Virtual Water Accounting: A New Framework for Managing Great Lakes Water Resources

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Organization of webinar

- Introduction and background
- Project phases
  1. Groundwater availability in the Great Lakes region
  2. Water scarcity in the Great Lakes region
  3. Water scarcity, spatial scale, and resilience in Great Lakes watersheds
  4. Virtual water flows in the Kalamazoo watershed: A case study
- Questions
Background – Alex Mayer
Background: The Compact

• “…each Party [the Great Lakes states] shall create a program for the management and regulation of New or Increased Withdrawals and Consumptive Uses by adopting and implementing Measures consistent with the Decision-Making Standard.”

• “The Withdrawal or Consumptive Use will be implemented so as to ensure that…. no significant individual or cumulative adverse impacts to the quantity or quality of the Waters and Water Dependent Natural Resources and the applicable Source Watershed…”

• “The proposed use is reasonable, based upon a consideration of the following factors...The balance between economic development, social development and environmental protection of the proposed Withdrawal and use and other existing or planned withdrawals and water uses sharing the water source…”
Background: Our project

- Frameworks are needed to quantify, manage and regulate new or increased uses according to a set of sustainability principles.
- These frameworks need to
  - be based on rigorous sustainability indices linking water use to economic production and ecosystem impacts, in the context of the Compact
  - anticipate the possibility that one water use may need to be chosen over the other and as such should provide a way to assess the value and benefits of competing uses
- The overarching goal of our project is to investigate, develop, and implement a *virtual water* framework to sustainably manage water withdrawals in the basin.
Background: What is virtual water?

- Virtual Water is the water associated with a traded good or service, and is the water resource impact associated with the production of that good or service.
- The concept is useful for visualizing how water impacts are outsourced (or insourced) through trade, and how trade creates or substitutes for local water impacts.
- Historically, consumptive-use 'Water Footprints' have been the basis for virtual water methods, but we aim to develop an approach that considers resource impact thresholds.
Background: What is virtual water?

Exports and imports of water through food and commodities, 1996-2005

Source: [waterfootprint.org](http://www.waterfootprint.org/Reports/Hoekstra-Mekonnen-2012-water-footprint-of-humanity.pdf)
Background: What is virtual water?

- Virtual water balance
  \[ VWB = V_{in} - V_{out} + R \]

- \( VWB \) allows us to determine the net consumption of water associated with
  - goods and services exported from a watershed
  - goods and services imported to the watershed

\( V_{out} \) is the consumptive use that occurs in an area associated with exports from the area.

\( V_{in} \) is the consumptive use that occurs in the area from where imported goods and services were produced.

\( R \) is the local capture of water used to produce exports.
Background: **What are ecological flows?**

- ...the quantity, timing, and quality of water flows required to sustain aquatic ecosystems and the human livelihoods that depend on the ecosystems...

- Successive withdrawals can result in reduction of flows to the point where ecosystems are harmed

- Example: The Michigan Water Withdrawal Process (WWAP) utilizes threshold ecological flows based on
  - a watershed scale
  - average flows in a low flow (summer) month
  - the size and temperature of the river

⇒ threshold flows vary by location
Background: Putting it all together - the checking account

What is the appropriate measure of water use?
- withdrawals?
- consumptive use?
- VWB?
Background: Our project

- Assess water availability and scarcity across the Great Lakes basin.
- Determine virtual water imports and exports across the basin.
- Assess environmental and economic aspects of virtual water flow balances.
Phase 1: Groundwater availability in the Great Lakes region – Alex Mayer

Collaborators: Katelyn Watson and Howard Reeves
The Study

- Baseflow, supplied by groundwater aquifers hydraulically connected to streams, is key to maintaining stream flows.
- Groundwater pumping from hydraulically-connected, shallow aquifers can reduce baseflow and negatively impact the stream and associated ecosystem.
- The ecological capacity of a groundwater aquifer is defined as
  - the maximum amount of groundwater pumping that can be sustained before baseflow is reduced and a critical ecological flow limit is reached.
- Return of water pumped from deep aquifers to streams can actually increase stream flows!

http://ga.water.usgs.gov/edu/watercyclesummary.html
The Study

• Groundwater pumping capacity also is limited by aquifer hydrogeology.
• Aquifers with low permeability and/or thin saturated zones have limited pumping capacity.
• We assessed groundwater availability based on both ecological and hydrogeologic limitations.

http://wellwater.oregonstate.edu/groundwater/html/GroundwaterWells.htm
The Study

- **Hydrogeologic limits** were based on the pumping rate at where drawdown at the well is equal to half of the original water table height.

