Evolution of Human-Water Relationship and Impact of Climate Change: a Socio-hydrological Perspective in Tarim River Basin of China

Fuqiang Tian
Tsinghua University, Beijing 100084, China

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Socio-hydrology

A new science of people and water, which is aimed at understanding the dynamics and co-evolution of coupled human-water system

- Example: Peak water paradox

Water use is often assumed to increase with economic growth in demand projections. Yet many parts of the world are experiencing decreasing human water use despite sustained economic growth.

Sivapalan et al. 2012, 2014

Four phases of analysing human-water interactions

1) Until mid 20th century:
Effect of water on people (one way interaction ➔)
Examples: flood protection design
Flood inundations of Danube at Vienna (water → people)

Four phases of analysing water-people interactions

1) Until mid 20th century:
Effect of water on people (one way interaction ➔)
Examples: flood protection design

2) From mid 20th century (environmental movement):
Effect of people on water (one way interaction ←)
Examples: water quality, abstractions, land use, river restoration
Effect of lost inundation area on floods (water ↔ people)

<table>
<thead>
<tr>
<th>Year</th>
<th>Flood</th>
<th>Retention volume</th>
<th>volume (10⁹·m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1899</td>
<td>6.6</td>
<td>2</td>
<td>6.6</td>
</tr>
<tr>
<td>2013</td>
<td>6.1</td>
<td>&lt;0.5</td>
<td>6.1</td>
</tr>
</tbody>
</table>

Blöschl et al. (2013) HESS

Four phases of analysing water-people interactions

3) From 1990s (Integrated assessment):

Effect of people on water, effect of water on people (two way interactions, not coupled →, ↔)

Examples: Assessments for Integrated Water Resources Management (IWRM), Integrated Flood Risk Management (IFRM)
Four phases of analysing water–people interactions

3) From 1990s (Integrated assessment):
Effect of people on water, effect of water on people (two way interactions, not coupled $\rightarrow$, $\leftarrow$)
Examples: Assessments for Integrated Water Resources Management (IWRM), Integrated Flood Risk Management (IFRM)

4) 21\textsuperscript{th} century (interest in longer term view, change):
Effect of people on water on people on water .. (two way interactions $\leftrightarrow$)
Examples: Understanding how to deal with floods, droughts

Is Socio-hydrology different from IWRM?

<table>
<thead>
<tr>
<th>Integrated Water Resources Management</th>
<th>Socio-hydrology</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Decades</td>
<td>- Centuries</td>
</tr>
<tr>
<td>- Place based (case studies)</td>
<td>- Generic processes (universal)</td>
</tr>
<tr>
<td>- Details accounted for</td>
<td>- Focus on main dynamics</td>
</tr>
<tr>
<td>- Scenarios with assumed boundary conditions</td>
<td>- Dynamic Feedbacks</td>
</tr>
<tr>
<td>- Quantitative findings</td>
<td>- Conceptual findings</td>
</tr>
</tbody>
</table>
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General features of Tarim River basin

1. An inland basin surrounded by Tianshan and Kunlun Mts.
2. Four source rivers and one main stream nowadays
3. A junction between eastern and western worlds since Silk Road (138 B.C.), and 2000-year written history.
Silk Road

Climatic and Hydrological features

1. Hyperarid climate: annual precipitation is 50-100 mm/year, and water is an essential and scarce resource which dominates the dynamics of eco-environmental system
2. Hydrology: river runoff comes from thawed snow and glacier, which is significantly influenced by climate change/variation
3. Climate and hydrological change: experience significant variations of climate and frequent river course migration

River flows → Drying up
Climate change and settlements abandonments

Evolution of Tarim river system (10,000 yrs)

1. Two separated mainstreams flowing into Lop Nor in north and south Taklimakan desert before 18th century
2. 7-sources-1-mainstream pattern since 19th century
3. 4-sources-1-mainstream pattern since mid-20th century
**Social features**

- **Civilization interaction and evolution:**
  - Isolated scattered city-states civilization lasts for a long period
  - Influenced by eastern agricultural civilizations, northern nomadic civilizations and western commercial civilizations
  - Experienced settlement abandonments in 4th to 5th century, 7th to 8th century, 11th century and 13th century.

![Map of Xiyu 36 states during 200 BC](image)

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1) Natural stage ~18th century

- Natural factors dominated socio-hydrological change
- Historically, the Tarim River migration has two main features: 1) the river systems has experienced frequent and serious changes of its river courses and 2) its climate experienced back and forth swing between cool-dry and warm-wet regimes during the past 2000 years.
- The ancient human societies in TRB as a whole did not form a unified state but existed as the isolated star studded city-states for a long period, which could be explained by the low social productive force (SPF) as well as the mentioned frequent river courses migration and fierce climate change.

Liu Y. and Tian F., 2014, HESS

1) Natural stage ~18th century

- Special environmental conditions and human cultural and history leads to unique human water relationship.
- The abandonments of settlements coupled with rises and falls of nearby powerful civilizations, which intensified the negative impact of natural changes, and most settlements were abandoned in periods that poor climate conditions and social unrest co-existed, or in early warm-wet period that the eco-hydrological system was rebalancing.

ruin in middle Tarim reaches

ruin of Lou Lan in lower Tarim reaches, abandoned at about 6th century
2) Exploitation stage (from 18th to mid-20th century)

- Increasing impacts of human factors
- During this stage the southern Tarim river has gradually disconnected and separated into several small river systems in the south edge of TRB due to climatic and human causes, and since then the whole Tarim River evolved from 7-sources-1-mainstream to 4-sources-1-mainstream
- Agricultural activities expanded along with fast growing population, which was promoted by advanced policies, improved technologies and innovative socio-organization. A notable example is the tax policy of Tan-Ding-Ru-Mu carried out in late 18th century and the station-reclamation policy lasted for the whole Qing dynasty.
2) Exploitation stage (from 18\textsuperscript{th} to mid-20\textsuperscript{th} century)

- The over-exploitation of water resources caused serious degradation of natural ecological system together with significant invasion of desert. Ecological migrates appeared and the social economy in lower TRB was terribly threatened by the deteriorating human water relationship.
- Series of water conservancy projects were constructed and conducted by government and new founded water authorities.
- Water is artificially transferred to downstream for ecological system recover.

