Hydromorphology: The Shape of our Water Future

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CUAHSI Web Seminar

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Outline of Talk

- What is Hydromorphology?
- Hydromorphology Initiatives and Questions
- Why do we need Hydromorphology?
- A Few Examples
What is HYDROMORPHOLOGY?
A new branch of hydrology

GEOMORPHOLOGY is to GEOLOGY as HYDROMORPHOLOGY is to HYDROLOGY
Geomorphology deals with structure of the earth's surface and the evolution of processes controlling topography of the earth.
The evolution of earth's topography is due to both natural and anthropogenic processes.
How did the field of Geomorphology arise?

- First use of term “geomorphology” was around the time of McGee (1888)
- Sack (2002) cite many other ‘geomorphology’ studies prior to 1888 which did not use that term
- Field arose slowly, due to large number of new challenges relating to our understanding of the processes which govern evolution of landscapes
HYDROMORPHOLOGY
A subdiscipline of hydrology

Hydromorphology deals with structure and evolution of hydrologic systems due to complex coupling between human and natural systems.
Hydromorphologic problems represent scientific, social and engineering challenges related to how humans reshape fresh-water systems through modifications to the landscape, water infrastructure, and climate, and how our reshaped water systems influence life on the planet.

- Science Forum Article in progress by:

- A CUAHSI Hydrologic Synthesis Center Initiative
Why do we need a new field of HYDROMORPHOLOGY?

Human influences are now pervasive

Virgin watersheds no longer exist.
Virgin or Pristine Watersheds No Longer Exist – “Stationarity is Dead” (Milly et al., Science, 2008)
The Net Impact of Dams and Human Water Use

Colorado River Delta Runs Dry


Fig. 1. Colorado river flows below all major dams and diversions, 1905 to 2001. Data are flows of the Colorado River as measured at U.S. Geological Survey Gage 09-5222, 35 km downstream from Morelos Dam. As shown, flows reaching the Colorado River delta have dropped to near zero in most years.
It is no longer possible to ignore human impacts on hydrologic systems.
Tufts University

Human Impacts on Hydrologic Systems

Proposal to Link Major Indian River Systems

$160 Billion Capital Cost

33 Dams (9 Major)

30 Major Canals covering 12,500km

34 million hectares to be irrigated (12x Area of Bangladesh) = 30% of current

34GW of hydropower

Flood Control and Navigation
Hydromorphology deals with the impacts of humans on hydrologic systems
Hydromorphology deals with the natural hydrologic processes

Human modification of global water vapor flows from the land surface

Line J. Gordon*, Will Steffen+, Bror F. Jónsson§, Carl Folke*, Malin Falkenmark†, and Åse Johannessen*

Before Human Impacts

* Department of Environmental Sciences, Tufts University, Medford, Massachusetts, USA
† Institute of Environmental Sciences, Uppsala University, Uppsala, Sweden
‡ Department of Physical Geography, Stockholm University, Stockholm, Sweden
§ Department of Geography, Stockholm University, Stockholm, Sweden

Fig. 1. Spatial distribution of annual water vapor flows (mm/yr) from potential vegetation, illustrating water vapor flows before human impacts. The figure illustrates the importance of vapor flows from the humid tropics. The total global vapor flow amounts to 67,000 km³/yr.
Hydromorphology also deals with the impacts of humans on natural hydrologic processes.

Human modification of global water vapor flows from the land surface

Line J. Gordon*, Will Steffen*, Bror F. Jönsson§, Carl Folke*, Malin Falkenmark†, and Åse Johannessen*

After Deforestation

Fig. 2. Spatial distribution of changes in vapor flows due to deforestation (mm/yr), based on the change in vapor flows between potential vegetation and actual vegetation in deforested areas. The total decrease in vapor flows is ~3,000 km³/yr.
Hydromorphology also deals with the impacts of humans on natural hydrologic processes.

Human modification of global water vapor flows from the land surface

Line J. Gordon*, Will Steffen+, Bror F. Jönsson§, Carl Folke*, Malin Falkenmark†, and Åse Johannessen*

Irrigation Only

Fig. 3. Spatial distribution of changes in vapor flows due to irrigation (mm/yr), defined as the change in vapor flows when irrigation only is added to actual vegetation. The total increase in vapor flows amounts to 2,600 km³/yr.
Hydromorphology also deals with the impacts of water on humans

Water Pollution and Water Scarcity

Are the two biggest water challenges of the 21st Century
Hydromorphology also deals with the impacts of water on humans.

Today, 1 out of 6 people, more than a billion suffer from inadequate access to safe freshwater.
Hydromorphology also deals with the impacts of water on humans.
Defining HYDROMORPHOLOGY

- The Science of Hydrologic Change
  - Detection, Attribution, Prediction and Management

- Anthropogenic Influences on Hydrosphere
  - Land Use, Climate Change, Water Infrastructure
  - Interactions and Consequences

- Natural Influences on Hydrosphere
  - Climate Variability
  - Interactions and Consequences

- How Do We Plan For Nonstationarity?
  - Design, Adaptation and Mitigation
## Hydromorphology: A Field/Word Needing Definition

<table>
<thead>
<tr>
<th>Field</th>
<th>Google Hits (in millions)</th>
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<tbody>
<tr>
<td>Geology</td>
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<tr>
<td>Geomorphology</td>
<td>16.3</td>
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<tr>
<td>Hydrology</td>
<td>30.9</td>
</tr>
<tr>
<td>Hydromorphology</td>
<td>0.024</td>
</tr>
</tbody>
</table>
Recent Conflicting Definitions of Hydromorphology:

- Classification system for soils (Rabenhorst et al., 1998)
- Structure of soil systems (Wilding and Lin, 2006)
- Physical habitat constituted by the flow regime (hydrology and hydraulics) and the physical template (fluvial geomorphology) (Newson and Large, 2006; Orr et al., 2008)
- The hydrological and geomorphological elements and processes of waterbody systems (European Commission, 2000).
Human Induced Hydromorphologic problems are in their infancy

Global Population Growth

Population in Billions

YEAR (AD)
Hydromorphologic problems are in their infancy.
Example Questions Motivating Hydromorphology

- How have humans reshaped fresh-water systems through modifications to the landscape, water infrastructure, and climate?
- How have our reshaped water systems influenced life on the planet?
- How has water constrained and determined climate?
- When/how will human induced hydrologic change dominate that due to climate change?
- How will we manage such changes?
Röckström et al. (2009, Nature) argue that human impacts are now so pervasive that at least 3 of 9 planetary boundaries have been crossed relating to:

- climate change,
- biodiversity loss
- nitrogen & phosphorus cycles.
Figure 1 | Beyond the boundary. The inner green shading represents the proposed safe operating space for nine planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change, and human interference with the nitrogen cycle), have already been exceeded.
Human Impacts are Pervasive: Groundwater Depletion Reduces Streamflow

River and Well Hydrographs from North China Plain
(from Konikow and Kendy, ”Groundwater depletion: A global problem, 2007)
2005 Headline: “Low flow in the Colorado River Basin Spurs Water Shortage Discussion Among Seven States”

The “Observed” Lees Ferry Flows

- Colorado River Comp.ex
- Compact allocation (18.5 MAF)
- Lowest observed flow (1977: 5.5 MAF)

Data source: Bureau of Reclamation, May 2006
Natural Hydrologic and Climatic Variability

Data analysis courtesy of Dave Meko
Which Is It?

Increasing risk of great floods in a changing climate

P. C. D. Milly*, R. T. Wetherald†, K. A. Dunne* & T. L. Delworth†

No upward trends in the occurrence of extreme floods in central Europe

Manfred Mudelsee¹*, Michael Börngen¹, Gerd Tetzlaff¹
& Uwe Grünewald²
Tufts University

Water and Climate

Carbon Dioxide in the Atmosphere

Carbon Dioxide Levels Today are Higher than over the Past 650,000 Years

Industrial CO₂ Levels

Pre-industrial CO₂ Levels


New Antarctic ice core data extends the record back to 650,000 years before the present and shows that CO₂ levels were below 300 ppmv.
“Today the time for doubt has passed. The IPCC has unequivocally affirmed the warming of our climate system, and linked it directly to human activity.” (UN Secretary General, November 2007)
Do you think human activity is a significant contributing factor in changing mean global temperatures?

The answer is generally yes.

A Gallop Poll
Shrinking of Arctic Sea Ice
(from Epstein, 2008)

Extent of Ice Cover (millions of sq. mi)

Arctic sea ice

1978  Year  2008
Glacial Melt – Reduction in Long Term water storage and fluxes

Figure 6. Field photograph of terminus region of Chhota Shigri glacier, Lahaul and Spiti district, of HP taken in 1988 and 2003. In 1988, glacial ice is exposed on the surface and small portion of the terminus is covered by debris. By year 2003, the entire terminus zone is covered by debris.

