-12 apparent age was poor (Figures 7). Samples tend to have older CFC-12 apparent ages, consistent with anaerobic degradation. CFC-11 and CFC-12 contamination is defined in this study as concentrations greater than equilibrium values determined with the Scripps Institute of Oceanography atmospheric data set (Figure 2) assuming a recharge temperature of 18.5°C. Four out of the 24 wells sampled showed both CFC-11 and CFC-12 contamination and one well was contaminated with only CFC-12. The contaminated samples were found most often in the shallower wells from the northern and central sections of the KWB. The CFC concentrations of the Kern River were greater than equilibration values, suggesting that there were upstream CFC point sources.

3.2 Kern Water Bank Hydrogeological Model

Calibration carried out with the PEST™ optimization module resulted in only a modest improvement in match between simulated and observed hydraulic heads (Table 3). Anderson and Woessner (1992) present two statistical measures commonly used to evaluate calibration: mean absolute error and root mean squared of the difference between simulated and observed groundwater levels. These values were computed for the 7 year modeling period (Table 4).

Mean absolute error (MAE) is the mean of the absolute value of the differences between simulated (h_s) and measured hydraulic heads (h_m).

$$MAE = \frac{1}{n} \cdot \sum_{i=1}^{n} \left| (h_s - h_m)_i \right| \tag{4}$$

This measure is preferable as it cancels the effects of negative and positive hydraulic head differences. The average mean absolute error was found to be 4.5 m.

The root mean squared (RMS) error is the square root of the average of the squared differences in simulated and measured hydraulic heads.

$$RMS = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} (h_s - h_m)_i^2} \tag{5}$$

It is considered to be one of the best statistical measures of a model's calibration when errors display a normal distribution. Mean absolute error distribution does not fit a Gaussian distribution for the KWB data set. The RMS error average was found to be 8 m with a range spanning 3-22 m. The highest RMS error was detected in the northern areas where post 1990 artificial recharge has been most active.

The difference between the observed and simulated hydraulic head varied over the model run period (see Meillier 2001). For the first 400 days, the simulated hydraulic head fits or slightly overestimates the observed hydraulic head. Thereafter, the calculated heads diverge from the observed with an irregular pattern. The simulated hydraulic heads show relatively low sensitivity to artificial recharge rates while the observed field hydraulic heads show a greater degree of response to inter-annual artificial recharge rate.

Field groundwater elevation maps of hydraulic heads were compared with maps summarizing simulation outputs for Spring 1996. During the first two years of the model run (Spring 1994-Spring 1996), hydrologic flows from layer 1 moved predominantly from the northeastern boundary of the model to the northwestern area with minor flows exiting in the southwestern area of the model boundary. This groundwater flow pattern is in agreement with regional groundwater flow partly driven by the Kern River inflow located in the northeastern boundary of the modeled area. A comparison of simulated groundwater hydraulic heads with field recorded hydraulic heads in the Spring 1996 showed good agreement. Field observation of groundwater mounding linked to the artificial recharge program was also detected within the KWB property boundaries.

4. DISCUSSION

4.1 Geochemistry

The hydrogeologic environment as well as the land use practices on and around the Kern Water Bank present serious challenges to the CFC dating methodology. Most of the recent recharge in the KWB has occurred in spreading ponds located in the northern and central area during the last 6 years. No samples with CFC apparent ages less than 6 yrs were collected. Four shallow wells had CFC concentrations greater than equilibrium values and may represent this young water. Shallower wells usually were younger indicating that the groundwater system is stratified in terms of age. The heterogeneity of the aquifer material and recharge locations is suggested by the CFC data. Some wells with similar screen intervals located a few kilometers apart have very different inferred groundwater recharge as illustrated in the northeastern region (Figure 6). The screen intervals for these wells are rather large complicating the interpretation of the CFC apparent ages.

An improved understanding of the relationship between mean annual air temperature and equilibration temperature in the unsaturated zone at the time of recharge is warranted. Artificial recharge usually occurs during the late winter to early spring concurrent with the occurrence of major rain storms and snowmelt release. Natural recharge of Sierra run-off that occurred prior to the construction of the KWB probably had a similar seasonal trend. Furthermore, the water table may be close to the surface and it may be influenced by the seasonal temperature cycle. The average air temperature calculated over the months of November through April was found at 12.3°C for Bakersfield, significantly lower than the mean. It is also very likely that the equilibration temperature is lower than air temperature during that period due to cooler soil and river temperatures. This would have a direct consequence on the CFC model recharge year by decreasing the number of contaminated samples. If the recharge temperature were 9° C, than the CFC apparent ages would be older and only one well would show CFC contamination.

4.3 KWB model

The Kern Water Bank numerical flow model provides a versatile tool for managing potable water in the region. The CDWR model was one of the first attempts to develop a thorough description of the groundwater flow within the KWB and adjacent area. The hydrogeological characteristics of the field area are very heterogeneous (*e.g.,* Table 3) reflecting the riverine and overbank deposits of the Kern River alluvial fan. Due to the prohibitive cost in obtaining detailed hydrogeological data, CDWR used regression analysis and krieging methods to infer parameter values between well borings (White, 1993; Swartz, 1995).

