Assessment of Agricultural Water Management in Punjab, India using Bayesian Methods

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Abstract

The success of the Green Revolution in Punjab, India (**Figure 1**) is threatened by a significant decline in water resources (**Figure 2**). The detailed data required to estimate future agricultural impacts on water supplies or develop sustainable water management practices is not readily available, therefore we use Bayesian methods to estimate hydrologic properties and irrigation requirements for an under-constrained mass balance model. Using the known values of precipitation, total canal water delivery, crop yield, and water table elevation, we present a method using a Markov chain Monte Carlo (MCMC) algorithm to solve the value distribution for each unknown parameter in a conceptual mass balance model. Model results are used to test three water management strategies, which show that replacement of rice with pulses may be sufficient to stop water table decline. This computational method can be applied in data-scarce regions across the world, where integrated water resource management is required to resolve competition between food security and available resources.

Figure 1. Map showing the location of Punjab in northwestern India, and the districts of Punjab. The three districts analyzed in the study: Gurdaspur, Jalandhar, and Sangrur, are shown in gray.

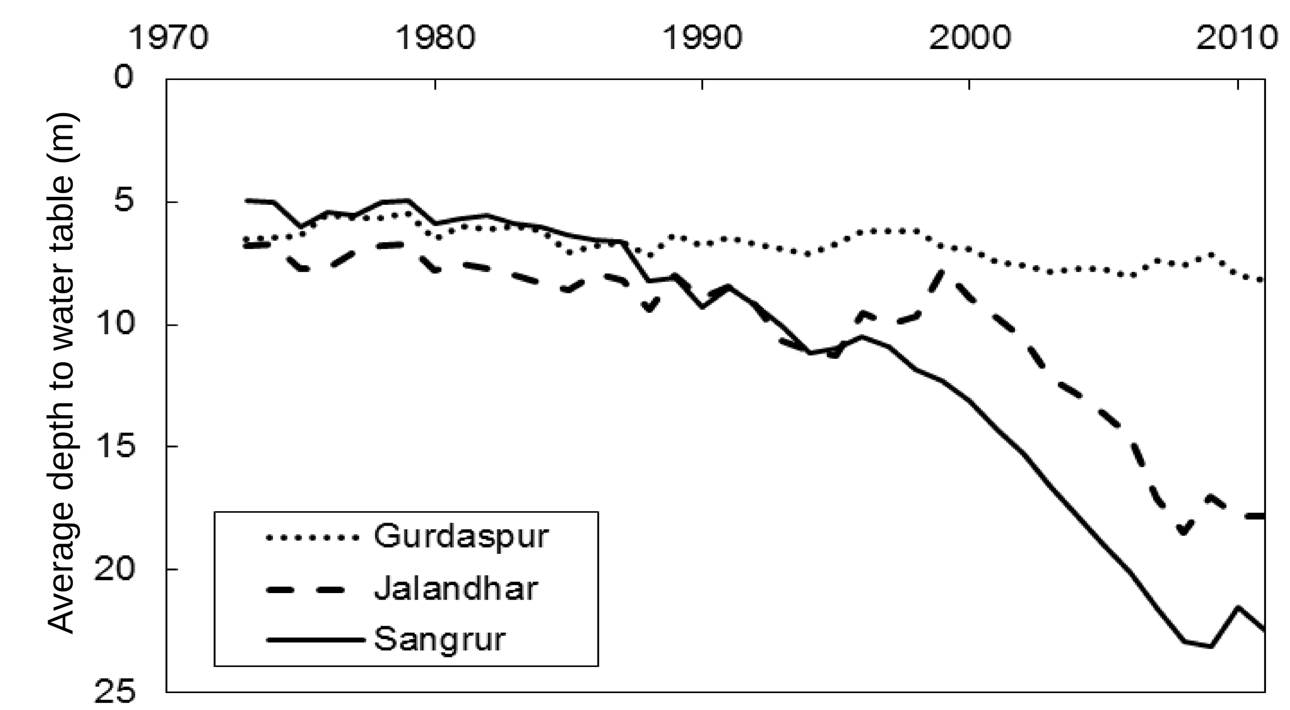

Figure 2. Annual average water table elevation between 1973 and 2011.

