Streamline simulation of Non Point Sources Pollution in unconfined aquifers based on adaptive moving mesh and domain decomposition methods

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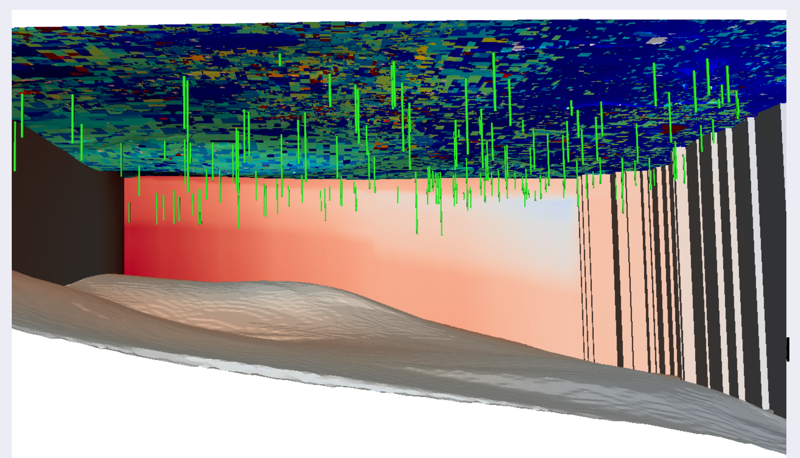
Abstract

Groundwater contamination in semi-arid agricultural regions is increasing around the globe. Communities in such areas typically rely on groundwater resources for domestic and irrigation uses. Intensive farming practices are a significant source of groundwater contamination, which affects communities via well pumping and ecosystems via groundwater return flow to streams. Agricultural contamination or diffuse pollution is generally difficult to simulate due to large amount of sources and the large number of distributed wells, requiring high resolution flow and transport simulations. Individual contributing sources are on the order of few hectare to a few tens of hectare, while many of the larger agricultural groundwater basins encompass hundreds to thousands of square kilometers. Classical 3D transport modeling approaches are intractable across such scales with the current computing power.

In this study we develop an efficient, highly parallelizable transport method known as streamline transport simulation. The approach decomposes a multi-dimensional problem into multiple one-dimensional subproblems which are trivial to solve. The streamline modeling requires a highly detailed 3D velocity field. The simulation of highly detailed groundwater flow in large agricultural basin is achieved by developing a substructuring iterative domain decomposition method or Complement Schur method for obtaining the velocity field. For unconfined aquifers, we illustrate that it is critical to use a moving mesh such that finite element adapts according to the head field. We therefore combined an iterative moving mesh approach with the Complement Schur domain decomposition method. The importance of using the moving mesh approach is illustrated with a hypothetical example and with an application to a real case study in the southern Central Valley, California

Motivation

- Simulation of Non Point Source Pollution (NPS) in large unconfined groundwater basins
- Examine the effect of neglecting the unconfined non-linearity in the context of the NPS



