Anthropogenic Basin Closure and Groundwater SALinization (ABCSAL): An Unrecognized Threat to Water Quality Sustainability

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1. ABSTRACT

Global food systems rely on irrigated agriculture, and most of these systems depend on fresh sources of groundwater. In this study, we demonstrate that groundwater development, even without overdraft, can transform a fresh, open basin into an evaporation dominated, closed-basin system, such that most of the groundwater, rather than exiting via stream baseflow and lateral subsurface flow, exits predominantly by evapotranspiration from irrigated lands. In these newly closed hydrologic basins, just as in other closed basins, groundwater salinization is inevitable because dissolved solids cannot escape. We first provide a conceptual model of this process, called **A**nthropogenic **B**asin **C**losure and groundwater **SAL**inization (**ABCSAL**). Next, we introduce a mixing cell solute transport model to calculate the timescales under which salinization threatens groundwater quality in California's Tulare Lake Basin, and compute the water and salt budgets across these timescales. Results indicate that under modern water management practices in the Tulare Lake Basin, shallow aquifers (46 m deep) exceed maximum contaminant levels for total dissolved solids on decadal time scales, and intermediate (163 m), and deep aquifers (228 m) are impacted within two to three centuries, posing threats to water supplies for drinking water and irrigation, and thus, crop yield. Hence, ABCSAL resulting from groundwater development in agricultural regions worldwide constitutes a largely unrecognized constraint on groundwater sustainable yield, and raises a serious challenge to global groundwater quality sustainability, even where water levels are stable.

