Water-land nexus relationships in socio-economic system

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Along with the rapid urbanization, the expansion of metropolitan has resulted in severe coupled problems of water and land resources.

The interaction between water-land resources is complex, which not only exists in natural system, but also in human dominated socio-economic system.

The tracking of flows and pathways within the concerned system can facilitate the regulation of virtual water circulation, land footprint flows and the adjustment of the sectors’ responsibilities.

The urban water and land resource utilization system is often viewed simply as a consumer, or as a consumption process.

However, such human dominated water circulation and land utilization has an overlapping part between the natural and artificial water cycles, which could be better understood by analysis of function and structure and driving mechanisms in the context of “ecological network”.
Water - land network

• The systematic configuration of virtual water network (VWN) and embodied land network (ELN) should be explored to describe the network structures of inner interactions and distribution of water and land resources throughout the socio-economic system.

• The tracking of virtual water and embodied land fluxes and pathways within the system will facilitate the regulation of resources circulation and the adjustment of the sectors’ responsibilities.

Ecological network analysis

• Reveal indirect and cycling flows concealed in system

• Show the interdependence and interactions between different sectors

• Figure out the configuration of pathways diversity and connectivity

• Discover robustness of the water system
Water circulation

- Often viewed within the basic natural hydrologic.
- It has an overlapping part between the natural and artificial water cycles.
- Analysis of function and structure, socio-economic factors and driving mechanisms in the context of VWN.
Heihe River

• The second largest inland river basin in arid Northwest China.
• Water resources: Limited but vital for development.

Ganzhou District

• One of the most economically developed regions in Heihe River Basin.
• Water consumption: Agricultural.

Policies:

• Control total amount of water
• Standard allocation of water in different regions
• Reducing agricultural water consumption
Network construction

Network

Data source

- Gansu Statistical Yearbook 2012
- Zhangye Statistical Yearbook 2012
- Using environmental input-output model to establish the VWN.
- Each of the aggregated sectors consists of a block of sectors with similar water use habits.
- To distinguish the pairwise relationship between similar sectors as a block and the other remaining blocks.
How to evaluate the robustness of the socio-economic network, and the interaction between pairwise sectors?
A flow system’s long-term judicious balance of **Size** and Internal **Structure** (Daly, 1997; Ulanowicz, 1980).

<table>
<thead>
<tr>
<th>Size</th>
<th>Structure</th>
</tr>
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<tbody>
<tr>
<td>Total volume water flow in the system</td>
<td>Configuration of flow diversity and connectivity</td>
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</table>

**Ecological network indicators:**
- Throughflow
- Cycling Index
- Aggradation

**Information-based network indicators:**
- Ascendency (efficiency)
- Redundancy (resilience)
- Development capacity (diversity)
Ecological network indicators

Flow intensity

\[ g_{ij} = \frac{f_{ij}}{T_j} \]

Integral flow intensity

\[ N = G^0 + G^1 + G^2 + G^3 + \ldots + G^m + \ldots = (I - G)^{-1} \]

Throughflow

\[ TST = M0 + M1 + M2 \]

Total boundary first cycled
System = flow + passage + flow throughflow flow
Efficiency: Sufficient *directed power* to maintain its *integrity* over time.

System is regular and orderly, but less connected.

Resilience: A reverse of *flexible actions* that can be used to meet the exigencies of novel disturbances

System is highly connected, but irregular and disorderly.
### Information-based network indicators

#### Ascendancy (A)

**Average Mutual Information (AMI)**

\[
AMI = K \sum_{i,j} \left( \frac{T_{ij}}{T_{..}} \right) \log \left( \frac{T_{ij}T_{..}}{T_{i.}T_{.j}} \right)
\]

\[A = AMI \times TST\]

AMI shows how well organized these flows are. E.g., a network with *more flow along fewer links* will have a higher AMI.

