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Developing a Regional Hydro-Economic Model to Simulate Human-Crop-Stream-Aquifer Dynamics in the Ogallala Aquifer Region

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Colorado State University

Introduction

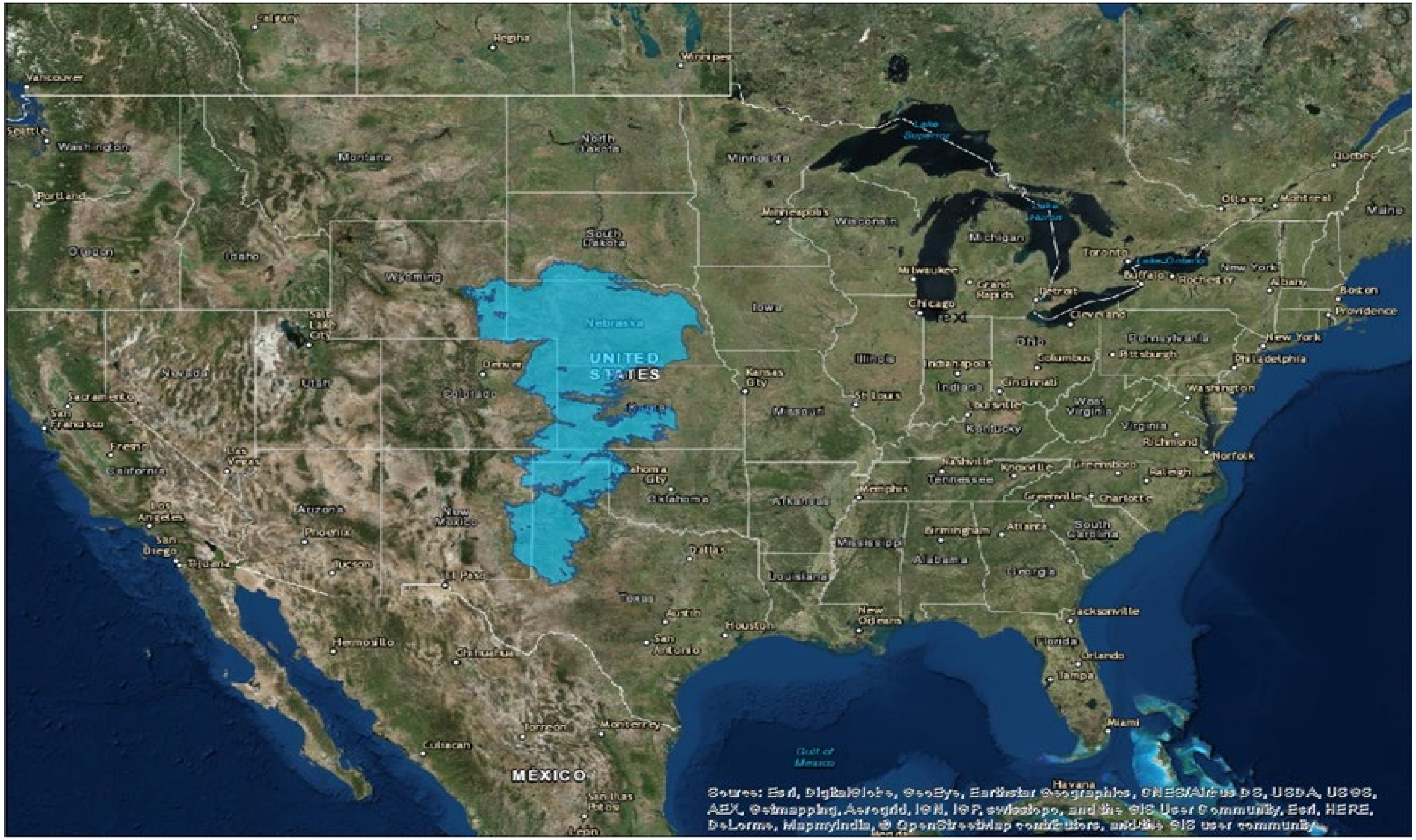
Methods

Results

Summary

❑ Ogallala Aquifer (High Plains Aquifer)

- Underlies approximately 452,600 km^2 of the High Plains Region of the U.S. (parts of CO, KS, NE, NM, OK, SD, TX, and WY)
- The largest freshwater aquifer in the world
- Main source of agricultural and public water for the Ogallala Aquifer Region (OAR)



Introduction

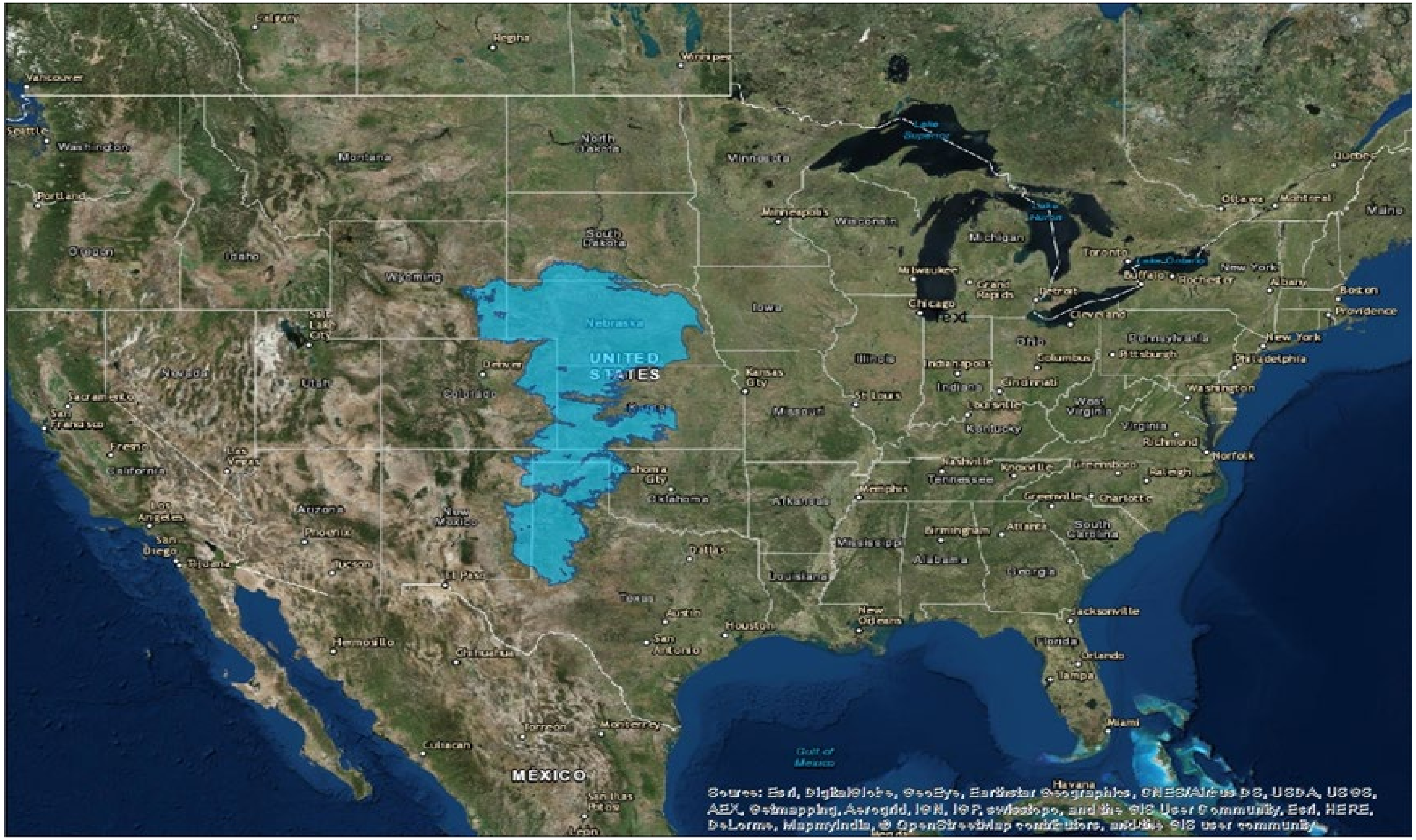
Methods

Results

Summary

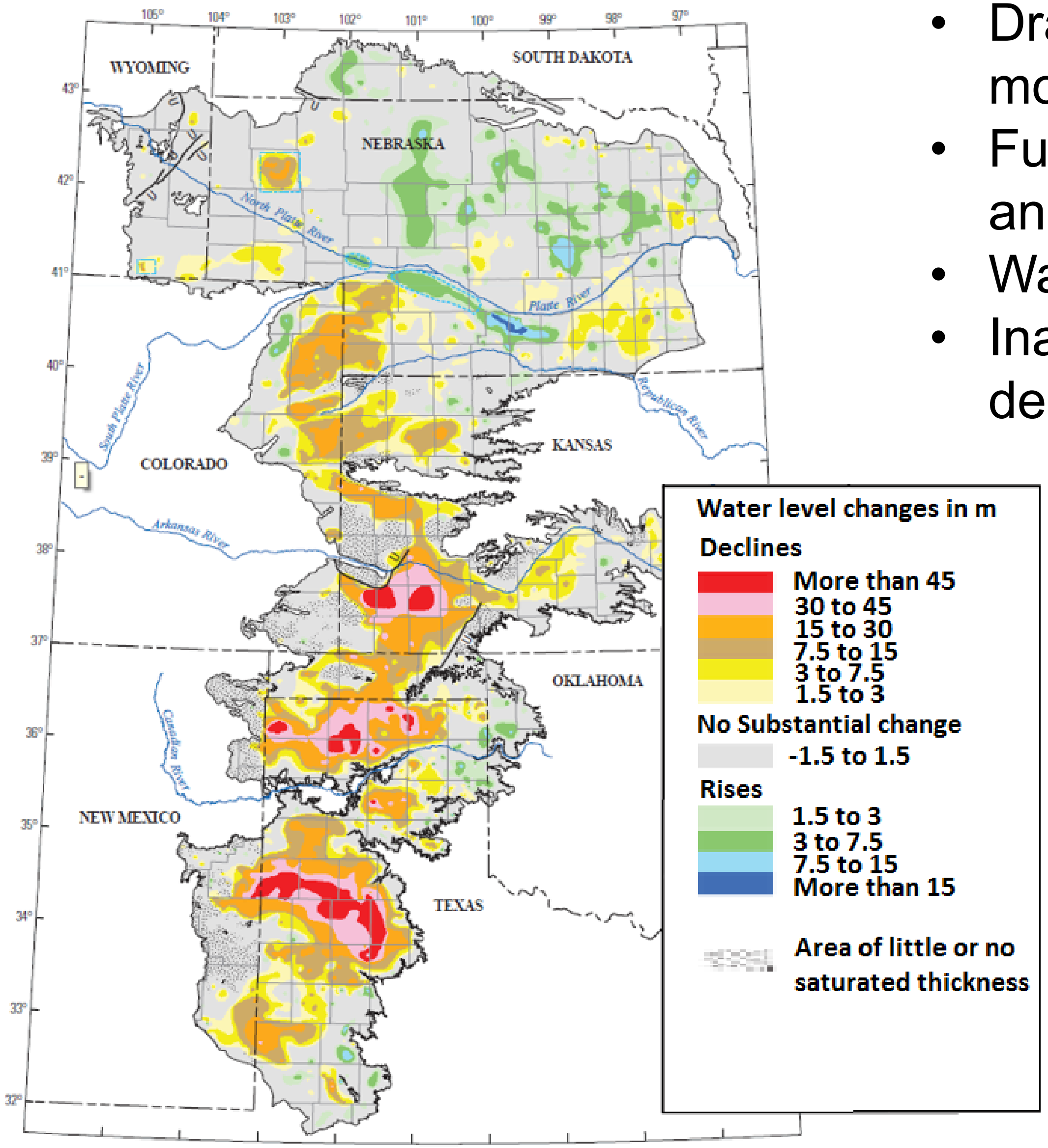
❑ Ogallala Aquifer (High Plains Aquifer)

- Significant groundwater development in OAR since the 1950s
- Accounts for approximately 30% of total crop and food production in U.S.
- More than 90% of the pumped water is used for irrigated agriculture
- Ogallala Aquifer is an exhaustible resource



❑ A National Issue

- Drastic water level declines in some of the most ag productive regions of OAR
- Future increase in drought severity, frequency, and persistence with climate change
- Water resources depletion in OAR
- Inadequate groundwater supply for the coming decades with current rates of extraction



Groundwater level changes
Predevelopment (about 1950) to 2013
(USGS Investigation Report 2014-5218)

❑ To Address This Issue

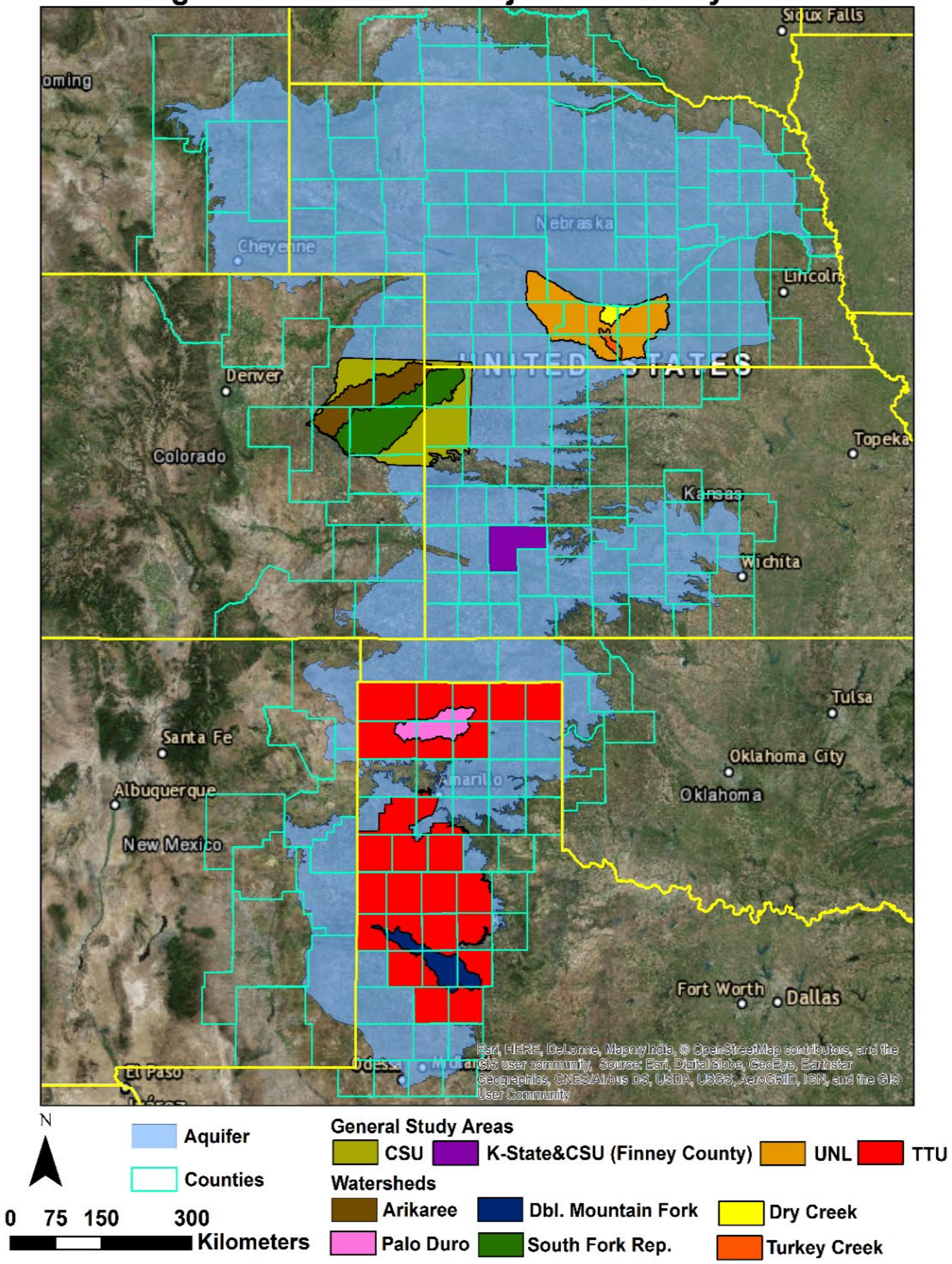
Introduction

Methods

Results

Summary

Ogallala Water CAP - Objective 1 Study Areas



- The Ogallala Water Coordinated Agriculture Project (OWCAP) was funded in 2016 by the National Institute of Food and Agriculture (NIFA), U.S. Department of Agriculture (USDA)

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USDA NIFA United States Department of Agriculture National Institute of Food and Agriculture

- Seeking a range of strategies to optimize groundwater use in OAR
- Integration of hydrologic, crop, soil, and climate models (1st objective of OWCAP)
- Creating a set of decision support tools for evaluation of management strategies and conservation policies

Our main goal is to address water resources depletion in OAR by constructing a regional hydro-economic model at the field level

- Introduction
- **Methods**
- Results
- Summary

❑ Hydro-economic Models

- Represent spatially distributed water resource systems, infrastructure, management options and economic values in an integrated manner
- Have an undeniable role in addressing agricultural water management problems
- One of the main components : Hydrologic models

Determine performance and reliability of outputs

- In many cases, hydrologic component fails to accurately simulate processes
- Employing already constructed hydrologic models that lack the spatial and temporal resolution to account for field scale agronomic and economic decisions

The main problems with previously developed hydro-economic models

- **We construct an integrated surface water-groundwater hydrologic model with the prospect of integration with field scale crop and economic models**

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Introduction

Methods

Results

Summary

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❑ Hydro-economic Models

Our hydro-economic model consists of 3 components:

- SWAT-MODFLOW Model (Coupled Surface-Subsurface Hydrology)
- DSSAT Model (Crop Growth Model)
- Economic Model

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Introduction

Methods

Results

Summary

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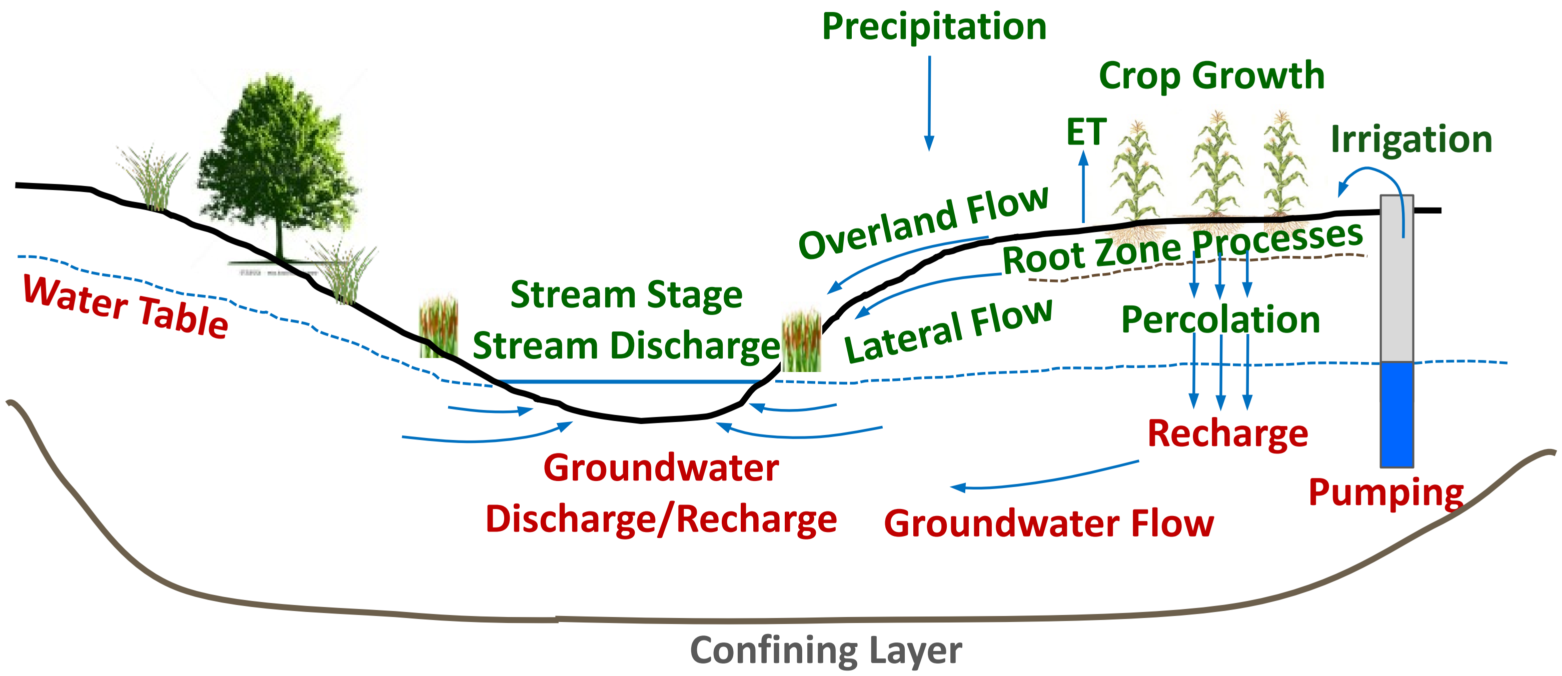
❑ SWAT-MODFLOW Model (Coupled Surface-Subsurface Hydrology)

- Leverages strengths of each separate model

  SWAT : **Overland** and **stream flow routing**

  MODFLOW : **groundwater flow** and **groundwater-surface water interactions**



SWAT components in green

MODFLOW components in red

In our hydro-economic model, irrigation demand and crop growth are modeled by DSSAT

❑ DSSAT Model (Crop Growth Model)

- Calculates **crop growth** and **irrigation demand** and simulates water and nutrient balance at a daily time step

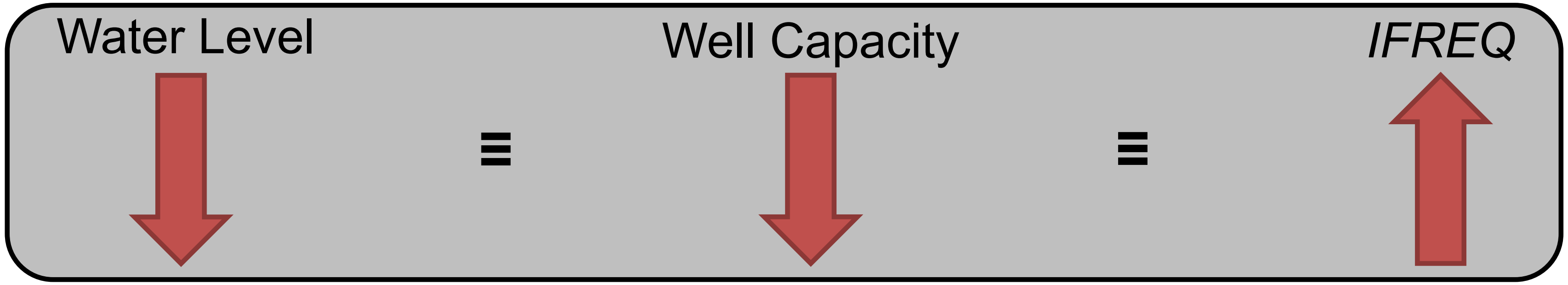
DSSAT
Decision Support System
for Agrotechnology Transfer

- Using different combinations of **Critical Plant Available Water (*PAWc*)** and **Irrigation Frequency (*IFREQ*)** to develop irrigation scenarios for a unit area (a representative hectare)

  PAWc is a threshold that triggers irrigation events
  IFREQ is the minimum time required to irrigate a cropland in each irrigation event

- Enables us to study impacts of reduced **well capacity** on irrigation and crop yield

  Well capacity (well yield) is the pumping rate that can be sustained throughout irrigation season