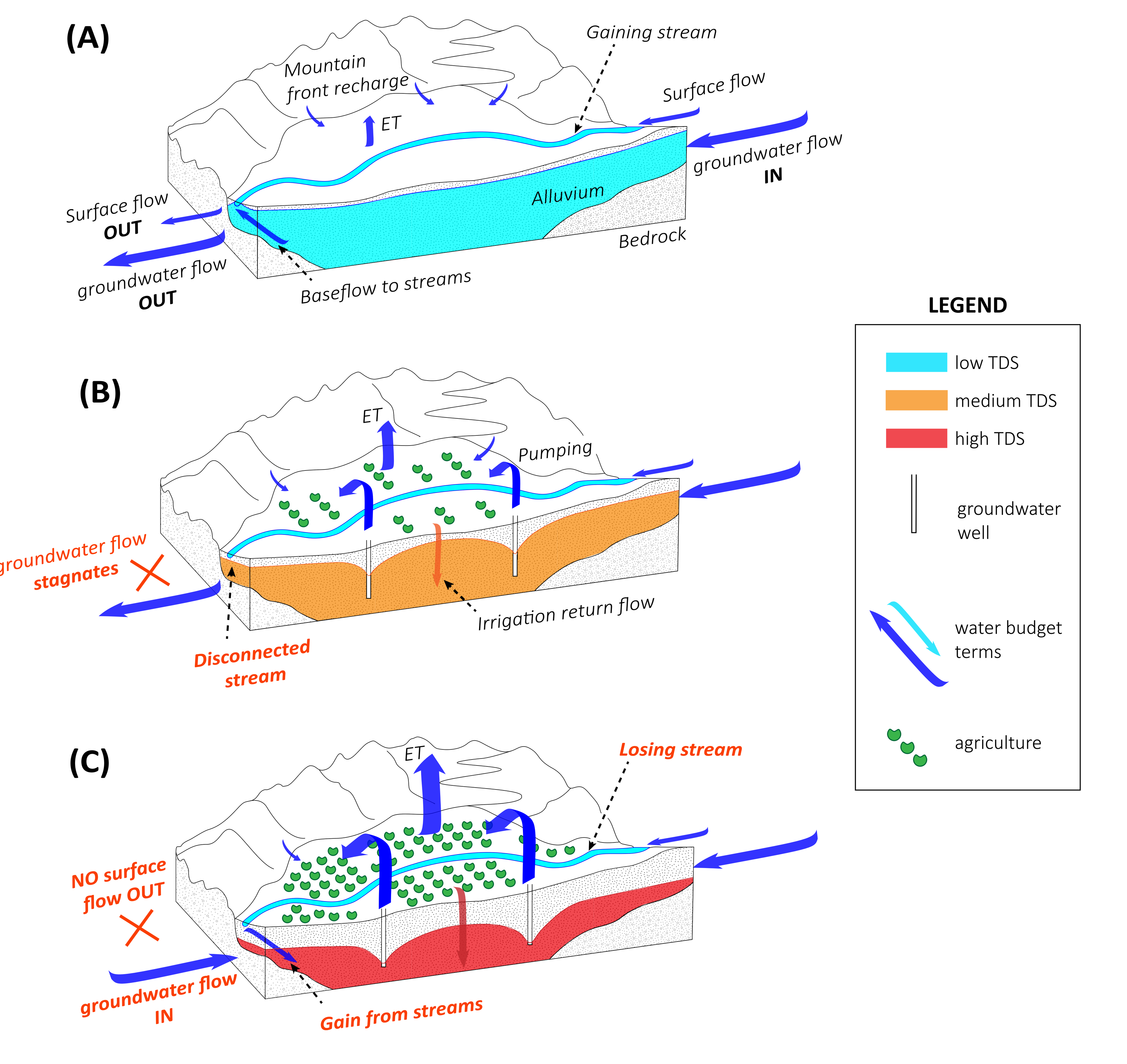

*Figure 1: Conceptual model of ABCSAL. **(A)** Open basin, pre-groundwater development: surface and groundwater systems connect. Groundwater discharges dissolved solids into surface water which exits the basin. Groundwater at this stage is predominantly fresh (e.g., < 1,000 mg/L). **(B)** Partial basin closure: groundwater pumping causes reduction or elimination of baseflow to streams. Pumped groundwater returns to the basin via irrigation return flow. Dissolved solids begin to accumulate in shallow groundwater. **(C)** Closed basin: lower groundwater levels cause subsurface inflow to drain adjacent basins. Streams lose to groundwater. Water primarily exits via evapotranspiration (ET), which further concentrates dissolved solids in groundwater. Salts migrate into the production zone of the aquifer, driven by vertical hydraulic gradients from recharge and pumping.*

