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A partial exponential lumped parameter model to evaluate groundwater age distributions and nitrate trends in long-screened wells

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SUMMARY

A partial exponential lumped parameter model (PEM) was derived to determine age distributions and nitrate trends in long-screened production wells. The PEM can simulate age distributions for wells screened over any finite interval of an aquifer that has an exponential distribution of age with depth. The PEM has 3 parameters – the ratio of saturated thickness to the top and bottom of the screen and mean age, but these can be reduced to 1 parameter (mean age) by using well construction information and estimates of the saturated thickness. The PEM was tested with data from 30 production wells in a heterogeneous alluvial fan aquifer in California, USA. Well construction data were used to guide parameterization of a PEM for each well and mean age was calibrated to measured environmental tracer data (^{3}H, ^{3}He, CFC-113, and ^{14}C). Results were compared to age distributions generated for individual wells using advective particle tracking models (PTMs). Age distributions from PTMs were more complex than PEM distributions, but PEMs provided better fits to tracer data, partly because the PTMs did not simulate ^{14}C accurately in wells that captured varying amounts of old groundwater recharged at lower rates prior to groundwater development and irrigation. Nitrate trends were simulated independently of the calibration process and the PEM provided good fits for at least 11 of 24 wells. This work shows that the PEM, and lumped parameter models (LPMs) in general, can often identify critical features of the age distributions in wells that are needed to explain observed tracer data and nonpoint source contaminant trends, even in systems where aquifer heterogeneity and water-use complicate distributions of age. While accurate PTMs are preferable for understanding and predicting aquifer-scale responses to water use and contaminant transport, LPMs can be sensitive to local conditions near individual wells that may be inaccurately represented or missing in an aquifer-scale flow model.

1. Introduction

The susceptibility of a well to contamination depends on the distribution of groundwater age captured by the well. The age distribution reflects the combined effects of velocity, dispersion, and travel distance on parcels of water that recharged the aquifer and traveled to a well. Calibration of lumped parameter models (LPMs) to environmental tracer data has been the most common method for estimating groundwater age distributions at wells (Maloszewski and Zuber, 1982; Turnadge and Smerdon, 2014). Recent work has focused on the inclusion of mixed tracers of young and old groundwater in the calibration process (Corcho Alvarado et al., 2007; Solomon et al., 2010; Jurgens et al., 2012, 2014; Visser et al., 2013) and ways to improve the estimation of age distributions given uncertainty in tracer concentrations and their history in recharge, model complexity, transient distributions of age, or by using shape-free or general distributions such as the gamma or log-normal distribution (Long and Putnam, 2006; Massoudieh et al., 2012, 2013, 2014; Massoudieh, 2013; Green et al., 2014).

As work in this area progresses, there is still a need for the development and testing of simple, physically based age distribution models. The calibration of LPMs to tracer data can often be limited to a single tracer at a well and so it may not be possible to obtain an estimate of the age distribution using a complex LPM (2 or more model parameters) without estimating values of the other parameters. Even when the collection effort includes

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several tracers, the data may not yield multiple tracer concentrations that can be used in the calibration process because of the absence of measurable concentrations, or because degradation, contamination, or sampling issues lead to unreliable results.

The purpose of this study was to (1) develop a partial exponential model (PEM) for groundwater age distributions and (2) test the model in an aquifer where hydrogeology and groundwater age was previously studied (Burow et al., 2008; Green et al., 2010, 2014), where multiple environmental tracer data were available, and where nonpoint-source nitrate contamination trends have been documented (Landon et al., 2011). In this paper, we present the equations for a partial exponential model (PEM) that can be parameterized using well construction information and saturated thickness. The PEM was calibrated to environmental tracer data for 30 long-screened production wells (mostly public-supply) in the central eastside of the San Joaquin Valley, California. In this aquifer, heterogeneity of the sediments is expected to give rise to complex distributions of age that would not be expected to mimic the simpler distributions predicted by an exponential distribution of age with depth in the aquifer. For comparison with the PEMs, age distributions for each well also were generated using advective particle tracking models (PTMs) within a numerical groundwater flow model of the regional aquifer. Each age distribution was used to evaluate the histories of tracer concentrations in recharge for travel time delays through the unsaturated zone (UZ) and for dilution or enrichment of tracer concentrations from the application of surface water and groundwater for irrigation. Mean ages, recharge rates, and age distributions from the PTMs and PEMs were compared in order to understand the limitations of the different approaches, given the complexity of hydrogeology and land use in this system. Finally, current and historic nitrate concentrations were simulated for the calibrated PTMs and PEMs. These predictions can provide an independent evaluation of model performance, information about the stability of groundwater age in wells over time and factors affecting nitrate transport in the aquifer.