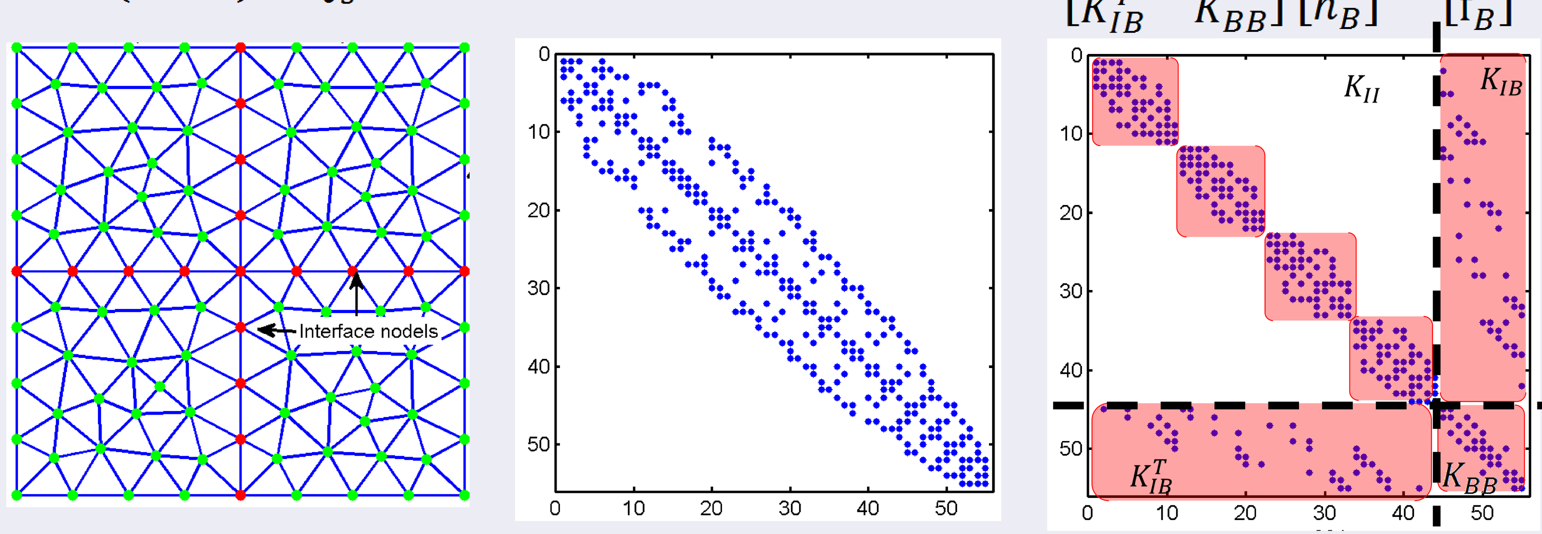
Methods

- Non-Point Source Assessment Toolbox (NPSAT) (Kourakos et al., 2012)
  1) Steady State Groundwater Flow Simulation
     - Iterative Complement Schur Domain Decomposition Methods are used to solve large scale problems with many millions of degrees of freedom
  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

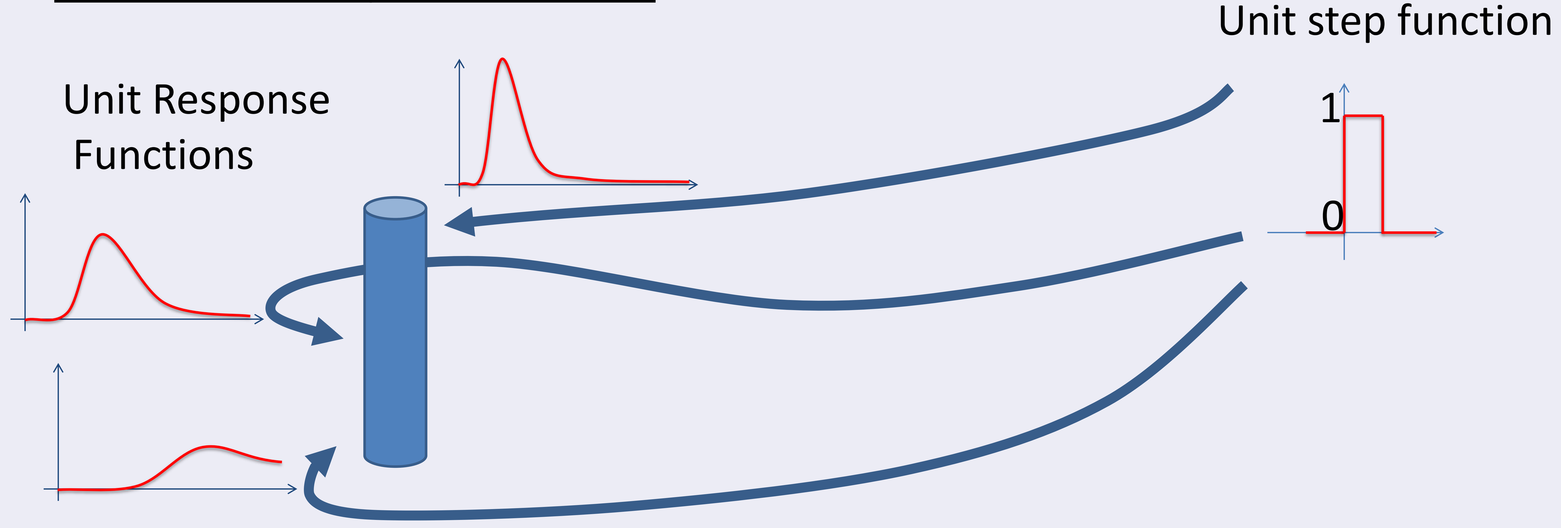
(NPSAT is written in Matlab/Octave in a highly vectorized manner)

