Restoration of Regulated Rivers: New Perspectives

River Restoration International Symposium
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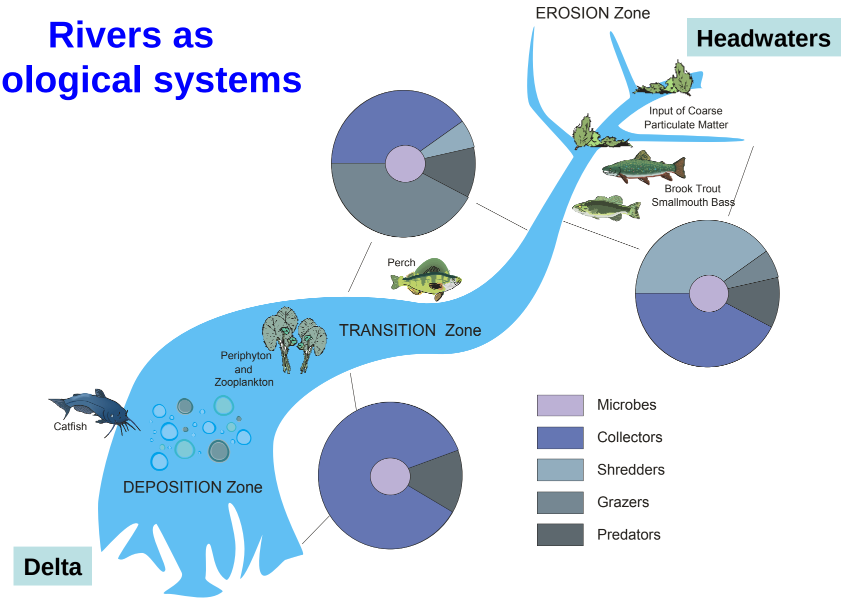
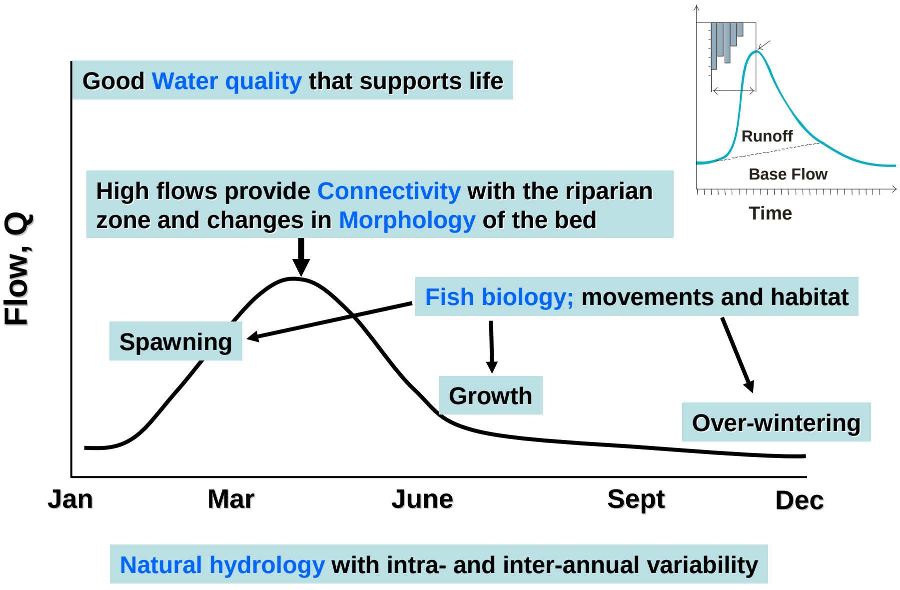
Rivers as ecological systems



The river continuum concept: The evolution of abiotic variables along a spatial gradient (upstream to downstream) is the main feature defining biota assemblages and distribution in rivers (Vannote et. al. 1980).

Inter-relationships of major riverine components



Good Water quality that supports life

High flows provide Connectivity with the riparian zone and changes in Morphology of the bed

Fish biology; movements and habitat

Spawning

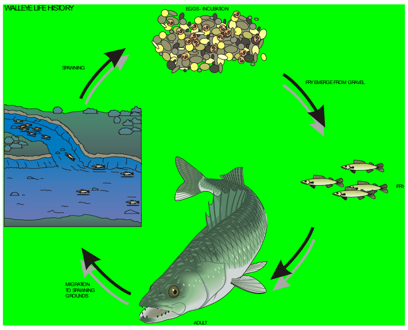
Growth

Over-wintering

Natural hydrology with intra- and inter-annual variability

Biota movements and habitat

- The dynamic river processes form and control habitat suitability and movements for biota (e.g. fish, organisms). Biota diversity characterizes natural rivers.
- Aquatic life has adapted well and thrives in dynamic river conditions.
- Control of dynamic river processes, changes in flow, sediment or ice regimes, may alter ecological processes, biota movements and habitats.



Dams and river works

Restoring rivers through removal of dams and other river works

- ➢ Rehabilitate watershed, ecosystem or specific site;
- ➢ Rehabilitate ecological functions: habitat, flow regime, morphodynamics, water quality and movements of biota, particularly fish passage;
- ➢ Assist species recovery, particularly for species at risk

Other reasons for removal of dams and other river works

- safety considerations
- economically obsolete
- structural deterioration
- lack of maintenance
- orphan dams
- legal and financial liability
- more creative solutions for water supply, flood protection and other uses

Dam removal impacts

- Contaminated sediments in reservoirs or tailings need extra care (e.g. disposal or capping), since shallow waters or exposure may allow aquatic toxic pathways to connect with terrestrial ones (e.g. from fish predators to bird predators).

- It is important in dam removal projects to demonstrate that reservoir sediment erosion, transport and deposition will avoid long-term adverse impacts.

Dam removal impacts

Such impacts include changes, particularly downstream of dams:

- physico-chemical
- morphological
- effects on ice regime
- ecological changes

Examples:

- filling pools
- burying riffles
- increasing contaminant bioavailability
- introducing exotic or invasive species (e.g. sea lamprey in the Great Lakes).

River morphodynamics

- Natural rivers are dynamic and shape their own channels and floodplains which evolve over time. Regulated rivers are controlled and morphodynamically constrained.

- Rivers have characteristic planform, longitudinal profile and cross-sectional geometries, which reflect hydrodynamic interactions of bed and bank materials, sediment transport processes and watershed hydrological regimes.

River morphodynamics

- River channels are characterized by bankfull geometries of average widths and depths at bankfull discharge, the discharge when the river spills onto the floodplain.

- Restoration projects which take into account natural river planform, longitudinal profile and cross-sectional geometry at bankfull discharge are more likely to be successful.

Gravel-bed and sand-bed rivers

- Rivers are classified by the characteristic median grain size D_{s50} or geometric mean grain size D_{sg} of their surface bed sediment.

- Sand-bed rivers have characteristic grain sizes between 0.0625 mm and 2 mm.

- Gravel-bed rivers have characteristic grain sizes between 16 mm and 256 mm.

Transitional and boulder-bed rivers

- Rivers with characteristic grain sizes between 2 and 16 mm (pea gravel) are transitional. Such rivers are much less common than either sand-bed or gravel-bed rivers.

- Boulder-bed rivers have characteristic grain sizes larger than 256 mm.

Bankfull geometry for gravel-bed & sand-bed rivers

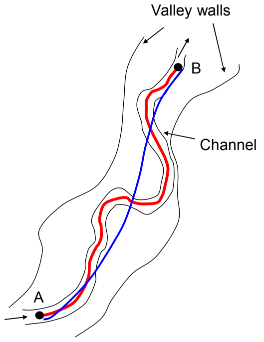
Q_{bf} = bankfull discharge (m^3/s)
B_{bf} = bankfull width (m)
H_{bf} = bankfull depth (m)
S = river bed slope (m per m)
D_{s50} = median surface grain size (mm)
g = gravitational acceleration (9.81 m/s^2)
Σ= sinuosity, river bed to valley bed slope (S/S_v).

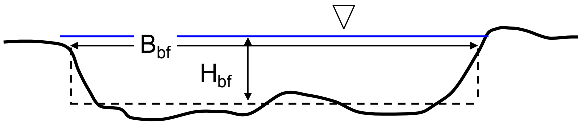
Often the following forms are used in regressions:

$$B_{bf} \sim Q_{bf}^{0.5}$$

$$H_{bf} \sim Q_{bf}^{0.4}$$

$$S \sim Q_{bf}^{-0.3}$$





Modified from Gary Parker

Bankfull geometry

Using dimensionless parameters to express universality

A dimensionless parameter from the Ancient Greeks: π = C/D for all circles

Dimensionless bankfull discharge: $$\hat{Q} = \frac{Q_{bf}}{\sqrt{gD_{s50}}D_{s50}^2}$$

Dimensionless bankfull depth: $$\tilde{H} = \frac{H_{bf}g^{1/5}}{Q_{bf}^{2/5}}$$

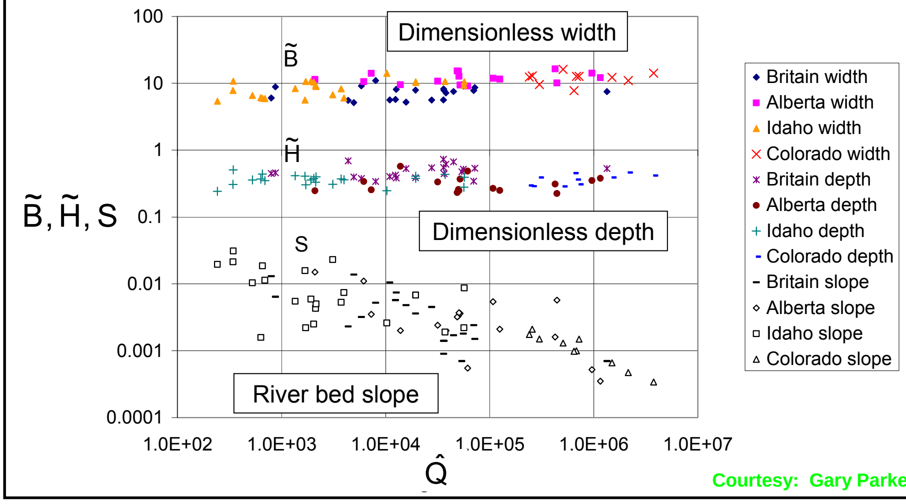
Dimensionless bankfull width: $$\tilde{B} = \frac{B_{bf}g^{1/5}}{Q_{bf}^{2/5}}$$

Note: all units should be consistent; for SI units convert D_{s50} from mm to m.

Adapted from Gary Parker

Bankfull geometry: gravel-bed rivers

The four data sets are consistent for bankfull channel characteristics

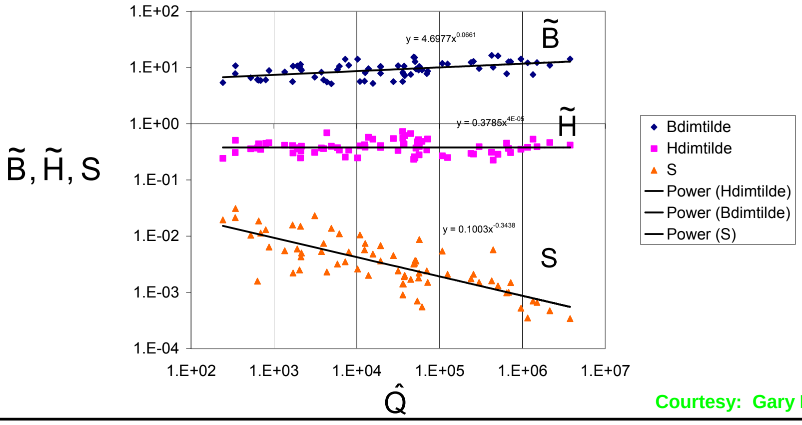


Courtesy: Gary Parker

Bankfull geometry: gravel-bed rivers

$\tilde{H} = 0.3785\,\hat{Q}^{0.00004}$, $\tilde{B} = 4.698\,\hat{Q}^{0.0661}$, $S = 0.1003\,\hat{Q}^{-0.3438}$

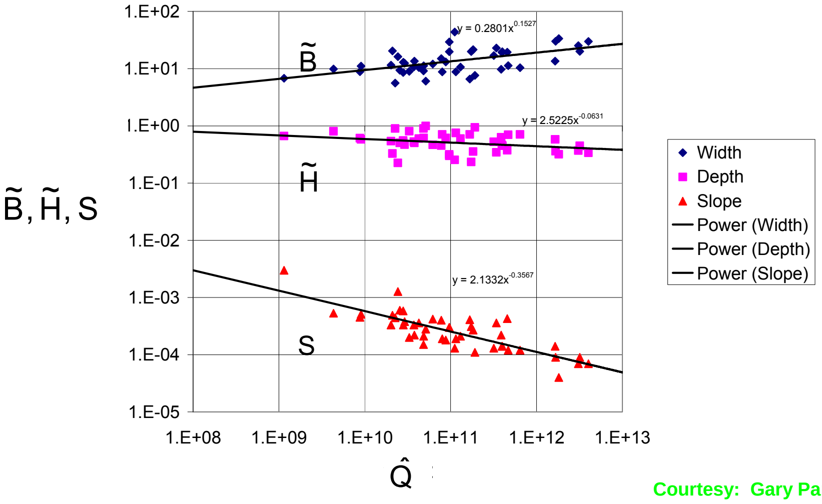
To a high degree of approximation: $\tilde{H} = \tilde{H}_c \equiv 0.3785$



Courtesy: Gary Parker

Bankfull geometry: sand-bed rivers

$\tilde{H} = 2.52\,\hat{Q}^{-0.063}$, $\tilde{B} = 0.280\,\hat{Q}^{0.153}$, $S = 2.13\,\hat{Q}^{-0.357}$



Courtesy: Gary Parker

River restoration and bankfull geometry

- Rivers change bankfull depths and widths over short geomorphic times (hundreds to thousands of years).

- Changes to river valley slope require long geomorphic times (tens of thousands of years), since they involve moving large amounts of sediment over long reaches.

- Valley slope is often considered constant for short geomorphic times. **River restoration projects need to consider this.**

- Changes to river sinuosity allow some variation in river bed slope, which may be used in reconstructing river channels.

River restoration and bankfull geometry

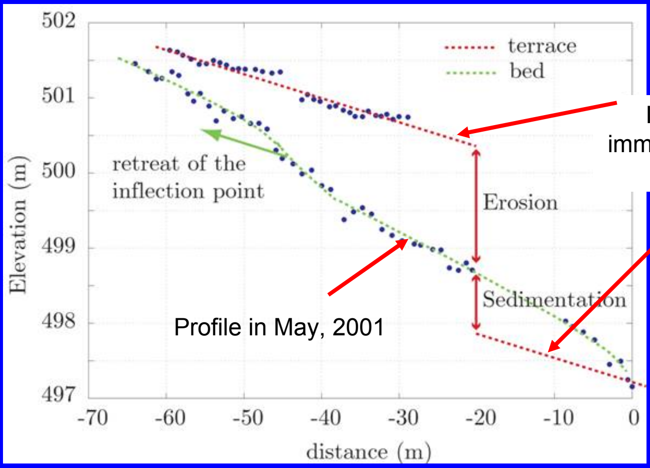
- Channel and floodplain formation, cleaning of the gravel bed and renewal of the riparian ecosystem all require both high and low flows.

- Attempts to restore a river by supplying it with a constant year round discharge are futile.

- The restored flood hydrograph should have a duration and magnitude similar to the natural one before regulation.

- Short duration flood hydrographs will be insufficient to overturn gravels and remove excessive vegetation.

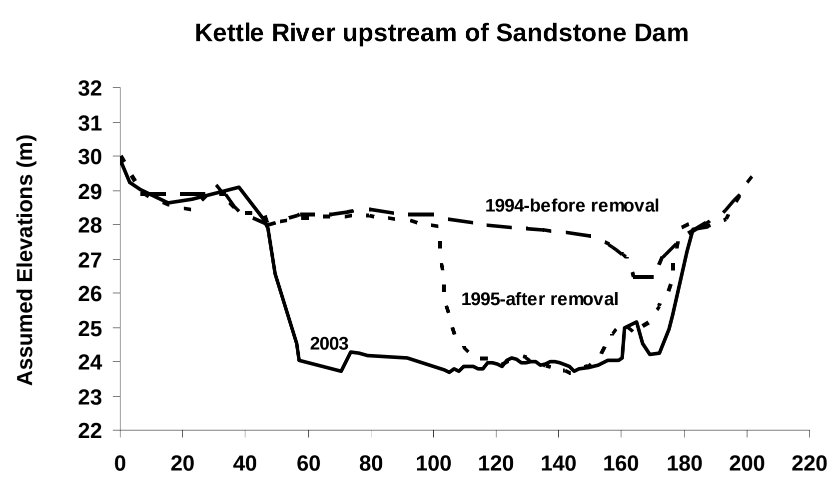
River response to sudden vertical faulting caused by an earthquake



Inferred initial profile immediately after faulting in November, 1999

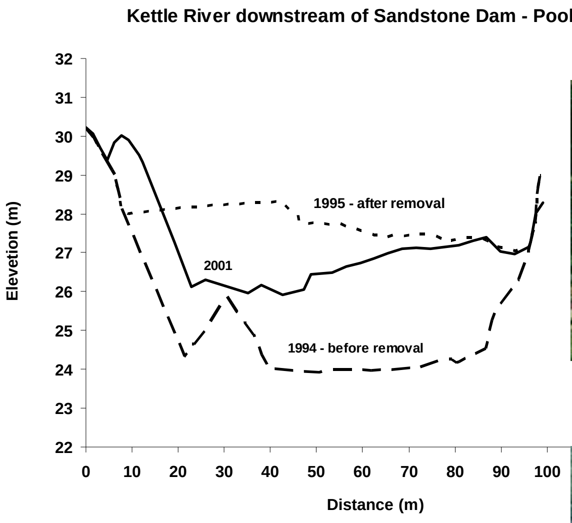
Profile in May, 2001

Upstream degradation (bed level lowering) and downstream aggradation (bed level increase) are realized as the river responds to the knickpoint created by the earthquake (Lawrence 2003).