- **Ecological limits** were based on a maximum depletion (10% or 20%) of the average stream flow during a low-flow month.

- Hypothetical wells were placed randomly in a watershed and pumped to determine the maximum pumping rate.

- Groundwater models were used to estimate maximum pumping rates.

- Maximum pumping rates were averaged across the hydrologic unit code 8 (HUC-8) watershed scale.

- Result: relative capacity for ground pumping in a watershed
Results

Manistee watershed

- Dominant factors:
  1. Saturated thickness
  2. Aquifer material permeability
Results

- Relative availability varies considerably around the Great Lakes region

**Explaination**

HUC-8 watersheds

mean Q<sub>w,max</sub> (m<sup>3</sup>/d)

- 30 - 200
- 200 - 500
- 500 - 1500
- 1500 - 3500
- 3500 - 6000
- 6000 - 11000
- 11000 - 19000

- High permeability, thick aquifers, low flows
- Low permeability and/or thin aquifers
Results

- The importance of the hydrogeologic vs. ecological constraint varies across the region.

Hydrogeology dominates in certain areas, while ecological flows dominate in others.
Implications

• These maps show where there may be greater capacity to support water-intensive agriculture.

• The maps may also help communities understand how sensitive their groundwater supply is to use and plan appropriately for future land use development.

• Additionally, the maps may inform water use planning and permitting decisions made by state agencies.
Future work

• Model the cumulative impacts and the seasonal affects of multiple groundwater users on the flows downstream.
• Explore the consequences of setting non-uniform environmental limits for streamflow depletion based upon stream type.
Questions?
Phase 2: Water scarcity in the Great Lakes region – Ben Ruddell
Water Scarcity in the Great Lakes

• Geographic focus: Great Lakes Basin

• Explore spatial and temporal location and human causes of freshwater ecosystem water scarcity

• Use ecological flow thresholds derived from legal definitions and empirical science

• Develop appropriate water sustainability indices based on these thresholds

• Begin with a typical watershed: the Kalamazoo

Where (scales, locations, times) does water scarcity currently exist in the Great Lakes Basin, and how do economic water uses contribute to scarcity?
Adverse Resource Impact (ARI) Thresholds are widely utilized to impose limits on natural resource use that establish maximum allowable cost.

An individual process’s Footprint is part ‘free’ and part ‘adverse’; we need to distinguish between these in sustainability indices or water footprints are dramatically over-estimated, in water-rich systems.

Indices for a Resource Stock, ‘r’

\[
\frac{F'_r}{T_r} = \text{Threshold-Based Stress Index}
\]

\[
\frac{F'_r}{S_r} = \text{Availability-Based Stress Index}
\]
Fish Curve ARI’s

\[ \frac{D}{T} = \text{Water Scarcity Index} \]

(Fitzgerald et al., 2013, Mubako et al., 2013)
ARI Thresholds \((T)\) are a general method for resource management implying maximum acceptable costs of cumulative impacts.

Because of thresholds, sustainability indices must consider scale, upstream effects, and augmentation/storage when calculating impacts.

Part of a process’s impacts are ‘free’ and part create ‘adverse’ costs.

The simple consumptive-use ‘blue’ Water Footprint is equivalent to the threshold-based Water Scarcity Footprint if and only if \(T = 0\).

Either total Water Footprints or Water Scarcity Footprints of processes can be used as indices for Virtual Water trade or economic value analysis; we are exploring both approaches.
DATA SOURCE: The Michigan Water Withdrawal database, and the MI WWAP tool, are available online at: http://www.miwwat.org/
Methods

- Pilot watershed: Kalamazoo River
- Time scales: Monthly, Low-Flow Season (August)
- Database of large annual withdrawals* obtained from state agencies for 2009: \( W_a[(x,y), \text{use category}] \)
- Annual withdrawals converted to seasonal (monthly):
  \[ W_m = fW_a \]
- Consumptive use calculated by use category:
  \[ W_{c,m} = cW_m \]
- Convert individual \( W \)'s to streamflow depletion \( d_x \) using the Hunt equation and other assumptions

*greater than 100,000 gal/d or (~80,000 L/d) in any 30-day period,
Low flow month (August) adjustment factor = August monthly withdrawal rate ÷ by annual average withdrawal rate taken from the Michigan Water Database

Agricultural irrigation = 3.95
Public/Community = 1.35
Industry = 1.11
Golf course irrigation = 2.6
Power generation = 1.19
Public water supply = 1.14