- Complement Schur Domain Decomposition Methods

$$\nabla(kh\nabla h) + Q_s = 0 \longrightarrow Kh = \mathrm{f} \longrightarrow \begin{bmatrix} K_{II} & K_{IB} \\ K_{IB}^T & K_{BB} \end{bmatrix} \begin{bmatrix} h_I \\ h_B \end{bmatrix} = \begin{bmatrix} \mathrm{f}_I \\ \mathrm{f}_B \end{bmatrix}$$

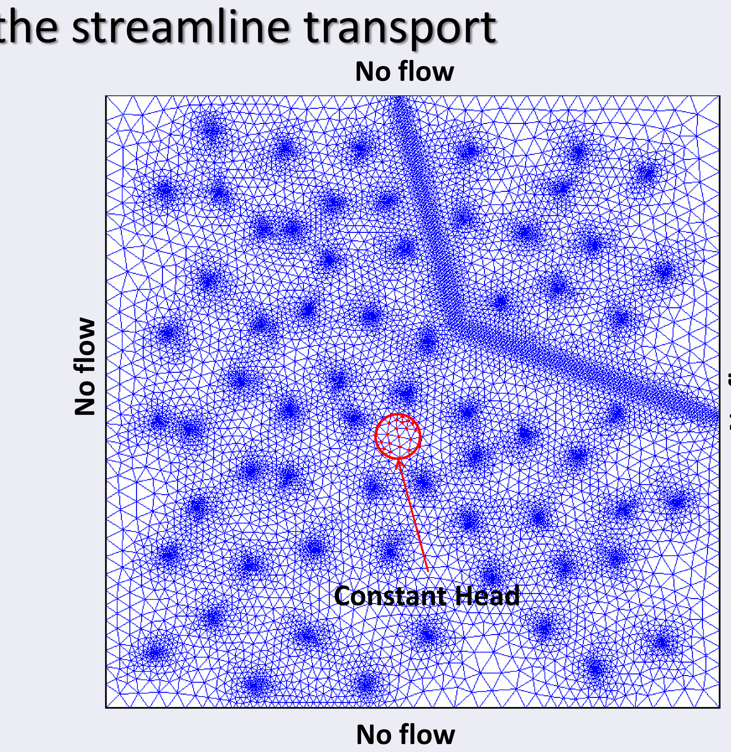


- Streamline Transport Simulation

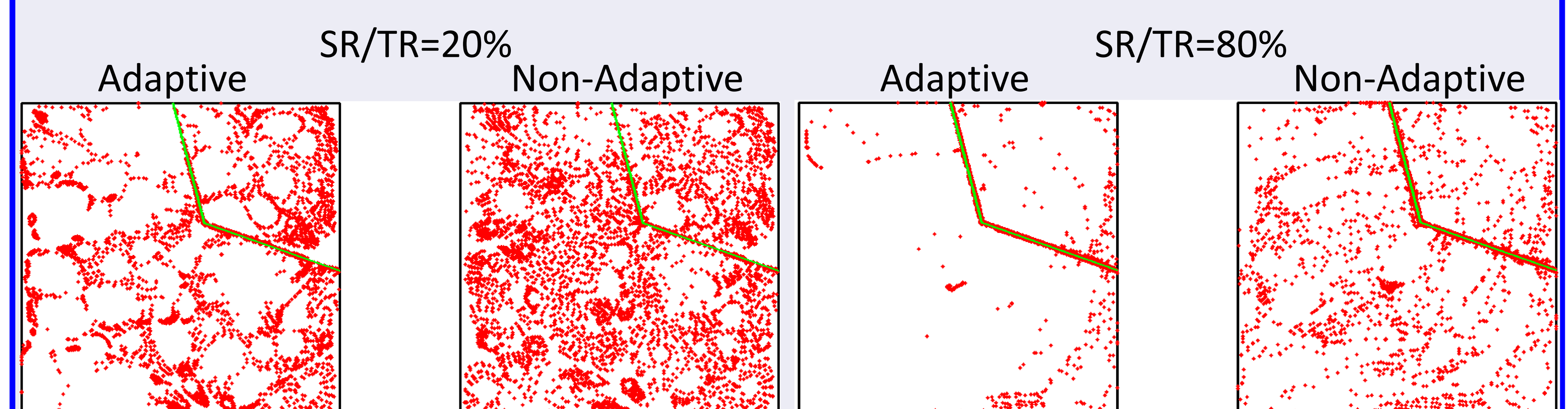


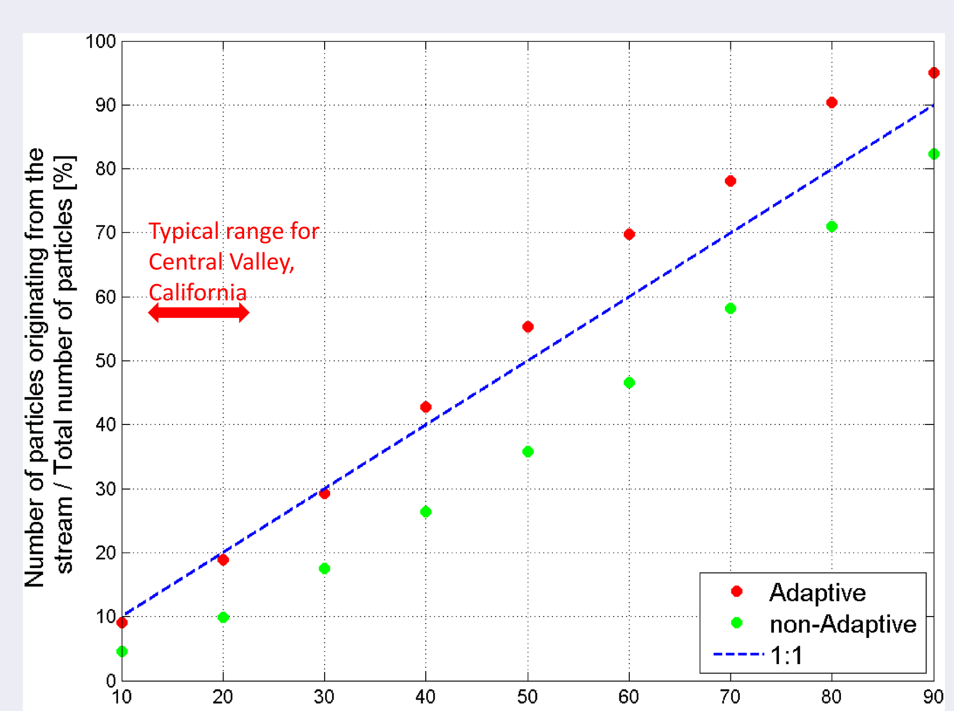
Effect of Mesh adaptation on the streamline transport

- Hypothetical Example :
  - Domain size : 40 x 40 km
  - Heterogeneous Hydraulic Conductivity
  - Total Recharge : 160000 m^3/day
  - Total Pumping : 145217 m^3/day
  - Discharge from bottom : 14783 m^3/day



- The Recharge was divided into diffuse and stream recharge.
