Evaluating Alternative Hydraulic Solutions to Limit Nutrient Contamination of an Aquifer in Southern California

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ABSTRACT

Many small communities depend on groundwater sources for drinking water and they often use septic tanks for wastewater treatment and disposal. Nitrate and other pollutants leaking from poorly designed septic tank systems can percolate to the aquifers and alter quality of the groundwater. This study describes a groundwater model developed using Visual MODFLOW for an aquifer that is used as a water supply source for the communities of Beaumont and Cherry Valley, CA. The aquifer has been contaminated by nitrates leaking from septic tank systems. The model will assist in clarifying the extent of interactions between nitrate pollutants, percolation from a recently established series of artificial recharge ponds, natural groundwater recharge, and production wells. The primary objective of the study is to evaluate alternative hydraulic solutions that would limit the movement of contaminants and minimize the risk of polluting production wells. The study will identify artificial recharge scenarios that would limit movement of the nitrates so that polluted waters may be remediated in the future, rather than allowed to encroach on critical production wells or forced away from production wells to become a problem for future generations or neighboring areas. The data needed to build the model including geological logs, aquifer properties, hydrologic data, well locations, pumping schedules, water levels and septic tank density have been collected from various sources. The groundwater model is calibrated to accurately simulate observed groundwater levels and the extent of pollution corresponding to historical pumping rates, recharge rates and climate. The calibrated model is used to evaluate alternative hydraulic solutions that would localize the nitrate pollutions thus limiting impact on public welfare.

INTRODUCTION

Many communities depend on groundwater as a primary source for drinking water. United States Geological Survey (USGS) estimates that in 2005, about 20% (82,600 MGD) of all water withdrawals in the United States came from groundwater sources, and about 98% of domestic water use (3,740 MGD) was from groundwater sources (USGS 2011). Many rural communities, that may not have access to or the ability to develop a centralized wastewater removal and treatment infrastructure, also use septic tank systems to handle wastewater treatment and disposal (USEPA 2002). Contaminants leaking from septic tanks to groundwater could pose health risks to the public.

One of the major pollutants that can come from septic tank systems is nitrogen. According to the United States Environmental Protection Agency, “Nitrogen is an aquatic plant nutrient that can contribute to eutrophication and dissolved oxygen loss in surface waters, especially in lakes, estuaries, and coastal embayments….Excessive nitrate-nitrogen in drinking water can cause methemoglobinemia in infants and pregnancy complications for women" (USEPA 2002). Methemoglobinemia, or blue baby syndrome, is a condition from excessive nitrogen ingestions where nitrates in the body prevent blood from delivering oxygen to the skin and organs, causing a blue tint to the skin. In severe cases, methemoglobinemia can cause coma or death (USEPA 2011). To avoid excessive ingestion of nitrates, the U.S. EPA has set the maximum contamination level (MCL) for nitrate as nitrogen in drinking water at 45 mg/L. The typical mass loading of total nitrogen in residential wastewater ranges from 6-17 grams/person/day, and the typical concentration of total nitrogen in residential wastewater ranges from 26-75 mg/L (USEPA 2002)

Proper understanding of contaminant sources and leakage rates, and how their movement and attenuations are affected by aquifer characteristics and local hydrology would help to assess the extent of pollution and to devise remediation techniques. Groundwater flow models can help in understanding as well as mitigating contaminants from aquifers. The objective of this study is to develop a groundwater model for an aquifer that is used as water supply source for the cities of Beaumont and Cherry Valley, CA. The aquifer has been contaminated by nitrates leaking from septic tank systems. The model is developed to examine the extent of nitrate contamination, and to understand the interaction between nitrate pollutants, percolation from a recently established series of artificial recharge ponds, natural groundwater recharge, and production wells. The model will be used to evaluate potential hydraulic solutions that would limit the movement of contaminants and minimize the risk of polluting the production wells.

BACKGROUND

The study aquifer is located around the communities of Beaumont and Cherry Valley, in southern California. Beaumont is located approximately 80 miles east of Los Angeles, in Riverside County in the valley between the San Gorgonio and San Jacinto mountains. As of 2010, the population of Beaumont was approximately 36,000, and is primarily a commuter community. Cherry Valley, CA, is an unincorporated area to the north of Beaumont, with a smaller 2010 population of 6,300 residents. The majority of domestic water for these communities is provided by the Beaumont-Cherry Valley Water District (BCVWD), which draws water from the local Beaumont Basin aquifer to serve all water needs. There are a few entities within the model area that do not use water provide by BCVWD and also draw water from wells in the Beaumont Basin, but the majority of these users tend to have relatively small well productions compared to wells operated by BCVWD (Davis, Email conversation 2011), and thus likely have a negligible effect on the overall water table elevations within the Beaumont Basin. The BCVWD maintains several production wells in Beaumont and Cherry Valley, as wells as a distribution network that includes pipelines, pumps, and reservoirs. The BCVWD also maintains the Noble Creek Recharge Project, which began recharging the California State Water Project (SWP) water deliveries to the Beaumont Basin in 2006. (Beaumont-Cherry Valley Water District 2011). In Cherry Valley, the majority of homes are not connected to a sewer system, and instead rely on septic tank systems to dispose of domestic wastewater.

