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Stochastic Simulation of Groundwater Age Using Transient Large Scale Integrated Modelling Frameworks

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Abstract

The estimation of groundwater age has important implications in groundwater simulation frameworks such as, contaminant transport, model calibration, source area identification etc. The calculation of simulated groundwater age is executed via particle tracking where virtual particles are injected into the aquifer domain and they are traced within the groundwater flow field. This approach has two major drawbacks. First, the resolution of the model has to be very refined near the features with rapid hydraulic head changes, e.g. near wells, streams, or near irrigated lands and MAR cites etc. Second, the groundwater velocity is generally low, e.g. a few meters per day, therefore transient state simulation models need to span over a few centuries in order to capture representative travel times of irrigation and public supply wells. However, constructing groundwater simulation models that meet both requirements is practically not feasible. Regional groundwater models usually span a few decades while their resolution is in the order of 1-5 km2..

In this work we propose a stochastic framework where we assume that the deterministic transient state flow field of a relatively coarse integrated surface groundwater flow model that spans several decades is representative of the groundwater flow of the near future. We convert the simulated groundwater velocity field to a pool of potential velocities and use bootstrap to trace particles independently of the model time span. By performing multiple realizations we can approximate a distribution of groundwater ages and source areas.

The stochastic framework is applied to two transient stated models: the Central Valley Hydrologic Model (CVHM), developed by USGS and the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim) developed by the Department of Water Resources of California. We convert the transient state flow fields into their respective stochastic fields and used them to predict the groundwater age of typical irrigation/public supply and domestic wells. The distribution of the simulated ages is then compared to actual measured aged data.

Motivation

- Particle tracking is an important post process method that allows for a wide range of analyses (Well capture zone delineation, contaminant transport, calibration etc).
- Particle tracking requires detailed spatial discretization around features with rapid hydraulic head changes, e.g. near wells, streams etc.
- Due to computational cost, groundwater simulation models are often using detailed discretization under a steady state assumption or use less detailed discretization on a transient state conditions.
- In addition, transient state simulations have relatively short time span (in the order of decades) while groundwater travel times are in the order of centuries.
- For large scale regional groundwater simulation models at basin scale the above issues are even more apparent.
- **Objective:**
  Develop a stochastic particle tracking method that can better exploit the transient state groundwater velocity of large-scale models.

Methodology

- We assume that the velocity field at each time step of the transient state simulation is an independent event.
- However, it is unrealistic to assume that succession between time steps is totally random.
- To account for the seasonality that exists in the hydrologic cycle we group the time steps (e.g. by month, season).
- Besides the seasonal variability it is important to consider the climate variability.

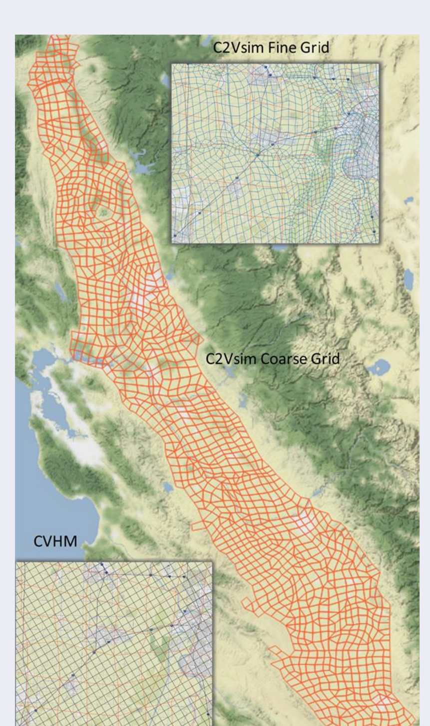
- Here we propose to group the transient velocity field into $N_{clim}\ x\ N_{per}$ groups where:
  N_{clim} is the number of climate groups (i.e. wet, dry, normal)
  N_{per} is the number of periods (i.e. month, seasons)

- A transition matrix $T\ [N_{clim}\ x N_{clim}]$ can guide the transitions between climate groups.

