Modeling River Basins as Coupled Human and Natural Systems

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What is the next generation of models for river basin management?
Watershed model development: From the STANFORD model TO BASINS, and next?

- HSPF Release 5.0 (1980), 12.0 (2001) …
- The Hydrologic Modeling System (HEC-HMS)
- Soil and water Assessment Tool (SWAT, 2003-2012)
- Storm Water Management Model (SWMM, starting from 1971) for Urban Watershed Management

The human dimension has not been well represented by any model yet!
Co-evolution of Human and Natural Systems in Watersheds

Headwaters
Major tributaries
Main stem
Past
Present
Future

(Source: Loucks and Van Beek, 2005)
Co-evolution of Human and Natural Systems in Watersheds

- **Need to study connected systems as a whole** *(Liu, et al., 2007)*
  - Discover processes that link the human and environmental systems
  - **Include interactions and feedbacks not only** between humans and their environment but also between the environment and the human system
  - Understand how these interactions lead to emergent properties unique to the coupled system.

(Courtesy: Mary Yaeger)
- **Historical trajectory** – “layers of change”
- **Location** – watershed spatial “mosaic of change”
- **Nonlinear response** - same forcing at different locations gives different trajectories and spatial “mosaic”

(Courtesy: Mary Yaeger)
Interactions and feedbacks

Human behaviors influence the frequency, magnitude, or form of human interferences.

Human interferences (long-term press and short-term pulse disturbances) interact to alter biotic and abiotic structure and function.

Altered ecosystem dynamics negatively affect most ecosystem services.

Changes in vital ecosystem services alter human outcomes, which further affect human behavior.

Altered ecosystem dynamics negatively affect most ecosystem services.

(After Collins et al. 2011)
An example of CHNS: the Illinois River Basin
Coupled biophysical and institutional network

DD: drainage districts
SWCD: soil & water conservation districts
IDNR: Illinois Dept of Natural Resources
Evolution of biophysical Processes

Evolution of Institution systems
Modeling River Basins as CHNS

- Develop tools for scientific exploration towards the understanding of coupled human-nature system dynamics

- Develop both physically and institutionally sound models that can be used (not only useful) for real world water resources management problems

- Create a computationally tractable framework for the cyber-physical system
Case study: The Republican River Basin
Pre-development: precipitation, recharge, evapotranspiration, and stream gain are the only significant stresses.

Post-development: groundwater pumping introduces new stresses into the system.

Increasing Irrigation pumping, steady pumping, heightened water use regulations - water level and stream flow is low.

Case study: The Republican River Basin.

Cumulative Number of Active Wells in the Republican River Model Domain.
Modeling the RRB as a CHNS

Simulation of the dynamics of human systems and how behaviors respond to environmental changes

1. Simulate human system dynamics using an agent-based model (ABM)
2. Simulate environmental change
3. Couple both systems to observe the coevolution of environmental and social phenomena
Agent-based model (ABM)

- ABMs establish the relationship between simple individual behaviors, collective structures and interactions with the environment (Macy and Willer 2002; Robinson et al. 2002)

- ABMs are based on rules of behaviors and the rules to change these rules

- Agents’ intelligence can be modeled by machine learning
Agent-based model

Sphere of influence
Regulation change

Well activation
Irrigation
Coupling agent-based model and environmental model

Over years

Updating behaviors, as well as natural and social conditions

Agent-Based model: 1 year

1993

1994
Behavior representation based on economics

Assuming every water user (agent) is a utility optimizer and setting an optimization model for each agent

\[
\text{MAX } U(\pi) = E(\pi) - \lambda \cdot \text{Var}(\pi)
\]

Subject to:

- Response to climate prediction
- Response to market prediction
- Altitude to risk
Behavior representation based on empirical rules

How is the behavior factor of the farmers introduced in the model?

\[ D_c = D_p + ET_{corn} - P - I \]

Soil water deficit

\[ ET_{corn} = ET_0 \times K_c \times K_{st} \]

Crop water demand

\[ K_{st} = \left( \frac{TAW - D_p}{(1 - MAD) \times TAW} \right) \]

Crop stress coef

Goal of farmers

\[ D_c \leq MAD \times AWC \times D_{rz} \]

Managed Allowed Deficit multiplied by behavior factor $\beta$

High behavior factor $\rightarrow$ High water deficit allowed $\rightarrow$ Low pumping

AWC is available water capacity for soil and $D_{rz}$ is rooting depth
Behavior representation based on empirical rules

How is the behavior of the farmers defined?

All agents have a behavior factor $\beta$ reflecting the sensitivity to crop water stress.

Heterogeneity of $\beta$ is introduced through a standard normal distribution.

For each soil type, $\beta$ is normally distributed among the farmers with a different mean between 0.87 for fine sand and 0.96 for silty clay loam.

Behavior factor based on physical conditions:

Diffusion of behavior factor:

$$\beta_{\text{new}} = 0.75 \cdot \beta_{\text{old}} + 0.25 \cdot \max(\beta_{\text{neighbors}})$$

(At each time step for each farmer)
Learning process based on Bayesian Inference

**D: Decisions**
Crop acreage, irrigation

**P: Perceptions**
updating on uncertain water requirement/availability, production prices etc.

**O: Observations**
Precipitation, crop price

Agents are heterogeneous in terms of:
- Initial perceptions (prior knowledge)
- Weight of the prior against the new information
- Information availability (observation)

(Also see Ng et al., 2011, WRR)
Coupling ABM with MODFLOW 2000
Demonstration
Virtual ABM-MODFLOW: Design of a web application to couple a multi-agent system and an environmental model for watershed management analysis in a Cloud environment

- Virtual exercises for education and outreach activities
- Support participatory modeling
- Collect data especially those reflecting agents’ opinions and behaviors

http://waterproject.web.engr.illinois.edu/
Estimating unknown behavior data through Sensitivity analysis and self-calibration with MapReduce for large-scale socio-hydrological models in a Cloud environment. *MapReduce* is used to write applications which process vast amounts of data (multi-terabyte datasets) in-parallel on large clusters (thousands of nodes) of commodity hardware.
Derive farmer agent’s decision path: Use Probabilistic Graphical Models (PGM) for deriving a cognitive map
Summary

- CHNS, a new systems concept based on physical and social sciences, facilitates new model formulation and solution algorithms for water resources systems analysis.

- System approaches featured with CHNS support both scientific research and management of water resources in a holistic context.

- A scientific framework is still under development.
Coupling distributed decision making with distributed hydrologic modeling

Scientifically sound

(Distributed hydrologic modeling)

+ Institutionally Realistic

(Distributed decision modeling)

Computationally tractable

ICPDR - International Commission for the Protection of the Danube River
Scientific framework integrating hydrology and social sciences

- Hydro-economic modeling (Cai, 2008, EMS; Harou et al., 2009, J of HYDRO)

- Hydromorphology (Vogel, 2011, JWRPM)

- Social-hydrology (Sivapalan et al., 2012, HYDRO PROC)
Building scientifically sound, institutionally realistic, and computationally tractable models: Why can we do better today?

- **Data**: Increasing availability of datasets especially from remote sensing products (e.g., digital watersheds) and enhanced in-situ monitoring systems
- **Models**: Advances in distributed watershed modeling
- **Forecasts**: Enhanced hydro-climatic and socioeconomic forecasts
- **Practices**: Real-world management practices involving multidisciplinary expertise
- **Institutions**: improved institutional support
- **Sciences**: Integrated sciences (hydrology, ecology, economics, sociology, political science, etc.)
- **Computers, Algorithms and Information Support**: Cyber-infrastructure
Thanks! Questions?
### Regulatory agents

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<th></th>
<th>NRDs</th>
<th>IDs</th>
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<tr>
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<tr>
<td>Interest in streamflow</td>
<td>2</td>
<td>1</td>
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<tr>
<td>Interest in pumping</td>
<td>1</td>
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**Sphere of influence**

**Average Annual Flow**

**Water Use Regulations**
ABMs for watershed management


- Coupling learning process with agents’ models (Ng et al. 2011)

- Use of classic MP or DP to model individual agents as utility optimizers (e.g., MILP, Berger and Ringler 2002; DP, NLP, Yang et al. 2011; DP, Ng et al. 2011)

- Coupled ABM-physical modeling for watershed management
  - Farmer decision making coupled with hydrologic-agronomic modeling (Barreteau et al., 2004; Ng et al. 2011)
  - Land-use change coupled with forest hydrological simulation (Monticino et al. 2005)
  - Ecosystem performance coupled with watershed simulation (land & water) (Doran, 2001)
  - Water users’ decisions coupled with urban watershed simulation (Giacomoni, 2012)