Riverscapes are composed of dynamic habitat mosaics determined by complex biophysical processes and interactions.
Bear digging increases meadow plant diversity

Stanford unpubl. data

Nyack Floodplain Research Natural Area
Middle Fork, Flathead River
5th order
Northwest Montana
SaRON reference site: ultra-oligotrophic, protected, no salmon.

Funded by –
NSF awards:
Biocomplexity in the Environment; Microbial Observatory; Ecology programs
GB Moore Foundation
National Park Service
1.5 km from river channel!

Stanford and Gaufin (1974) *Science*
Presence of abundant, large invertebrates shows that zones of preferential flow (rapid gw-sw exchange) characterize alluvial aquifers of gravel-bed rivers.

Pumped from gw monitoring wells – Flathead River, Montana

*Kathroperla perdita* amphibite

*Sweltsa coloradensis* occasional hyporheos

*Stygobromus sp.* stygobite
Mark Lorang, Bigfork MT

Depth and velocity data (3D-spatially continuous)
River Analyzer: data fusion and products

Lidar Digital Elevation Data/Model (DEM)

River Analyzer Data Products:
- 3D Flow hydraulics for all active channels
- Location and volume of ground-surfacewater interactions
- Bedload: real time cut and fill documentation

Add DIDSON sonar to get particle size (fish, substratum)
Nyack Floodplain, Middle Flathead River, Montana
A LIDAR image of The Nyack Flood Plain showing the landscape features, including the channel network and the mass wasting on the GNP (right) side.
A portion of the LIDAR image in the previous slide that has been processed to finer detail using a GIS. Here the water is dark black and dry flood-and paleo-channels show up as dark grey channels that bisect lighter-colored benches. These benches are covered by riparian forests.
Habitat change at the Nyack Flood Plain of the Flathead River, Montana 1945-2004

Whited et al., 2006. *Ecology*
Nyack Floodplain – Middle Flathead River, Montana
Bimodal gravel “tubes”: open framework gravel-cobble in fining-upward sequences; attached biofilms – DOM limited; abundant meiofauna; 80+ species of amphibionts & stygobionts (hyporheos); occasional benthos.

Meiofauna
large protists
archiannilids
bathenellids
copepods

Stygobionts:
Stygobromus spp. and
other amphipoda
Ascellus

Amphibionts:
Paraperla 2spp.
Katrhoperla 1sp
Isocapnia 6spp. and
many benthic species
in early life stages

Huggenberger et al. 1998. FWB
• Fishes and other vertebrates can find optimal thermal conditions if their habitats are hydraulically connected and/or accessible.
• Invertebrates limited by habitat-specific thermal conditions.
• Stoneflies desynchronize life cycles in the aquifer (little temperature variation).

Stanford et al., in press.

Alluvial aquifer is 5-10 °C.
Lateral habitats

Main channel

Unique taxa

Ephemeroptera

Plecoptera

Trichoptera

Coleoptera

Odonata

Gastropoda

Stanford et al., unpubl. data
Primary drivers of the SHM:
- Geomorphic setting (slope, geologic legacies)
- Climate (flow, temperature, fire)
- Cut and fill alluviation (sediments and wood)
- Ground-surface water interactions
- Plant succession
- Animal modifications (including humans)

Dynamic, inter-connected habitats
Emerge from the river and wells in huge numbers

Migrate within the aquifer

Tolerant to hypoxia

delta13C: -20 to -70

CH₄: BDL – 10% saturation in the wells coming from contemporary, ancient (methanogenic) and fossil (thermogenic) sources: Amanda DelVecchia
Dr. Amanda Delvecchia
Postdoctoral Research Scholar
North Carolina State University
Imbalance in the aquifer carbon budget

Labile DOC increases

Reid (2007) U. of Montana
Helton et al. (2015) L & O
$\delta^{13}C$ values in stonefly biomass suggest methane contribution

\[ \delta^{13}C\text{ OM} = -26.2 \pm 2.5 \, \text{‰} \]

\[ \delta^{13}C\text{ CH}_4 = -68.8 \text{ to } -100.8 \, \text{‰} \]

Biofilm, POC

Methane oxidation

Redox interface

CH\textsubscript{4}
Methane mostly methanogenic (microbial)

- **δ^2H (‰)**
  - Acetoclastic: Low-quality organic matter
  - Hydrogenotrophic CO\(_2\) and H\(_2\)

- **δ^13C (‰)**
  - Methane mostly methanogenic (microbial)
  - Heterotrophic
  - Chemoautotrophic \(\text{CO}_2\) and H\(_2\)
  - Geologic

**Well**
- Old methane
- New methane
- Occasional methane

**Old methane C**
- 6,910 ± 140 years BP (n=3)

**New methane C**
- 990 ± 200 years BP (n=3)
Methane-derived C in stonefly biomass across Nyack

Proportion of individuals in well

River well

Closest to the river channel

Old methane

All others

% Methane derived carbon in biomass

Proportion of individuals in well

n=528
Stonfly tissue has millennial-aged methane-derived C
Increasing trophic level $\rightarrow$ Decreasing use of methane-derived carbon $\rightarrow$

Methane-based food web

$\delta^{13}C$ (‰)

$\delta^{15}N$ (%)

Meiofauna: Reid (2007)
Modern OC

Stored (millennial-aged to ancient) OC

CO₂ (modern)

methylene oxidation

Geologic methane (ancient)

- Paradox of hyporheic explained.
- Other redox mediated carbon sources? Fe, Mn pathways
- Relevance to pollutant toxicity, fracking.
Age scrolled point bar – Krutogorova River, Kamchatka
Formation of ridge and swale topography characteristic of alluvial floodplains in unregulated rivers.

Primary drivers of ridge and swale genesis:
• Geomorphic setting
• Climate (flow, temperature)
• Cut and fill alluviation (sediments and wood)
• Ground-surfacewater interactions
• Plant succession
• Animal modifications
• Biophysical connectivity

Mouw et al., 2014. RRA
Riparia substantially modified by beavers (A versus B)  
Mouw et al., 2013. RRA

Salmon production potential reduced 3X by beavers – Malison et al., 2015. CJFAS

But beavers promote plant diversity  
Mouw et al., 2013. RRA

Coho juvenile – Jonny Armstrong
Floodplain Modification By Beavers

12% of entire study reach is beaver influenced habitat
55% of aquatic off-channel habitats modified by beavers

Malison et al, 2014. FWB
Kwethluk Kol

<table>
<thead>
<tr>
<th></th>
<th>Kwethluk</th>
<th>Kol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floodplain slope</td>
<td>0.0020</td>
<td>0.0022</td>
</tr>
<tr>
<td>River width</td>
<td>42m</td>
<td>50m</td>
</tr>
<tr>
<td>Watershed area</td>
<td>3846 km²</td>
<td>1502 km²</td>
</tr>
<tr>
<td>Total Floodplain area</td>
<td>$2.49 \times 10^8$ m²</td>
<td>$1.04 \times 10^8$ m²</td>
</tr>
<tr>
<td>Total aquatic habitat</td>
<td>283 ha</td>
<td>409 ha</td>
</tr>
<tr>
<td>Main Channel total area</td>
<td>219 ha</td>
<td>325 ha</td>
</tr>
<tr>
<td>Off-channel habitat area</td>
<td>64 ha</td>
<td>84 ha</td>
</tr>
<tr>
<td>Spring brook total area</td>
<td>11 ha</td>
<td>83 ha</td>
</tr>
<tr>
<td>% off-channel spring brook area</td>
<td>0.17</td>
<td>0.99</td>
</tr>
<tr>
<td>Beaver pond area</td>
<td>51 ha</td>
<td>0</td>
</tr>
</tbody>
</table>

Huge mdn subsidy in the Kol

5-10M salmon/yr 100k salmon/yr
**SHM of the Okavango Delta, Botswana, South Central Africa**

<table>
<thead>
<tr>
<th>Island genesis</th>
<th>Island coverage</th>
<th>Island class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Form classification</td>
<td>Coverage classification</td>
</tr>
<tr>
<td><strong>Primary islands</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scroll bar</td>
<td>Grassland</td>
<td>Grassland</td>
</tr>
<tr>
<td></td>
<td>Scroll bar</td>
<td>Riparian forest</td>
</tr>
<tr>
<td></td>
<td>Scroll bar</td>
<td>Mixed</td>
</tr>
<tr>
<td>Inverted channel</td>
<td>Riparian forest</td>
<td>Riparian forest</td>
</tr>
<tr>
<td>Termite mound</td>
<td>Tree/grassland</td>
<td>-</td>
</tr>
<tr>
<td><strong>Secondary islands</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amoeboid (grown from a primary island nucleus)</td>
<td>Riparian forest</td>
<td>Riparian forest</td>
</tr>
<tr>
<td></td>
<td>Central salt crust with rim of riparian forest</td>
<td>Salt/Mixed with salt</td>
</tr>
<tr>
<td></td>
<td>Central riparian forest with rim of salt</td>
<td>Mixed with salt/(riparian forest)</td>
</tr>
<tr>
<td></td>
<td>Grassland</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Mixed grassland/riparian forest</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Dry woodland</td>
<td>-</td>
</tr>
</tbody>
</table>

*Priority class in the classification.*

Range of *O. mykiss*

**Anadromous sh**
- Inland rb extirpated

**Observatory rivers**
- Utkholok
- Kol
- Zhupanova

**Synoptic rivers**
- Kwethluk
- Mulchatna
- Aniak
- Copper
- Taku
- Stikine
- Skeena
- Kitlope

**Restoration rivers**
- Flathead
- Flathead Lake Biological Station, University of Montana

**Salmonid Rivers Observatory Network (SaRON)**
- Flathead - reference
- Flathead, Argentina
- Rio Grande, Argentina

**Maps and Figures**
- Image of salmonids: rb (rainbow trout) and sh (steelhead trout)
Juvenile Salmonid Densities
(all rivers combined)

- Main shoreline
- Parafluvial
- Orthofluvial
- Backwater
- Beaver ponds
- Trib, mountain
- Trib, tundra
- Overall

Juvenile Salmonid Density (#/m2)
Juvenile Salmonid Densities
(all biotopes combined)
Kol River: Complex, 5-10M salmon

Utkholok River: Simple, 10K salmon

Kol – *O. mykiss* resident (rainbow)

Utkholok – *O. mykiss* anadromous (steelhead)

Same species, 6 life history strategies

C:N = 8.1 - 14.4

## Salmon Subsidy of Foliar N


<table>
<thead>
<tr>
<th>Ecology</th>
<th>molar C:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kol floodplain</td>
<td></td>
</tr>
<tr>
<td>– <em>Salix A</em></td>
<td>13.7</td>
</tr>
<tr>
<td>– <em>Salix B</em></td>
<td>12.6</td>
</tr>
<tr>
<td>– <em>F. camtschatica</em></td>
<td>14.4</td>
</tr>
<tr>
<td>– Nettle</td>
<td>8.1</td>
</tr>
<tr>
<td>Temperate broadleaf$^1$</td>
<td>35.1</td>
</tr>
<tr>
<td>Nyack cottonwoods$^2$</td>
<td>38.1</td>
</tr>
</tbody>
</table>

Разнообразие жизненных стратегий камчатской микижи

Типы чешуи

Типично
проходная

Продидная-Б
(включающая
стадию
«полуфунтовика»)

Эстуарная

Речная
остуарная

Речная

5,7 кг
(2,5 - 10,5)

4,9 кг
(1,0 - 9,3)

2,1 кг
(0,6-3,2)

1,3 кг
(0,4 - 2,5)

1,4 кг
(0,4 - 2,7)
Изменения типа жизненной стратегии
(по данным соотношения Sr/Ca в отолитах)

<table>
<thead>
<tr>
<th>Географическое положение</th>
<th>Стратегия материнской особи</th>
<th>Стратегия потомка</th>
</tr>
</thead>
<tbody>
<tr>
<td>Море</td>
<td>Материнская особь – речная</td>
<td>Потомок – речная</td>
</tr>
<tr>
<td>Море</td>
<td>Материнская особь – речная</td>
<td>Потомок – проходная</td>
</tr>
<tr>
<td>Река</td>
<td>Материнская особь – проходная</td>
<td>Потомок – речная</td>
</tr>
<tr>
<td>Река</td>
<td>Материнская особь – проходная</td>
<td>Потомок – проходная</td>
</tr>
</tbody>
</table>

Графики показывают изменения соотношения Sr/Ca в отолитах в зависимости от географического положения и типа жизненной стратегии.
Воямполка
Тигиль
Снатахавям
Квачина
Утхолок
Сопочная
Саичек
Крутогорова
Кехта
Коль

<table>
<thead>
<tr>
<th>Typical anadromous</th>
<th>Riverine</th>
<th>Estuarian</th>
<th>River-estuarine</th>
<th>Half pounders</th>
<th>Anadromousb</th>
</tr>
</thead>
</table>

Соотношение рыб с разной жизненной стратегией на ареале
Kol River: Complex, 5-10M salmon

Kol – *O. mykiss* resident (rainbow)

C:N = 8.1 - 14.4

Utkholok River: Simple, 10K salmon

Utkholok – *O. mykiss* anadromous (steelhead)

Same species, 5 life history strategies

Kuskokwim R., Alaska tributaries
Greater complexity, more salmon

\[ y = 3 \times 10^{-5}x \]

\[ R^2 = 0.8649 \]

See Whited et al., 2012. Fisheries…… for Riverscape Analysis Project (RAP) tools and data for 1500 Pacific Rim Rivers in Alaska tributaries.
Rankings for the 158 catchments over 1,000 km² as mean of principal components and mean feature class physical complexity. Labels are for the 22 catchments larger than 10,000 km². Blue circles are SaRON sites.

100% female (12.8 mm), migrating at 12.8 cm s\(^{-1}\)
67 neonates per female
Anisogammarus kygi

Mean amphipods m$^{-1}$

Month

V
VI
VII
VIIb
VIII
IX
X

carcasses
Primary drivers of the SHM:
- Geomorphic setting (slope, geologic legacies)
- Climate (flow, temperature, fire)
- Cut and fill alluviation (sediments and wood)
- Ground-surface water interactions
- Plant succession
- Animal modifications (including humans)

Dynamic, inter-connected habitats
Alexander, L.C., 2015. Science at the boundaries: scientific support for the clean water rule. Freshwater Science 34, 1588e1594.
Water table level
Aquatic transport or movement
Overland transport or movement (aerial or terrestrial)
Surface-subsurface exchange of water, materials, organisms
Biochemical transformation and transport (e.g., nutrient spiraling)
PHYSICAL & CHEMICAL INTEGRITY
• Habitat quality
• Water quality
• Toxicity

BIOLOGICAL INTEGRITY
• Community structure
• Indicator species
• Functional groups
• Population attributes

ECOSYSTEM INTEGRITY, SUSTAINABILITY, RESILIENCY

ASSESSMENT

ENDPOINTS & METRICS
Biodiversity
Distribution & Abundance

Environmental Change

Resources
Storage & Flux

Genomes
Adaptation

Exports
Water; hydrology; coal; wood, ag and footloose Products; and ecosystem services

Ecosystem Benefits

Stressors & Stewardship

Externalities
Climate change; Governmental policies; National and international social and economic condition; Invasive species; Connectivity to adjacent systems (air pollution; Immigration, emigration)

Human Diversity
Distribution & Abundance

Socio-economic Change

Knowledge
Values & Interactions

Institutions
Markets & Governance

Vital Signs
Land cover; Water and air quality; Reactive nitrogen capital; Soil fertility; Local amenity values; Contaminant burdens; Adaptive governance capacity; Disposable household income
Flathead River, Canadian North Fork near Cranbrook BC
Coal strip mine near Fernie BC – mountain destruction mining
Mt Polley Mine tailings blown into Quesnel Lake BC from failed tailing retention dam
Salmon phenology varies across the landscape – adaptation to SHM that creates a regional salmon portfolio (see also Schindler et al. 2011. Nature)
Primary drivers of the SHM:
- Geomorphic setting (slope, geologic legacies)
- Climate (flow, temperature, fire)
- Cut and fill alluviation (sediments and wood)
- Ground-surface water interactions
- Plant succession
- Animal modifications (including humans)

Dynamic, inter-connected habitats