Artificial recharge was difficult to evaluate spatially and temporally because only the total amount is recorded. In our initial simulations, recharge was applied at a constant rate for each year rate into all cells that have spreading ponds. Recharge through the spreading ponds occurs mainly in the winter and early spring months and is restricted to a few ponds each year (J. Parker, personal communications). Various spatial and temporal scenarios were evaluated and the optimal recharge distribution was integrated into the final version of the model. The contribution of recharge from the Kern River as well as seepage from the aqueduct channels is not well quantified. Due to the absence of a long term record of artificial and natural recharge in the field area, no attempt was made to use the CFC inferred groundwater recharge years to verify the model. Artificial tracers, such as in the study by Gamlin et al. (2001), would be helpful to elucidate transport processes and to re-calibrate the KWB numerical simulation model.

The hydrogeological parameters imported had been previously optimized by the CDWR modeling team. Our re-calibration yielded only a modest improvement in the match between simulated and observed hydraulic heads. The parameters that were most sensitive to changes in the optimization analysis were, in order of importance: vertical hydraulic conductivity, recharge magnitude and location, and specific storage. Monitoring wells located throughout the field study area were very helpful in providing a detailed picture of hydraulic heads over the seven years modeling period. However, errors generated in the field measurements of hydraulic heads are always possible. These measurements were taken in the winter/early spring, over a 1 to 2 month period when the system is changing due to artificial recharge operations. Time scale effects resulting from differences between the model's monthly time steps and actual dates of hydraulic heads measurements might generate errors in the fit between simulated and field values. Areal scale effects resulting from comparing point-well measurements to modeled water levels for nodes that represent hydraulic heads in the middle of cells ranging in size from 0.16 to 0.65 km^2 is another potential source of discrepancy. This is especially true near the spreading ponds.

Improved fits between simulated and observed hydraulic heads were predominantly detected in deep wells in the southern and south central areas of the KWB where recharge is least active. Due to the highest hydraulic heads values found in observation points closer to the land surface groundwater flow will have a prevalent downward direction. However, the actual flow direction is also governed by the permeability of the porous medium and by the geology of the field area. If the aquifer is homogeneous and isotropic with respect to hydraulic conductivity, groundwater flow is parallel to the hydraulic gradient (or perpendicular to the equipotential lines). This is a weak assumption in the KWB as hydraulic conductivities are direction dependent. In anisotropic and heterogenous aquifers groundwater flow is oblique to the hydraulic gradient. The deviation in direction depends on the degree of anisotropy and heterogeneity. Anisotropy and heterogeneity in terms of hydraulic conductivity is prevalent in layers 2 and 3. However, the uppermost layer is predominantly isotropic and heterogeneous (Table 3). In conclusion, the assumption of prevailing piston flow conditions in the aquifer is an approximation of field conditions requiring further research.

Another component requiring improved investigation is the contribution of regional Sierran groundwater flow to the Kern Water Bank aquifers. This component could be significant in the ancestral path of the Kern River away from more consolidated sediments. Furthermore the Coast Ranges might supply the Kern Water Bank with a regional groundwater element at the western boundary of the modeled area. The constant hydraulic head boundary conditions could vary more dynamically than the yearly basis used in the model. This constant hydraulic head boundary is located about 6 km from the eastern KWB boundary. On the western section of the model the no-flow boundary conditions is within 100 m of the KWB boundary. The proximity of the boundary might have an influence upon the general hydrogeological dynamics. Hydrologeological characterization at this interface could be improved by further understanding how impermeable this area is to the Elk Hills hydrological basin.

5. CONCLUSIONS

- Relatively young (<20 yr) groundwater is found in the northern and central areas in the shallowest wells sampled. A less recent (20-40 yr) groundwater set is found in the deeper wells of the northern and central areas of the Kern Water Bank. Finally, oldest (>40 yr) ground waters are found in the southern and western areas of the Kern Water Bank. At each location the deeper water is usually older. This time scale distribution is compatible with post 1990 artificial recharge records, decreasing hydraulic conductivity with depth and higher travel time of groundwater with increasing depth.
- CFC-11 and CFC-12 contamination was found in the Kern River and some well samples. These samples with excess CFC might have been generated by a variety of factors such as urban and agricultural sources or an incorrect assumed equilibration temperature.
- No spatial pattern was found in the distribution of $\Delta^{18}O$ and ΔD in groundwater from the KWB. KWB groundwater has an isotopic signature comparable with high elevation (2800 m altitude) Southern Sierra Nevada surface waters and is significantly lighter than California aqueduct waters.
- The fit between simulated and observed hydraulic heads yielded heterogeneous but encouraging results. The best agreement was usually found in the deep wells in southern section of the field area far from the recharge ponds.
- The CDWR numerical flow model used in this study was optimized for an earlier time period, under different recharge and pumping scenarios. This hydrological model responded well to the hydrological inputs we integrated in this study.

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