The Scientific Basis for Freshwater Sustainability

BZ 580, GEOL 692
Spring 2012
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Why this course?

Focus mostly on II
Water in the 21st Century?

• Water Security for human consumption
• Food Security
• Energy Security
• Human well-being
• Scarcity and Political Conflict
• What about Environmental Sustainability?
  – Largely ignored in water resources planning
    • Conflicts with human demand (often perceived)
    • Scientists done poor job of making clear costs
    • What does Nature “need”?
    • What does Society want?

The Bonn2011 Nexus Conference facilitates the definition of key elements of a common agenda for the different sectors and stakeholders to better achieve water, energy and food security for all.

The United Nations General Assembly has decided to convene a Conference on Sustainable Development in June 2012 as the twenty-year follow-up to the groundbreaking “Earth Summit” of 1992.

... a platform for all stakeholders to develop a common policy agenda to achieve Water, Energy and Food Security and specific recommendations on how to position the nexus-perspective in the Rio+20 process.

The Conference results will represent an important contribution to the United Nations Conference on Sustainable Development.
Freshwater ecosystems - the hidden natural capital

The Global Water System Project (GWSP) is an international scientific research initiative focused on the study of the global water system. The GWSP is a partnership of the International Water Management Institute (IWMI), the United Nations Environment Programme (UNEP), and the International Institute for Applied Systems Analysis (IIASA).

GWSP's mission is to advance understanding of the global water system, its interactions with the Earth system, and its role in supporting human well-being and ecosystem health.

The GWSP conducts research on a wide range of topics, including climate change, water scarcity, river basin management, and the impacts of land use change on water resources. The project also develops tools and methodologies to support decision-making in water resources management.

The GWSP is a collaborative effort involving scientists from around the world, and its findings are used to inform policies and practices aimed at sustaining the global water system.

The GWSP is headquartered in Bonn, Germany, and has a network of partners and partners worldwide.

The GWSP's work is supported by a diverse range of funding agencies, including the United States Agency for International Development (USAID), the European Union, and the governments of Japan and Switzerland.

The GWSP is committed to sharing its research findings with the global community, and it regularly publishes its results in scientific journals and through its website.

The GWSP is a key player in the global effort to address the challenges facing the world's water systems, and its work is helping to inform policies and practices that are essential for sustaining the planet's water resources for future generations.

For more information, visit the GWSP's website at www.gwsp.org.
Distribution of Earth’s Water

<table>
<thead>
<tr>
<th>Table 1. Major stocks of water on Earth (34)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution area, Volume, Percent of total water, Percent of fresh water,</td>
</tr>
<tr>
<td>$10^4$ km$^2$, $10^3$ km$^3$, $%$, $%$</td>
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<tr>
<td>Total water</td>
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<tr>
<td>Total freshwater</td>
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<tr>
<td>World oceans</td>
</tr>
<tr>
<td>Saline groundwater</td>
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<tr>
<td>Fresh groundwater</td>
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<tr>
<td>Antarctic glaciers</td>
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<td>Greenland glaciers</td>
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<tr>
<td>Arctic islands</td>
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<tr>
<td>Mountain glaciers</td>
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<tr>
<td>Ground ice/permafrost</td>
</tr>
<tr>
<td>Saline lakes</td>
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<tr>
<td>Freshwater lakes</td>
</tr>
<tr>
<td>Wetlands</td>
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<tr>
<td>Rivers (as flows on average)</td>
</tr>
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<td>In biological matter</td>
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<td>In the atmosphere (on average)</td>
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Gleick (2010, PNAS)

Why should society care about freshwater ecosystems?

Adapted from Carpenter & Postel 1997
Mekong River Fisheries Provide Primary Source of Protein for 55 million people

Adapted from Costanza et al. 1997
Why care about freshwater ecosystems?
Unraveled Biodiversity

Compared to marine and terrestrial systems on a per unit area basis.

United States contributes greatly to global freshwater biodiversity.

(Tables and graphs from various sources, including Strayer & Dudgeon 2010, Master et al. 1998, Rivers of Life, Gleick 2010, PNAS)

Why is freshwater diversity so high?
Naturally isolated nature of FW ecosystems combined with natural barriers to gene flow has facilitated great evolutionary diversification.

- linear stream channels surrounded by hostile terrestrial matrix
- upstream-downstream barriers

Is there “enough” water given projected future population growth?

“Peak oil” – ca. 1970 (crude oil is finite resource)

“Peak Water”?

Renewable runoff

“Non-renewable” groundwater
Peak Ecological Water?

Social Questions:

- What "services" are "valued"?
- How do we quantify it?
  (Ecosystem Good & Services Analysis)

- What do humans "value"?
- How do we quantify it?
  (Economic Analysis)

Science Questions:

- How do we define/quantify this curve?

- What natural processes allow a system to continue to provide services?

Can construct relationship between value of human services and water

Gleick (2010, PNAS)
And cost of obtaining that water ...
There will also be a cost of removing obsolete infrastructure (which probably wasn’t included in the initial calculations)

Figure 5: (A) Dam removal in the U.S. by (A) decade and (B) structure height. Data taken from American Rivers et al. (1999) and Doyle et al. (2000).

Mega-dams globally

(B. Lehner, WWF)
Have we passed Peak Ecological Water?

Global: Freshwater Ecosystem Degradation

Inland water habitats and species are in worse condition than those of forest, grassland or coastal systems ... It is well established that for many ecosystem services, the capacity of inland water systems to produce these services is in decline and is as bad or worse than that of other systems ... The species biodiversity of inland water is among the most threatened of all ecosystems, and in many parts of the world is in continuing and accelerating decline. (Millennium Assessment, 2005)

Rivers and their floodplains, lakes and wetlands have undergone more dramatic changes than any other type of ecosystem. (Secretariat of the Convention on Biological Diversity, 2010)

Biodiversity

Species declines in freshwater are twice that of terrestrial and marine systems

10,000-20,000 freshwater species are extinct or imperiled
Many impacts to streams and rivers

**Causes**
- Land-use
  - Agriculture
  - Urbanization
  - Timber harvest
  - Grazing
  - Mining
- Channelization
- Diversions
- Dams
- Species introductions
- Climate change

**Consequences**
- Nutrient enrichment
- Sediment delivery
- Contaminants
- Habitat modification
- Altered flow regimes
- Altered thermal regimes
- Biotic simplification
- Species extinctions
- Altered ecosystem function
- Loss Good & Services

**Actions**
- Mitigation
- Restoration
- Conservation

Biomonitoring to quantify effects and guide management actions
Effects of Dams and Diversions

• Alter downstream water and sediment flux and severely alter aquatic ecosystems
• Disconnect floodplains and cause collapse of riparian forests
• Eliminate nursery grounds for fishes (floodplain wetlands)
• Reduce potential carbon sequestration in floodplain vegetation
• Reduce natural flood storage and encourage human settlement of floodplain
• Displace people

Modify downstream hydrologic regime

Green River Hydrograph below Flaming Gorge, WY

Lytle and Poff (2004, TREE)
Colorado River does not regularly reach the Sea of Cortez

Draining of Aral Sea (Uzbekistan) for cotton irrigation
Global Reservoir and Dam (GRanD) database
(Lehner et al., 2011, Frontiers in Ecology & Environment)

Trap sediment – deprive estuaries and increase human vulnerability

Vulnerability of New Orleans

River Fragmentation Rivers by Dams

Interrupt movement of species: Salmon in the Columbia River Basin

The Lower Snake River, Western Washington State, part of the Columbia River Basin

Projections into future

Southwestern U.S.
Drying of SW U.S. (Lettenmaier et al. 2008)

**Figure 4.10** Median changes in runoff interpolated to USGS water resources regions from Mily et al. (2005) from 24 pairs of GCM simulations for 2041-2060 relative to 1901-1970. Percentages are fraction of 24 runs for which differences had same sign as the 24-run median. Results replotted from Mily et al. (2005) by Dr. F.C.D. Mily, USGS.

Future Dam Growth:
Developed Hydropower Capacity

"Green Energy"
Water Security and Biodiversity Threats

Figure 1 | Global geography of incident threat to human water security and biodiversity. The maps demonstrate pandemic impacts on both human water security and biodiversity and are highly coherent, although not identical. (Biodiversity threat = 0.964 × human water security threat + 0.018; r = 0.97, P < 0.001). Spatial correlations among input drivers (stream order) varied, but were generally robust (means [r] = 0.24, n = 235 comparisons). Regional maps exemplify main classes of human water security threat (see main text and Supplementary Fig. 6). Spatial patterns proved robust in a variety of sensitivity tests (Supplementary Methods and Supplementary Discussion). Threat indices are relative and normalized over discharging basins.

Vörösmarty et al. (2010, Nature)
A key premise:

If we aim to support functional, self-sustaining ecosystems that provide ecosystem goods & services and that maintain native biodiversity, then ...

we need to know how these ecosystems function and how resilient this function is to magnitude of current and projected environmental change
Future water demand will further stress ecosystems

**Surface water abstraction stress to rivers**  
*(Stress is ratio of water use to water availability)*

(World Wildlife Fund: www.feow.org)

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**Major Challenges**

How to sustain health of freshwater ecosystems when human demand for fresh water is increasing?

How do we “value” ecosystems as part of long-term human well-being

Must manage catchments and rivers with process-based understanding of what maintains resilience and self-sustainability
River flows and river health are intimately connected to the watershed

Rivers vary dynamically over time

Two key points:

1) dynamic character is critical for the health of the natural river ecosystem

2) dynamic pattern varies from place to place with climate (precipitation pattern)
The “Natural” Flow Regime

The structure and function of river ecosystems, and the adaptations of constituent species, are dictated by the pattern of temporal variation in river flows.

**The Natural Flow Regime**

A paradigm for river conservation and restoration

N. LeRoy Poff, J. David Allan, Mark B. Bain, James R. Karr, Karen L. Prestegaard, Brian D. Richter, Richard E. Sparks, and Julie C. Stromberg

Humans have long been fascinated by the dynamics of free-flowing waters. Yet we have expended great effort in tame rivers for transportation, water supply, flood control, agriculture, and power generation. It is now recognized that harnessing of streams and rivers comes at great cost: Many rivers no longer support socially valuable ecological integrity. However, current management approaches often fail to recognize the fundamental scientific principle that the integrity of flowing-water systems depends largely on their natural dynamic character; as a result, these methods frequently prevent successful river conservation or restoration. Streamflow quantity and timing are critical components of water

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**Dams and diversions**

The flow regime is a “master variable” that directly and indirectly dictates ecological processes and ecosystem states

... a key link between human use and ecosystem needs
How are dams managed for environmental benefit?

- Minimal flows, often for single (exotic) species.
  - Coldwater fish below dams globally
- Seasonal floods attenuated.
  - Natural dynamics that maintain habitat and provide opportunities for disturbance-adapted species are eliminated.
- Management failures: Occasional failures reinstate the natural order.
  - Major floods around the world

International Concern and Consensus

http://www.diversitas-international.org/activities/research/freshwaterbiodiversity/resources/Brisbane_Declaration.pdf
ENVIRONMENTAL FLOWS are “about the equitable distribution of and access to water and services provided by aquatic ecosystems. They refer to the quality, quantity, and timing of water flows required to maintain the components, functions, processes, and resilience of aquatic ecosystems that provide goods and services to people.”

Scientific Challenge

Define the water needs of freshwater ecosystems to legitimize their protection and restoration in the face of rapid human population demand and global change.
How to go about determining and implementing environmental flows?

Rules of thumb? – we can do better than this!

Fraction of mean annual flow requirement to maintain a river basin in some agreed ecological condition.

Natural Flow Regime Perspective

- Different aspects of flow regime play important ecological functions that can be identified
- Modify regime component → modify function

ELOHA (Ecological Limits of Hydrologic Alteration)

Define flow regimes for networks of reaches and explicitly consider geomorphic context.

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**Scientific Process**

1. **Step 1. Hydrologic Foundation**
   - Baseline Hydrographs
   - Hydrologic Model and Stream Gauges
   - Developed Hydrographs

2. **Step 2. Stream Classification**
   - Stream Hydrologic Classification
   - Geomorphic Stratification

3. **Step 3. Flow Alteration**
   - Degree of Hydrologic Alteration
   - Hydrologic Alteration by River Type

   - Flow - Ecology Hypotheses
   - Ecological Data and Indices
   - Flow Alteration-Ecological Response Relationships by River Type

**Social Process**

- Implementation
- Acceptable Ecological Conditions
- Environmental Flow Standards
- Societal Values and Management Needs

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**Summary**

The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards.

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The Social-Ecological Challenge of Rapid Climate Change