Evaluating FEW Nexus in the Coupled Natural-Human System with Agent-Based Modeling

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Outline

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- Water-Food-Energy-Environment Nexus
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Introduction

Overarching Science Question:

How do the complex interactions between humans and nature affect the Earth system at different spatial and temporal scales?

A systems approach with nexus thinking
Introduction

- **Systems approach**
  - We need to break down the big question and understand all different parts of the it

- **Nexus thinking**
  - We also need to understand the connections between different parts
Water-Food-Energy-Environment Nexus

- Water-Food-Energy-Environment (WFEE) Nexus

- Why is it important?
  - 1.1 billion have no access to clean water
  - 1.3 billion live without electricity
  - 1.02 billion are hungry

→ Need more in the future!
Water-Food-Energy-Environment Nexus

- Conventional solutions treat these security issues *separately*, but they are connected to each other.

- Without nexus thinking, *solving a problem* in one sector can cause negative effects in another one.
Water-Food-Energy-Environment Nexus

- Science Questions for understanding the WFEE Nexus using the systems approach with nexus thinking:

**What is the first step to quantify human-ecosystem interaction in the WFEE Nexus?**

Human-ecosystem interaction in the WFEE Nexus - the Yellow River
(Yang et al. 2009; Yang et al. 2012)

**How can we accommodate the dynamics of natural variability in the WFEE Nexus?**

Coupling a human model with a process-based model - the Mekong River
(Khan et al. 2017; Yang et al. 2018)

**How can we address the human behavioral uncertainty in the WFEE Nexus?**

Developing the human model using Bayesian Inference Map – the San Juan River
(Hyun et al. 2018)
Methodology – Agent-based Modeling

- What do you mean by a “human model?”
- Not just a traditional socioeconomic model, but a more complex and realistic modeling approach:
- Agent-Based Modeling (ABM)
Methodology – Agent-based Modeling

- What is ABM?
  - From Computer Science: Distributed Artificial Intelligence
  - An agent is an object that
    - is driven by its "own" utility function
    - follows behavioral rules
    - interacts with other agents and the environment autonomously

- Why ABM?
  Most “top-down” model regarding human decision in WFEE Nexus study suffer from various limitations such as policy implementation, complete information exchange, and large computational costs.
ABM Study 1 - Human-ecosystem interaction

What is the first step to quantify human-ecosystem interaction in the WFEE Nexus?

Human-ecosystem interaction in the WFEE Nexus - the Yellow River

(Yang et al. 2009; Yang et al. 2012)
ABM Study 1 – Human-ecosystem interaction

- The **second largest** river in China flows through nine provinces
- Arid to semi-arid climate
- Overuse of water resources results in **streamflow cutoff** since 1972

![Graph showing zero-flow days and zero-flow distance (km) from 1972 to 2001.](image)
ABM Study 1 - Human-ecosystem interaction

- Traditional management approach: Unified Water Flow Regulation (UWFR, top-down control)

- Water market scenario (bottom-up management)

- A water trading mechanism is used to account for water rights violations, i.e., water users (defined as agents) are allowed to buy or sell water
ABM Study 1 - Human-ecosystem interaction

- Agent system map
  - 52 water use agents
  - 5 reservoir agents
  - 3 ecosystem agents

Water use agents
Water use agents with source flow
Reservoir agents
Ecosystem agents

Mainstream inflow source
Tributary inflow source
Mainstream
Tributary
ABM Study 1 - Human-ecosystem interaction

Water consumption vs. Water price

Equilibrium state

Numerical loop

Water price: $p_i^*$

Water consumption: $x_i^*$

Water selling: water right $> x_i^*$

Water buying: water right $< x_i^*$

Water availability
ABM Study 1 – Human-ecosystem interaction

- ABM calibration

![Graphs showing observed and UWFR Water Content, Storage, and Streamflow data over different months and agents.](image-url)
ABM Study 1 - Human-ecosystem interaction

- Basin-wide water consumption and GDP

- Conventional water consumption: 34.52 billion m³
  - Water Market: 33.80 billion m³

- Conventional GDP: 1246.68 billion RMB
  - Water Market: 1270.01 billion RMB
  - Difference: 23.33 billion RMB
### ABM Study 1 - Human-ecosystem interaction

- **Effect on ecosystem agents**
  - Total water buying by agents
    - $\rightarrow$ $4.25$ BCM/year
  - Total water selling by agents
    - $\rightarrow$ $7.51$ BCM/year
  - Difference
    - $\rightarrow$ $3.26$ BCM/year
  - Cost for governments
    - $\rightarrow$ $2.95$ billion RMB $< 23.33$ billion RMB

**Cost $<$ Benefit $\rightarrow$ self-sustaining system!**
So, what’s next?

- Quantify the natural-human interaction was the easiest part of this WFEE nexus (that’s why I did it)
- A bigger challenge of this is how to simulate human’s decision making under year-by-year natural variability?
ABM Study 2 – Accommodating natural variability

How can we accommodate the dynamics of natural variability in the WFEE Nexus?

Coupling a human model with a process-based model - the Mekong River
(Khan et al. 2017; Yang et al. 2018)
### ABM Study 2 – Accommodating natural variability

- The Mekong River Basin is the **sixth** largest river basin in the world.
- Over **50 million people** depend upon the River for **food, water**, and economic sustenance, and the Basin is home to several diverse **ecosystems**.
- The primary energy sources in the Mekong River Basin is **hydropower** (China-72%, Myanmar- 75%, Laos- 91%, Cambodia- 57%, Vietnam- 47% and Thailand- 30%).

Similar water use agent definition as the Yellow River study, 32 dams, 23 eco hotpots.
ABM Study 2 – Accommodating natural variability

- Soil and Water Assessment Tool (SWAT)
  - A river basin scale model developed to quantify the impact of land management practices in large, complex watersheds.
  - Open-source
  - Physical process-based daily simulation
  - Fully or semi-distributed - HRU

ABM Study 2 – Accommodating natural variability

- Streamflow variability will affect human decision
ABM Study 2 – Accommodating natural variability

- Rule-based simulation ABM setup
ABM Study 2 – Accommodating natural variability

- How streamflow variation + agent’s preference affect results?

Agent’s water use preference on AG

AG rank = 1

AG rank = 3

Agent’s water use preference on HP

HP rank = 1

HP rank = 3
ABM Study 2 – Accommodating natural variability

- **Level of Cooperation**
  - Drought in Vietnam (Mekong Delta) causes it to **request for help** from upstream countries
  - Tham Theun 2 Dam in Central Laos **releases more water** as response
- **Third party impacts**
  - Negative - Reduced food production in Central Laos
  - Positive - Increased food production in Cambodia
Ok, and then?

- So if you think natural variability is hard to model, modeling human behavior for WFEE nexus is even harder.
- Human behavior is affected by so called “common sense.”

- Which route will this guy take to go home with shortest time?
ABM Study 3 – Addressing human behavior uncertainty

How can we **address the human behavioral uncertainty in the WFEE Nexus?**

Developing the human model using Bayesian Inference Map – the San Juan River (Hyun et al. 2018)
ABM Study 3 – Addressing human behavior uncertainty

- The **San Juan River Basin** is located at the borders of four States: Utah, Colorado, Arizona, and New Mexico. It is the **largest tributary** of the Colorado River Basin.

- A typical “Western US basin” that involve **multiple water users** (farmers, cities, and power plants) and need to consider **not fully utilized Indian water right**.
ABM Study 3 – Addressing human behavior uncertainty

- River-routing and reservoir management modeling: **RiverWare**

- ABM (farmers are defined as agents, how much to irrigated is the decision)

  ➔ “Looking **backward** but acting **forward**”
ABM Study 3 – Addressing human behavior uncertainty

- **Bayesian Inference (BI) map**
  - As the *internal* thinking process in farmer’s brain to decide the probability of expanding the irrigated area

- **Cost-Loss model**
  - As the *external* economic factors that affect the probability of expanding the irrigated area

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ABM Study 3 – Addressing human behavior uncertainty

- How do we know the coupled ABM-RiverWare model can provide reasonable results? → Check historical irrigated area change
ABM Study 3 – Addressing human behavior uncertainty

- How can we use this model to address **risk perception**?

**Basin-wide results**

**Individual farmer results**

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(a) Total Irrigated Area
(b) Navajo Reservoir Water Level
(c) Flow Violation Frequency
(d) Flow Violation Volume

(a) Group1: Jicarilla
   - Risk Averse
   - Risk Seeking
   - Optimal BC-ABM

(b) Group3: Hammond
(c) Group2: NMAnimas
(d) Group3: Hogback
ABM Study 3 – Addressing human behavior uncertainty

- What will happen if the **expanding irrigated area** becomes expensive?
Remark and the way forward

Coupled human-natural complex system

WFEE Nexus

Quantify Human-nature interaction in the WFEE Nexus

Evaluate natural variability in the WFEE Nexus

Address human behavior uncertainty in the WFEE Nexus
Remark and the way forward

- The ongoing DoE project to dig deeper into the **spatial and temporal scale** issue in WFEE Nexus.
  - How can we use the ABM approach to "upscale" human decision uncertainty?
  - Compare the San Juan-ABM model vs. *Colorado River Simulation System (CRSS)-ABM*

- A new NSF project to develop a coupled ABM framework (a food module, an energy module and a water module) for the *Columbia River* Basin’s WFEE **reliability, resilience, and vulnerability**.
  - How can we adopt structured **public participation** in the ABM framework?
  - Can we use the ABM framework to facilitate the **treaty negotiation**?
Ph.D. student and postdoc positions available in CAWS!

Please contact me if you are interested yey217@lehigh.edu