- We examine the following ratios: Stream recharge (SR)/ Total recharge (TR) {10,20,…90}%.
- For each recharge case we computed the flow field using adaptive and non-adaptive mesh.
- For each solution we computed the streamlines by backward particle tracking.
- For each well we released 100 particles and identified their exit points.
- $\frac{SR}{TR} = \frac{\text{Number of particles originating from stream}}{\text{Total number of particles}}$

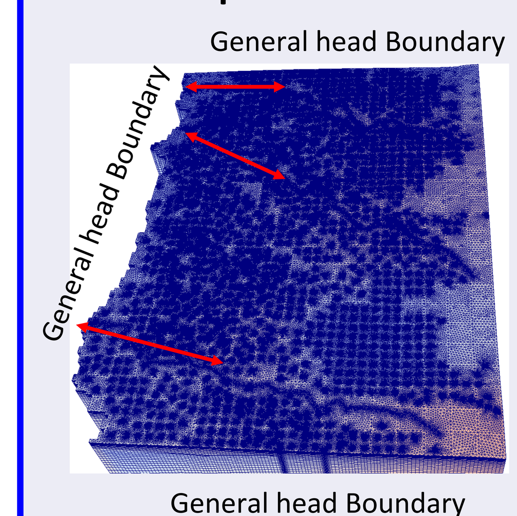




- For Typical to Central Valley Basins (e.g. SR/TR≈0.2), the error for using non adaptive mesh is ~ 50%.
- The error of the adaptive mesh method is small for SR/TR <50%.
- In NPS, stream water is considered clean, therefore significant errors can propagate in the transport simulation in non adaptive case.