2. METHODS

2.1 Study Site

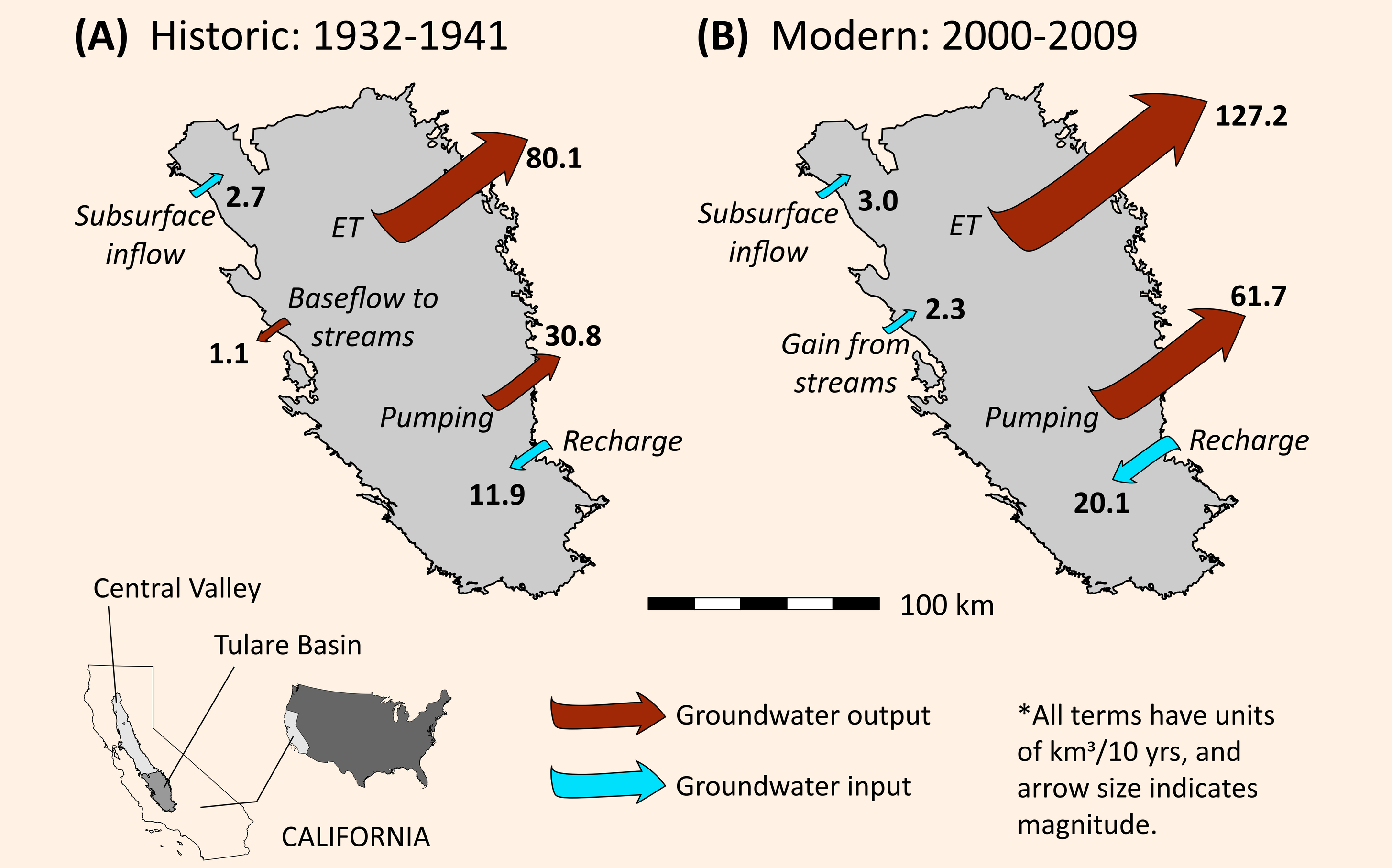

*Figure 2: The Tulare Lake Basin (TLB) overlies an agriculturally intensive sedimentary aquifer in the southern third of California's Central Valley. Selected decadal hydrologic year water budget terms derived from C2VSim [1] at **(A)** early-groundwater-development and **(B)** post-groundwater-development timescales in the TLB show significant changes. Notably, gaining streams transition to losing streams, and increases are observed in pumping, evapotranspiration (ET), and recharge. All terms are aggregated at the scale of the TLB, except for subsurface inflow, calculated at the northern TLB boundary.*

2.2 Mixing Cell Model

We calculate the basin salt balance based on the estimated water budget (C2VSim) and salt loads using a mixing cell model approach [2-6].

Given the predominance of vertical downward flow at the aquifer system scale, we represent the TLB as a one-dimensional, vertical column of discrete control volumes (cells). Each cell consists of a fraction ***f*** of aquifer material (i.e., sands and gravels) with porosity ***η***. Flows and rock-water interactions in non-aquifer material (i.e., silts and clays) of proportion 1- ***f*** are neglected.

The concentration of cell ***k*** is a balance of initial mass (***m***), influx (***m^in***), efflux (***m^out***), and rock-water interactions (***ρV***), normalized by cell volume (***Vfη***):

$$C_{k+1} = \frac{m_k + m_k^{in} - m_k^{out} + \rho V}{V f \eta} \qquad (1)$$

ρ is a zero order source term proportional to the slope of the TDS-volume profile, inferred from the depth to the base of fresh water in the TLB [7-8]. To turn rock-water interactions off, we set ***ρ*** = 0.