Source: USGS, Shaffer (2009)
Impact Accumulation Methods

(1) For stream segments ‘C’ and processes ‘x’,

\[ \overline{D}_C = \sum_{x \text{ in } C} (d_x) \]

*\( d_x \) can be negative!
(discharge from storage)

(2) To aggregate depletions,

\[ D_C = \overline{D}_B + \overline{D}_A + \overline{D}_C \]

Sum over all upstream tributaries to C

MI WWAP:

- Linked models determine water withdrawal impacts on fish populations (Steinman et al. 2011).
- Based on assumed Q_{50} median streamflow baselines for low-flow summertime months.
- Establishes ARI thresholds for summertime streamflows based on maximum allowable fish costs; these are from 1% to 13% of Q_{50}, usually 10%. 

Methods

MI WWAP: Linked models to determine water withdrawal impacts on fish populations (Steinman et al. 2011).

- **Ecosystem Flow Scarcity Thresholds** (Zorn et al. 2008)
  - Ecological model: Flow reduction acceptable for fish communities

- **Modeled Stream flows** (Reeves et al. 2009)
  - Withdrawal model: Index flow for Kalamazoo stream segments

- **Streamflow model**: Index flow for Kalamazoo stream segments

- **Withdrawal Flow Impact Hunt** (1999)

- **Economic Water Use GIS analysis** (Proximity, Weighted distance etc.)

- **Compare Flow Depletion from Economic Use to Scarcity Thresholds**
Results: August Low-Flow Water Scarcity

Summer irrigation

Kalamazoo and Battle Creek

Legend
- Withdrawal location
  - Cold stream
  - Cold transitional small river
  - Cold transitional stream
  - Cool small river
  - Cool stream
  - Warm large river
  - Warm small river
  - Warm stream

D/T ratio
- 0 - 0.08
- 0.08 - 0.26
- 0.26 - 0.55
- 0.55 - 1.00
- 1.00 - 2.25
- >2.25
A strong linear relationship exists between flow depletion and spatial scale in the Kalamazoo.

Red dot above blue dot indicates water stress in a stream segment.
The ratio of Instream Flow Depletion D to the Scarcity Threshold T is a Water Scarcity Index. Dots above the blue T-line represent stream segments experiencing scarcity. The result is very sensitive to how consumption coefficients are calculated for water uses.

Threshold flows range from 1% to 13% of lowest monthly median discharge, with an average of 10%.
Conclusions

• Human or Economic uses are concentrated on mainstems and otherwise evenly distributed in space; a strong linear relationship between flow depletion and scale exists.

• Economic uses are concentrated in time during the low flow month (i.e. August), and also during June and July.

• Aggregated economic consumptive use of groundwater and surface water, i.e. the “blue” Water Footprint impacting a stream segment, sometimes results in instream ecosystem water scarcity and “Adverse Flow Impact” according to the WWAP-established thresholds, i.e. a ‘Water Scarcity Footprint’.

• Most scarcity occurs at small scales below 150 mi² (400 km²) due mostly to a combination of concentrated urban uses, sensitive cool/cold stream types, and irrigated agriculture. Few cumulative impacts occur at larger scales.

• Of course, climate variability and drought processes can create cumulative impacts, and these should also be considered in decisions.
Questions?
Phase 3: Water scarcity, spatial scale, and resilience in Great Lakes watersheds – Ben Ruddell
Water Scarcity, Spatial Scale, and Resilience in Great Lakes Watersheds

• What is the statistical distribution of water use and water scarcity?
• How does the distribution vary based on scale?
• How can we model water stress in watersheds without fine-scale water use data?
• What can we say about the resilience of this system, based on the statistics?

What are the statistical properties of the socio-hydrological system in the Great Lakes, at different spatial scales?
Water Scarcity and Spatial Scale

- Water scarcity (adversity) shows up below 400 km².
- Most streams have no scarcity; D/T < 1.
- But... we rarely have small scale data.
- To expand our research to the Great Lakes Basin, we need models of water scarcity and scale.
Impact Accumulation Methods

- A logistic distribution fits D/T at all scales
- The mean is positive, but decreases with scale
- Width of the distribution decreases with scale
- D/T in small catchments and stream segments is much less predictable with a significant fraction >1

And… we can now statistically model D/T for watersheds where we don’t have detailed small scale data! (as in most watersheds in Great Lakes…)

![Graph showing distribution of D/T at different scales](image-url)
Depletion, Randomness, and Resilience