❑ Economic Model

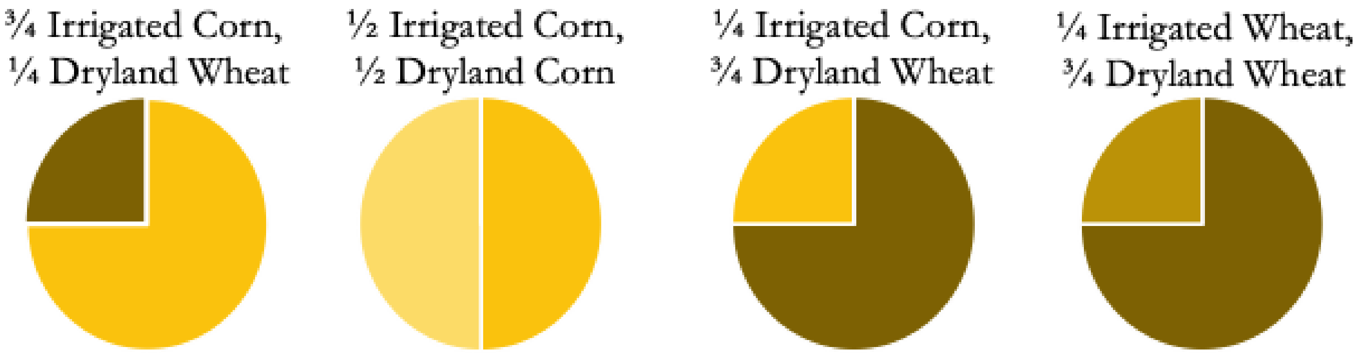
- A model of an **expected profit-maximizing producer**
- Considers different **irrigation decisions** available to producer to apply groundwater

  Crop choice – Acres of land allocated to each crop - *PAWc*

- Defines an objective function and utilizes DSSAT simulations to solve it

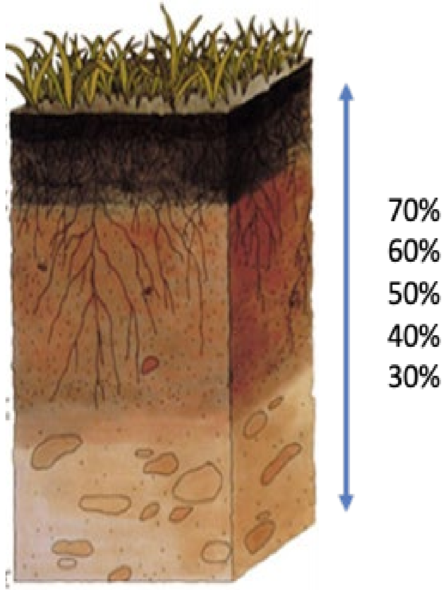
  Solution : a set of irrigation decisions maximizing expected profit

- Takes into account heterogeneity in soil type, climate, and well capacity



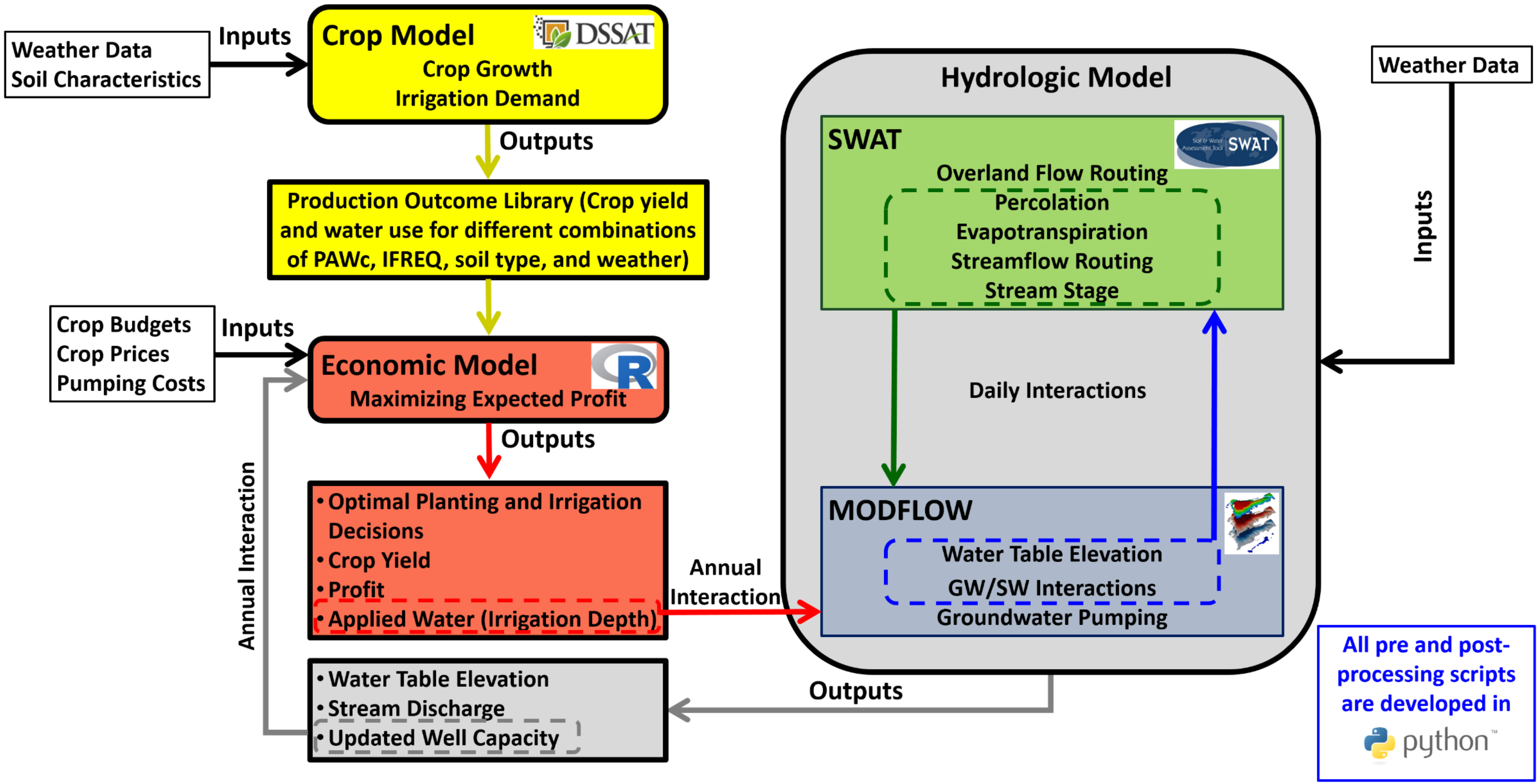
Crop and Acreage Choices

Decision making unit is a quarter circle (32.5 acres)



PAWc Choices
(% of plant available water)

❑ Hydro-economic Model Framework



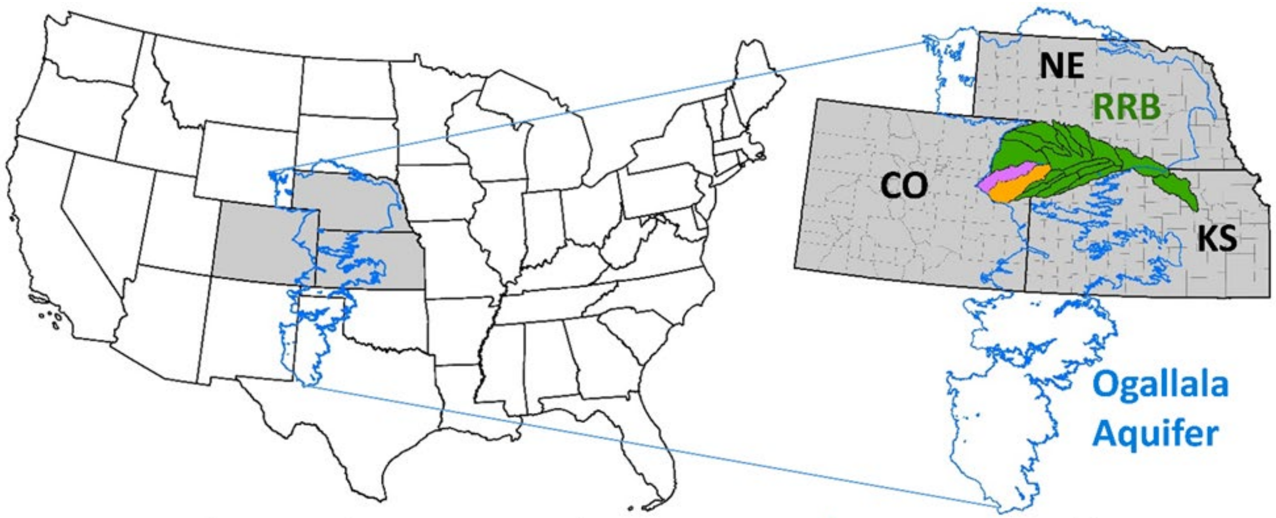
Introduction

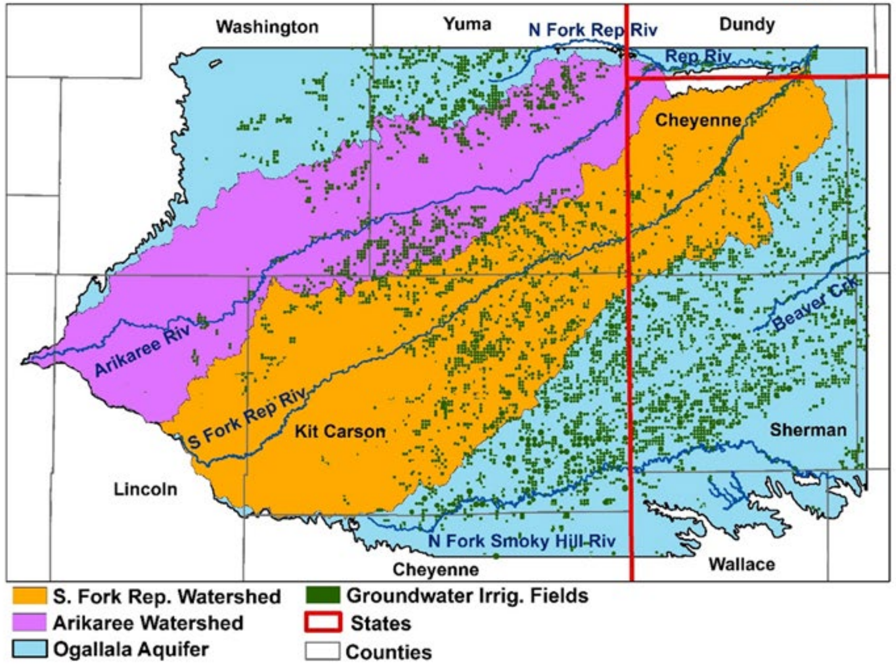
Methods

Results

Summary

❑ Study Area





- Republican River Basin (RRB) encompasses approximately 130,000 km^2 in eastern CO, northwest KS, and southwest NE
- Thousands of farms irrigated by the Ogallala Aquifer
- Significant decline in aquifer water levels as well as stream flows

Our study area:

- Incorporates western portion of RRB
- Encompassing the entire HUC-8 watersheds of Arikaree River and South Fork Republican River as well as portions of 8 other HUC-8 watersheds plus the underlying Ogallala Aquifer (approximately 21,000 km^2)