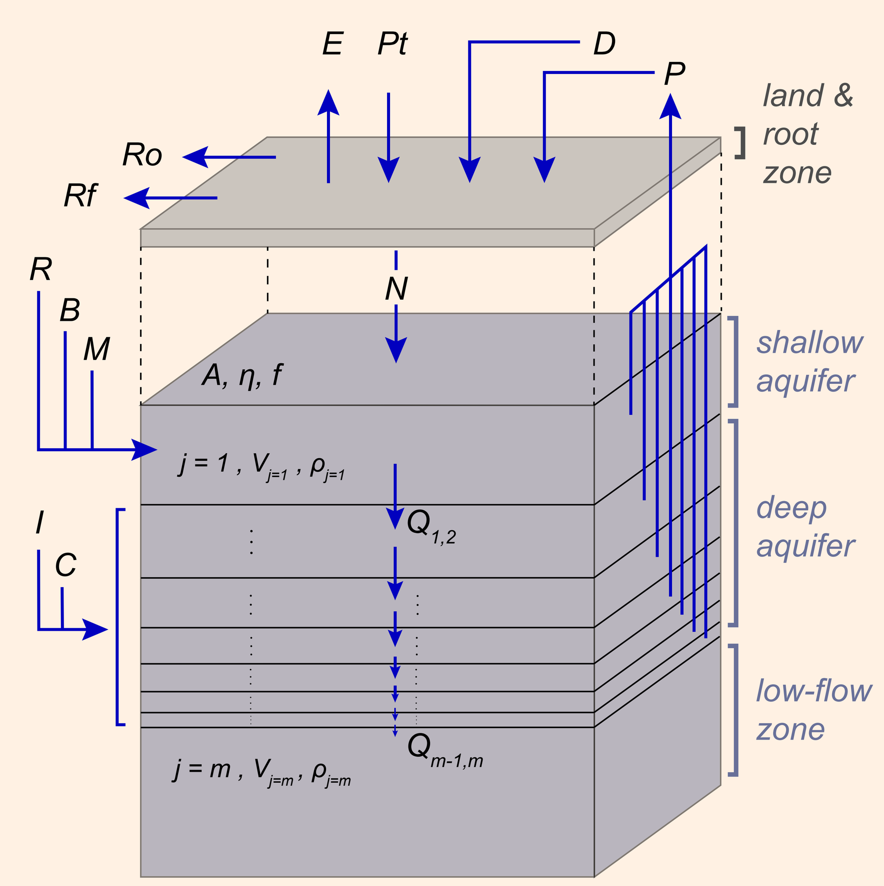

*Figure 3: Conceptual land and root zone model and groundwater mixing cell model with surface area **A**, porosity **η**, aquifer fraction **f**, and **m** layers, each with a different volume **V**. The TDS in layer **j** is described in Equation 1. The land and root budget accounts for pumping (**P**), surface water diversions (**D**), precipitation (**Pt**), evapotranspiration (**E**), runoff (**Ro**), return flow (**Rf**), and net deep percolation (**N**). **N** enters the top of the mixing model along with recharge from streams, lakes, and watersheds (**R**), boundary inflow from mountain front recharge (**B**), and managed aquifer recharge (**M**). Internal fluxes come from subsurface inflow from the north (**I**) and subsidence flow (**C**). Pumping (**P**) occurs in all aquifer layers.*

3. RESULTS

3.1 Salt budget

Surface water diversions add 1.6 Metric Mtons salt / year. Pumped groundwater adds 2.6- 5.7 times more salt, depending on the time frame considered and whether or not rock water interactions are included. As salt accumulates in the aquifer due to basin closure, pumped water contains more salt.

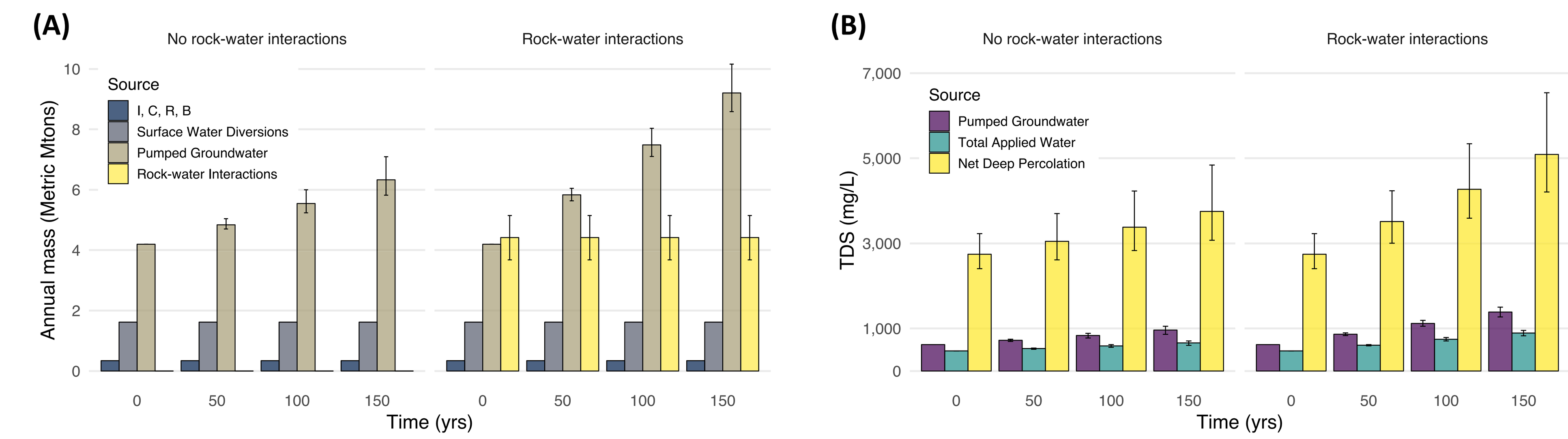

*Figure 4: **(A)** Annual mass flux by source. Pumped groundwater contributes more TDS than surface water diversions, and any other water budget term combined (represented by their symbol: **I, C, R, B**). **(B)** TDS of **pumped groundwater** is diluted when mixed with imported surface water, which forms **total applied water**. Evapotranspiration concentrates total applied water, which enters groundwater as **net deep percolation**. The height of each column represents the 1,000 scenario ensemble median result, and the width of error bars (if present) represent the interquartile range (IQR) of the ensemble distribution.*

3.2 Progression of groundwater salinization

Under no-overdraft (ΔS = 0) conditions in the TLB, shallow aquifers (depth = 46 m) exceed the freshwater concentration threshold (1,000 mg/L) on decadal time scales.

Intermediate (depth = 163 m) and deep aquifers (depth = 228 m) exceed 1,000 mg/L on century-long time scales.

When rock-water interactions are modeled, the resulting concentrations are amplified, and deep groundwater salinates faster.

In both scenarios, the slope of the TDS-depth profile (Figure 5) gradually inverts and amplifies, indicating that shallow groundwater becomes saltier than deep groundwater.