2. Description of study area

The study area is located within the Central Valley of California (Fig. 1). The Central Valley is a large, northwest-trending, asymmetric structural trough filled with marine and continental sediments up to 10 km thick (Page, 1986). The southern two-thirds of the Central Valley is the San Joaquin Valley (SJV), which is more than 400 km long and 30–90 km wide. East of the Central Valley, the Sierra Nevada rise to an altitude of more than 2500 m; west of the Valley, the Coast Ranges form a series of parallel ridges up to 1500 m high (Gronberg et al., 1998). Streams in the northern part of the SJV drain northward through the San Joaquin River to the San Francisco Bay; the southern part of the SJV is a hydrologically closed basin.

The study area is about 2700 km^2 and is bounded on the west by the San Joaquin River, on the north near the Stanislaus River, on the south near the Merced River, and on the east by the Sierra Nevada foothills (Fig. 1). These boundaries correspond to those used for the numerical groundwater flow model used in this paper (Phillips et al., 2007a,b).

Land-surface elevation in the study area rises from near sea level along the axial trough in the center of the SJV to more than 100 m at the top of dissected older alluvium near the valley margins. The climate is arid-to-semiarid, characterized by cool, wet winters and hot, dry summers. Precipitation averaged 315 mm annually from 1931 to 1997 (National Oceanic and Atmospheric Administration, 2005).

The aquifer system can be generally described as an unconfined to semi-confined aquifer underlain by a confined aquifer, where separated by a regional lacustrine clay unit commonly referred to as the Corcoran Clay (Williamson et al., 1989; Bertoldi et al., 1991). Aquifer materials are dominated by eastern and western alluvial fan deposits interspersed with fine-grained basin and floodplain deposits, and coarser-grained fluvial deposits.

Since 1850, diversion of surface water from streams and intensive groundwater pumping associated with agricultural irrigation and urban growth has substantially altered the natural flow system (Davis et al., 1959; Page and Balding, 1973; Londquist, 1981; Williamson et al., 1989). Development of the groundwater resource accelerated after about 1930 due to improvements to the turbine pump, which allowed farmers to pump groundwater from greater depths at greater rates (Williamson et al., 1989). At the time of this study, percolating irrigation water was the primary form of groundwater recharge, and pumping was the primary form of groundwater discharge (Faunt, 2009).

The widespread use of groundwater has caused water-level declines in many parts of the SJV and has greatly reduced the extent of artesian conditions. Depth-to-water varies east-to-west and north-to-south. In the study area (Fig. 1), depth-to-water can be more than 35 m near the SJV margins in the east and less than 3 m near the axial trough in the center of the basin. In urban areas, focused groundwater pumping and relatively low recharge rates have caused water-level depressions within Modesto and Turlock (Burow et al., 2004; Phillips et al., 2007b).

Agriculture is the primary land use in the area and increased annual application of nitrogen fertilizers over the last 50 years resulted in concentrations of nitrate in recharge that were significantly higher than background levels (approx. 2 mg/L as N). Recently, the Priority Basin Project of the California Groundwater Ambient Monitoring and Assessment (GAMA-PBP) program found nitrate concentrations were either high (above USEPA MCL of 10 mg/L as N) or moderately high (above ½ the USEPA MCL) in 16.7% of the aquifer used for public-supply in the central eastside San Joaquin Valley (Landon et al., 2010).

3. Conceptual model of groundwater age

The age structure of groundwater in the Central Valley Aquifer has been radically altered over the last 150 years (Fig. 2). Prior to development, recharge to the aquifer was low (<10 mm/yr) and was mainly fed by streams draining the Sierra Nevada. Although the aquifer has sediments up to several km thick, increased clay content and consolidated material below 150 m may limit the connection to deeper parts of the aquifer (Burow et al., 2004). Consequently, the groundwater age structure of the predevelopment system likely resembled an exponential distribution with some component of piston flow away from the streams and having a mean residence time greater than 10,000 years (blue line in Fig. 2). Currently, irrigation with groundwater and imported surface water is the primary source of recharge and recharge rates can be 100 times higher than pre-development rates. The application of irrigation water and pumping from deep parts of the groundwater system have increased the downward movement of shallow groundwater and stratified both the chemistry and age of water in the aquifer (Fig. 2) (Landon et al., 2010, 2011). The groundwater age structure in the shallower part of the aquifer system reflects the rapid, post-development recharge rates and could resemble the age structure of an exponential model (black line in Fig. 2) if allowed to evolve through the entire saturated thickness. In contrast, the deeper part of the system reflects the low recharge rates of the pre-development system (blue lines in Fig. 2). The interface between groundwater recharged in pre- and post-development times (50 and 70 m below the water table in Fig. 2) is not uniform across the valley and may be deeper or shallower