Study Area

Historical groundwater development in the region

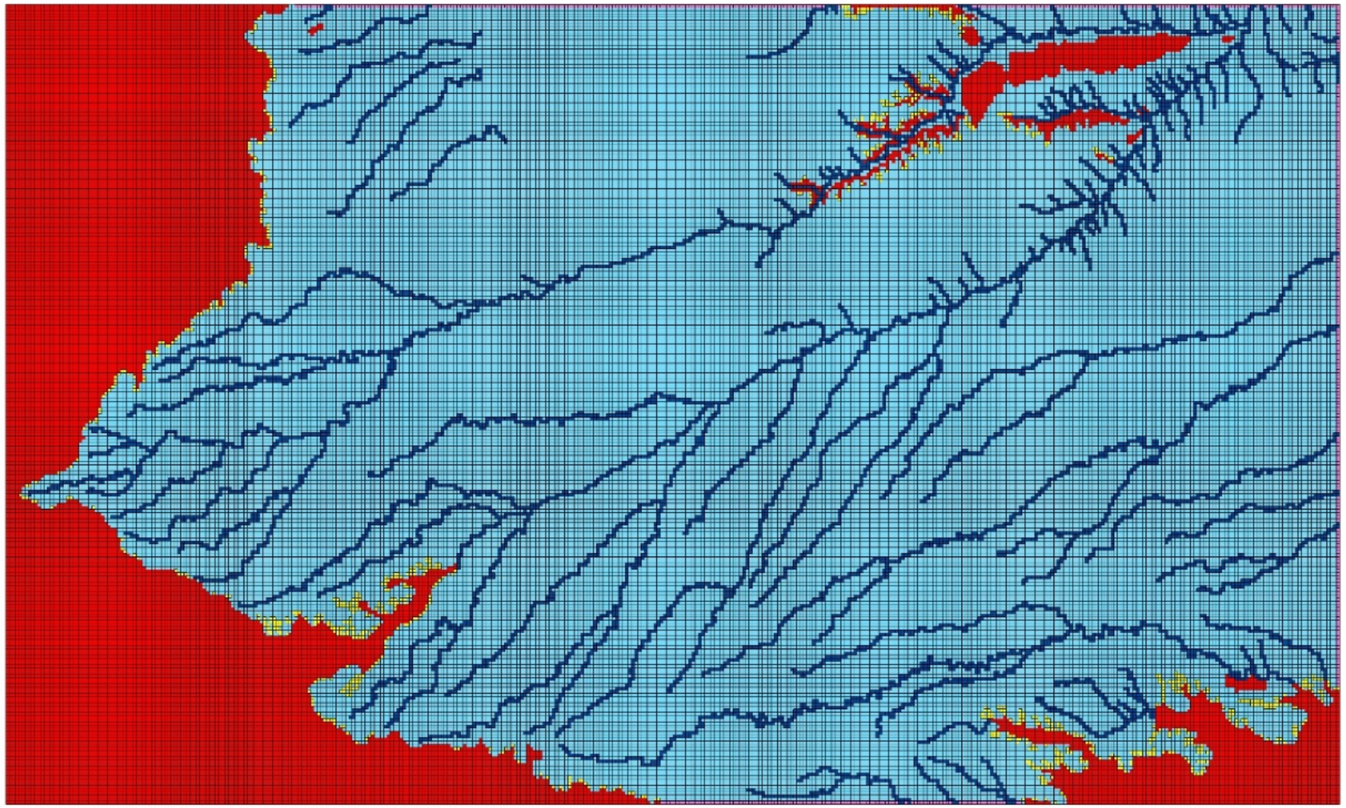
Irrigation Wells Development

GW Irrigated Lands Development

❑ MODFLOW Model (Subsurface Hydrology)

- Introduction
- **Methods**
- Results
- Summary

MODFLOW Model Configuration



Cell Type

- Variable Head
- Drain
- General Head Boundary
- No Flow
- Stream

The MODFLOW model is calibrated for predevelopment and 1946-2010 periods (using PEST)

General Features:

- Single-layer model
- Uniform and equally spaced cells : 500 x 500 m
- 83,713 active cells
- Covers approx. 21,000 km^2

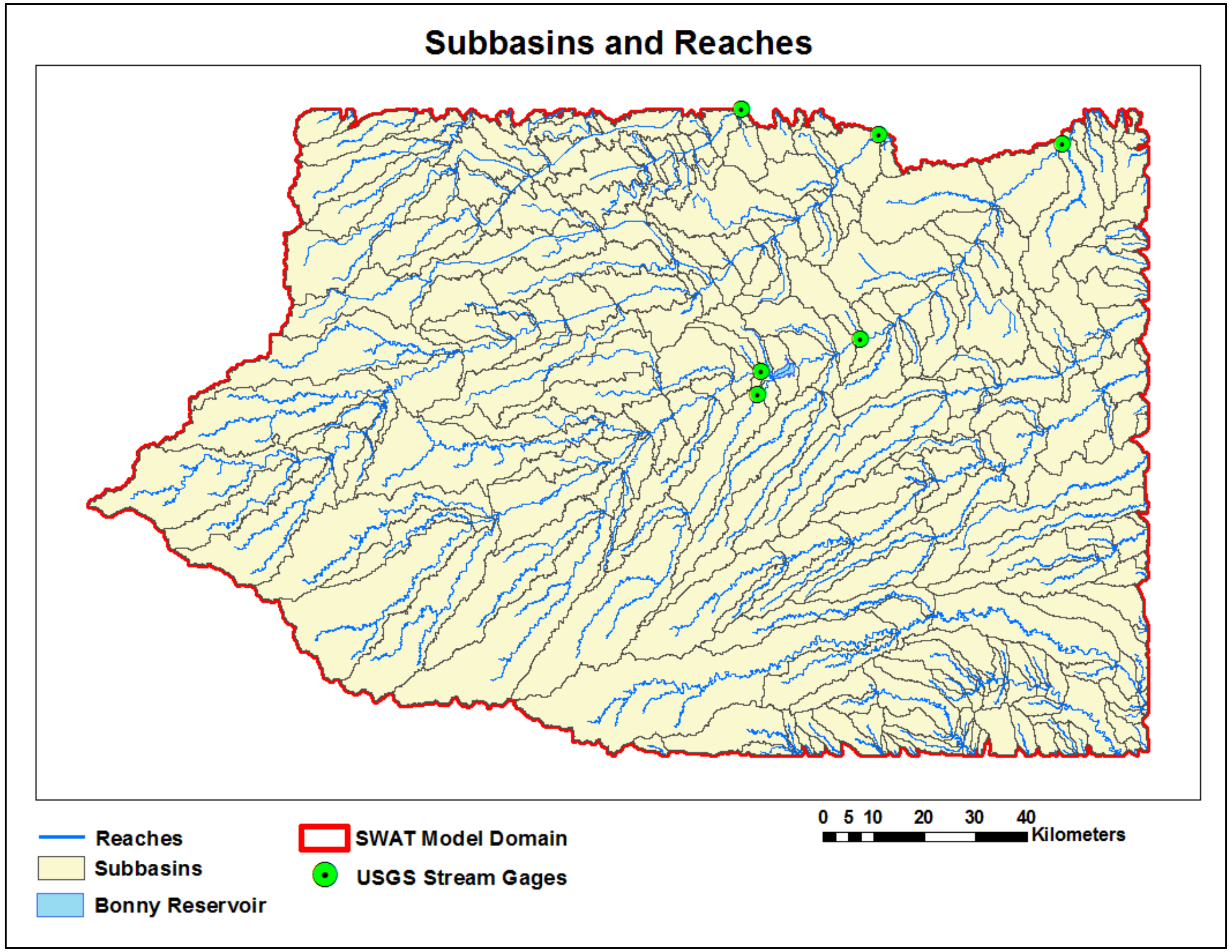
Stress Periods:

- 2 stress periods in each 12 month period:
  - Pumping period (May-Sep)
  - Recovery period (Oct-Apr)
- Daily time step

Historical Simulations:

- 2 main periods:
  - Pre-development (before 1946) simulations via a steady-state model
  - Post-development (1946-2018) simulations via a transient model

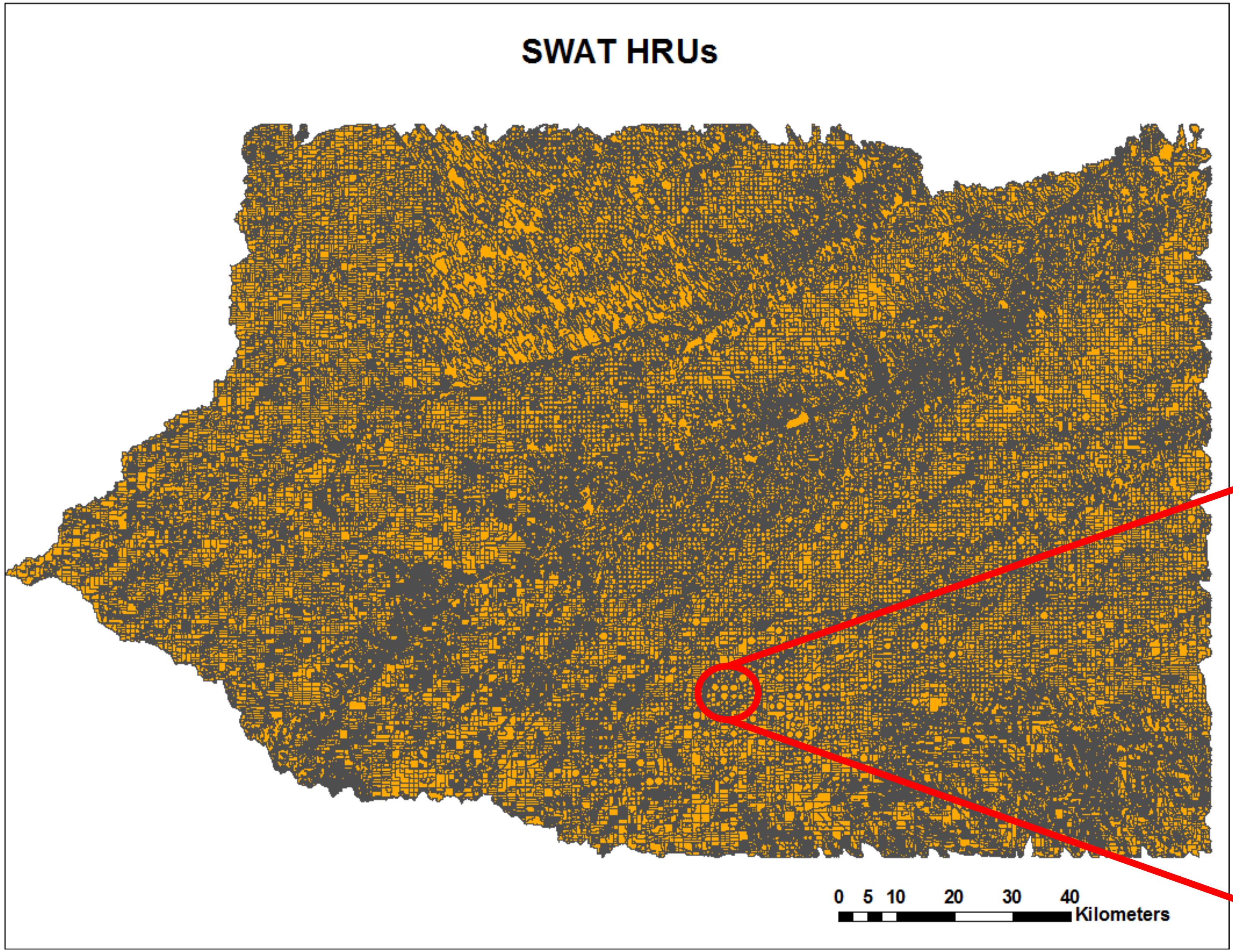
❑ SWAT Model (Land Surface Hydrology)



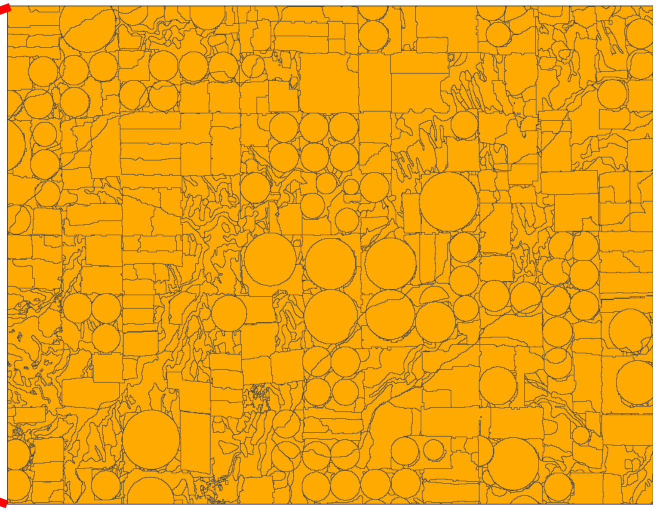
- Constructing a SWAT model for the entire Arikaree River and South Fork Republican HUC-8 watersheds as well as portions of 8 other HUC-8 watersheds
- 280 subbasins
- 21528 HRUs (one HRU for each cropland)
- Historical simulation: 1946-2018

The SWAT model is constructed and being linked to the MODFLOW model and the SWAT-MODFLOW model will be calibrated (using PEST)

❑ SWAT Model (Land Surface Hydrology)

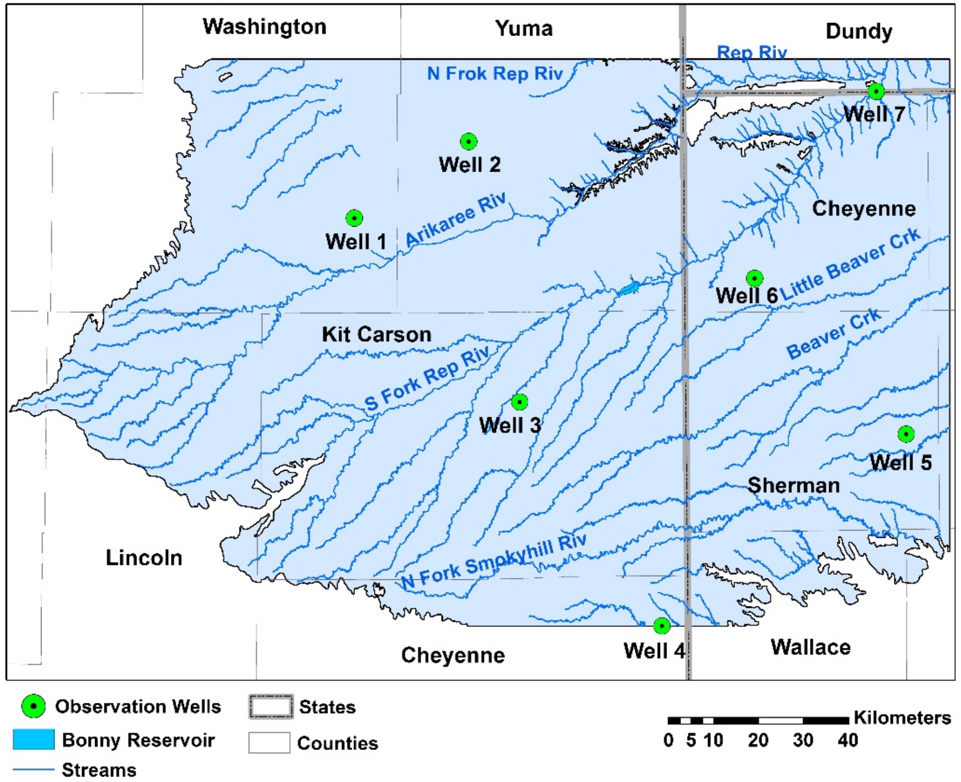


One HRU for each cropland

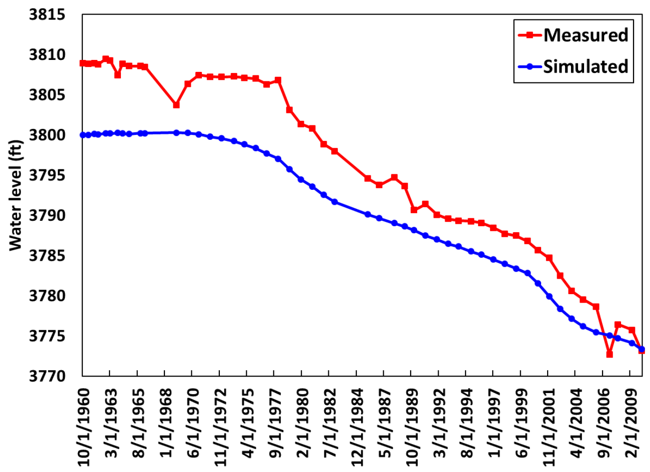


MODFLOW Model (Water Levels)

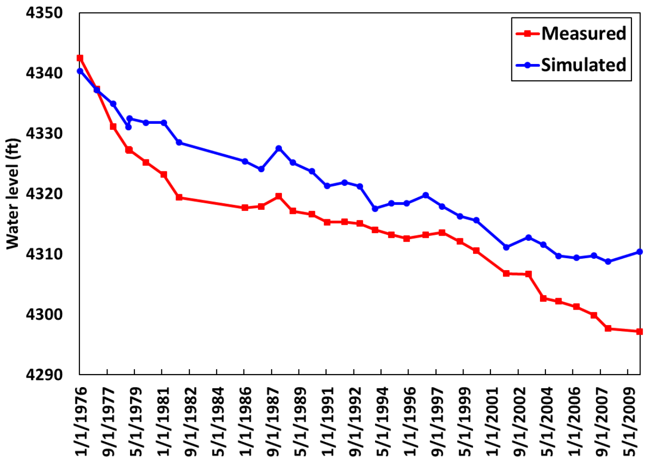
MODFLOW Model Performance in Selected Wells



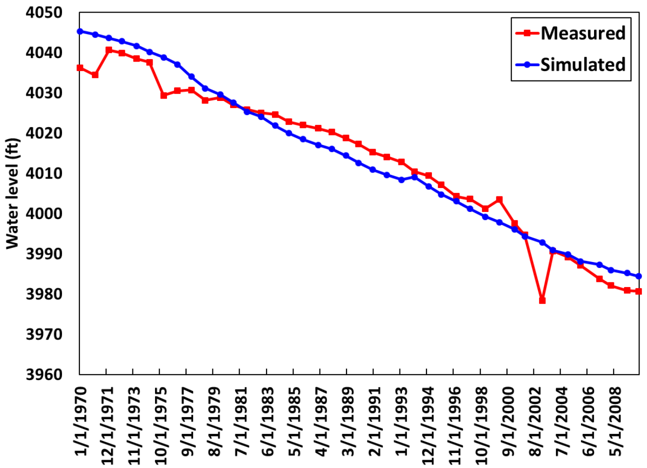
Well 4



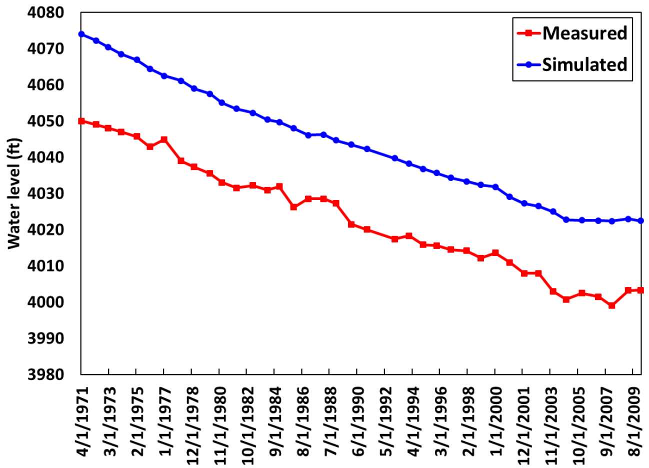
Well 1



Well 2

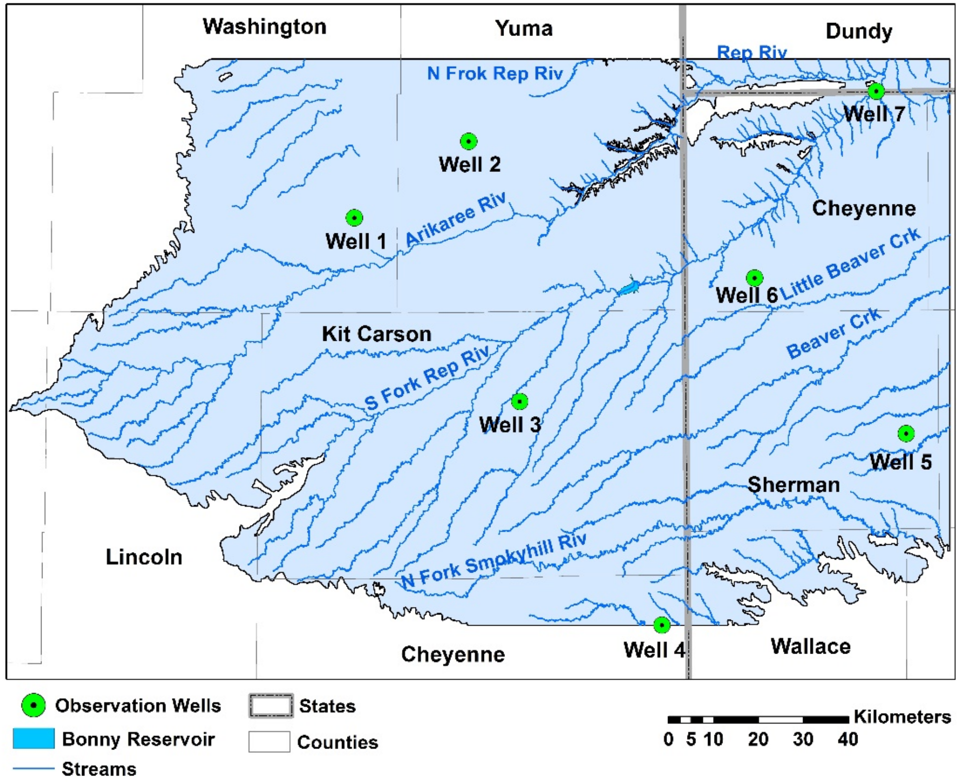


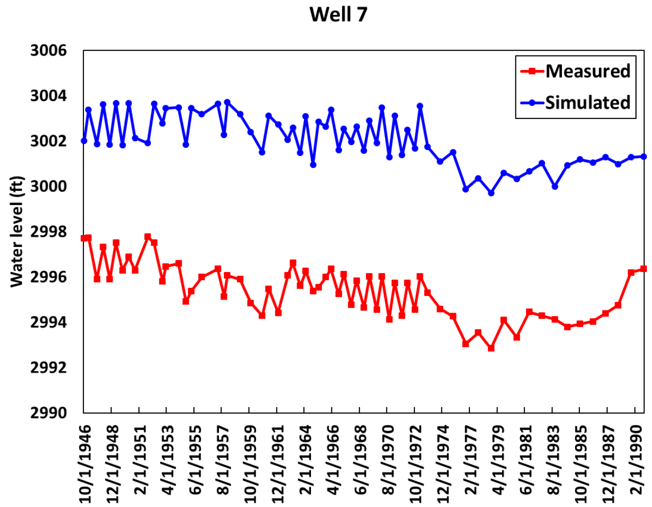
Well 3

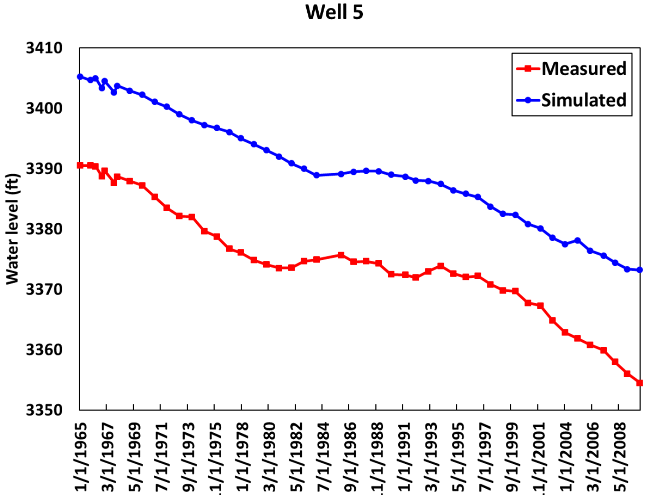


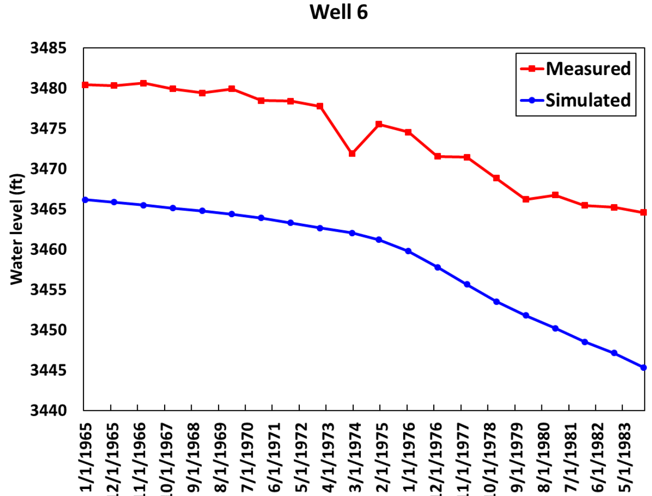
❑ MODFLOW Model (Water Levels)

