Poro-elastic modulation of aquifers explain seasonal and decadal geodetic signals in Southern Louisiana.

Pritom Sarma[1,2], Carolina Hurtado-Pulido[2], Einat Aharonov[1,3], Renaud Toussaint[4,2], Stanislav Parez[5], Eduardo Arzabala[2] & Cynthia Ebinger[2]

1) Institute of Earth Sciences, Hebrew University of Jerusalem, Israel.
2) Department of Earth and Environmental Sciences, Tulane University, New Orleans, US
3) PoreLab, The Njord Centre, Departments of Physics and Geosciences, University of Oslo, Norway.
4) Université de Strasbourg, CNRS, Institut de Physique du Globe de Strasbourg, Strasbourg, France.
5) Faculty of Science, Jan Evangelista Purkyně University in Ústí nad Labem, 400 96 Ústí nad Labem, Czech Republic.

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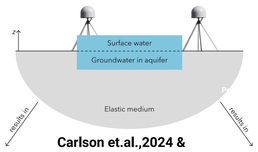
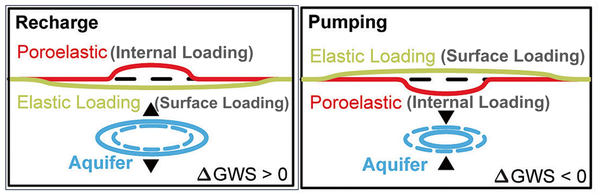
Abstract QR:

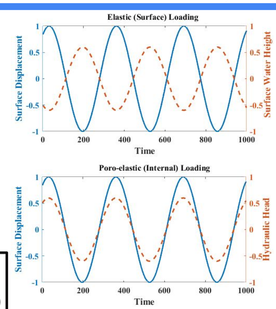
1) Background:

- Hydrological Loading can produce vertical deformation by either:
  a) **elastic (surface loading)**: weight of surface water
  b) **poroelastic (internal loading):** in/out flow of water into aquifers producing swelling/shrinking



Carlson et.al.,2024 & Larochelle et. al., 2022





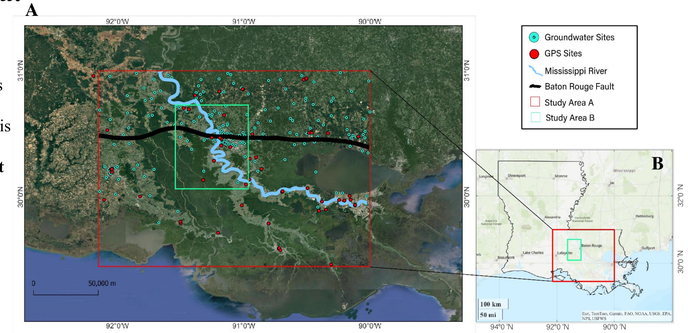
The correlation between geodetic **signal and hydraulic signal:**

- Poroelastic load: **positive correlation** w/ **hydraulic head.**
- **Surface load: negative correlation** w/ river height.

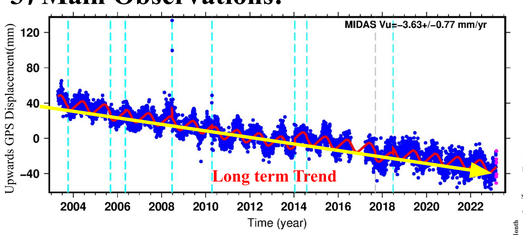
2) Study Area:

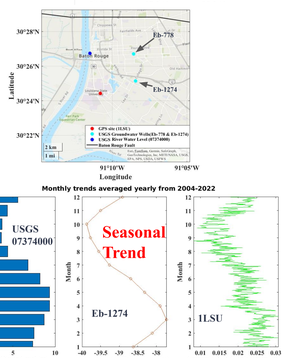
- **Coastal Southern Louisiana**: the **Mississippi river** is cross-cut by young **Normal Faults**. This study focus on the **Baton Rouge Fault Zone (TBRZ)** intersection w/ the river.