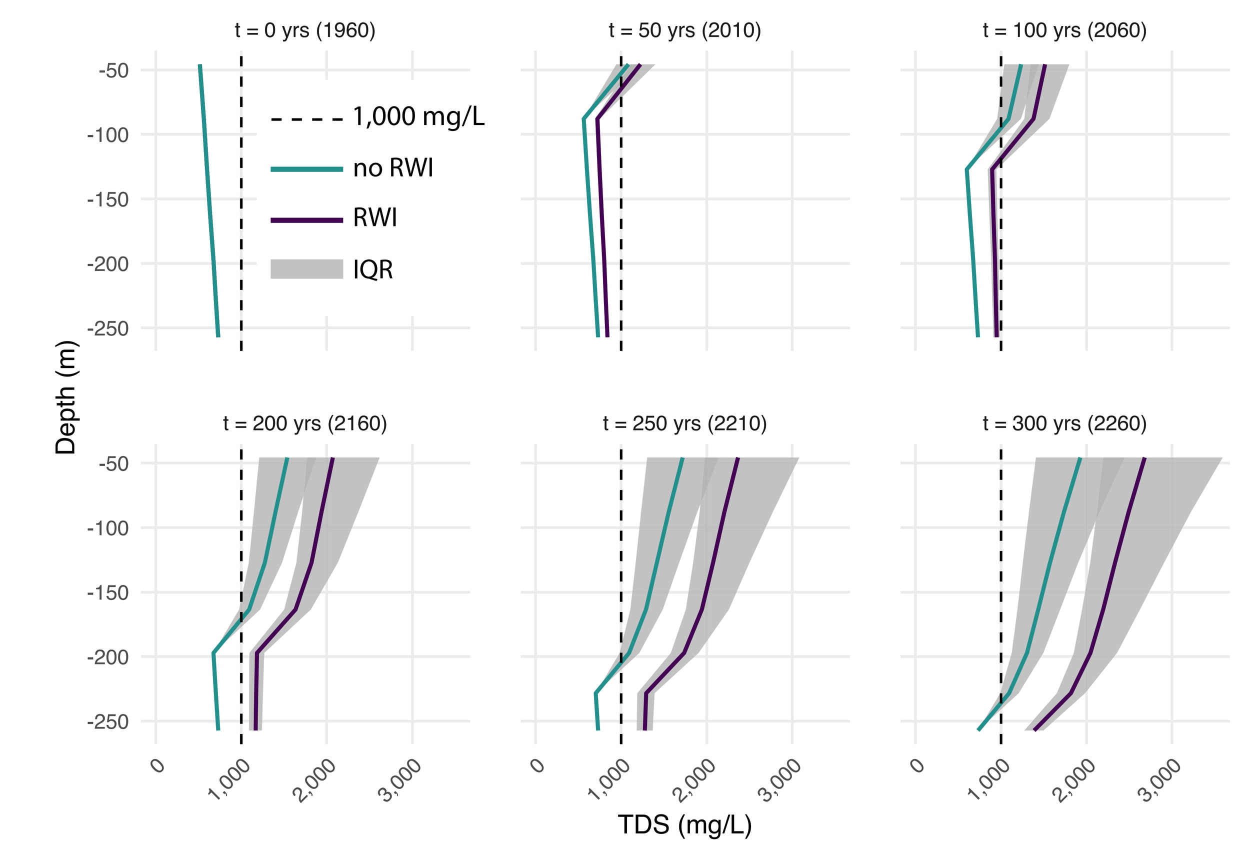

Figure 5: Progression of groundwater salinization ensemble results for two scenarios (with and without rock-water interactions). RWI stands for rock-water interactions. The blue and purple lines show the ensemble mean concentration for each set of ensemble runs, and the interquartile range (IQR) of the ensemble simulations is shown as a grey shaded area.

4. DISCUSSION

Measured TDS change from historic (1910) to modern (1993-2015) timescales in the TLB [9] agree with this study's modeled TDS changes (1960 to 2010). ABCSAL transport times are consistent with salt and nitrate particle transport simulations in detailed 3D heterogeneous alluvial aquifers [10-11].

Even limited groundwater development for irrigation may advance basin closure and salinization. A basin not in a state of groundwater overdraft still salinates if it is closed.

Basin re-operation to increase subsurface storage may "open" a basin and improve groundwater quality via clean recharge.

5. KEY POINTS

Although pumped groundwater is widely used for drinking water and irrigation, there is little recognition that pumping itself may close a basin, and gradually lead to the accumulation of dissolved solids, and hence worsening water quality.

We describe **A**nthropogenic **B**asin **C**losure and groundwater **SAL**inization (**ABCSAL**)-- a new form of regional groundwater quality degradation with significant constraints on groundwater sustainable yield -- and develop a method to estimate the rate of ongoing ABCSAL in a groundwater basin in California.

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