Glacial retreat in Himalaya using Indian Remote Sensing satellite data

Anil V. Kulkarni¹, I. M. Bahuguna¹, B. P. Rathore¹, S. K. Singh¹, S. S. Randhawa², R. K. Sood² and Sunil Dhar³
Examples of human-induced climate change are now apparent on every continent.

Source: IPCC 2007: Climate Change Impacts, Adaptation and Vulnerability
Increased Coastal Flooding under Climate Change

Wetland Inundation and Loss
Increased Coastal Flooding under Climate Change

-More coastal erosion

Dr. Norbert Psuty

Brandt Beach Long Beach Island, NJ
Coastal Flooding in Boston under Present and High Emission Sea Levels

Source: NECIA/UCS 2007
Boston: The Future 100-Year Flood under the Higher-Emissions Scenario

Source: NECIA/UCS, 2007 (see: www.climatechoices.org/ne/)

Landmarks

A. Commonwealth Avenue
B. Newbury Street
C. Old South Church
D. Copley T Station
E. The Esplanade
F. Copley Square
G. Trinity Church
H. John Hancock Tower
I. Hatch Shell
J. Arlington T Station
K. Public Garden and Swan Boats

Current 100-year flood zone
Projected 100-year flooded area (higher-emissions scenario)
New York City:

Today’s 100-Year Flood Could Occur Every 10 Years under the High-Emissions Scenarios

Hydromorphology Example 1

How well do we understand the influence of urbanization processes on streamflow?

What are the effects of:

Land Use Changes
Climate Changes
Water Infrastructure
All Together?
Aberjona River, Massachusetts
24 sq. mi. urban catchment northwest of Boston
Annual Maximum Flood Discharges have been steadily increasing

Aberjona River, MA

\[ Q = \text{Annual Maximum Floodflow (cfs)} \]

\[ \ln(Q) = 0.0147 \text{ Year} - 23 \]

\[ R^2 = 0.2186 \]

\[ p=0.000 \]
Note how 100-year flood has steadily increased from one decade to the next.
It is not only floods which are influenced by urbanization.
Annual evapotranspiration decreased due, in part, to conversion from forest to urban land use.
Consider another urbanizing watershed near Boston – Neponset River
Another nearby urbanizing watershed just south of Boston …

Here, like the textbook says,
Like clockwork, low flows have been dropping over time as impervious area has increased.
<table>
<thead>
<tr>
<th>Hydromorphologic Processes</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impervious Cover</td>
<td>↑</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>↓</td>
</tr>
<tr>
<td>Stormwater System Leaks</td>
<td>↑</td>
</tr>
<tr>
<td>Water Withdrawals</td>
<td>↑</td>
</tr>
<tr>
<td>Return Flows and Imports</td>
<td>↑</td>
</tr>
</tbody>
</table>
As Urbanization Increases, Streamflow Tends to …?

Hydromorphologic Processes

- Impervious Cover
- Evapotranspiration
- Stormwater System Leaks
- Water Withdrawals
- Return Flows and Imports

Impact on River

- High Flows
- Low Flows

Net Impact on Streamflows

?
Example 1 - Summary

Understanding relationships between changes in:

land use
climate
water infrastructure

and

hydrologic processes

is a central challenge of hydromorphology
Example 2: Flood Trends
US Rivers

First consider four basins in New England

Gage 1120500

\[ \ln(Q) = 0.015t - 23 \]
\[ R^2 = 0.22 \]
\[ p=0.00 \]

Gage 119400

\[ \ln(Q) = 0.022t - 35 \]
\[ R^2 = 0.23 \]
\[ p=0.00 \]

Gage 1052500

\[ \ln(Q) = 0.0046t - 0.65 \]
\[ R^2 = 0.074 \]
\[ p=0.01 \]

Gage 1122680

\[ \ln(Q) = 0.0413t - 76 \]
\[ R^2 = 0.2429 \]
\[ p=0.01 \]
Flood Trends

Define Flood Magnification Factor,

\[ M = \frac{Q_T(t + \Delta t)}{Q_T(t)} = \frac{T - \text{year flood in year } t + \Delta t}{T - \text{year flood in year } t} \]