Data Source: **Nevada Geodetic Laboratory** and **USGS**
All data from 2018-2024



3) Main Observations:





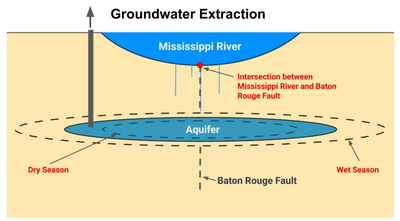
- The **geodetic signal** shows both a long-term **trend** and a **seasonal trend**, which is correlated with the **hydrological signal**(hydraulic head & river height)

4) Research Objectives

- To **theoretically model aquifer deformation** due to a) **long term** and b) **seasonal changes** in groundwater.
- To explain **long-term** and **seasonal** geodetic signals in **Southern Louisiana.**

5) Conceptual Model

- **A buried aquifer** (actually multiple aquifers), **is recharged seasonally by river water**. In addition, **long-term GW extraction**.
- **Vertical deformation at the earth surface u_z** is predicted by modeling the aquifer **as an oblate spheroid Eshelby Inclusion**.
- Parameters: **shear modulus (μ) Poisson's ratio (ν), fluid pressure (Δp).**



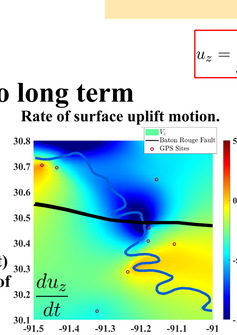
$$u_z = \int_0^z \frac{(1-2\nu)(2-\nu)}{2(1-\nu^2)\mu}\Delta p\, dz \quad \text{1)}$$

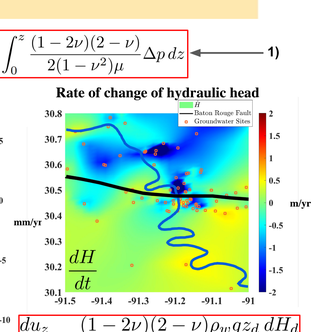
6) Surface uplift due to long term hydraulic loading.

- Assume **change in aquifer pressure is hydrostatic**, wrt the **change in hydraulic head (ΔH_d)**.

$$\Delta p = \rho_w g \Delta H_d$$

- Then **rate of surface uplift (du_z/dt)** will scale with the **rate of change of hydraulic head (dH/dt)** in an **aquifer at depth (z_d)**.



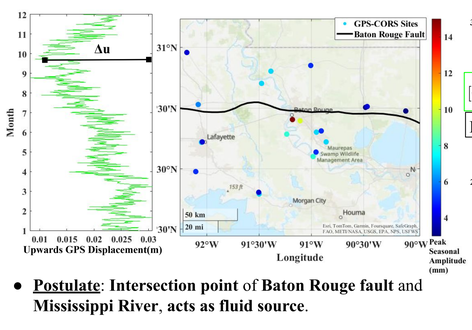


Data Source: **Nevada Geodetic Laboratory** and **USGS**
All data from 2018-2024

$$\frac{du_z}{dt} = \frac{(1-2\nu)(2-\nu)\rho_w g z_d}{(1-\nu^2)\mu}\frac{dH_d}{dt}$$

7) Seasonal Surface Uplift

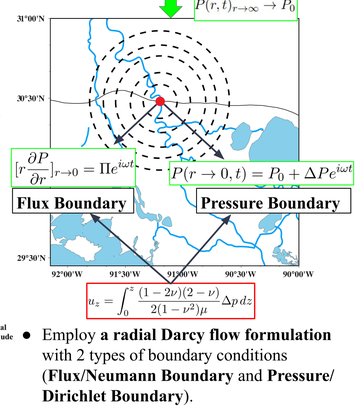
- **Amplitude of seasonal geodetic surface uplift (Δu)** shows **specific spatial distribution**:
- **Δu decays as function of distance from the intersection** of **the Baton Rouge fault** and **the Mississippi River**.