“Let the river recover” example

Katopodis and Aadland 2006



Kettle River pool (1995), right after dam removal

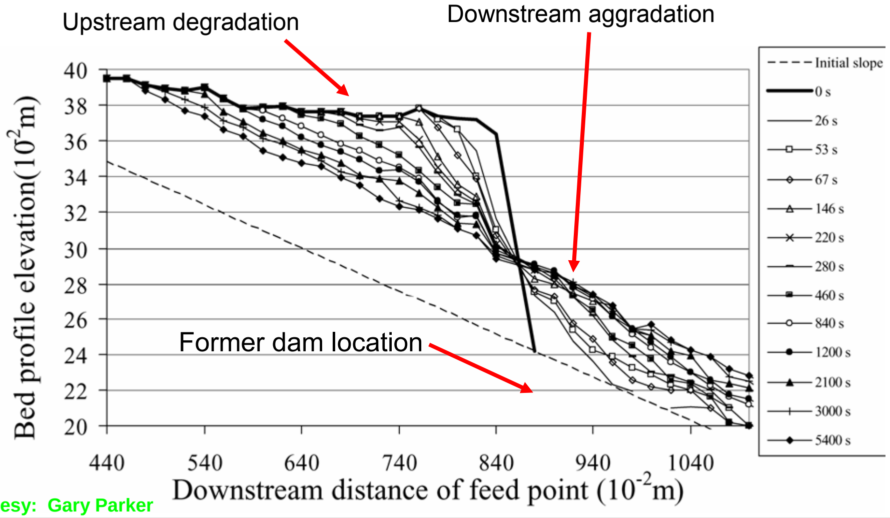
Kettle River pool (1998), 3 years after dam removal

Katopodis and Aadland 2006

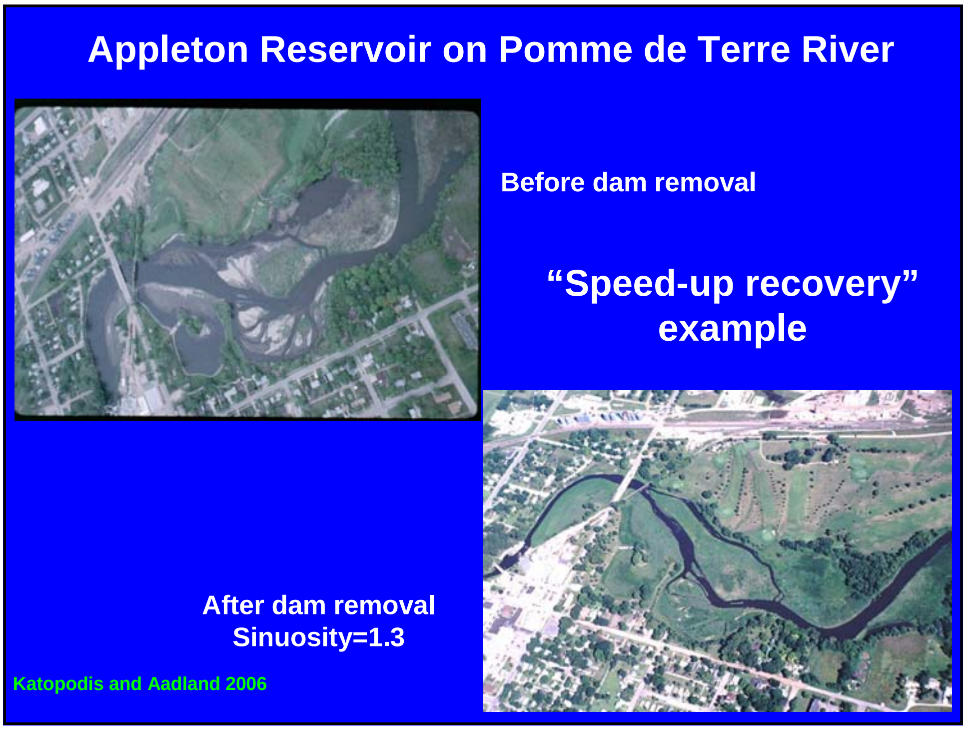
The *DREAM* model

Cui, Parker et al. 2006

Evolution of centerline profile upstream (x < 9 m) and downstream (x > 9 m) of the dam



Courtesy: Gary Parker



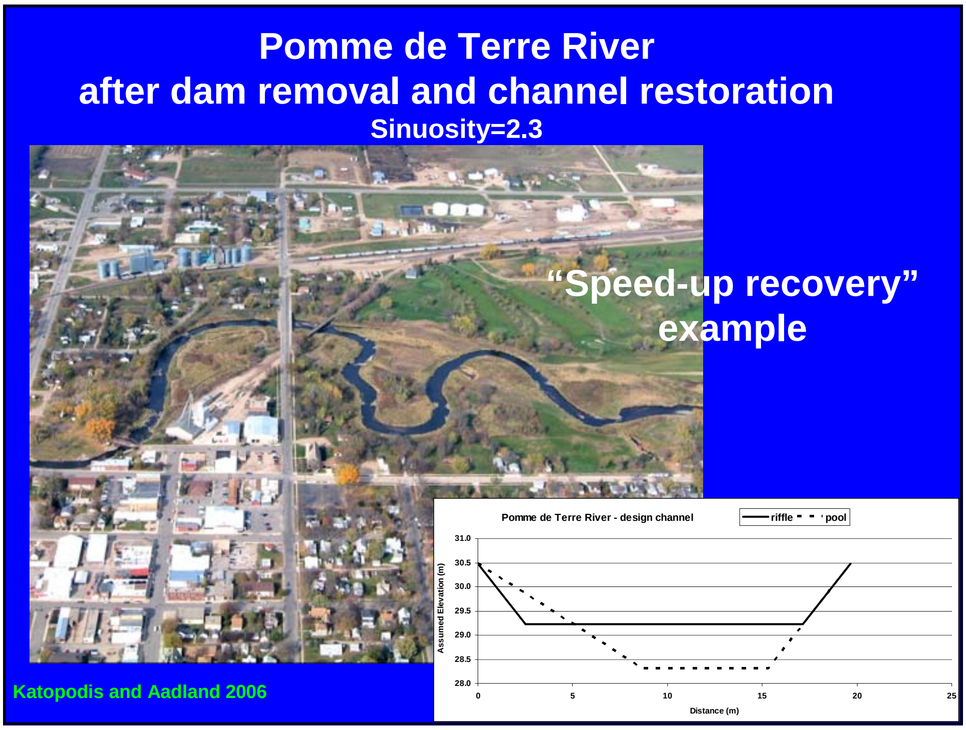
Appleton Reservoir on Pomme de Terre River

Before dam removal

“Speed-up recovery” example

After dam removal
Sinuosity=1.3

Katopodis and Aadland 2006

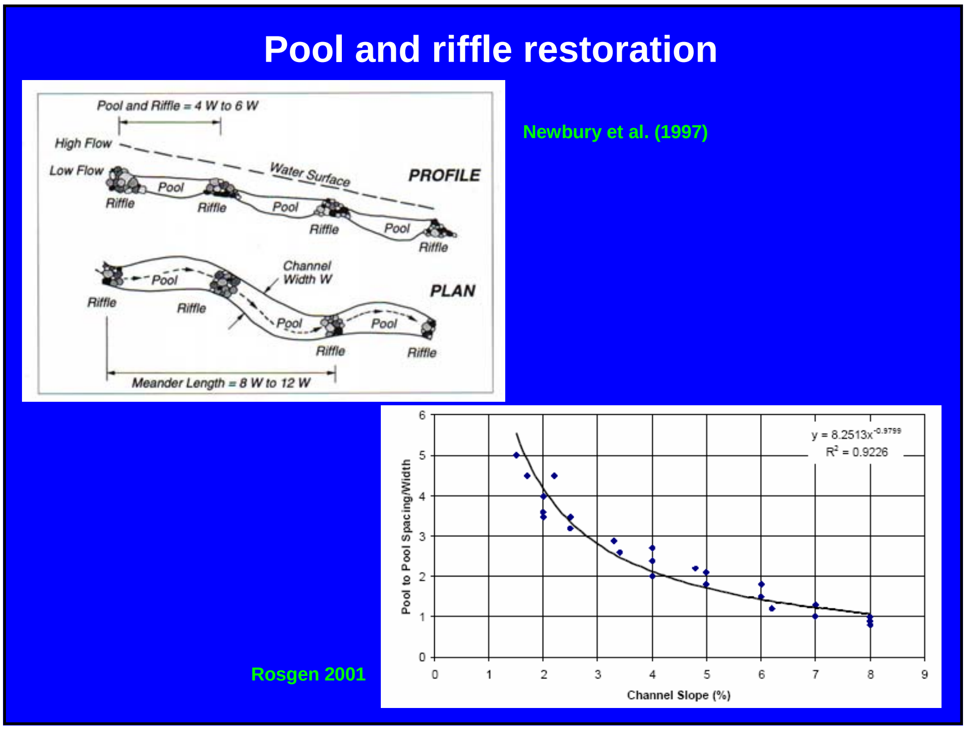


Pomme de Terre River after dam removal and channel restoration

Sinuosity=2.3

“Speed-up recovery” example

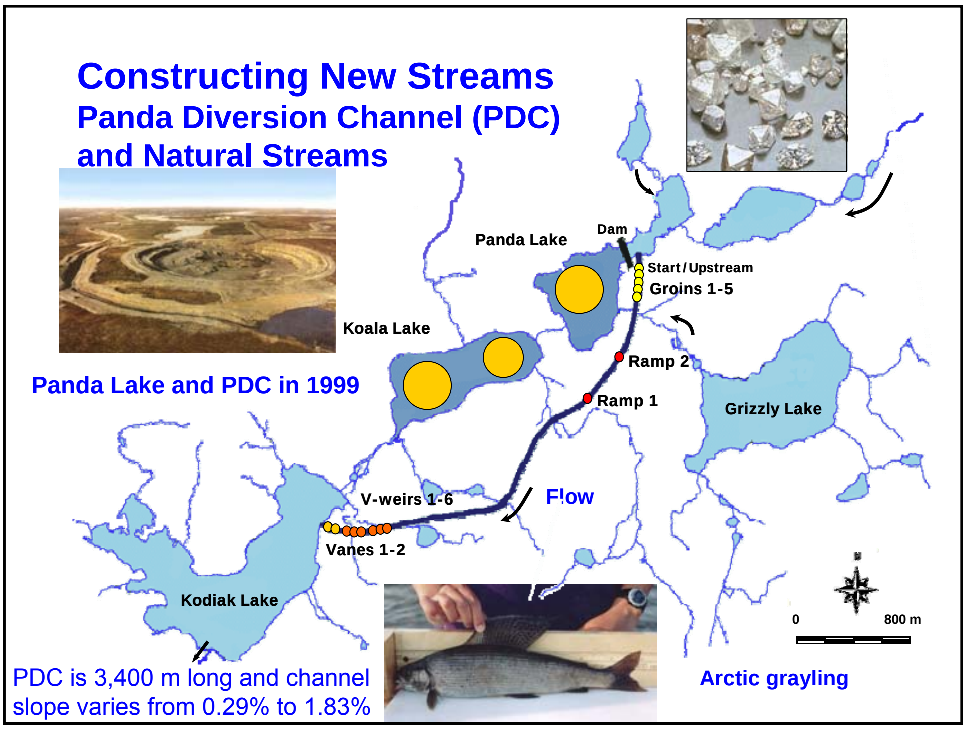
Katopodis and Aadland 2006



Pool and riffle restoration

Newbury et al. (1997)

Rosgen 2001



Constructing New Streams
Panda Diversion Channel (PDC) and Natural Streams

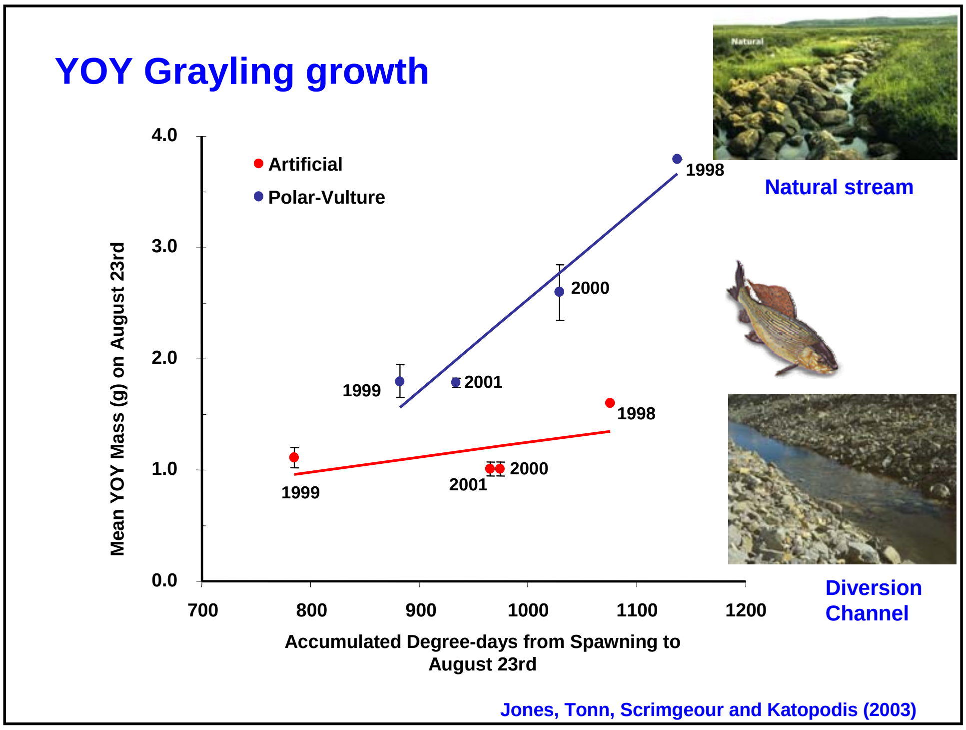
Panda Lake and PDC in 1999

PDC is 3,400 m long and channel slope varies from 0.29% to 1.83%

Arctic grayling

Spawning in Panda Diversion Channel

Young Arctic grayling in Panda Diversion Channel



YOY Grayling growth

Natural stream

Diversion Channel

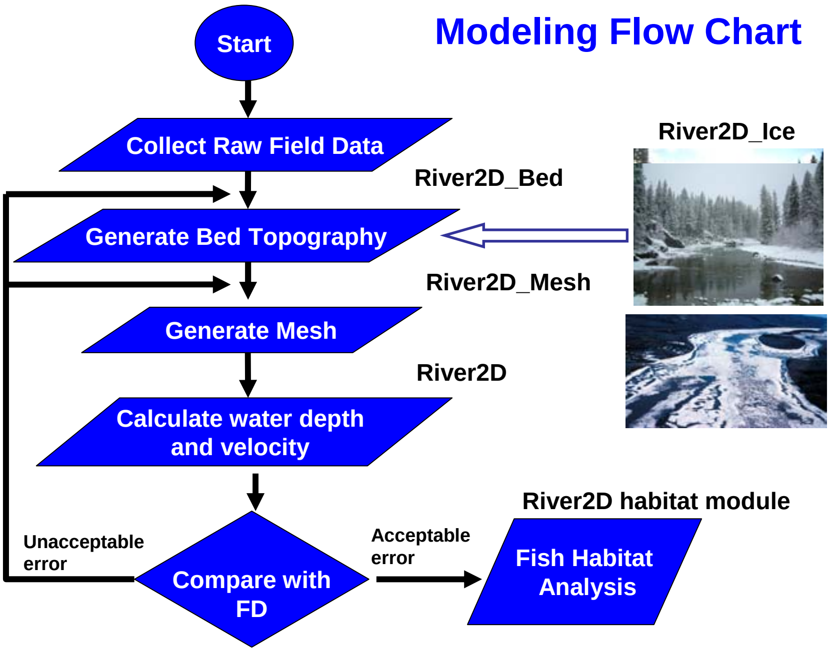
Jones, Tonn, Scrimgeour and Katopodis (2003)

Restoring river flow regimes

www.river2d.ca

The “river2d” developed and tested collaboratively between the Freshwater Institute in Winnipeg (C. Katopodis), the Civil and Environmental Department of the University of Alberta in Edmonton (P. Steffler and several graduate students), the Midcontinent Ecological Science Center of the U.S. Geological Survey in Ft. Collins (T. Waddle), and the Fisheries Division of the Alberta Government in Cochrane (A. Locke). Used in Canada, U.S.A. and elsewhere for ice-free and ice-covered conditions.

Modeling Flow Chart



Start

Collect Raw Field Data

River2D_Bed

Generate Bed Topography

River2D_Ice

River2D_Mesh

Generate Mesh

River2D

Calculate water depth and velocity

Unacceptable error

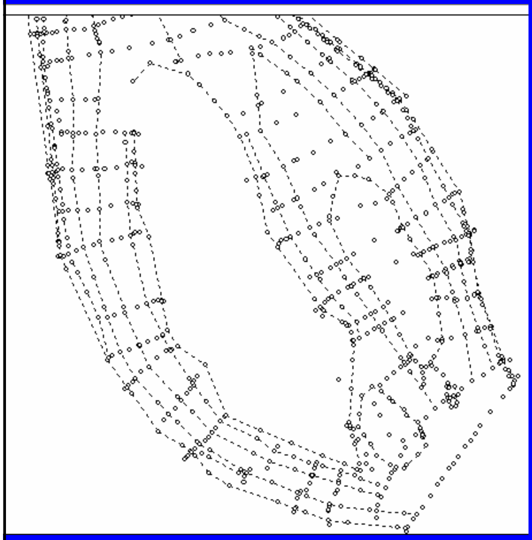
Compare with FD

Acceptable error

River2D habitat module

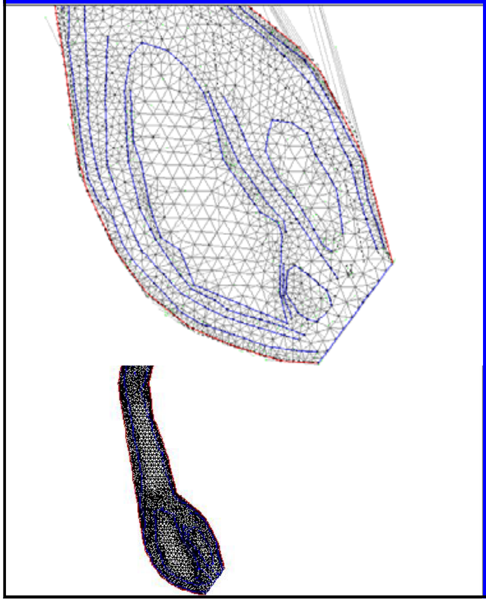
Fish Habitat Analysis

Bed Topography



- Digitize bed topography by creating a triangulated irregular network (TIN) from the field bed topography data.
- If possible, define the top and bottom of bank, where high variation in the bed topography occurs, as break lines in the bed data file.
- Break lines are lines that maintain the values of the nodes they are connected to.

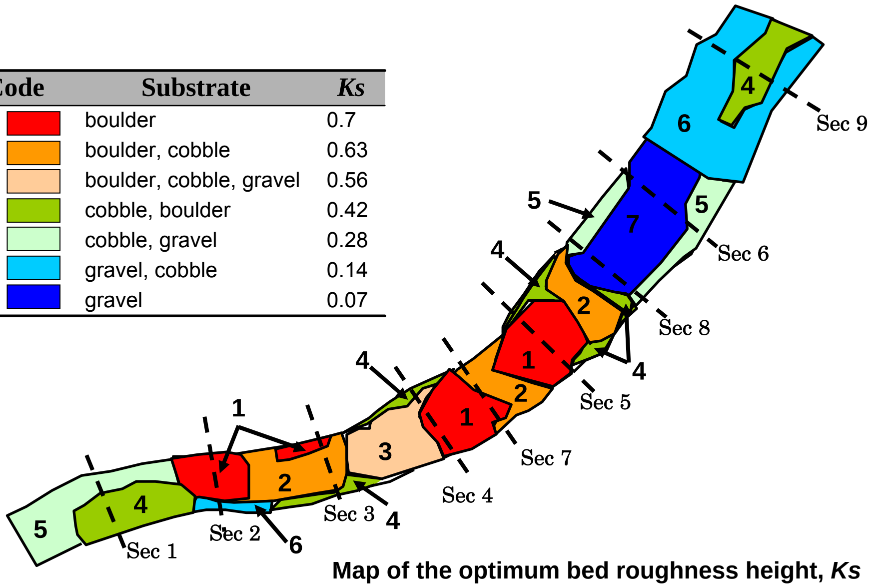
Computational Mesh



- Generate unstructured triangular element computational mesh.
- Typically, a channel is first defined by overlaying the entire surveyed area with a uniform spacing of nodes.
- Higher densities of nodes are selected at places of high variations in river characteristics.
- Additional floating nodes and break lines are incorporated into the mesh to improve the contours created by the computational mesh.

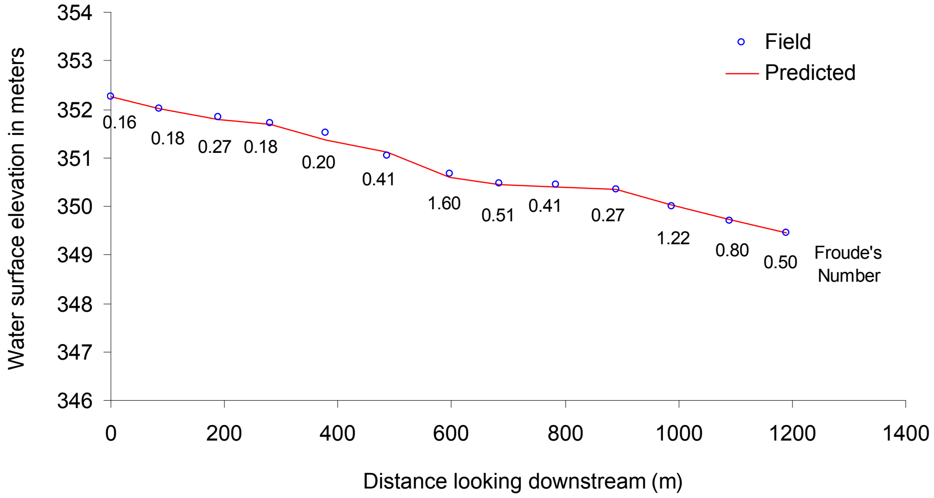
Bed roughness height

Code		Substrate	*Ks*
1	🟥	boulder	0.7
2	🟧	boulder, cobble	0.63
3	🟧	boulder, cobble, gravel	0.56
4	🟩	cobble, boulder	0.42
5	🟩	cobble, gravel	0.28
6	🟦	gravel, cobble	0.14
7	🟦	gravel	0.07