#### Redundancy (Φ)

**Residual uncertainty (\(H_c\))**

\[
H_c = -K \sum_{i,j} \left( \frac{T_{ij}}{T_{..}} \right) \log \left( \frac{T_{ij}^2}{T_{i.}T_{.j}} \right)
\]

\[\Phi = H_c \times TST\]

\(H_c\) shows the ability of system to withstand perturbations. E.g., a network with all flows *equally distributed along all links* will have a higher \(H_c\).
Information-based network indicators

**Ascendency (A)**
Average Mutual Information (AMI)

**Redundancy (Φ)**
Residual uncertainty ($H_c$)

**Development Capacity (C)**
Flow diversity ($H$)

$$H = -K \sum_{i,j} \left( \frac{T_{ij}}{T_{..}} \right) \log \left( \frac{T_{ij}}{T_{..}} \right)$$

$$C = H \times TST$$

$H$ shows how the diversity of flows.
E.g., a network with all flows equally distributed along all links will have a higher $H$.

$C = A + Φ$

$A$: Efficient end-to-end circulation of products
$Φ$: rebound from the loss or disruption of pathways.

Both $A$ and $Φ$ contribute to robustness.
But essentially complementary and in opposite direction.

How to keep the balance?
Information-based network indicators

System Robustness \((R)\)

\[ a = \frac{A}{C} \]

\[ R = -k \ a \ \log(a) \]
System Robustness

The Window of Vitality/Viability

Natural Ecosystem

$\alpha = A/C$

Greater Resilience

Optimal Balance

Greater Efficiency

Towards stagnation

Towards brittleness

Towards Efficiency

Improved Resilience
Research Results

What makes the differences here?

- Improve Efficiency
- Reduce Diversity

$R_{VWN}$

$\alpha$

Redundancy

Efficiency
Flow-based network indicators

Network control analysis

\[
\text{CD} = [cd_{ij}] = [n_{ij} - n_{ji}]
\]

\[
\text{CR} = [cr_{ij}] = \begin{cases} 
    n_{ij} - n_{ji} > 0, & cr_{ij} = \left\lfloor \frac{n_{ij} - n_{ji}}{\max(n_{ij}, n_{ji})} \right\rfloor \\
    n_{ij} - n_{ji} \leq 0, & cr_{ij} = 0
\end{cases}
\]

\[
\text{SC} = [sc_{j}] = \sum_{k=1}^{n} cd_{kj}
\]

NCA

- To evaluate the control/interdependence degree between sectors within the VWN.
- CD explains the influence of one sector exerted on another within the overall system configuration.
- If the CD value is positive, it stands for the control intensity; otherwise, it shows the dependent intensity.
Results

Network control Analysis

Stronger pathways:
- Far–Liv
- FHF–Liv
- Ser–Liv
- FHF–Con
- Ind–Con

Weaker pathways:
- Liv–Con
- Ind–Ser
- Ser–Con
Flow-based network indicators

Network utility Analysis

**D** = \[ d_{ij} \] = \[ \frac{f_{ij} - f_{ji}}{T_i} \]

\[ U = D^0 + D^1 + D^2 + \cdots + D^n + \cdots = (I - D)^{-1} \]

\[ NM \equiv \text{Sign}U(+) / \text{Sign}U(-) \]

\[ SI \equiv \sum_{j=1}^{n} \sum_{i=1}^{n} u_{ij} \]

NUA

- Quantifying the net gain or loss of utility between pair-wise sectors in the context of ENA.
- It can be used to investigate the relevant benefit/cost relation between the pair-wise compartments within the network.
Results

Network utility Analysis

- The Exploitative relationship is the dominating one.

- The virtual water transaction structure of network inclines to a relationship of competition between sectors.
Conclusions

- ENA is a powerful tool considering its detailed pathway focused analysis based on the network configuration and nodes’ interactions.
- It uncovers the indirect flows and influences hidden in the network systems from a whole systematic perspective.
- ENA can evaluate the stability of the whole system from the balance between efficiency and redundancy, which is vital for the system’s stability long-term sustainability.
- The anatomy of the network can be characterized by NCA and NUA based on how flows are distributed within a network at the sectoral and pathway levels.
- It uncovers the dominators and dependents along with the beneficiaries and contributors of the system.
Thank You