Key Points

1. We estimate macro-scale parameters in a data scarce region using MCMC methods
2. Lateral groundwater inflow is required to balance observations with reasonable recharge values
3. In Gurdaspur and Jalandhar, replacing high water demand rice with traditionally grown pulses will stabilize the declining water table
4. Irrigation management is beneficial, but must be coupled with other water conservation or recharge enhancement methods to halt water table decline

Statistical Modeling

We use a Bayesian method to estimate parameters in the under-constrained hydrologic mass balance for each study district in Punjab with following groundwater mass balance equation:

$$R + L - ET - X - \Delta S = 0$$

where R is recharge from precipitation, L is canal leakage, ET is evapotranspiration, X is total groundwater pumped for irrigation, and ΔS is change in groundwater storage which includes lateral groundwater flow in and out of the district. The study includes irrigation for the eight major crops in Punjab, accounting for >90% of the gross cropped area.

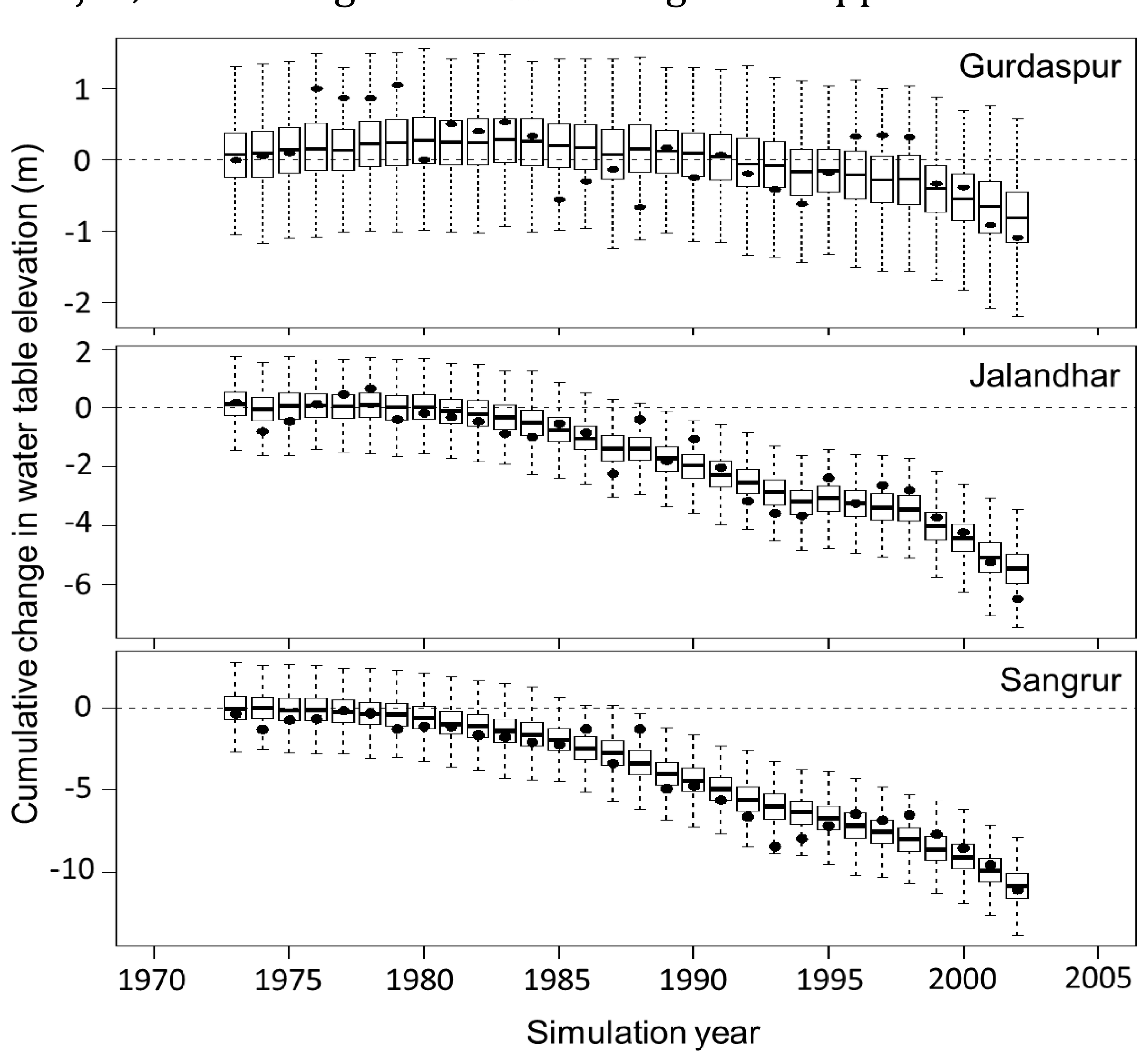

Figure 3. Observed and modeled water table elevations for Jalandhar, Sangrur, and Gurdaspur districts. The boxplots show the calculated distribution of water table elevations for each simulated year, and the filled circles represent observations.

The coefficients for precipitation recharge (β), canal leakage (ε), net groundwater influx (γ), and volumes of pumped irrigation (x), were estimated using an MCMC method. For each individual district (Gurdaspur, Jalandhar, and Sangrur) we use the MCMC method to simulate the complete posterior distribution of values for each unknown model parameter ($\beta, \varepsilon, \gamma, x$). Uniform prior distributions based on physical properties constrain acceptable values for each unknown parameter.

The two governing equations of the MCMC algorithm are shown below, which describe the relationship between the parameters of the mass balance equation and two known values, change in water table elevation (ΔGW) and observed annual yield (Y_i), respectively:

$$\Delta GW(t) \sim N\left(\gamma\left(\frac{\beta P(t)A_T(t) + \varepsilon B(t) - \sum_{i=1}^{n}(x_i(t)A_i(t))}{S_y A_T}\right), \tau_{gw}^2\right)$$

$$Y_i(t) \sim N\left(\frac{x_i(t)}{CWR_i(t)} Y_i^{max}(t), \tau_y^2\right)$$

P: Annual precipitation
B: Total canal release
A_i: Area of crop i
S_y: Specific yield
A_T: Total area
CWR: Crop water requirement

The model parameters were fit using observed groundwater and yield data. Annual groundwater elevation changes were summed to give the cumulative water table elevation change for each simulation year (**Figure 3**). The three study districts vary in climate and cropping patterns, in addition to geologic properties and density of surface canals – as such, the coefficient distributions vary across districts (**Figure 4**).

Discussion of value distributions

β
- Large range, perhaps need to use more frequent precip data

ε
- Reasonable values given Gurdaspur has major canal branch and Sangrur is far from the canal headwaters
- ~20 to 30% of total surface recharge

γ
- Greatest net inflow near recharge region and in driest district
- Similar to recharge from precipitation