- Depletions are **random** in space.
- Size of depletion is partially **correlated** with stream size.
- Some users actually **augment** streamflow (negative $d_x$) due to wastewater release from storage or use of deep aquifers.
- The **average** segment’s depletion is positive but $D/T << 1$.
- These four properties create **Resilience** to water scarcity because they prevent localized scarcity from propagating downstream.
- But, it is still important to manage $D$, especially at small scales.
Conclusions

• The statistical processes of this streamflow network result in resilience of the system to ecological damage due to water use, to a degree.
• It is nevertheless necessary and sufficient to manage small scale and localized impacts in order to avoid cumulative impacts.
• We can statistically model D/T and the socio-hydrological relationships between economic water use and streamflow depletion at multiple scales.
• Statistical models can estimate D/T at HUC-8 scale where data is lacking.
• Because D/T <<1 on average, this is a water-rich system and it is very important to use threshold-based sustainability indices & footprints.
• Future work is needed to establish the generality of these statistical models for different watersheds and different socio-hydrological regimes.
Questions?
Phase 4: Virtual water flows in the Kalamazoo watershed: A case study – Stanley Mubako
Introduction

• Movement of goods and services associated with direct and indirect inputs in production processes: “embedded” or “virtual.”

• This case study builds on previous studies: water use efficiency indicator- value intensity is determined & virtual water trade incorporated at the watershed level.

• We are calculating virtual water imports and exports at the watershed level because watersheds are the most appropriate entity for managing freshwater resources and ecosystems.
Research Questions

(1) What are the localized virtual water exports and imports in the Kalamazoo watershed?

(2) What are the major economic activities impacting freshwater ecosystems in the Kalamazoo watershed?

(3) Are there any linkages between water use, virtual water trade, and impacts on freshwater ecosystems?
Methods

- Economic data
- Economic / water use sectors
- Water withdrawal data
- Consumptive use coefficients
- IMPLAN data
- Water use intensities
- Multiplier matrices
- Trade flows (County)
- Adjustment factors (GIS, etc.)
- VW flows (Watershed)
Coupling of water use and economic data

- Applied input output (IO) analysis uses monetary transactions to quantify how various sectors of a complex economic system are mutually related to each other.

- Water use categories are defined based on water use and IMPLAN data categories were used to generate IO tables.

- Economic data are coupled with water use data using matrix operations to calculate direct water use intensities and value intensities.

Adjustment of county-wise data to watershed-wide data for virtual water imports

• Agriculture sector adjustments are based on actual irrigated area and agricultural land proportions.

• Thermoelectric adjustments are based on population and income data.

• Commercial sector adjustments are based on population data.

• Industry adjustments are based on GDP and population data.
Data Sources

- Water withdrawal: MI DEQ
- Consumptive use coefficients: USGS
- Economic: Bureau of Economic Analysis (BEA); Minnesota IMPLAN Group; Federal Reserve Economic Data (FRED)
- Land cover data: USGS
- Irrigated area and other agricultural: FAO; US Department of Agriculture (USDA)
- Socio-economic: US Census Bureau
Industry and Commercial sectors produce the largest economic output ($ for each m$^3$ of water consumed)
VW Imports and exports by county* & sector

Total VW imports = 17 Mm$^3$/yr.
Total VW exports = 8 Mm$^3$/yr.

Agriculture responsible for the bulk of VW flows

Total Net VW flow = + 9 Mm$^3$/yr.

*Refers to portion of county in the Kalamazoo watershed
Overall, the Kalamazoo watershed is a net virtual water importer
Some preliminary findings

• Value intensity (\$/m^3) is largest for Industry and Commercial sectors in all counties of the Kalamazoo watershed.

• In terms of water consumption, Industry and Commercial produce the largest economic output ($) for each m^3 of water consumed.

• The Kalamazoo watershed is a net VW importer: avoids impacts of local water resource withdrawals through “offsets” from vw imports.
Some preliminary findings

• Total net VW trade volumes normalized by area are largest for Allegan, Kalamazoo, Eaton, Ottawa and Calhoun counties.

• The Agriculture sector accounts for the largest proportion of VW imports and exports in the Kalamazoo watershed.

• VW import and export volumes are related to economic aspects that include agricultural land proportions, per capita income, population density, etc.
Ongoing work

- Conforming Kalamazoo virtual water calculations to smaller, “HUC 14” sub watershed scale.

- Comparison of ecological flows to net virtual water flows.

- Analysis covering the whole Great Lakes Basin.
Questions?

We gratefully acknowledge funding from the Great Lakes Protection Fund.