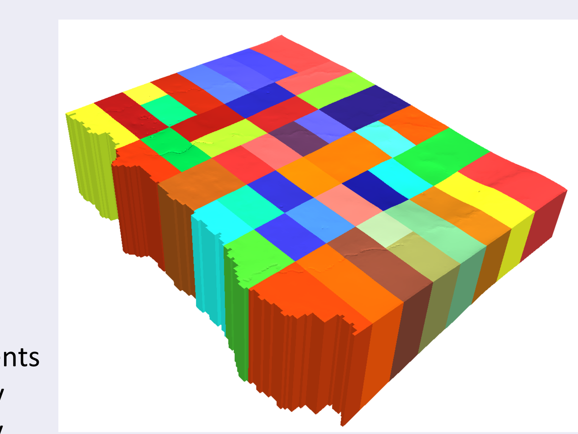
Modesto Case Study

Aquifer Characteristics

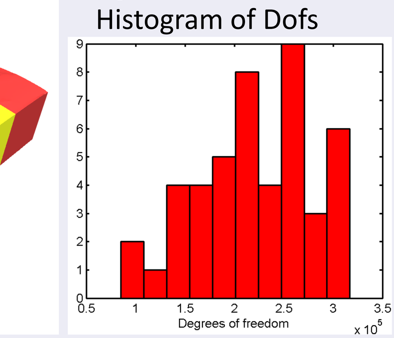


- 2653.6 km^2
- 1501 wells
- Smallest Element 40m
- Largest Element 400m
- 32 layers
- ~ 10 million nodes
- ~ 20 million elements
- TR=3.5 10^6 m^3/day
- SR=1.4 10^5 m^3/day
- **SR/TR=3.9%**

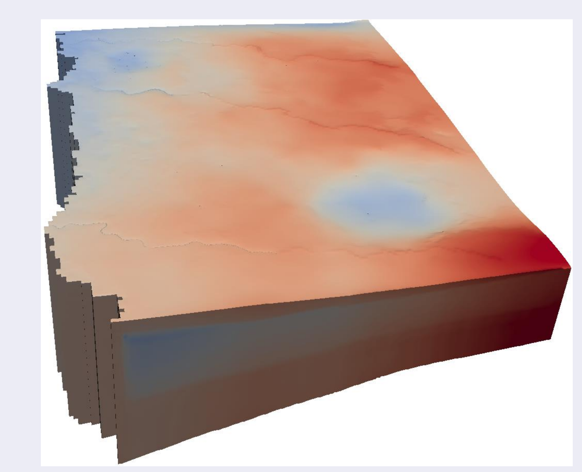
Domain Decomposition Partition



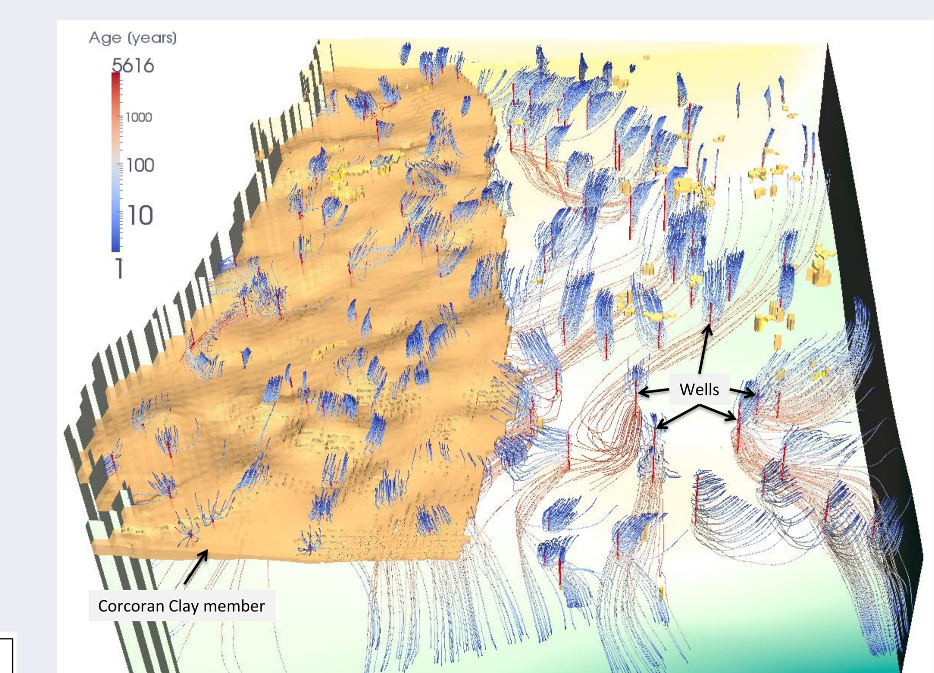
# of Subdomains : 46
N_B = 182490
Histogram of Dofs



