Groundwater Flow in a Desert Basin Complexity and Controversy

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ABSTRACT

A large chromium plume that evolved over a period of about 45 years from releases in a groundwater system in a Basin and Range valley along the Mojave River was used as a tracer to study the dynamics of a basin and range groundwater system. The valley that was studied is naturally arid with high evapotranspiration such that essentially no precipitation infiltrates to the water table. The dominant natural hydrogeologic processes are recharge to the groundwater system from the Mojave River during the infrequent episodes when there is flow in the river, and groundwater flow toward a playa lake where the groundwater evaporates. Agricultural pumping in the valley from the mid-1930's to the 1970's significantly altered groundwater flow conditions by decreasing water levels in the valley by over 70 feet. This pumping declined significantly as a result of dewatering of the aquifer, and water levels have since recovered modestly.

The groundwater system was modeled using MODFLOW and chromium transport was simulated using MT3D. Several innovative modifications were made to these modeling programs to simulate important processes in this groundwater system. Modifications to MODFLOW include a new well package that estimates pumping rates from irrigation wells at each time step based on available drawdown. Modifications to MT3D included a revised BTN1BD subroutine and mass balance routines to account for mass trapped above the water table when the water table declines beneath non-irrigated areas, and to redistribute mass to the system when water levels rise.

INTRODUCTION

Blowdown cooling water from an industrial facility containing chromium as a corrosion inhibitor was discharged to unlined ponds for a 15-year period from 1952 to 1965 (Ecology and the Environment, 1988). This release of chromium to the groundwater system in the Hinkley Valley in the Mojave Desert, California has served as a tracer to study the dynamics of a Basin and Range groundwater system. Unlike most anthropogenic releases of contaminants, the timing and magnitude of the contaminant release at this site was documented, making this an excellent site to study the evolution of a groundwater plume.

The Hinkley Valley is a narrow northwest-trending alluvium-filled depression between uplifted ridges of Mesozoic or older igneous intrusive granitic rocks, Tertiary volcanics, and Precambrian sedimentary and metamorphic rocks located north of the Mojave River and west of Barstow, California (Dribblee, 1967). The valley averages about 8 miles in length and 4 miles in width and the axis of the valley is relatively flat with a gentle slope toward the northwest away from the river. The valley connects in the north to the Harper Valley, the center of which is occupied by a playa called Harper Lake, through a narrow break in the bedrock hills (Mojave Water Agency, 1983).

The total thickness of alluvial sediments along the axis of the valley is only about 300 feet. The alluvium in the valley consists of three distinct lithologic units; a basal unit of alternating layers of coarse sand and silt, a middle unit of lacustrine clay, and an overlying unit consisting of primarily sand and gravel layers that have alternating thin silt and clay layers along the axis of the valley grading to finer-grained deposits along the valley margins. The lacustrine clay, which averages about 40 feet in thickness in the center of the valley, represents deposits from a late Pleistocene Lake. Along the axis of the valley, the coarse deposits above the clay unit, referred to as the upper aquifer, represent recent alluvial deposits along an abandoned route of the Mojave River, which once flowed northward through the valley. These deposits range in thickness along the valley axis from 120 feet in the southeast to 90 feet in the northwest. The finer-grained deposits along the margin of the valley above the clay unit represent fan and alluvial deposits derived from the bedrock ridges. A schematic of the groundwater system in Hinkley Valley is shown on Figure 1.