There are over 200 septic tanks per square mile in areas of Cherry Valley, which provides a significant loading rate of nitrate and other contaminants (Wilfley 2009).

General geology of the Beaumont Basin includes a foundation of crystalline formations, and layers of older sedimentary, younger sedimentary, and surficial deposits. The crystalline basement formations are hard, low-permeability formations. Above the basement formations are the older sedimentary deposits that tend to be well-consolidated and can be considered relatively impermeable in modeling scenarios (Rewis, et al. 2006). Above the older sedimentary deposits lie the younger sedimentary deposits, which are categorized into a lower and upper layer. The lower layer consists of pale brown to yellowish-brown sand and sandstone, with some gravel and clasts of local San Gabriel Mountains-type. This lower layer tends to be more consolidated than the upper layer. The upper layer consists of grayish- to yellowish-brown sand and gravel layers, and is cut by caliche-lined faults, with some irregular seams and zones of caliche or calcrete. The upper layer has a higher borehole resistivity than the lower layer, which suggests fewer silt and clay particles in the upper layer and helps to determine a boundary between the upper and lower layers of the younger sedimentary deposits (Rewis, et al. 2006). Finally, the surficial deposits in the Beaumont Basin consist of interlayered sand and gravel with intermittent layers of clay and silt (Rewis, et al. 2006).

THE GROUNDWATER MODEL

Visual MODFLOW (Schlumberger Water Services 2010) has been selected for this study. MODFLOW-2005 (Harbaugh 2005), one of the most widely used groundwater models, is a modular program which allows the user to account for different aspects of the hydrology of a study area, such as recharge, hydraulic conductivity, storage, wells, etc., and develop a steady-state or transient model for the study area. MODFLOW-2005 can calculate approximate groundwater head levels and velocities as well as generate water budgets for a given aquifer. Thus, MODFLOW-2005 can aid in determining the effects of production wells and recharge on the water table of a study area or the movement of particles such as contaminants through the study area (Harbaugh 2005).

While MODFLOW is a strong program for developing groundwater models, it is not very user friendly and formatting input data files correctly, and interpreting output files can be time consuming and difficult. To make the groundwater modeling process more streamlined and easier to understand, a modeler can use software such as Visual MODFLOW that provide user friendly interface for MODFLOW. Using Visual MODFLOW, it is possible to import text files, Microsoft Excel spreadsheets, and other common file types to bring data for various study area properties into the model. Once saved in a Visual MODFLOW file, the Visual MODFLOW software can then generate the appropriate input data files for MODFLOW and run the MODFLOW computation engine to solve the groundwater flow problem (Schlumberger Water Services 2010).

There are a handful of previous groundwater studies that have been done for the Beaumont Basin. In 2006, the United States Geological Survey published Scientific Investigation Report 2006-5026 (Rewis, et al. 2006), which investigates the geology, groundwater hydrology, and geochemistry of the Beaumont Basin and the neighboring Banning Basin, and conducts surface water and groundwater simulations using the INFILv3 and MODFLOW-96 software, respectively. In 2004, the Water Resources Division of the USGS in Sacramento, California, created a groundwater model to evaluate the long-term infiltration and perched aquifer areas of the Beaumont Basin (Flint and Ellett 2004). Additionally, in 2002 the BCVWD conducted a study of the Noble Creek Recharge Facility area to determine the feasibility of developing a future recharge site (Geoscience Support Services, Inc. 2002). Data and findings of these previous studies will be used to develop the Visual MODFLOW model proposed for the Beaumont Basin in this study.