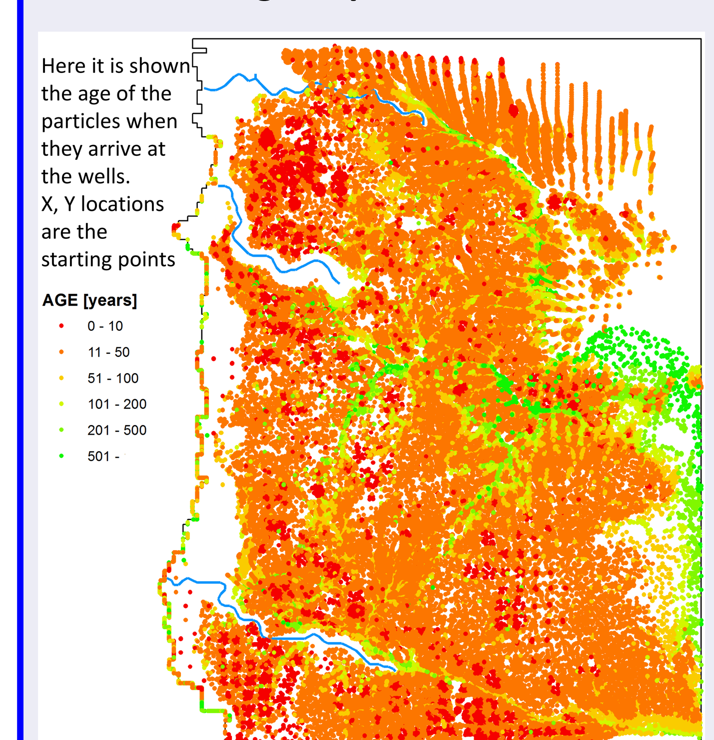
Hydraulic head distribution



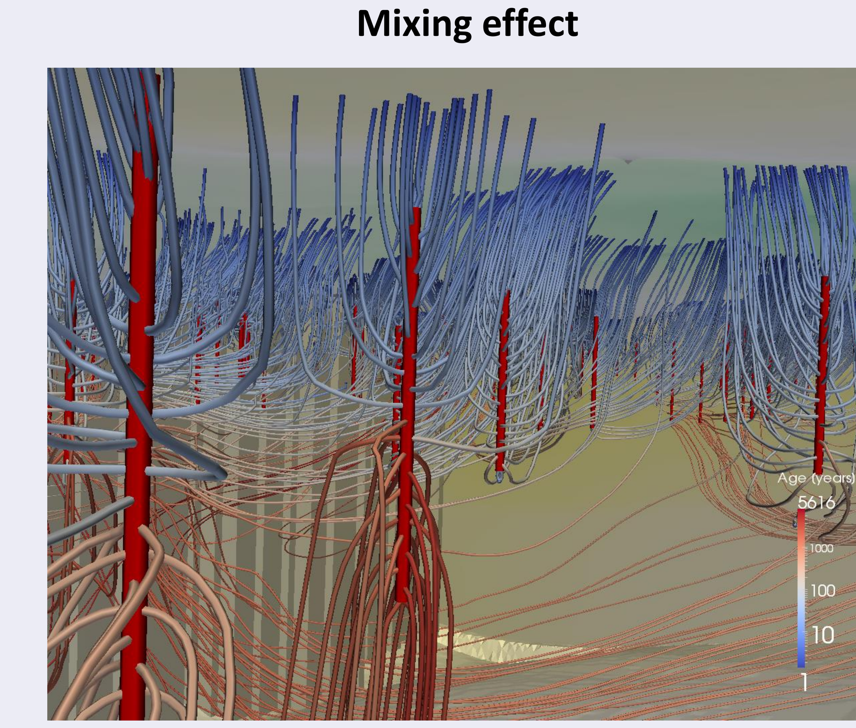
Streamline Transport



Age of particles



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)Philips, S.P., Green, C.T., Burow, K.R., Shelton, J.L., and Rewis, D.L., 2007, Simulation of mutliscale groundwater-flow in part of the northeastern San Joaquin Valley, California: U.S. Geological Survey Scientific Investigations Report 2007-5009, 43 p.

Conclusions

- •A Process based Non Point Source Assessment Toolbox is used for simulating large scale groundwater basins
- •A Complement Schur Domain Decomposition methods is employed to solve many-million degrees of freedom systems
- •The code is written in Matlab/Octave and will be soon available online (www.groundwater.ucdavis.edu)
- •The use of adaptive mesh methods for simulating unconfined aquifers is very important in the context of Streamline Transport Simulation

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