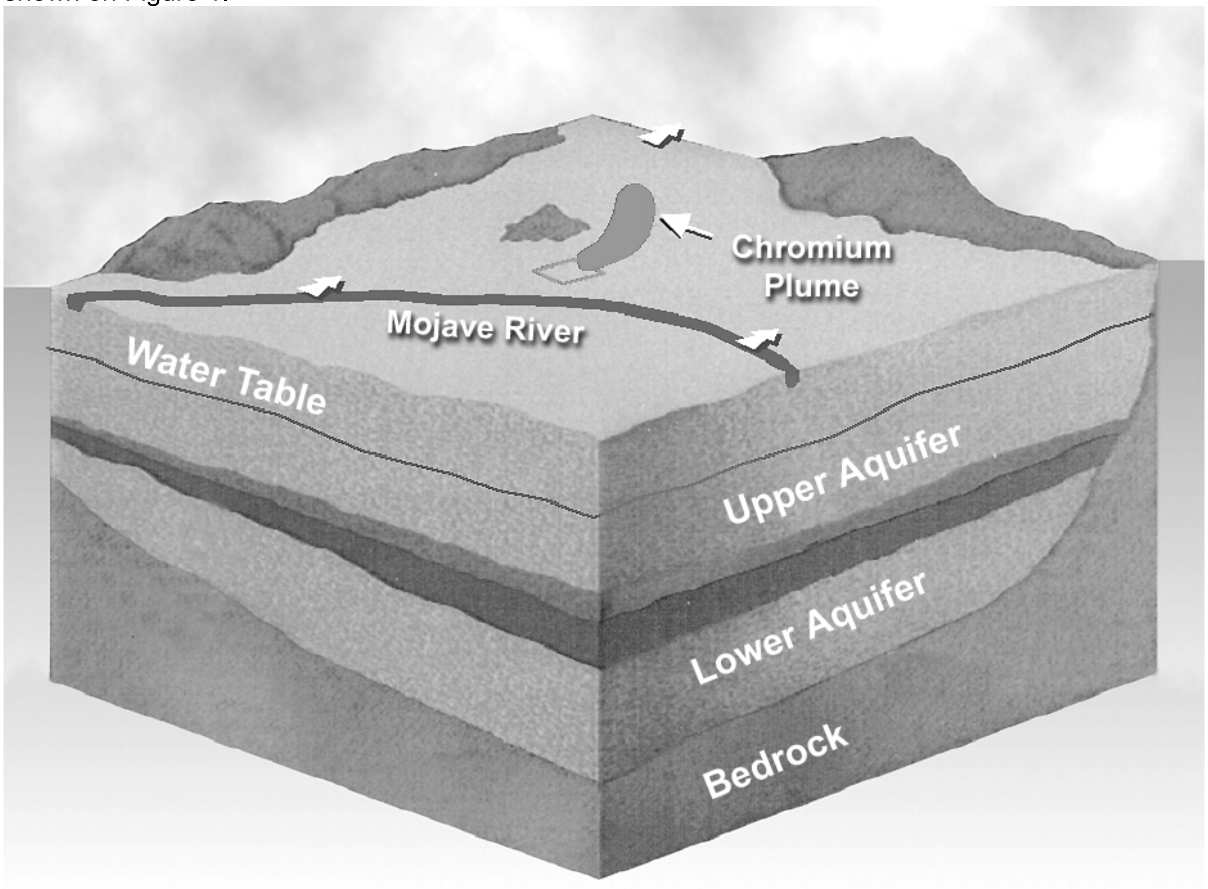

Figure 1. Schematic representation of the Hinkley Valley Groundwater system.

The estimated hydraulic conductivity of the materials comprising the upper aquifer range from 150 feet per day along the present course of the Mojave River, to 100 feet per day along the ancestral channel through the center of the valley, to 25 feet per day along the valley margins. The thickness and continuity of the lacustrine clay is such that there is little hydraulic communication between the upper and lower aquifer.

Historic groundwater flow in the Hinkley Valley was northward from the Mojave River toward the playa lake in Harper Valley, and the depth to groundwater in much of the valley was less than thirty feet. The Mojave River is the main source of recharge to the groundwater system in Hinkley Valley, but the Mojave River is mainly a river of white sand, as it seldom flows (Hardt, 1971). Between 1932 and 1994, the Mojave River only flowed on 23 occasions in the reach adjacent to the Hinkley Valley, thus providing an intermittent source of recharge. Precipitation is not a significant source of recharge as the average annual precipitation is only five inches per year.