DATA

Groundwater recharge is contributed to the model area from several sources, including intermittent stream flows from seasonal storms, golf course irrigation, septic tank infiltration, and the artificial recharge facility operated by the BCVWD. To simulate recharge for septic tank systems, it was necessary to develop a spatial distribution of the septic systems to show a more accurate distribution of recharge and potential nitrate contamination in the Cherry Valley region of the Beaumont basin. The majority of homes in Cherry Valley are not connected to the Beaumont sewer system; these homes were noted with placemarks in Google earth. Each placemark assigns a latitude and longitude to the homes in Cherry Valley, and these placemarks were then gathered into a single file where these latitudes and longitudes could be imported into Microsoft Excel and converted to UTM Zone 11 coordinates. Each cell in the model area that contained homes assumed to be on septic systems was assigned a recharge rate based on the number of homes per cell, an assumed effluent quantity of 70 gal/d/person (Rewis, et al. 2006), and an average of 2.4 residents per home and an estimated percentage of 71.5% for family homes (Onboard Informatics 2011). Artificial recharge from the BCVWD facility is added to the model by using SWP deliveries to the recharge ponds and assuming a recharge rate of up to approximately 10 ft/day, as reported by BCVWD. (Wilfley 2009)

Faults in the Beaumont Basin, which result as deformations caused by the San Andreas Fault, constitute the majority of the boundaries of each of the major storage units within the San Gorgonio Pass (Rewis, et al. 2006). Due to their key role in defining the storage unit, faults within the Beaumont Basin have been incorporated into the MODFLOW model. Visual MODFLOW uses the Horizontal Flow Barrier (HFB) package, "…or Wall Boundary as it is referred to in Visual MODFLOW…to simulate thin, vertical, low-permeability features that impede the horizontal flow of groundwater" (Schlumberger Water Services 2010). Similar to layer boundary elevations, the faults were scaled from the USGS SIR using relative coordinates, and then assigned UTM Zone 11 coordinates and row and column coordinates. Appropriate cells along these key faults were assigned Wall Boundary criteria, including hydraulic conductivities as calibrated and reported in the USGS SIR (Rewis, et al. 2006). Each fault is assumed to be 1ft thick, so that each fault is very thin compared to the thickness of each model cell, thus maintaining the validity of the Wall Boundary (Schlumberger Water Services 2010).

The hydraulic conductivity of the subsurface soil layers in the Beaumont Basin varies greatly, which makes assigning conductivity values to the aquifer somewhat difficult. To compensate for the widely varying hydraulic conductivity in the basin, a conductivity estimation scheme was devised for soils near each production well, and data interpolation methods within Visual MODFLOW were used to apply hydraulic conductivity values to the remaining areas of the Beaumont Basin. Using drilling logs provided by the BCVWD (Beaumont-Cherry Valley Water District 1995), elevations were assigned to each soil layer from the drilling logs to corresponding model layers. The approximate grain size of each soil layer in the drilling logs were also recorded, and compared to a standard grain size scale. Each grain size and category was then assigned an approximate hydraulic conductivity based on a table of grain sizes and corresponding conductivity values (Bear and Verruijt 1987). Transmissivity information from some of the production wells in the model area were taken from the USGS SIR (Rewis, et al. 2006) and an approximate saturated depth of the aquifer was computed at each of these wells. Using the following equations, an effective hydraulic conductivity was calculated for each soil layer for each applicable production well.

$$T = Kb \qquad (1)$$

$$K_{eq}^{P} = \frac{1}{B}\sum_{i=1}^{N} K_i B_i \qquad (2)$$

where T = transmissivity of the aquifer (m^2/d), K = effective hydraulic conductivity (m^3/d), b = depth of aquifer (m), K_{eq}^{P} = equivalent hydraulic conductivity parallel to the layers in the aquifer (m^3/d), K_i = hydraulic conductivity of the ith soil layer (m^3/d), B_i = depth of the i^{th} soil layer (m), B = total saturated depth of the aquifer (ft). (De Weist 1969) (Bear and Verruijt 1987)

Each of these conductivities was assigned to coordinates within the model area and conductivity values for the remaining cells in the model were determined through the *Natural Neighbors* method of interpolation (Schlumberger Water Services 2010). Another crucial aquifer parameter is storage coefficient. Initial storage values, including specific storage and specific yield, were determined based on calibrated data included in the USGS SIR groundwater model (Rewis, et al. 2006).

Monthly production well data was also obtained from the BCVWD for water district wells (Reichenberger 2012) and annual well data was obtained from the SGPWA for select water users in the Beaumont Basin that have a considerable amount of pumping (Davis and Rasmussen 2011). These pumping rates were assigned to the appropriate wells within the Beaumont Basin, and monthly stress periods were assigned based on the changes in monthly pumping rates for the BCVWD production wells.

