The Use of Integrated Modeling to Understand the Role of Groundwater Surface Water Interactions in Water Management Decision Making

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Why *anthropogenic*?

http://www.merriam-webster.com/dictionary/anthropogenic
There are many anthropogenic impacts on hydrology

- Climate Change
- Irrigation
- Groundwater Pumping
- Water projects
- Urbanization
Groundwater and Streamflow
Groundwater and Land Energy Fluxes

Energy Controlled (T, U, SW)

Groundwater Controlled

Moisture Controlled (P)

Percent Change in Monthly LE (Scenario – CNTRL)

(Kollet and Maxwell, Water Resources Research, 2008)
Integrated water resources management

- Sustainable management strategies require a shift from analyzing individual components of the hydrologic system in isolation to looking at the system as a whole.

- There are efficiencies that can only be understood when considering the system as a whole.

- Examples
  - Groundwater pumping
  - Groundwater surface water interactions
  - Ecological benefits
Questions to Ponder

- How do groundwater surface water interactions influence management decisions?
- When do operational models and traditional approaches break down?
- Can we improve resource efficiency using an integrated modeling approach?
- How do physical parameters impact groundwater land surface interactions, regional water budgets and the resulting management decisions?
Typical Modeling Approach

- Groundwater/Vadose Model
- Surface Water Model
- Land Surface Model
- Atmospheric Model
What about water management?

Example Decision Support System
Water allocation algorithms coupled to a linear reservoir ("bucket") model

Advantages:
- Ease of use
- Minimal computational time
- Easy to run long simulations and getting answers in real time

Disadvantages:
- Heavy emphasis on surface water
- Limited or no feedbacks between groundwater and surface water
- Limited feedbacks between management decisions and the physical system

- Pumping drawdown curves
- Rainfall Runoff Relationships

Groundwater

Demand

Water Allocation

Reservoir

River

- ET surface area curve
- Rule curve.
Can we do better?
ParFlow: a fully integrated physical hydrology model

• Growing number of integrated SW-GW models: HGS, CATHY, PIHM, InHM, we use/develop ParFlow

• Groundwater flow: variably-saturated three-dimensional Richards equation

• Overland flow/surface runoff: free-surface overland flow boundary condition (Mannings + kinematic wave or Diffusive wave)

• Land surface water and energy fluxes: Common Land Model (CLM), includes infiltration, canopy and vegetation processes, and coupled water-energy balance

• Fully-coupled, mass conservative, parallel implementation. Designed to run efficiently from Laptop to SuperComputer

Kollet and Maxwell (2008), Kollet and Maxwell (2006), Maxwell and Miller (2005), Dai et al. (2003), Jones and Woodward (2001); Ashby and Falgout (1996)
Little Washita watershed in OK

good site to study climate feedbacks

- Southern Great Plains, important region
- Seasonal precipitation, little persistent snow
- Rolling terrain
- Moderate sized watershed, 45x32km
What are irrigation impacts on hydrology, land-energy balance?

![Graph showing irrigation impacts on monthly mean temperatures in CA and NE.](image-url)

Lobell et al. (2009)
What are pumping’s impacts on hydrology and land-surface fluxes?

We have changed the water table depth substantially, can we quantify these effects?

Water Management Scenarios

- **Control**
  No pumping, no irrigation

- **Irrigation Only**
  Irrigate crop cells
  (May 1 - Sept 1, 20” (508 mm) total)

- **Pumping Only**
  Pumping from crop cells

- **Pumping + Irrigation**
  Pumping and irrigate crop cells

Ferguson and Maxwell, *ERL* 2011
Changes to energy fluxes not straightforward

<table>
<thead>
<tr>
<th>Water Table Depth [m]</th>
<th>Saturation [-]</th>
<th>LE [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. CNTRL</td>
<td>b. PUMP – CNTRL</td>
<td>c. IRRIG – CNTRL</td>
</tr>
</tbody>
</table>

Figure 2. (a) Monthly mean water table depth (m), ... by influencing infiltration, runoff generation, and groundwater recharge. Lastly, it should be noted that the three...
Water management impacts, feedbacks are complicated

From a hydrologic standpoint, pumping is dominant

From a feedbacks standpoint, irrigation is dominant

Ferguson and Maxwell, *ERL* 2011
Many water management models employ some form of optimization algorithm to allocate water (e.g. WEAP & RiverWare).

Generally the goal is to maximize the satisfaction of demand subject to system constraints and operating rules.

Given a well designed problem optimization algorithms can quickly yield complicated allocations with minimal user input.
Coupled Management Model

Linear Optimization Water Management Module

Spatially Distributed:
- Saturation
- Water Table
- Streamflow

Optimized:
- Diversions
- Pumping
- Irrigation

Coupled ParFlow
CLM Physical Hydrology Model

Municipality A

Farm A

Farm B

Farm C

Farm D

Farm E

Diversion

Well 1

Well 2

Well 3

Imported Water

Atmospheric Forcing

Moisture Dependent Irrigation

Water Table

Groundwater

Root Zone

Vadose Zone

Drawdown Range for Pumping Curtailment
Key Features of the Coupled model

- Fully integrated groundwater surface water interactions means that surface water supply is a function of groundwater depth.
- Land surface processes like evapotranspiration are partially dependent on soil moisture and in some cases groundwater.
- Irrigation demand is driven by plant processes.
- Groundwater availability can be dynamically determined based on well drawdown.
Test Problem: The Little Washita Domain
Water Management Problem

Legend
- First Priority Demand
- Second Priority Demand
- Third Priority Demand
- First Preference Source
- Second Preference Source
- Supply Point

Farm 1
Irrigation Demand*
19,000 m³/day

Well 2
Max pumping:
19,000 m³/day

Farm 3
Irrigation Demand*
19,000 m³/day

Well 1
Max pumping:
19,000 m³/day

Farm 2
Irrigation Demand*
19,000 m³/day

Well 3
Max pumping:
19,000 m³/day

Farm 4
Irrigation Demand*
19,000 m³/day

Farm 5
Irrigation Demand*
19,000 m³/day

Municipality A
Daily Demand
20,000 m³

Diversion 1
Instream Flow Minimum:
40,000 m³/day

* Irrigation is turned on when 50% of farm area drops below 35% Saturation. When triggered irrigation is applied at a constant rate of 0.396 mm/hr from 7:00-19:00 (Based on Ferguson and Maxwell 2011 & 2012)
Results

- Simulated one irrigation season from April – August
- Hourly historical meteorological forcings from 1999
- Simulated physical hydrology on an hourly time step and made management decisions daily
Daily Water Demand and Delivery Source by Farm
Daily Water Demand and Delivery Source by Farm

Irrigation turned on when 50% of farm area drops below saturation threshold

Farm 1
(Total Irrigation Days = 48  Total Days with Shortage = 8 )
Daily Water Demand and Delivery Source by Farm

First preference is surface water but when supply is insufficient groundwater is pumped to meet remaining demand.
Farm 4 is a third priority demand and it routinely gets shorted so that other demands can be satisfied first.
Daily Water Deliveries by Source

Legend
- Farm 1
- Farm 2
- Farm 3
- Farm 4
- Farm 5
- Municipality
- Total Available Supply
- Excess Surface Water Supply
- Unmet Surface Water Demand
Daily Water Deliveries by Source

Municipal demand is satisfied first then Farm 2.
Daily Water Deliveries by Source

When Surface water is insufficient to meet municipal demand it pumps from Well 1.
Daily Water Deliveries by Source

When Surface water is insufficient to meet Farm 2 demand it also pumps from Well 1.
Well 3 supplies first priority farms (1,2 &3) before providing for second priority farms (4 & 5).
Findings

- An integrated hydrologic and water management modeling platform has been developed and demonstrated for a real world application.
- Results demonstrate tradeoffs between surface water availability and groundwater demand.
- Findings illustrate the interplay between management decision and connections in the physical system.
High Resolution Modeling to Investigate urbanization impacts on stormwater routing and infiltration

**Goals:**

1. Use a high resolution model to investigate how stormwater routing and water quality (surface and subsurface concentrations) in an urban test domain change using various LID configurations.
2. Investigate under what conditions green infrastructure projects may produce positive benefit-cost ratios.
3. Determine how such infrastructure may impact optimal water resource management strategies.

**Test Domain:**
Located within the South Platte Basin
South of the Cherry Creek Reservoir

Drainage Area: 1535 km²
Urbanization growth since 1970 = 560%
Current Urban extent = 10%

![Map of South Platte River Basin and Watersheds showing locations and grid code legend.](image)
Bridging scales between fine-scale urban features and large-scale urban watersheds

Pressure [m]

Centralized over urban section, we can model at higher resolution (30m x 30m to 1m x 1m) to analyze stormwater routing and infiltration.
Efficient Allocation of San Francisco’s Water

The Problem

- SF sells 2/3 of its water to other utilities
- Purchasing utilities must disproportionately cut their use during droughts
- Different utilities suffer varying levels of economic losses due to such restrictions

The Solution

- Utilities can trade their allotments to efficiently allocate water (i.e., a water market)
- Two model components determine optimal allocations and the economic savings
  - Water resources model
  - Economic model
- These models can also consider the effects of climate change

Results of Economic Survey

<table>
<thead>
<tr>
<th>Variable</th>
<th>Elasticity</th>
<th>t-stat</th>
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</thead>
<tbody>
<tr>
<td>Price</td>
<td>-0.14</td>
<td>-7.5</td>
</tr>
<tr>
<td>Precipitation</td>
<td>-0.05</td>
<td>-1.3</td>
</tr>
<tr>
<td>Summer time max. temp</td>
<td>0.45</td>
<td>5.3</td>
</tr>
<tr>
<td>Median Income in 2000</td>
<td>1.03</td>
<td>30.3</td>
</tr>
<tr>
<td>Median lot size</td>
<td>0.35</td>
<td>11.5</td>
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<tr>
<td>Median vintage</td>
<td>-0.30</td>
<td>-14.8</td>
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<tr>
<td>Average household size</td>
<td>0.36</td>
<td>6.8</td>
</tr>
<tr>
<td>SFR accounts</td>
<td>1.09</td>
<td>161.1</td>
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<tr>
<td>San Francisco indicator</td>
<td>-0.78</td>
<td>-15.1</td>
</tr>
</tbody>
</table>

# Observations 395
R-squared 0.991
Acknowledgments

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MODFLOW and MORE 2013
Translating Science into Practice

The Integrated GroundWater Modeling Center (IGWMC) is pleased to announce that the MODFLOW and More 2013 conference will be held from June 2-5, 2013 at the Colorado School of Mines campus in Golden, Colorado.

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