Groundwater flow in the Hinkley Valley has been significantly influenced by groundwater withdrawals for irrigation (Durbin and Hardt, 1974). Significant irrigation pumping, primarily for the irrigation of alfalfa, began in the early 1930’s and peaked in the mid-1950’s when about 278,000 acre-feet per year was extracted for irrigation. The irrigation pumping significantly dewatered the shallow aquifer; water-level changes from 1930 to 1970 were over 70 feet in the center of the valley (California Department of Water Resources, 1967; Mojave Water Agency 1983). These large water-level changes effectively reduced pumping yields. As a result, much of the irrigated lands were abandoned during the next three decades, and in the early 1990's only about 130,000 acre-feet per was extracted for irrigation. Over 150 irrigation wells are reported in the valley (USGS, 1960)

MODELING APPROACH

Groundwater flow and the transport of chromium in the Hinkley Valley were simulated with MODFLOW (McDonald and Harbaugh, 1988) and MT3D (Zheng, 1996). A quasi-steady state model was developed to simulate conditions prior to settlement and initiation of irrigation pumping. The water levels simulated with this quasi-steady state model were used as the initial conditions for a transient simulation of the period 1930 to 1995.

The successful simulation of groundwater flow and chromium transport required addressing several difficult issues, including: 1) estimation of irrigation pumping; 2) estimation of infiltration rates from the Mojave River; 3) simulation of chromium retention in retained water above the water table; 4) simulation of chromium reactions in infiltrating irrigation water; and 5) understanding the chemical processes affecting chromium in the source area. Each of these issue is described below.

Irrigation Pumping

No records of irrigation pumping were available, and only a few electrical records were located to estimate pumping. Therefore, aerial photographs were utilized to estimate irrigated acreage for 11 time intervals between 1952 and 1995 in each 40-acre tract in the Hinkley Valley. During the period when flood irrigation was practiced, prior to the1970's, an irrigation rate of 8.8 feet was specified in the model based on reported usage rates for irrigating alfalfa in the desert areas of southern California, and a rate of 7 feet was specified for spray irrigation systems. One-half of the applied water was specified as recharge to the groundwater system.

A compilation of wells in the Hinkley Valley was completed based on published records and maps, and pumping rates were assigned to wells based on location relative to irrigated fields and reported well yields. As the water table in the valley fell, in many instances the existing wells had insufficient yield to satisfy the full irrigation demand. To simulate this condition, the pumping rate specified for each irrigation well was checked at each time step to insure that the well had sufficient yield given the current saturated thickness to satisfy the irrigation demand. If the yield was less that the irrigation demand, the pump rate was reduced to the calculated yield. The following equation was used to calculate the yield of the irrigation wells at each time step:

$$Q = \frac{4 \pi T \Delta s}{W(r^2 S / 4 T \Delta t)} \qquad (1)$$

where: T is the saturated thickness times the hydraulic conductivity, Δs is the allowable drawdown defined as the head in the node with the well at the end of the last time step minus the base of the aquifer, W is the Theis well function, r is the radius of the irrigation well, S is the storage coefficient, and Δt is the time-step size.

Recharge from the Mojave River

Recharge from the Mojave River was initially estimated from U.S. Geological Survey (USGS) gaging stations that straddle the model area. Gaging stations are located at Hodge, just upstream of the modeled area, and at Barstow, about 4 miles downstream of the modeled area. Data for the Hodge station dates back only to 1971, and flow data for earlier periods were estimated by developing a regression based on the period when data were available for both stations.

A simple approach, and the approach initially used for simulating the recharge from the Mojave River, was to develop an infiltration rate per surface area of the riverbed from the available flow data. This infiltration rate was then used to allocate the available surface-water flow beginning at the upstream end of the modeled area. It was necessary to allocate flow in this manner because our observations had indicated that the decrease in surface flow through the model area was dramatic; on April 5, 1995 we observed the river flowing bank to bank at the upstream end of the modeled area and observed a dry river bed at the downstream end of the modeled area. This approach proved unsatisfactory in simulating observed water levels, as recharge was not accurately distributed along the river reach, likely because of a large uncertainty in the estimated width of the river at various stages.

The approach ultimately used to simulate the recharge from the river was to represent the river as a transient head-dependent boundary condition using the MODFLOW general-head boundary package. The head-dependent boundary condition was applied for only those periods during which river flow data indicated there were losses from the river. The time-dependent heads along the river were initially specified on the basis of the observed water levels in two wells adjacent to the river with long historical water-level records and the differences in surface elevations between nodal points representing the river and the two wells. These initial estimates of heads along the river were adjusted by a constant factor during model calibration to produce a good correspondence between measured and observed water levels at the two wells near the river. The final step was to compare the total river recharge produced with the head-dependent boundary condition to the recharge estimated from the stream gaging data. The correspondence was excellent.