3) Degradation and recovery stage (since mid-20\textsuperscript{th} century)

- The over-exploitation of water resources caused serious degradation of natural ecological system together with significant invasion of desert. Ecological migrates appeared and the social economy in lower TRB was terribly threatened by the deteriorating human water relationship.
- Series of water conservancy projects were constructed and conducted by government and new founded water authorities.
- Water is artificially transferred to downstream for ecological system recover.
3) Degradation and recovery stage (since mid-20th century)

- Problems still exist: the wish to provide water for natural vegetation was usually defeated by the impulsion to make money
- Irrigation Efficiency Paradox: total amount of water consumption is increasing as efficiency increases
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Taiji-tire model

Structure of system

SHS: socio-hydrological system

Human-Water Taiji: The direct interaction of water and human consumptions

Boundary 1: Interaction human&water

Inner wheel

Outer tire

Drivers for the system

Boundary 2: Indirect impact from external factors on the internal human-water relationship

Human-Water Tire: Natural and social external factors and conditions
Structure of Taiji-Tire system

- Inner solid circle: a specific SHS under study, inner wheel
- Outer dashed circle: environmental system composed of human and nature, outer tire
- Socio-hydrological constitutive relationship: interactions between human and water via its water-centered inner eco-environment
- Outer environment: nature factors (climate, geological cond., ecological system, etc.), and human factors (other SHS at larger scale)

Evolution of Taiji-Tire system

- The evolution of a specific SHS is driven by inner Taiji and outer Tire simultaneously.
- For the outer Tire, the environment change especially climate variation will immediately impact the hydrological system in the specific SHS, which will further impact human part by the interactions between human and water.
- For the inner Taiji, all the internal interactions between human and water take their forms via water utilization and consumption activities, which are dominated by human aspects.
- Social productive force (SPF) is the principal driver of societal evolution, and therefore is an important interior force for the evolution
Modeling framework for socio-hydrology co-evolution of Tarim River

<table>
<thead>
<tr>
<th>System</th>
<th>State variable</th>
<th>Dependent factor</th>
<th>Modeling variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrological system</td>
<td>Water storage</td>
<td>Water consumption and policy</td>
<td>Water storage (W)</td>
</tr>
<tr>
<td>Ecological system</td>
<td>Natural vegetation area</td>
<td></td>
<td>Vegetation coverage (V_c)</td>
</tr>
<tr>
<td>Socioeconomic system</td>
<td>Irrigated crop area</td>
<td>Water and policy</td>
<td>Irrigated crop area</td>
</tr>
<tr>
<td></td>
<td>Population</td>
<td>Population</td>
<td>Population (N)</td>
</tr>
</tbody>
</table>

Industry is ignored in TRB

Differential equation set

\[
\frac{dW_U}{dt} = P_U A_U - E_{iU} A_U V_{CU} - E_{eU} A_U R_{IU} - E_{mU} A_U (1 - V_{CU} - R_{IU}) + Q_{inU} - Q_{outU}
\]

\[
\frac{dV_{CU}}{dt} = g_{vU} V_{CU} (V_{CMU} - V_{CU}) - m_{vU} V_{CU}
\]

\[
\frac{dR_{IU}}{dt} = g_{RU} g_{R2U} g_{R3U} R_{IU} (R_{IMU} - R_{IU}) - m_{RU} m_{R2U} m_{R3U} R_{IU}
\]

\[
\frac{dN_U}{dt} = g_{NU} g_{N2U} N_{U} (N_{MU} - N_{U}) - m_{NU} m_{N2U} N_{U}
\]
Four main Feedback loops

Upper reach

Middle and Lower reach

$E_{lu}A_{lu}V_{CU}$

$E_{IL}A_{IL}R_{IL}$

$g_{VDU}m_{VDU}$

$g_{RUL}m_{RUL}$

$g_{RU}m_{RU}$

$g_{VL}m_{VL}$

$g_{V}_{CL}$

$g_{RL}m_{RL}$

$Q_{out}$

$Q_{inL}$
Quasi-equilibrium state of SHS after 300-years
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Conclusions

1. Climate change could impact the evolution of SHS greatly when the hydrological response exceeds some critical thresholds.
2. Social productive is a key internal driver for evolution of SHS. With different level of SPF, the human water relationship presents totally different features.
   - Four types of SHS: Primitive agriculture, traditional agriculture, industrialized agriculture, and urban societies
   - When the SPF is low, natural factors dominate and the SHS changes with climate variations and the social responses followed.
   - With the upgrade of SPF, the SHS would evolved into a larger scale and the SPF becomes the main driver for system shift.

   Question: can we quantify social system and its adaptation to climate change so we can identify the threshold? At what scale we can resolve the question?
Conclusions

3. For a relatively short duration, the simple constitutive relations could reproduce the dynamics of social hydrological system
   ✓ Evaluate and design management policy
   ✓ Assess impact of climate change on social-hydrological system

☐ Question: how can we improve the constitutive relations?

Thank you for your attentions!

For details please refer to: