Spatially Distributed Stochastic Modeling of Non-Point Source Pollutants in Groundwater

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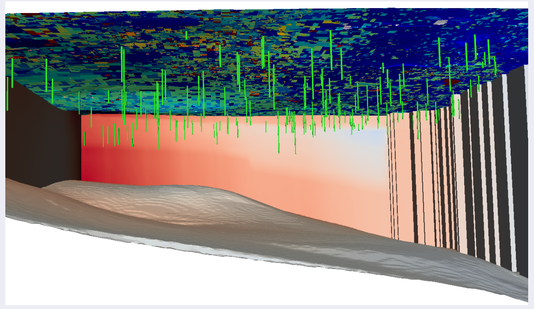
Abstract

Understanding the long-term effect of non-point source (NPS) pollution on groundwater of agricultural regions is an increasing challenge of global importance. A novel groundwater modeling framework is developed to assess and evaluate the dynamic, spatio-temporally distributed linkages between non-point sources above a groundwater basin and groundwater discharges to wells, streams, or other compliance discharge surfaces (CDSs) within a groundwater basin. The modeling framework allows for efficient evaluation of NPS pollution scenarios and of their short- and long-term effects on pollutant exceedance probabilities in CDSs. Using the model, we investigate the effect of aquifer heterogeneity, well design variability, and spatio-temporal nitrate source variability on nitrate in domestic and large production wells of a semi-arid, irrigated agricultural region. Results show that the timing of nitrate breakthrough in wells is significantly controlled by aquifer recharge and pumping rates in NPS areas and by the effective porosity of the aquifer system. Results further show that mixing within a domestic or large production well, not aquifer heterogeneity, is the dominant source of dispersive behavior in pollutant breakthrough. In production wells with shorter screens, macrodispersivity due to aquifer heterogeneity accelerates the earliest breakthrough. Variability in well construction and spatio-temporal variability of nitrate sources most strongly control the temporal dynamics of the nitrate exceedance probability and the variability of nitrate between wells, regardless of the degree of aquifer heterogeneity. Hence characterization of the heterogeneity of external sources and sinks (CDSs) is critical to understand variability of and uncertainty about nonpoint source pollution in groundwater CDSs across basins. We apply the model to simulate 100 years of nitrate pollution at high resolution in a 2 million hectare semi-arid, irrigated agricultural region with a large diversity of crops, but also natural lands and urban areas, and highly heterogeneous, temporally variable loading landscape. Simulated impacts to several thousand production wells are compares to a unique, extensive assemblage of historic and current groundwater nitrate data.

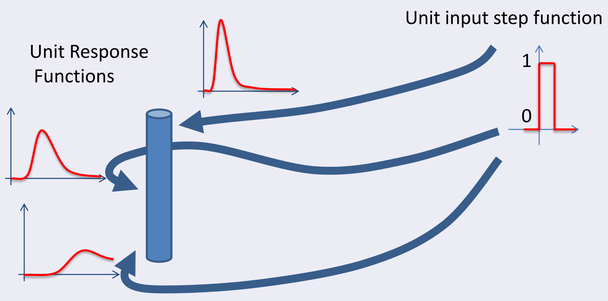
Motivation

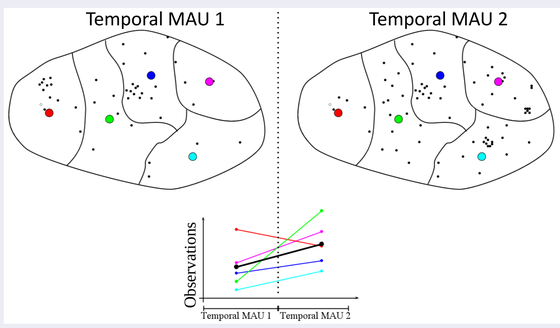
- Simulation of Non-Point Source (NPS) Pollution in large unconfined groundwater basins
- Examine the effect of porosity uncertainty
- Compare simulated with measured data and highlight data gaps
- Make future prediction of nitrate contamination due to agricultural activities



- Non-Point Source Assessment Toolbox (NPSAT) (Kourakos et al., 2012)
  1) Steady State Groundwater Flow Simulation
     - Algebraic Multi-grid implemented in HYPRE
  2) Streamline Transport simulation
     - Backward Particle Tracking
     - 1D Transport simulation along each streamlines assuming unit input concentration (Computation of Unit Response Functions, URF)
  3) The predictions of NPS Pollution are based on the convolution of URFs with loading functions

The NPSAT is written in Matlab and is available from www.groundwater.ucdavis.edu/msim



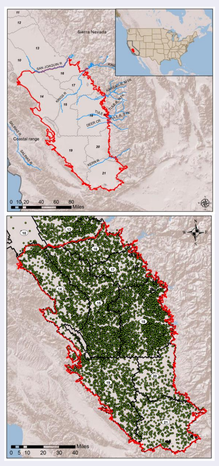


- Method to obtain average trends using spatially and temporally heterogeneous data
  1) Define spatial and temporal Minimum Analysis Units (MAU)
  2) For each MAU compute the median of all the observations that fall into the spatial and temporal MAU
  3) Using the medians, compute an unbiased average trend with confidence intervals. Optionally the data may need to be log-transformed

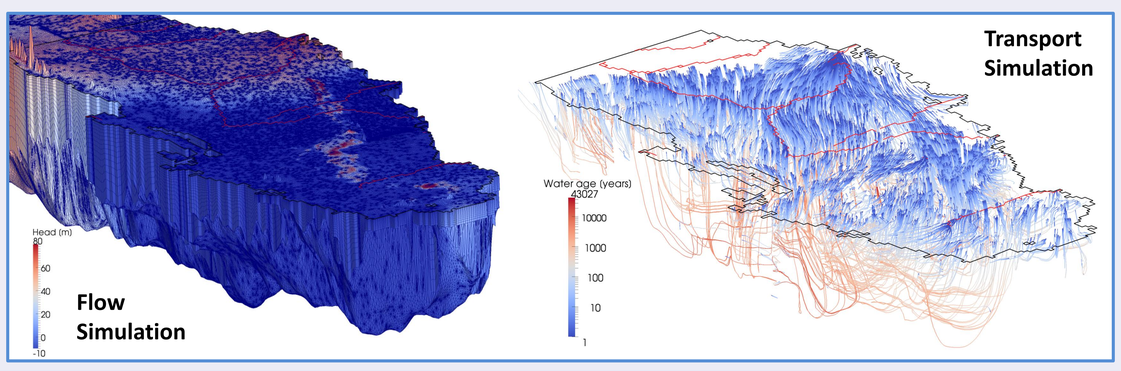
Study Area

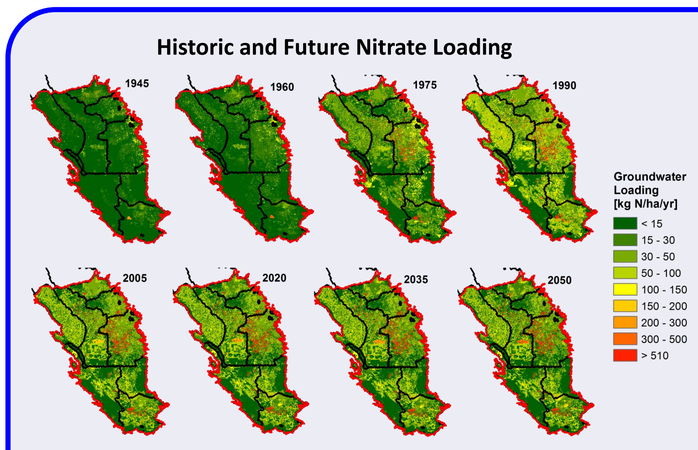
The study area is located in the southern Central Valley, CA.

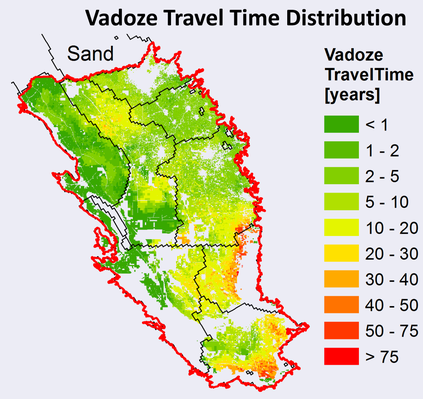
- Domain size: 21,301.40 km^2
- Highly heterogeneous hydraulic conductivity and porosity
- 85 % of total recharge is associated with agriculture
- 15 % of total recharge comes from streams
- Pumping is simulated by 7790 virtual wells, which correspond to production wells



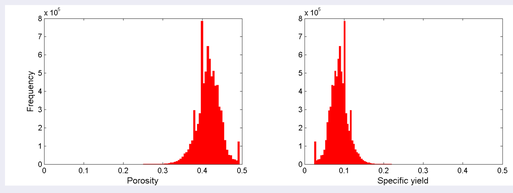
- CVHM (Faunt , C.C., ed., 2009) was used as parent model
- The flow domain was discretized into ~8 million degrees of freedom
- For the transport we used 779,000 streamlines