MODFLOW Model Performance in Selected Wells









❑ MODFLOW Model (Baseflows)

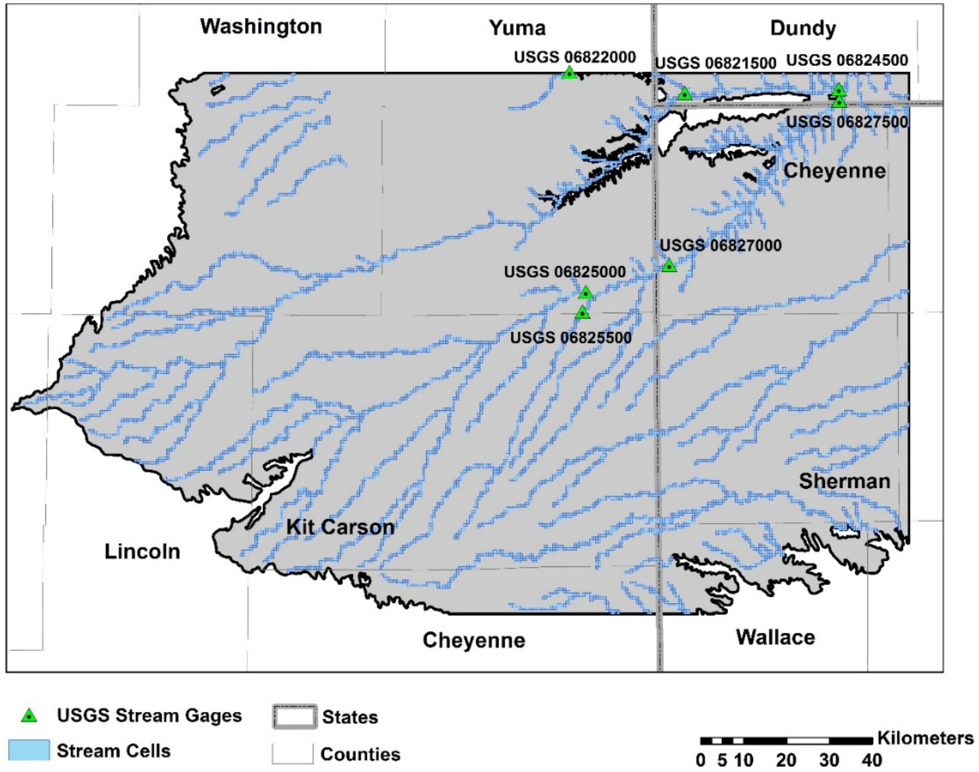
Introduction

Methods

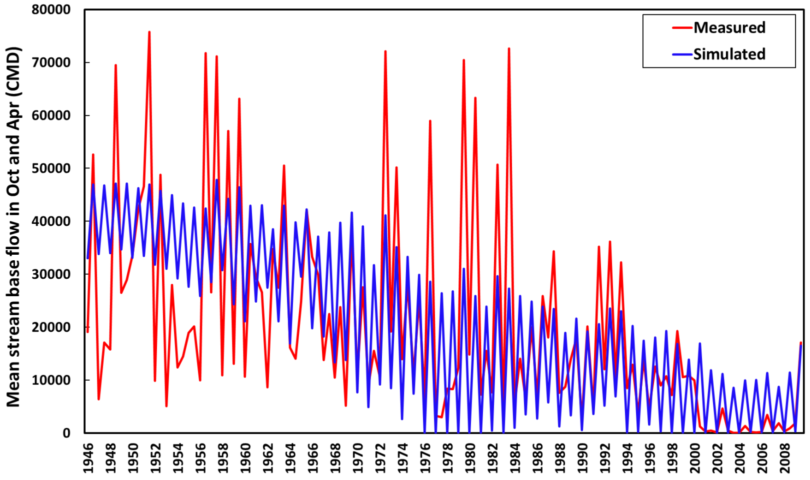
Results

Summary

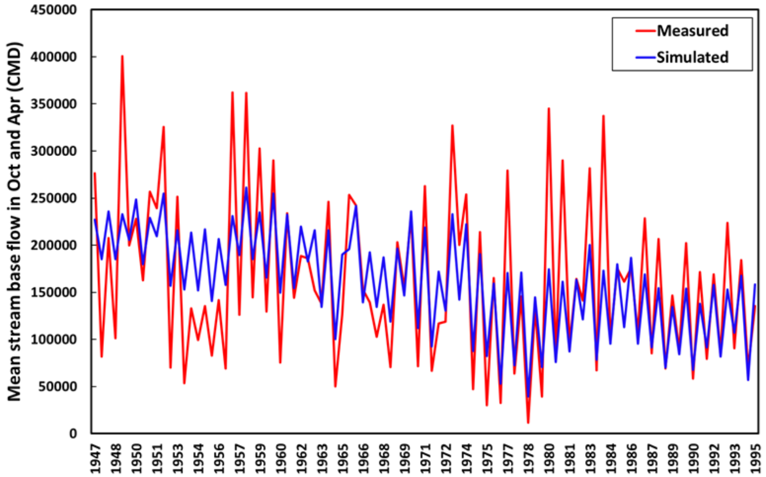
Stream Cells and USGS Stream Gages



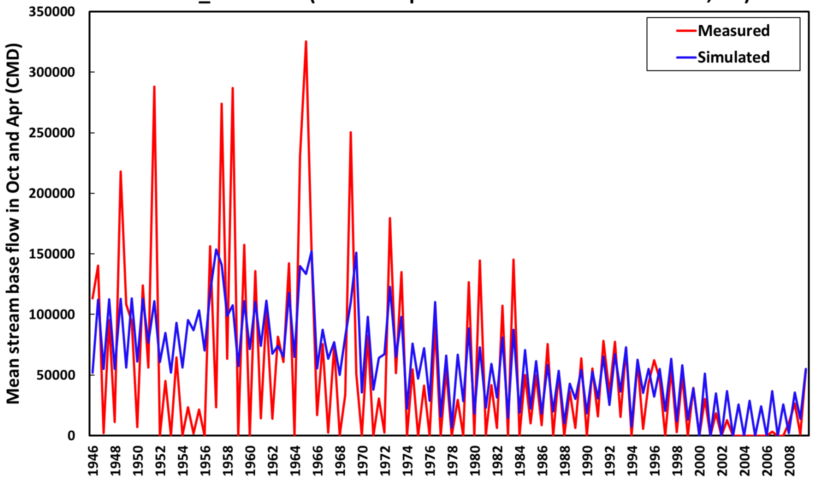
USGS_06821500 (Arikaree River at Haigler, NE)



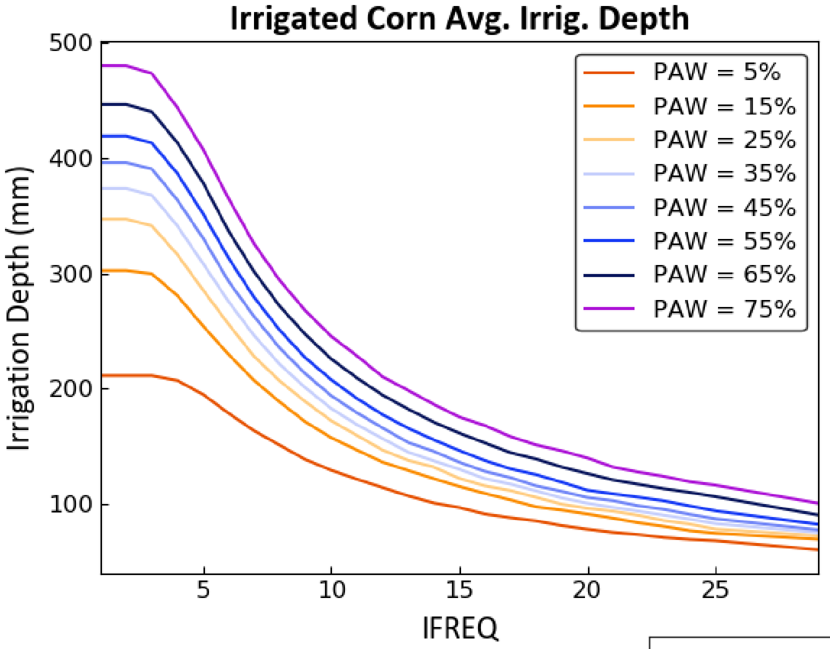
USGS_06824500 (Republican River at Benkelman, NE)

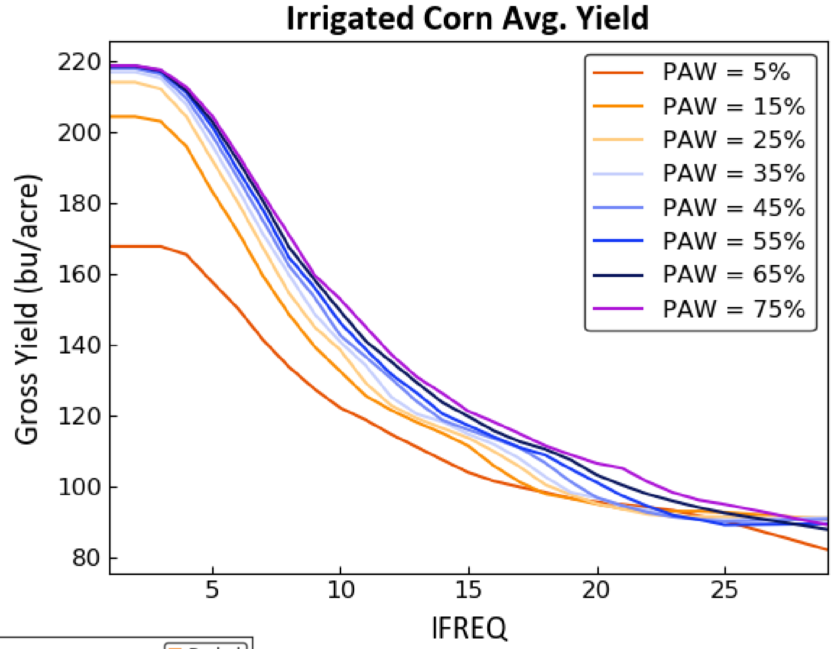


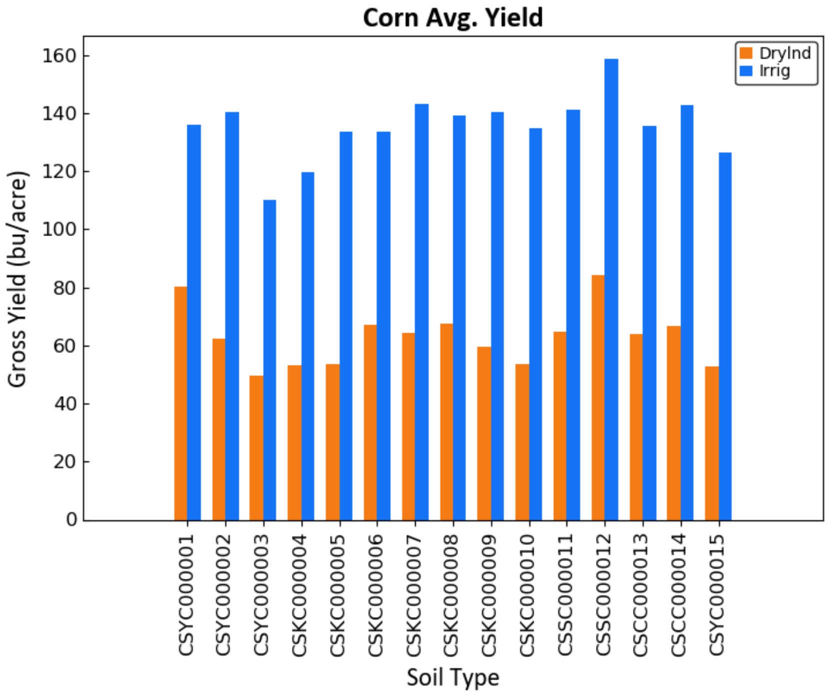
USGS_06827500 (S. Frok Republican River near Benkelman, NE)



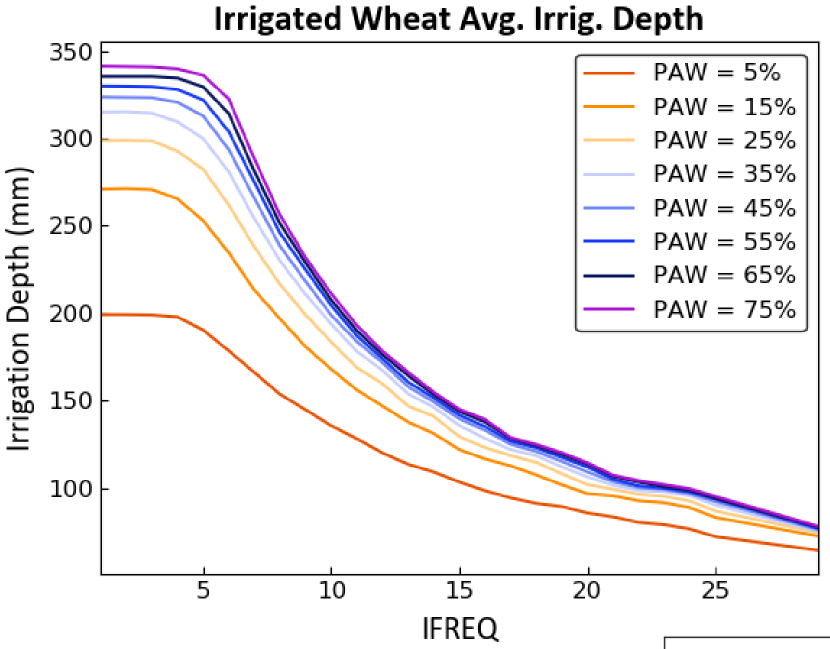
❑ DSSAT Model (Corn Simulations-1992 to 2019)

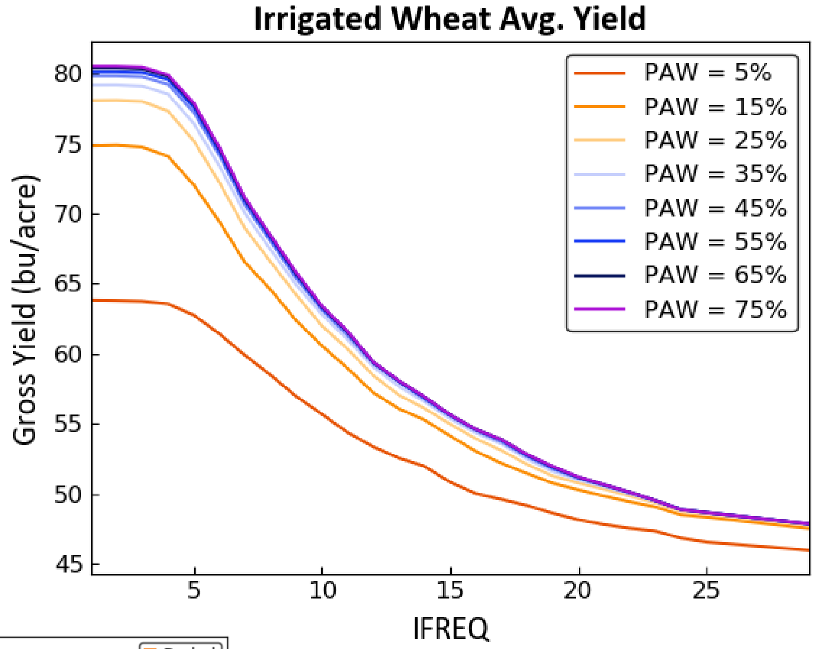


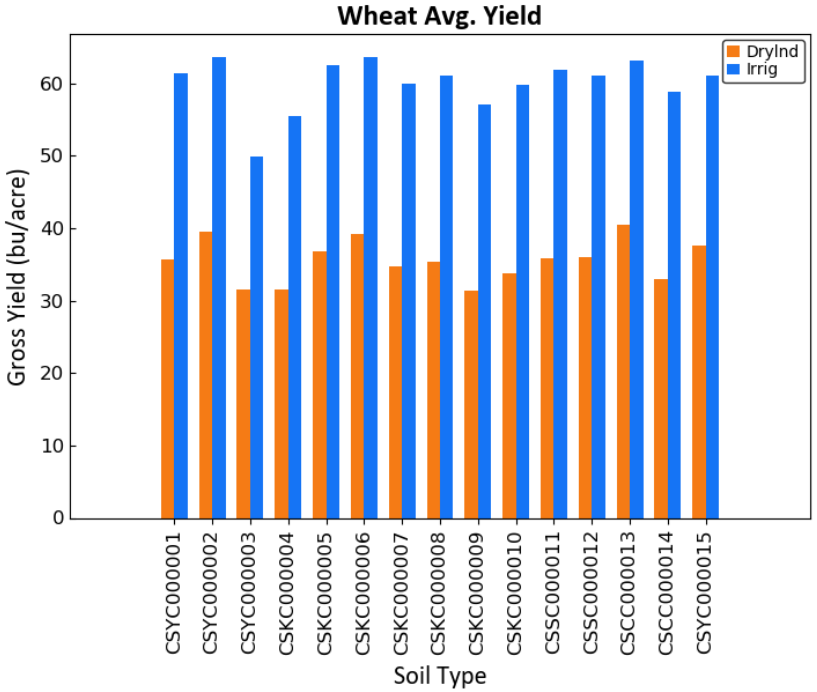




❑ DSSAT Model (Wheat Simulations-1992 to 2019)







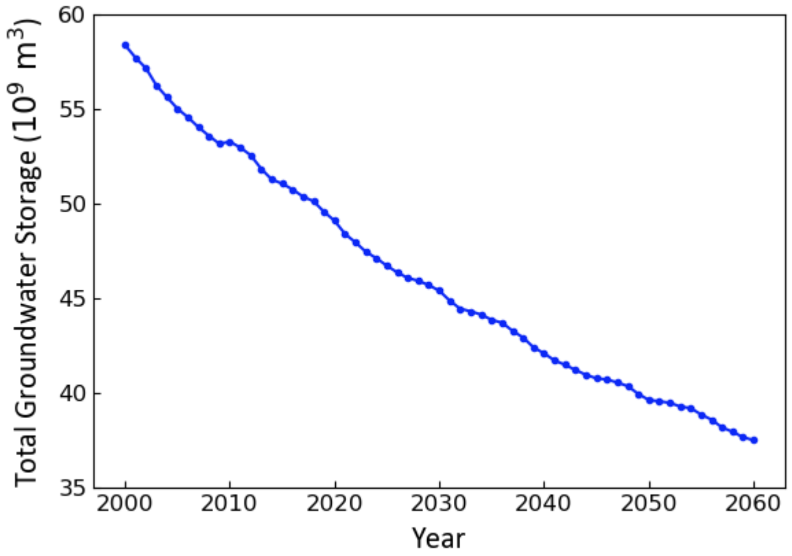
Introduction

Methods

Results

Summary

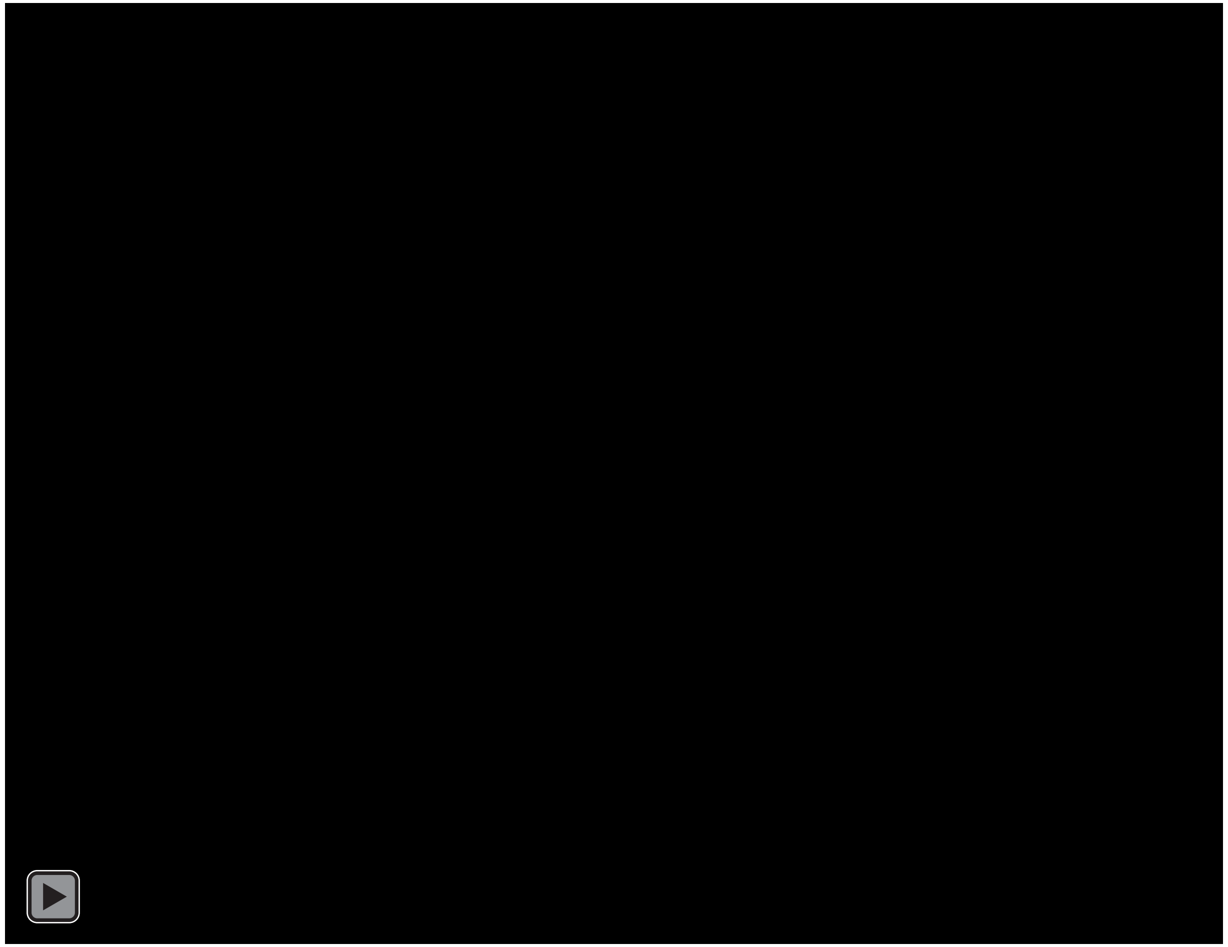
❑ MODFLOW-DSSAT-Econ Model (GW Storage-2000 to 2060)

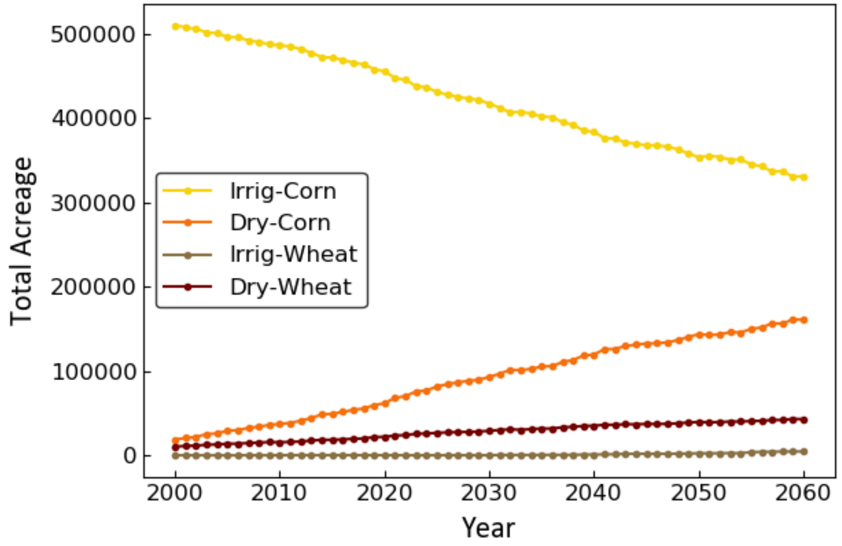


Saturated Thickness Variations

GW Storage

❑ MODFLOW-DSSAT-Econ Model (Planting Decisions-2000 to 2060)



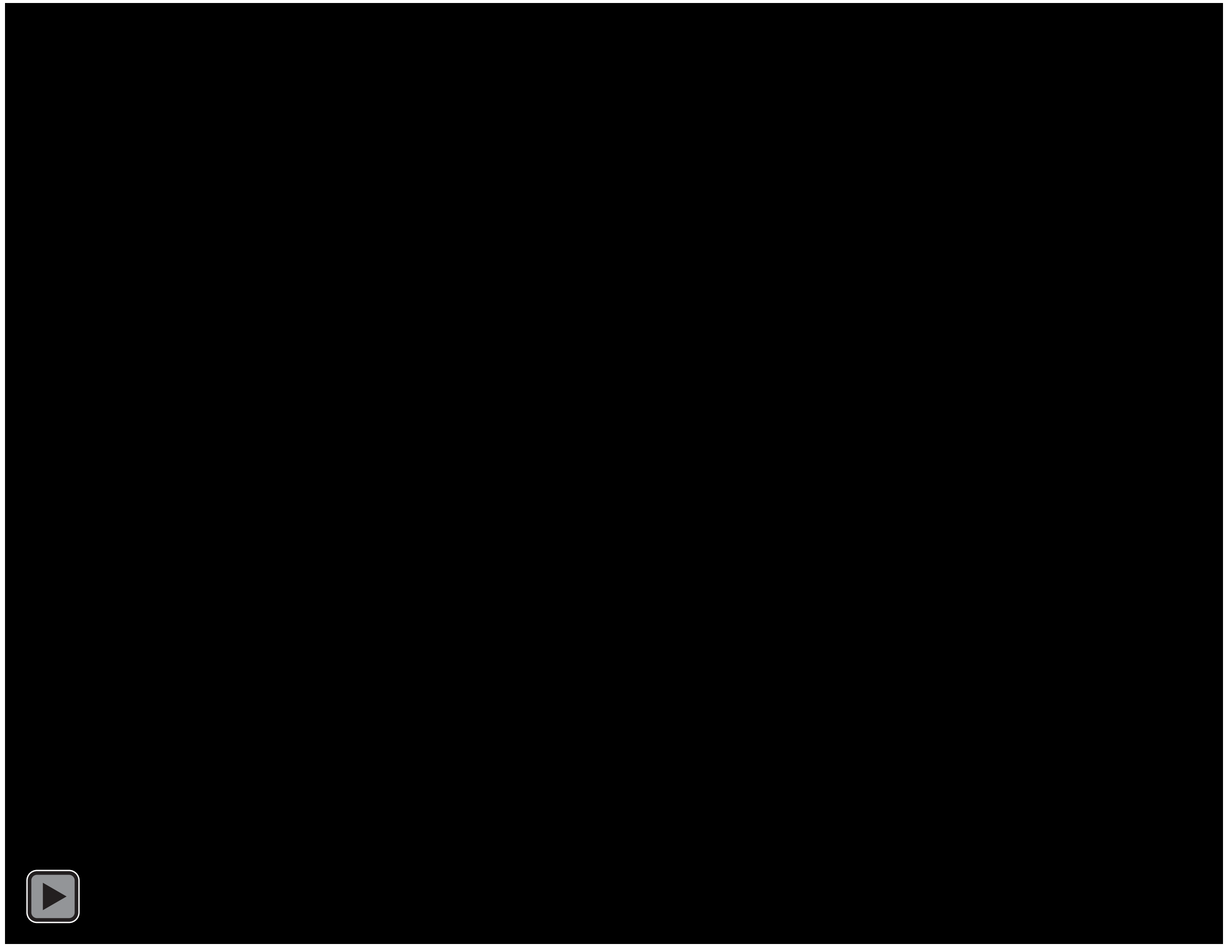


Crop Choices

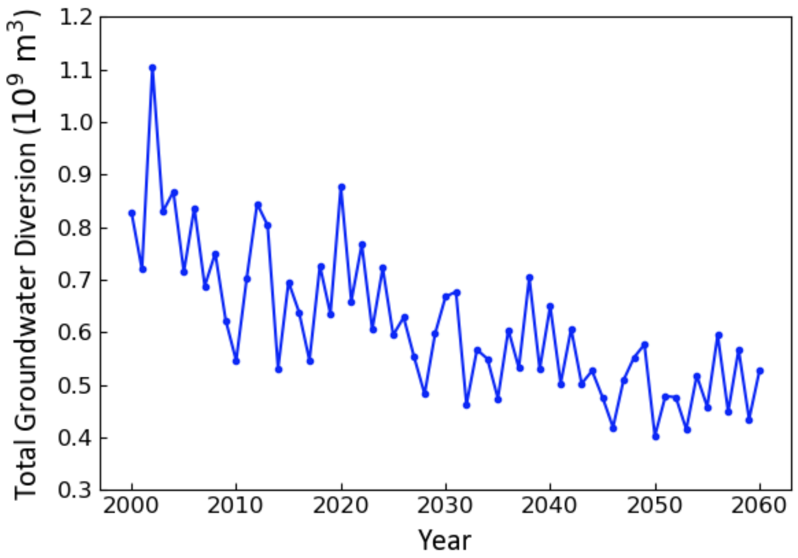
Crops Annual Acreages

MODFLOW-DSSAT-Econ Model (Irrigation Decisions-2000 to 2060)

Introduction
Methods
Results
Summary



Irrigation Depth



Annual GW Diversions

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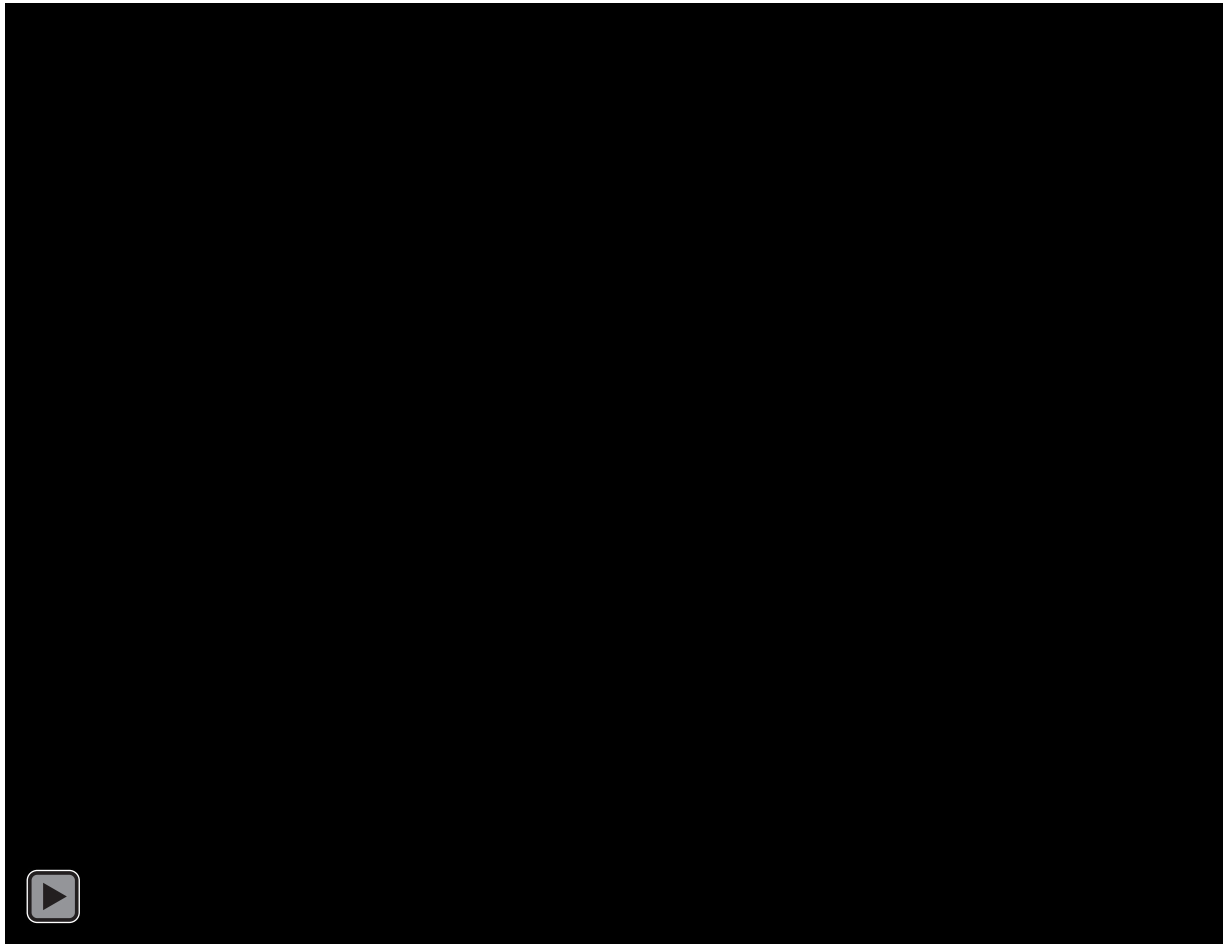
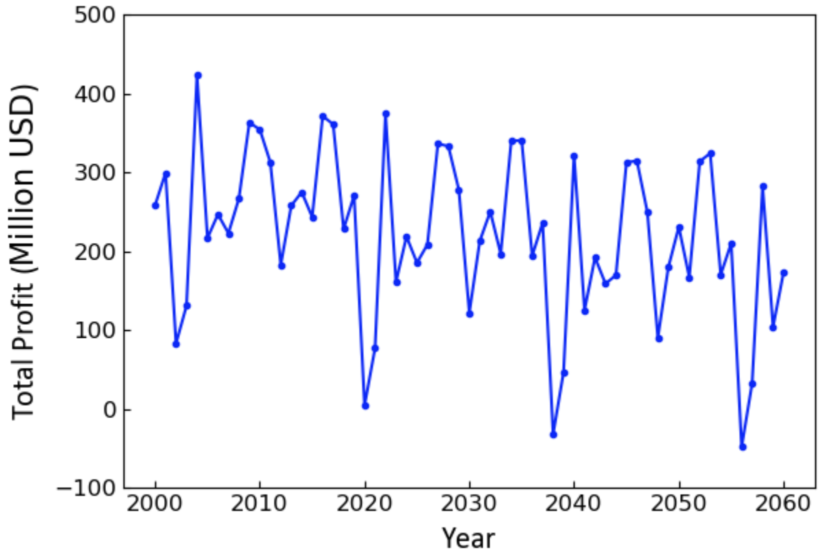
❑ MODFLOW-DSSAT-Econ Model (Profit-2000 to 2060)





Profit per acre

Annual Profit

Fixed expenses (land rental and machinery ownership) are not considered in profit calculations

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❑ Summary

- Developing a hydro-economic model that provides a realistic representation of human-crop-stream-aquifer dynamics at the field level
- Running the model for 2000-2060 period using historical weather data (repeating 2000-2017 weather data)
- Presenting and evaluating different model outputs

Questions that can be answered with the model:

1. What impact would potential policies designed to reduce pumping have on producers and the aquifer?
2. What are the tradeoffs in terms of benefits and costs between different groundwater management policies and how do these change over time and space?
3. Can we identify alternative practices that will minimize the impact of reduced pumping on producers and the regional economy?

Next steps:

- Finalizing the SWAT-MODFLOW model and replacing the MODFLOW model with it in the hydro-economic model
- Considering 38 climate change scenarios (2 RCPs and 19 GCMs) and running the hydro-economic model for them

Thank you!

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