- **Postulate**: **Intersection point** of **Baton Rouge fault** and **Mississippi River**, **acts as fluid source**.

$$\frac{\partial P}{\partial t} = \alpha_z \frac{\partial^2 P}{\partial z^2} + \frac{\alpha_r}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P}{\partial r}\right)$$

$$P(r,t)_{r\to\infty} \to P_0$$



$$u_z = \int_0^z \frac{(1-2\nu)(2-\nu)}{2(1-\nu^2)\mu}\Delta p\, dz$$

- Employ **a radial Darcy flow formulation** with 2 types of boundary conditions (**Flux/Neumann Boundary** and **Pressure/ Dirichlet Boundary**).

8A) Results I: Seasonal surface uplift due to radial fluid migration in aquifer

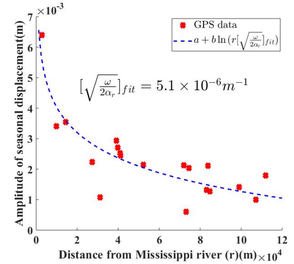
- The **approximate solutions, for both boundary conditions**, have **a radial decay of amplitude** as expected.
- But the **Neumann / Flux boundary** condition has the **best agreement** with the **spatial distribution of seasonal surface uplift.**

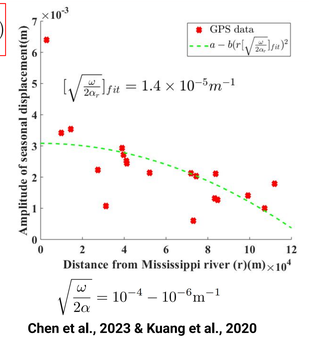
Dirichlet / Pressure Boundary Condition

$$u(r,t) \approx u_0 + \Delta u\cos(\omega t) - \frac{\Delta u\omega}{8\alpha}r^2\sin(\omega t)$$

Neumann / Flux Boundary Condition

$$u(r,t) \approx u_0 + \Delta u\cos(\omega t)\ln\left(\sqrt{\frac{w}{4\alpha}}r\right)$$





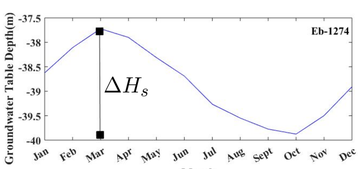
$$\sqrt{\frac{\omega}{2\alpha}} = 10^{-4} - 10^{-6}\mathrm{m}^{-1}$$

8B) Results II: Seasonal ground uplift near fluid source

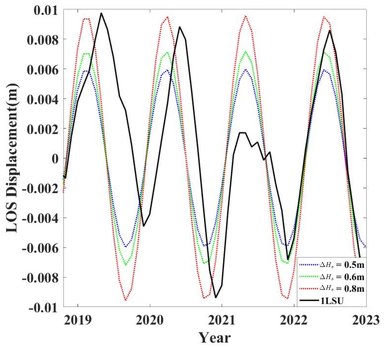
- Using **Newman B.C. & small r**
- **Model prediction**: **Ground uplift** depends on the **amplitude of seasonal hydraulic head variations (ΔH_s)** & **aquifer depth (z_d)**.

$$u \approx u_0 + \Gamma\cos(\omega t)$$

$$\Gamma = \frac{(1-2\nu)(2-\nu)\rho_w g z_d}{(1-\nu^2)\mu}\Delta H_s \log\left(\sqrt{\frac{\omega}{4\alpha}}r\right)$$



Chen et al., 2023 & Kuang et al., 2020



- Model prediction uses z_d = **500m** & **r=4 kms**,

9) Conclusions :

- **Poroelastic deformations** due to **changes in hydraulic loading** may control both **long-term** and **seasonal geodetic signals**.
- In **Southern Louisiana**, the intersection of **the Baton Rouge fault** and **the Mississippi river** serves **as a fluid source for buried aquifers**, producing max ground uplift there. **Ground uplift decays radially with distance the intersection.**
- The many **sub-parallel Pleistocene faults in Southern Louisiana** may, which intersect the **Mississippi river**, should be similarly **studied for such geodetic signals**.
- **Anthropogenic groundwater depletion** and **sea level rise** will **exacerbate the poroelastic modulation** of **vertical ground motion.**