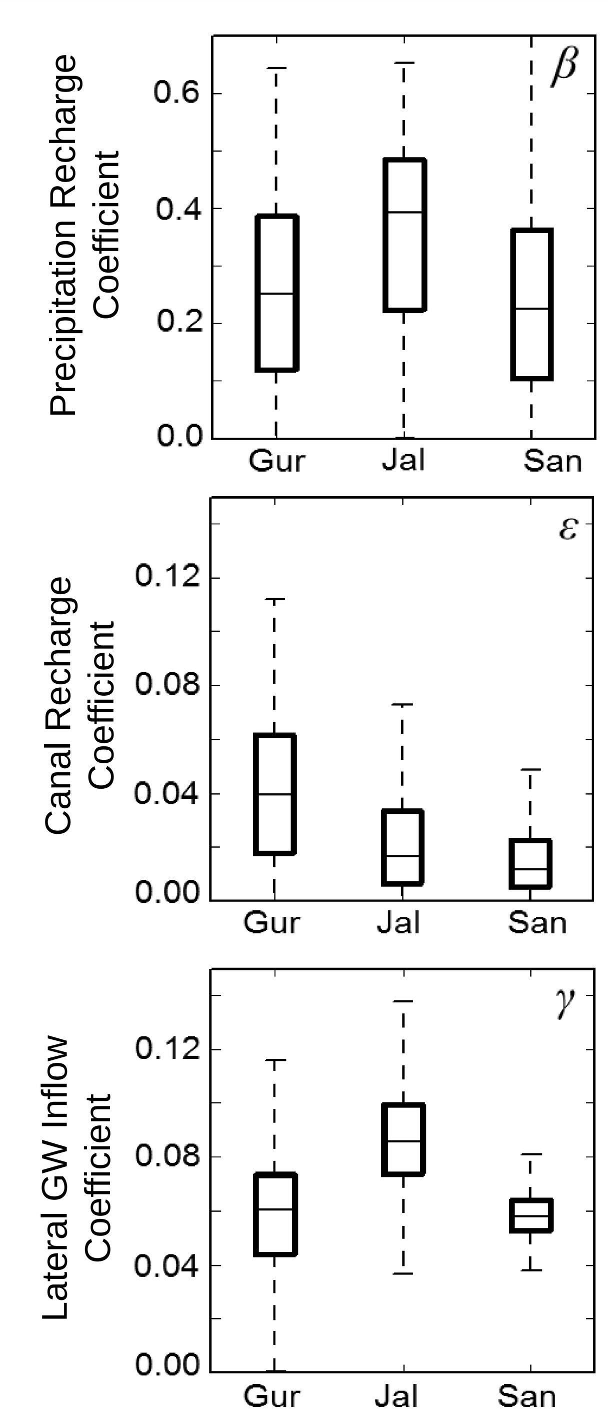

Figure 4. Boxplots show the 1st and 3rd quartiles of each distribution of coefficients for precipitation recharge (β), canal seepage (ε), and lateral groundwater flow (γ) for Gurdaspur, Jalandhar, and Sangrur districts. For γ, 1=net inflow of zero, <1 means positive net inflow.

Management Scenario Analysis

Model results were used to test three water management strategies:
(1) continue current practices
(2) reduce irrigation requirements by 30% (e.g. use soil moisture sensors)
(3) replace high water consuming rice with low water consuming pulses

Results indicate that replacement of rice with pulses may be sufficient to stop water table decline in two of the three districts (**Figure 5**). The relatively aggressive irrigation reduction scenario (2) would need to be coupled with crop changes in order to stabilize the water table. Results of this study can be used to inform and motivate the management changes required to ensure sustainable agricultural production in Punjab.

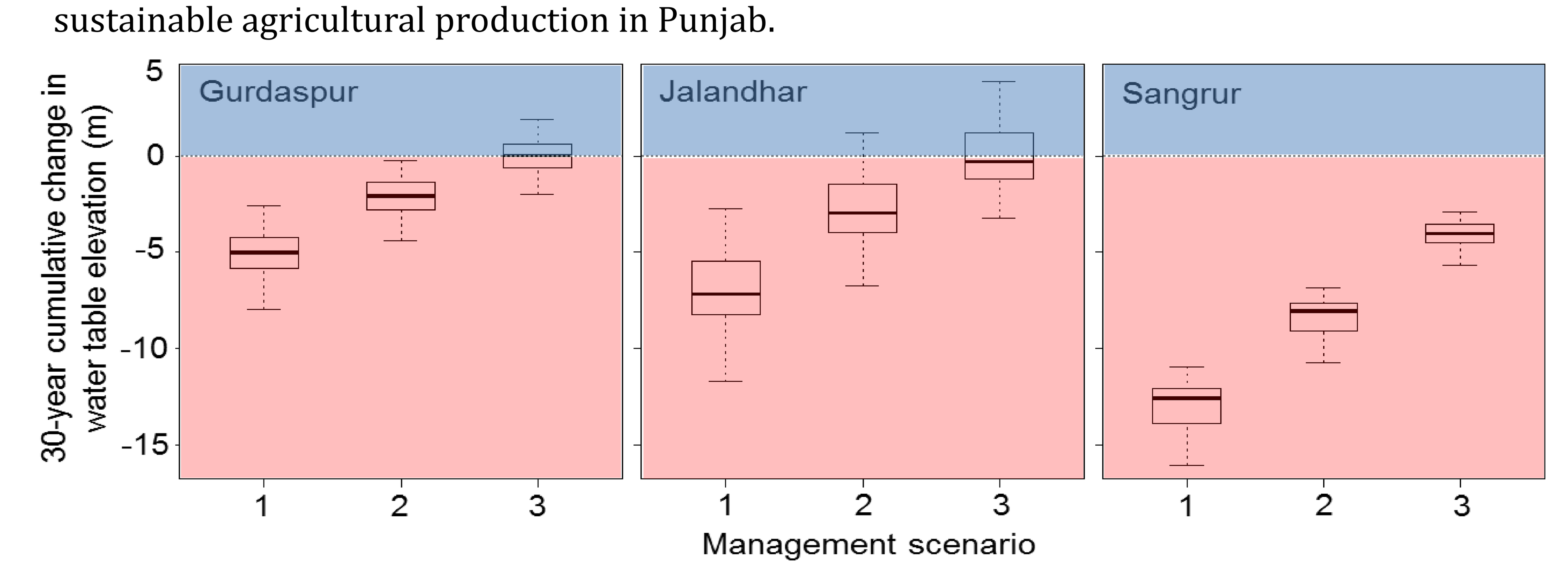

Figure 5. Simulated 30-year cumulative water table response to three management strategies in Gurdaspur, Jalandhar, and Sangrur. Strategy 1 represents continuing current practices, Strategy 2 represents 30% reduction in irrigation consumption, and Strategy 3 represents replacement of rice with pulse crops.

Acknowledgements

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