With log linear trend model and lognormal floods

\[ M = \exp[\beta \cdot \Delta t] \]

\[ \beta = \text{trend slope in } \ln(Q) = \alpha + \beta \cdot t \]
# Results

## Decadal Flood Magnification Factors

From Vogel et al. 2010, JAWRA, in press

### 3 Groups of USGS Gages

<table>
<thead>
<tr>
<th>Group Of Sites</th>
<th>Total Number of Sites</th>
<th>Number of Sites with Significant Positive Trends</th>
<th>Percentage of Sites With Significant Positive Trends</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unregulated</td>
<td>14,893</td>
<td>1,642</td>
<td>11%</td>
</tr>
<tr>
<td>Regulated</td>
<td>4,537</td>
<td>481</td>
<td>11%</td>
</tr>
<tr>
<td>HCDN</td>
<td>1,588</td>
<td>208</td>
<td>13%</td>
</tr>
</tbody>
</table>
Decadal Magnification Factors of Floods – Sites w/ no regulation

1,642 of 14,893 USGS Gage Sites

From Vogel et al. (2010) JAWRA, in press
Decadal Flood Magnification Factors
Sites With No Regulation

From Vogel et al., 2010, in press, JAWRA
Decadal Flood Magnification Factors - HCDN Sites

208 of 1,588 HCDN Gage Sites with

Legend
Magnification Factor (p>0.9)
- <1.25
- 1.25-1.5
- 1.5-2
- 2-5
- >5

From Vogel et al. (2010) JAWRA, in press
Summary

Magnitude of climate induced trends are minimal compared with other anthropogenic induced trends.

From Vogel et al., (2010) in press, JAWRA
Example 2 - Summary

Nonstationarity poses a central challenge to the field of hydromorphology

Hydromorphological Science Challenges:

Detection and Attribution of Change

Hydromorphological Engineering Challenges:

Design, Prediction and Management Under Change
Most Hydrology Texts Cover the “Scientific” Water Budget Without Humans

\[ P = \text{Precipitation}; \]
\[ ET = \text{Evapotranspiration} \]
\[ SW_{\text{out}} = \text{Surface-water runoff} \]
\[ GW_{\text{in}} = GW_{\text{out}} = \text{groundwater} \]
But We Don’t Live in a “Scientific Watershed”

P = Precipitation;
ET = Evapotranspiration
$SW_{out}$ = Surface-water runoff
$GW_{in}$ = $GW_{out}$ = groundwater
Special Thanks to:

Peter Weiskel (USGS) and other collaborators resulting in:

Adding Humans to the Water Balance

Influence of Water Use:

\[ H_{\text{out}} = \text{human withdrawals} \]

\[ H_{\text{in}} = \text{human return flows + Imports} \]
A new conceptual model of the terrestrial water balance:

...with three flux classes:

- Land-atmosphere fluxes (P, ET)
- Landscape fluxes (GW, SW)
- Human fluxes (Hin, Hout)
Water-use Regimes:
4 end-member (EXTREME) regimes

(from Weiskel, Vogel and others 2007)
Water-use regime plot

Shows relative magnitudes of withdrawals versus return flows and of human vs. natural fluxes.

(from Weiskel, Vogel and others, 2007)
Selected Water-Use Regimes
Watersheds

From Weiskel, Vogel and others., 2007
Selected water-use regimes

Aquifers

From Weiskel, Vogel and others., 2007
A Water Resource Development Pathway

Mississippi River Alluvial Aquifer, Predevelopment 1918 to 1998

Water use regimes are subject to trends

Based on transient simulations of Reed (2003)
Sustainable Water-Use Regimes

A rich topic for future research

Normalized Withdrawals

Normalized Return Flows
Summary

We can no longer ignore anthropogenic influences on the hydrologic cycle.

Hydromorphology provides a conceptual basis for improving our understanding of the coupling between human and natural water systems.

Hydrologic science and engineering methods must deal with a changing hydrosphere.
Improve interdisciplinary education and hydrologic literacy

- Give greater attention to interdisciplinary subjects and languages such as: statistics, GIS, systems analysis, information sciences,
- Innovative interdisciplinary programs are needed - see http://tufts.edu/water
- Integrate hydromorphologic perspective into undergraduate and graduate curricula.
Harmonize research with policy development

- Hydromorphology must support water resources design, planning and management.
- Hydromorphology accounts for coupling between societal and natural influences on water systems
- Linkages between hydrologic, social, and political systems are needed to improve decisions about sustainable water use, management and land use.
Ensure commitments to observational programs

• Keeling (2008) said “The only way to figure out what is happening to our planet is to measure it, and this means tracking changes decade after decade, and poring over the records.”

• Milly et al. (2008) said: “Modeling should be used to synthesize observations; it can never replace them.

• In a nonstationary world, continuity of observations is crucial.”
Summary

Hydromorphological Science

“understanding the role of land use, climate and infrastructure on the hydrologic cycle”

Hydromorphological Engineering:

“Hydrologic engineering in a changing hydrosphere”