Application to Central Valley, California

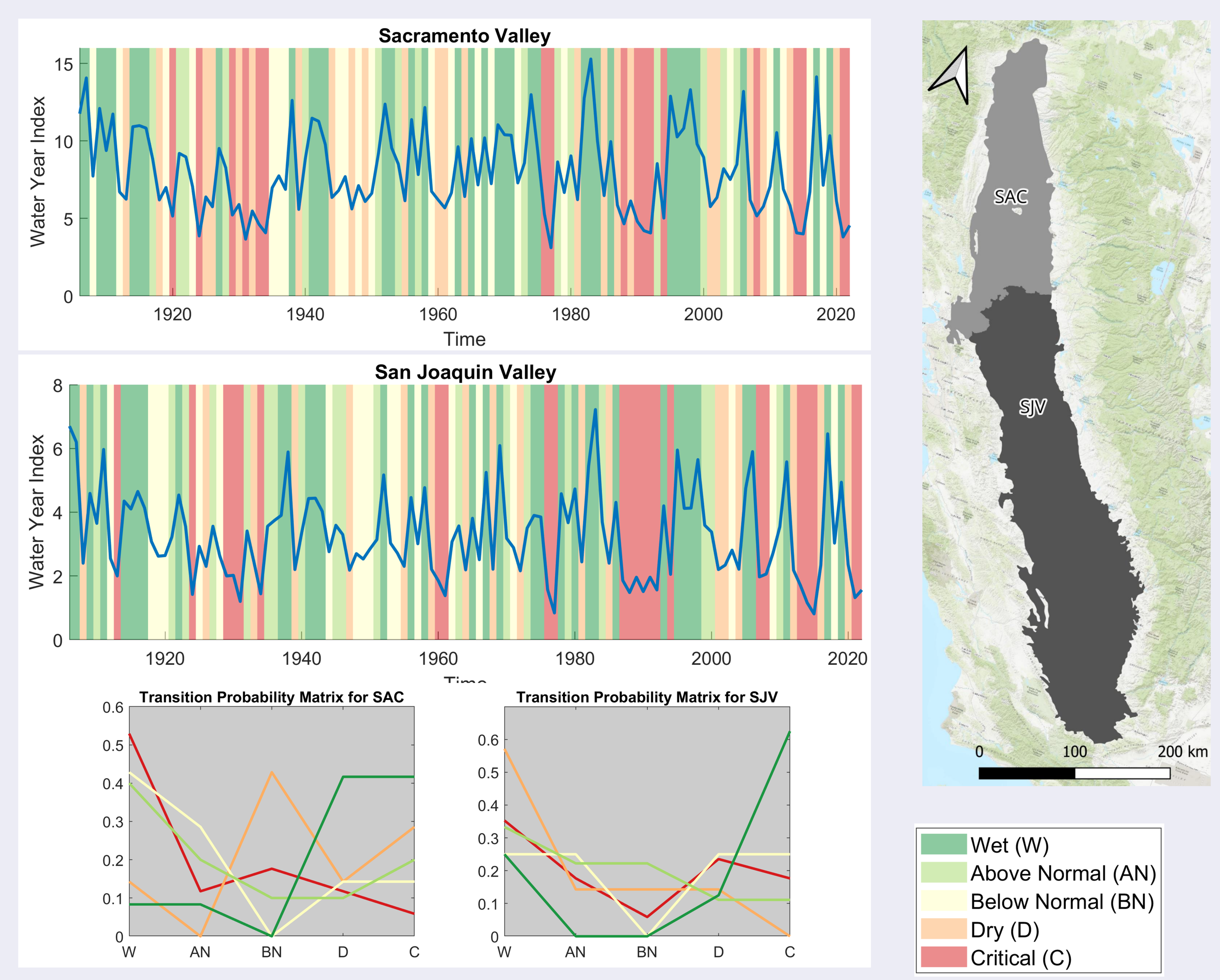
- **California Central Valley Groundwater-Surface Water Model Coarse Grid (C2VSimCG)**
  Finite element model based on IWFM,
  1,392 elements with size ~13 km²,
  4 layers,
  Simulates from 1974 – 2015 on a monthly step

- **California Central Valley Groundwater-Surface Water Model Fine Grid (C2VSimFG)**
  Finite element model based on IWFM,
  32,537 elements with size 2.6-7.7 km² ,
  4 layers
  Simulates from 1974 – 2015 on a monthly step



Transition Probability matrices in Central Valley

- Due to large extent of Central Valley (CV) basin and the difference in climate conditions between north and south CV, the area is divided into two subregions: i) Sacramento Valley (SAC) and ii) San Joaquin Valley (SJV).
- We calculate the transition probabilities between climate groups based on the Water Year Hydrologic Classification Indices.



Particle Tracking Simulation setup

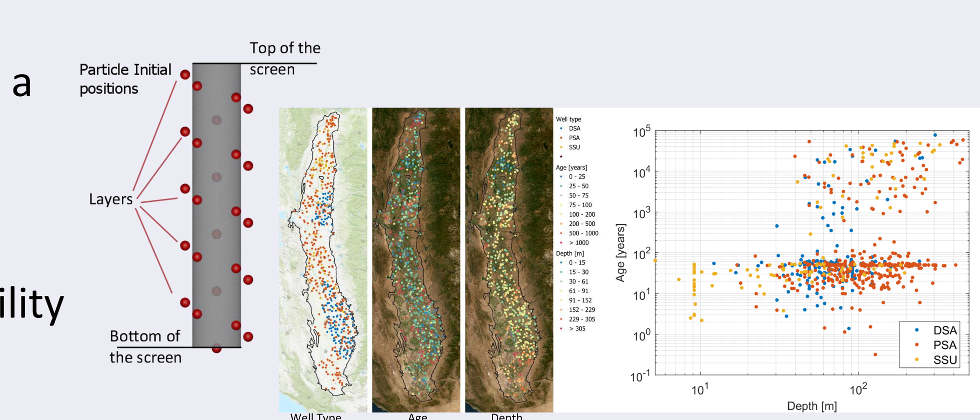
- C2VSim models consists of 504 monthly time steps
- The transient velocity field was grouped into 4 periods and 5 climate groups

	W	AN	BN	D	C
Months	15	5	2	6	14
Seasons	45	15	6	18	42

Algorithm
1. Start with an initial water year type and period.
2. Pick randomly a velocity state from the velocity pool and take a step.
3. Repeat 2 for one water year.
4. Pick another water year type based on the transition probability matrices.

- We selected 625 wells that were used by Faulkner et al., 2023
  - 364 Public Supply wells (PSA)
  - 153 Domestic Supply wells (DSA)
  - 108 Secondary Sites (SSU)

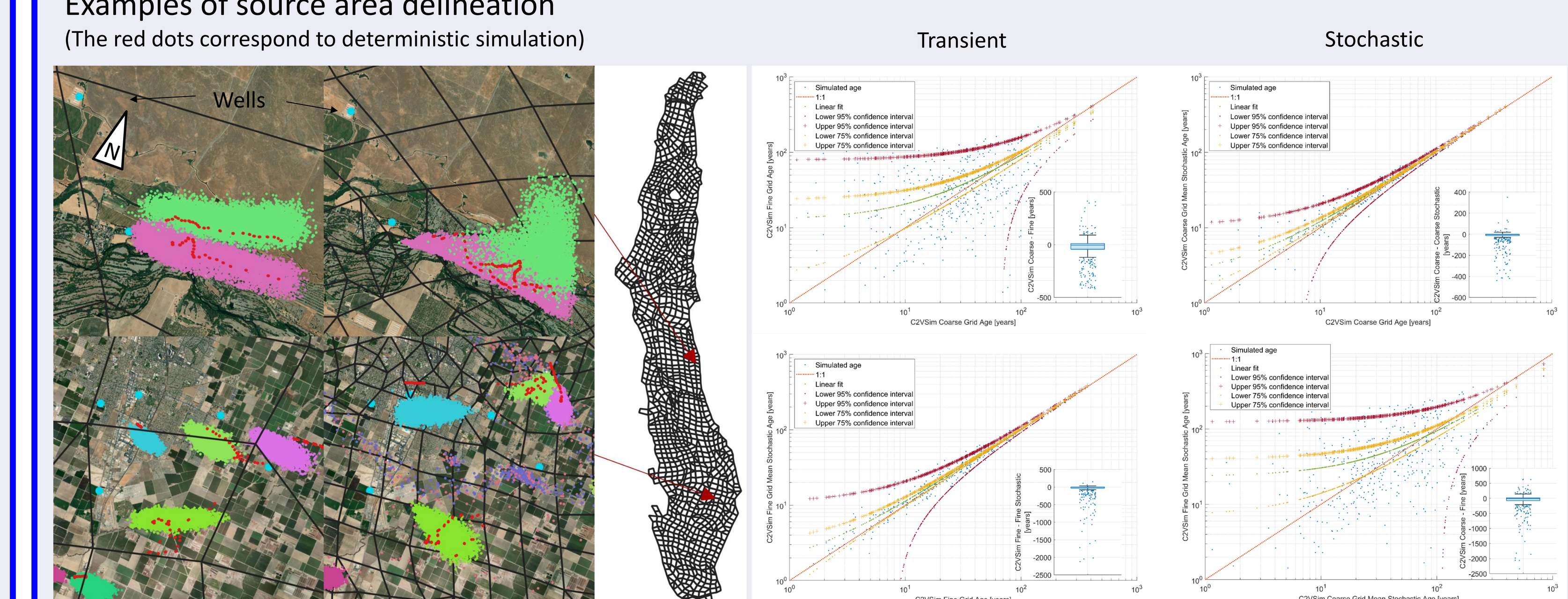
- For each well we release 100 particles distributed in along the well screen.
- We run 100 realizations.
- The transient Velocity field was grouped into 4 periods (seasons) and 5 climate groups.