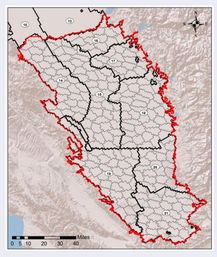




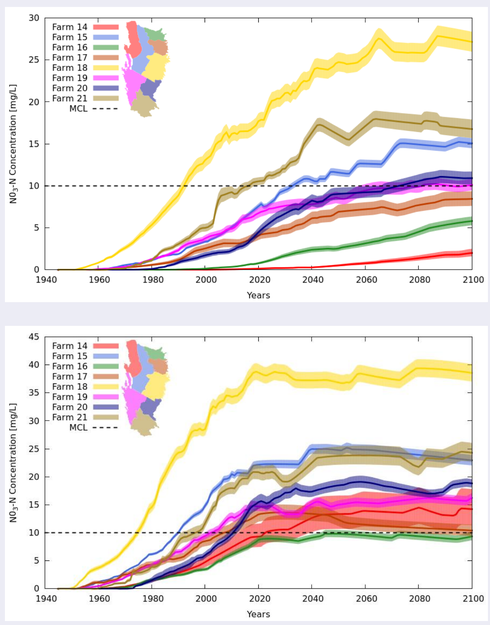
Due to porosity uncertainty the transport was simulated twice based on two different porosity distributions



Predictions

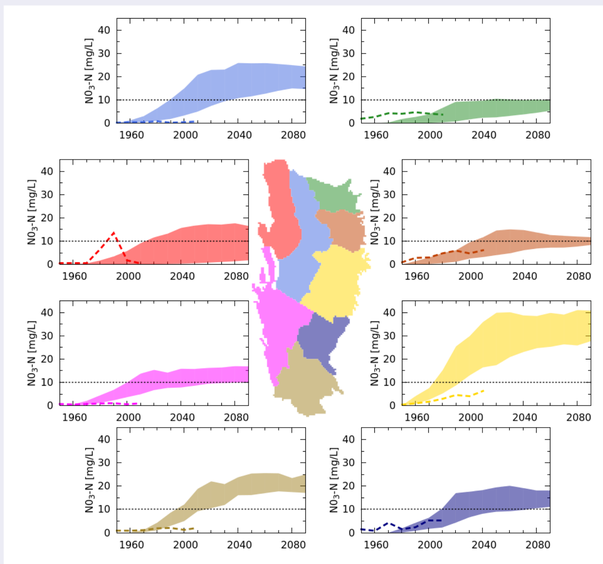


- Each sub-basin ("Farm") was divided into a number of equal area MAUs
- Temporally the data were grouped into decadal time steps
- For each decade we computed the median for each MAU
- The MAU medians were found to be log-normally distributed
- Based on the log-transformed medians we computed the average nitrate concentration trend and confidence intervals

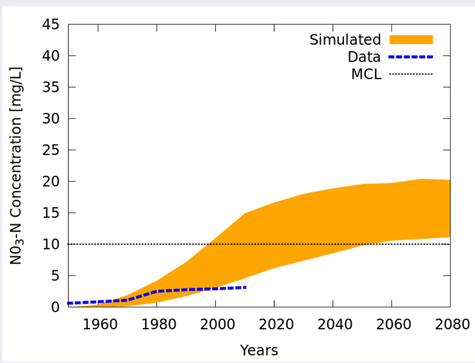


The solid line corresponds to the average trend per farm
The range corresponds to 95% confidence intervals
The dashed black line corresponds to the Maximum Contaminant Limit (10 mg/L)

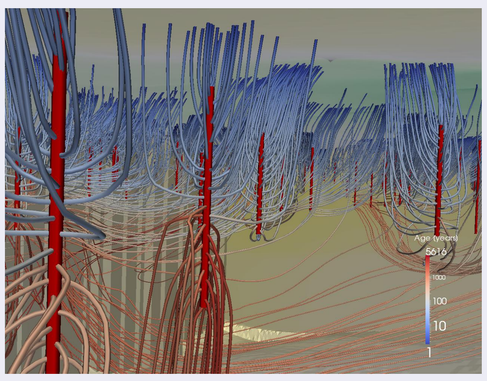
Simulated vs. measured data per virtual farm
The dashed line corresponds to measured data.
The range of the simulated data is defined by the two different porosity distributions.



Simulated vs. Measured data



Mixing effect



References

1) Kourakos, G., F. Klein, A. Cortis, and T. Harter (2012), A groundwater nonpoint source pollution modeling framework to evaluate long-term dynamics of pollutant exceedance probabilities in wells and other discharge locations, Water Resour. Res., 48, W00L13, doi:10.1029/2011WR010813.
2) Kourakos, G., T. Harter (submitted), mSim: A Vectorized Groundwater Flow and Streamline Transport Simulation tool.
3) Faunt, C.C., ed., 2009, Groundwater Availability of the Central Valley Aquifer, California: U.S. Geological Survey Professional Paper 1766, 255.

Conclusions

- A Process-based Non-Point Source Assessment Toolbox is used for simulating non-point source pollution in large-scale groundwater basins
- The code is written in Matlab/Octave and is available online http://groundwater.ucdavis.edu/mSim/
- The porosity is a significant time scaling factor which results in great uncertainties in future predictions
- The comparison with measure data revealed data gaps and the need for more intensive water-quality sampling.

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