DATA PRE-PROCESSING AND MODEL BUILDING

The groundwater model of the Beaumont Basin uses spatial data as determined from scaling various geologic figures in the USGS SIR (Rewis, et al. 2006) and digital elevation model data from the USGS Seamless Data Warehouse (USGS 2010). The USGS SIR depicts the extent of the Beaumont and Banning basins as well as some areas outside of these groundwater basins. The latitude and longitude coordinates that captured this extent were latitudes from 34º00’00”N to 33º52’30”N and longitudes from 117º07’30”W to 116º52’30”W (Rewis, et al. 2006).

These coordinates were used in the Seamless browser to obtain digital elevation model (DEM) files accurate to one third arc second from the National Elevation Dataset (USGS 2010). At latitude of 34ºN, one third arc second is approximately 8.53 m in length (Esri 2011). This resolution is very dense, and would result in a MODFLOW model that would take a very long time to compute, and since much of the data provided for this project are not detailed to the nearest 8.53 m, the original DEM was adjusted to create a coarser resolution. Using ArcMap 2009 by Environmental Systems Research Institute (ESRI), the DEM was converted into Universal Transverse Mercator (UTM) Zone 11 coordinates using a datum conversion tool built into ArcMap. The DEM data was then converted into a lower resolution Tagged Image File Format (TIFF) image, which had a resolution of 300 cells by 180cells. At this resolution, each cell is approximately 252.93 ft square, making each cell of the model comparable to home lot sizes. The elevations of the original cells within a new cell are averaged and assigned to the new cell, so that the elevations are maintained for each cell. The TIFF image data is then converted into a text file, which can then be manipulated by Microsoft Excel and Visual MODFLOW to assign ground surface elevations within the model.

The vertical space in the model is discretized by scaling cross sections of the various ages of sedimentary deposits from the USGS SIR (Rewis, et al. 2006). Each major feature, such as fault lines and intersections, of the cross sections provided were scaled for an appropriate elevation according to NGVD 29, and then converted to the appropriate elevation for NAVD 88, which is the elevation provided by the DEM used for the ground surface (USGS 2010). Each NAVD 88 elevation was generated using a conversion tool from the National Geodetic Survey (National Geodetic Survey 1999).

Once the elevation of every major feature was noted, each feature was assigned a row and column coordinate, as well as an x- and y-coordinate as compared to the model extents. Each layer of the model was imported into Visual MODFLOW using the Natural Neighbors method of interpolation (Schlumberger Water Services 2010), which assigned an elevation for each cell in each layer of the model. Once subsurface layers were imported, the ground surface was assigned to ensure none of the interpolated elevations for the subsurface layers were above the actual ground surface.

Many of the properties assigned to the aquifer require a spatial coordinate to relate to other properties within the aquifer. To maintain consistency within the model, and to avoid any warping in the model plane due to changes in latitude, any latitude and longitude coordinates for incoming properties were first converted to UTM Zone 11 coordinates, using calculations and a spreadsheet provided by Steven Dutch (Dutch 2011). Once UTM Zone 11 coordinates are assigned to data, model x- and y- coordinates are also assigned, as well as row and column coordinates. All location data that was linked to property data was imported into a Microsoft Access database to preserve any calculations and to ensure ease of import into Visual MODFLOW.

CALIBRATION OF VISUAL MODFLOW & ALTERNATIVE SOLUTIONS

Calibration process for the model uses the parameter estimation tools provided with the Pro version of Visual MODFLOW (Schlumberger Water Services 2010). All head elevations of the model are compared to water table elevations, as recorded by the USGS from observation and production wells in and around the Beaumont Basin (USGS 2011). The calibration process adjusts storage and hydraulic conductivity values so that the observed hydraulic head in the Beaumont Basin is consistent with the hydraulic head computed by the Visual MODFLOW model. The model is calibrated over a total period of one year.

A few alternative scenarios have been considered to test how the movement of nitrate within the aquifer will react to changes in the water management infrastructure in the Beaumont Basin. One alternative is to adjust the recharge rate of SWP water to the recharge ponds maintained by the BCVWD. In this scenario, the amount of SWP water delivered to the recharge site would be adjusted so that a smaller volume of water would be allowed to percolate at a given time. In theory, this will create a more gradual groundwater mounding effect near the recharge ponds, which may result in a smaller hydraulic gradient to push nitrates out of the Cherry Valley region of the Beaumont Basin. Another alternative would be to add a production well in the Cherry Valley region of the Beaumont Basin, with the goal of pumping out nitrate-contaminated groundwater out of the Beaumont Basin to be treated for contaminants. The treated water could then be recharged back into the aquifer through percolation beds or, potentially, added directly to the water supply if cleaned to a sufficient level.

Further details of the groundwater flow and contaminant transport model, the calibration process and results, and effectiveness of the alternative remediation solutions considered will be provided during the oral presentation.

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