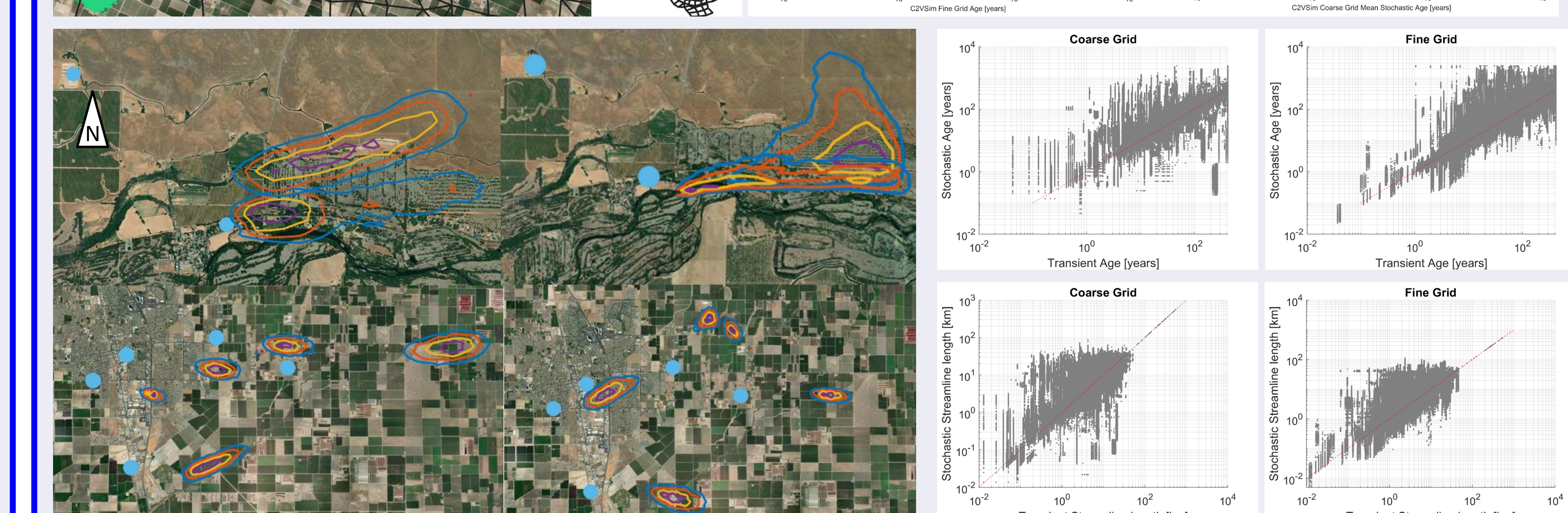


Results

- Comparison between stochastic and transient deterministic simulation

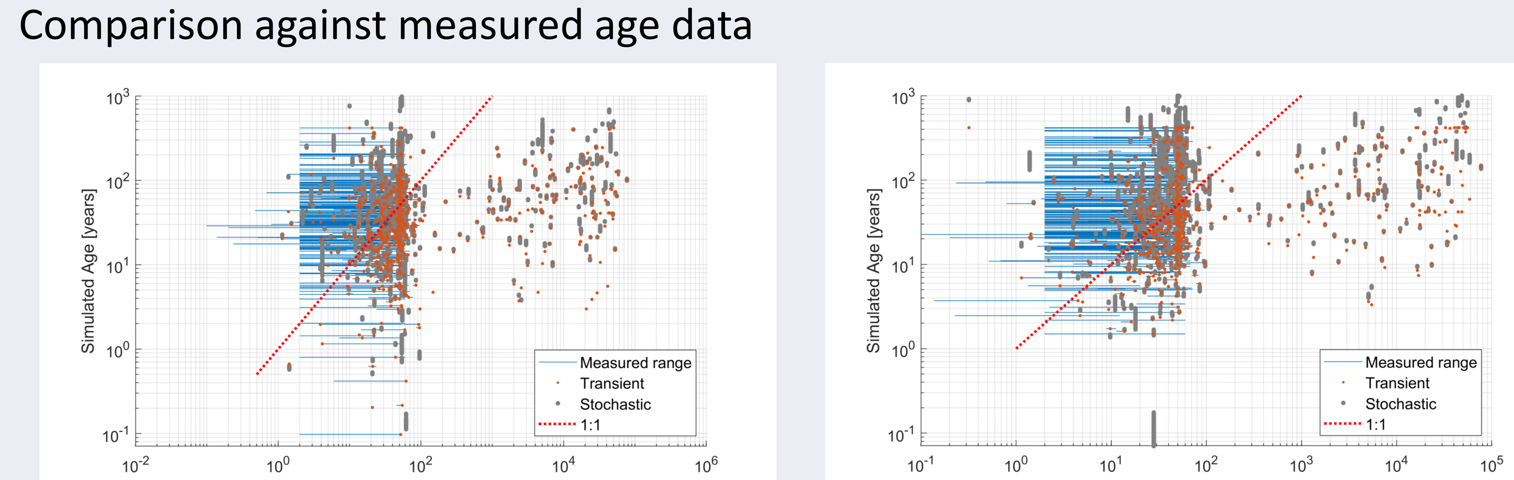
Examples of source area delineation
(The red dots correspond to deterministic simulation)





Per streamline comparison

- Comparison against measured age data



Conclusions – Next steps

- We developed a stochastic framework that takes advantage of large-scale transient groundwater simulations and allows an improved delineation of well capture zones.
- The approach can be used with very coarse models and produces results similar to a model that has significantly smaller elements.
- Our method can be used for probabilistic capture zone delineation under different climate conditions.
- It can be used with many different simulation frameworks, Finite elements, Finite differences, adaptive meshes, mesh free etc.
- Its open source and available from.
  https://github.com/giorgk/ichnos

For updates:
https://gwt.ucdavis.edu

References
1) Faulkner, K. E., Jurgens, B. C., Voss, S. A., Dupuy, D. I., & Levy, Z. F. (2023). Modeling the dynamic penetration depth of post-1950s water in unconfined aquifers using environmental tracers: Central Valley, California. Journal of Hydrology, 616. https://doi.org/10.1016/j.jhydrol.2022.128818

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