Chromium Retention in Pore Water

Chromium in the blowdown water was in the form of hexavalent chromium, chromate or Cr(VI), the active ingredient in the corrosion inhibitor. The chromate that was discharged to the ponds rapidly migrated to the water table, as chromate transport is not significantly retarded with respect to water in coarse-grained materials, and the recharge rates from the ponds were such that travel time from the ponds to the water table was less than one year. The chromate formed a plume that migrated northward from the location of the ponds in the direction of groundwater flow.

During the first 20 years after discharge of blowdown water to the ponds began, the water table in the shallow aquifer in the Hinkley Valley was declining rapidly. This decline in the water table trapped large quantities of chromate in the pore water above the water table (pore water is defined here as the water remaining in the aquifer materials after gravity drainage; or simply as total porosity minus specific yield). The chromate was retained in the pore water in all areas in the Hinkley Valley where recharge rates were negligible; essentially everywhere except beneath the irrigated fields. The chromate trapped in the pore water subsequently acted as a source of chromate to the groundwater when the water table rose. Beneath the irrigated areas, the recharge of irrigation water was sufficient to flush the chromate out of the pore water as the water table declined.

MT3D was modified to account for the mass retained in the pore water. A mass balance approach was developed to keep account of the retained mass. The retained mass was accounted for in a three dimensional array that was dimensioned as number of rows in finite difference grid times number of columns in the grid times one hundred, where one hundred represented the maximum decline in the water table from initial conditions in feet. When the water table was falling, at each time step the amount of mass of chromate retained for each foot decline in the water table was calculated. Mass retained per unit area per foot decline of the water table was calculated as the product of the concentration, the retardation coefficient and the difference between total porosity and specific yield. When the water table was rising, at each time step a check was made to determine if mass had accumulated in the interval through which the water table was rising during the previous period(s) when the water table was falling. If mass had accumulated, this mass was added to the water table aquifer as a source, and accumulated mass in the mass balance array was set to zero.

Chromium Reactions in Infiltrating Irrigation Water

The irrigation wells in the Hinkley Valley acted as a large groundwater containment system for the chromate plume. The water pumped from the irrigation wells was applied to the fields prior to the 1970's by flood or furrow irrigation, and later by spray irrigation. The chromate in the applied water was reduced to trivalent chromium, Cr(III), by the organic matter in the surface soils in the fields. Cr(III) is relatively insoluble, and as a result the chromate that was applied to the irrigated fields accumulated in the surface soils as Cr(III) minerals. Therefore, in the model, irrigation pumping was a sink for the extracted chromate. As a result of these processes, the irrigation pumping was an effective pump and treat system that contained the chromate plume.

Chemical Processes in Source Area

An enigma of the chromate plume was that in the 1990's the highest chromate concentrations were still found directly beneath the ponds where the blowdown waters were originally discharged. Initial model simulation has indicated that the highest concentrations in the 1990's should be downgradient of the source area as the result of the insignificant retardation of chromate. Several hypotheses were developed to explain the high concentrations of chromate beneath the ponds, but data were not available to test the hypotheses, and the cause of the high concentrations is still not satisfactorily explained. One hypothesis was that some chromium was adsorbed to oxide surfaces and organic matter in finer-grained silt and clay layers in the upper aquifer and at the base of the upper aquifer. Another hypothesis was that some of the chromate was precipitated as calcium and barium minerals and these minerals later dissolved re-releasing chromate to the groundwater (Davis and Olson, 1995; Nikolaos and others, 1994). In the model simulation, a high retardation coefficient was specified in the upper aquifer beneath the ponds to simulate the long-term retention of chromate/chromium in this area. This approach was utilized because it was pragmatic since the controlling processes were not understood.

RESULTS

A groundwater model was developed to simulate the evolution of a chromium plume over a 45-year period. The model successfully simulated observed chromium concentrations in groundwater during a period in which large changes in water levels and groundwater flow directions occurred. The chromium plume rapidly evolved to a relatively steady-state configuration due to the containment of the plume by the irrigation pumping. Then in latter years the plume began expanding again as irrigation pumping was curtailed and rising water levels remobilized chromium retained in the unsaturated zone during periods when water levels were falling.

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