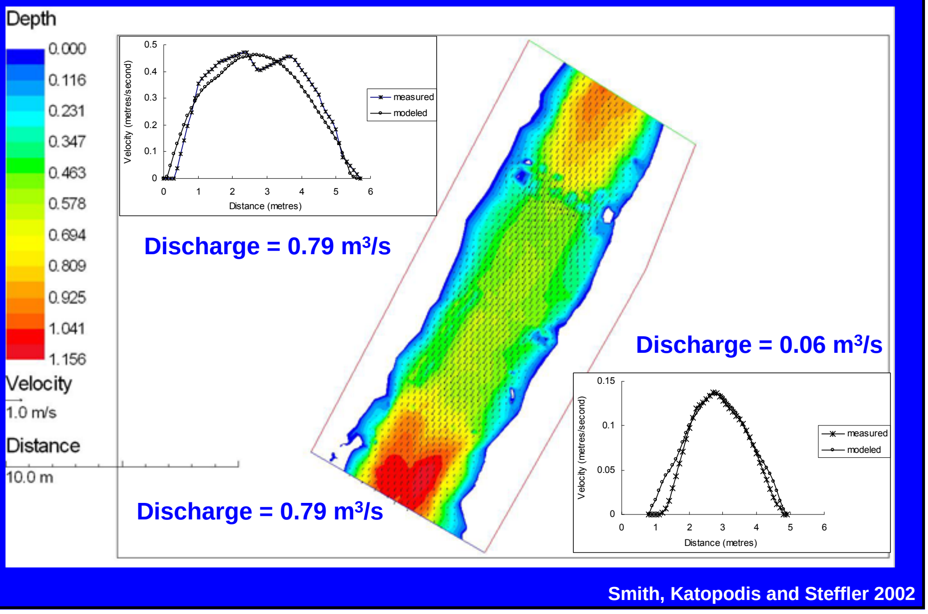
Map of the optimum bed roughness height, *Ks*

Calibrated vs measured water surface profiles



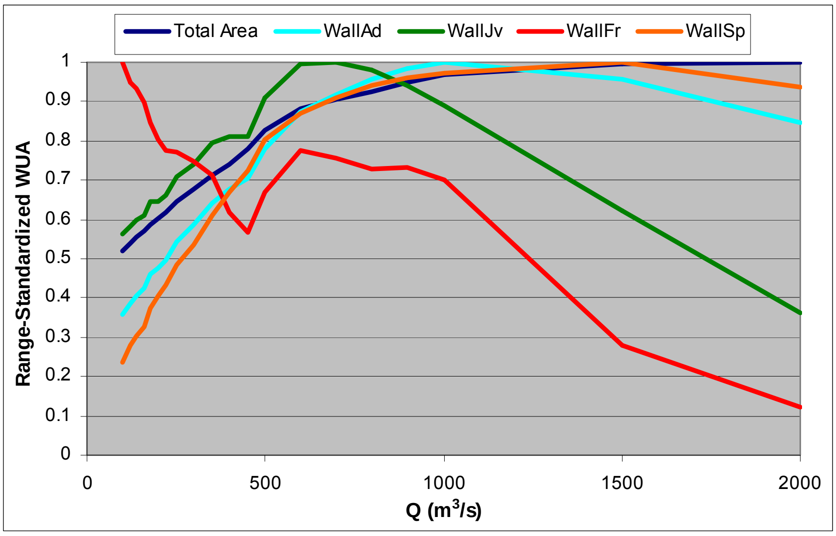
Rocky ramp reach in PDC

(hydrodynamic modeling using “River2D”)

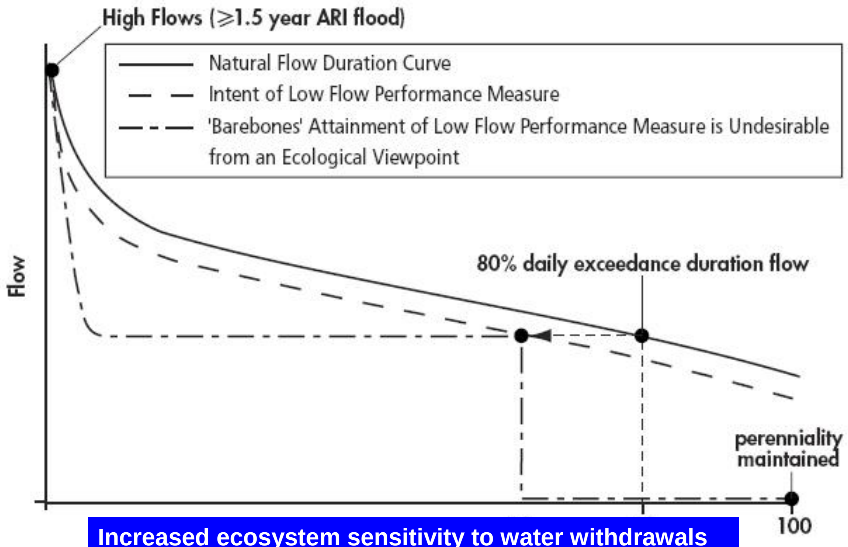


Smith, Katopodis and Steffler 2002

Habitat (WUA) vs discharge relationship



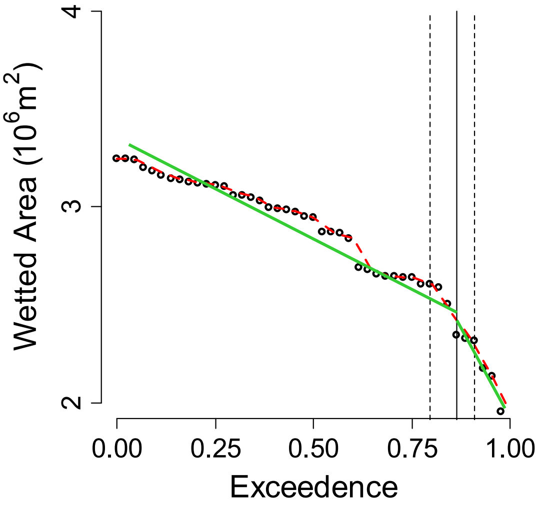
Flow duration or exceedence curve



Increased ecosystem sensitivity to water withdrawals at low flows compared to higher flows.

Ecosystem base flow (EBF)

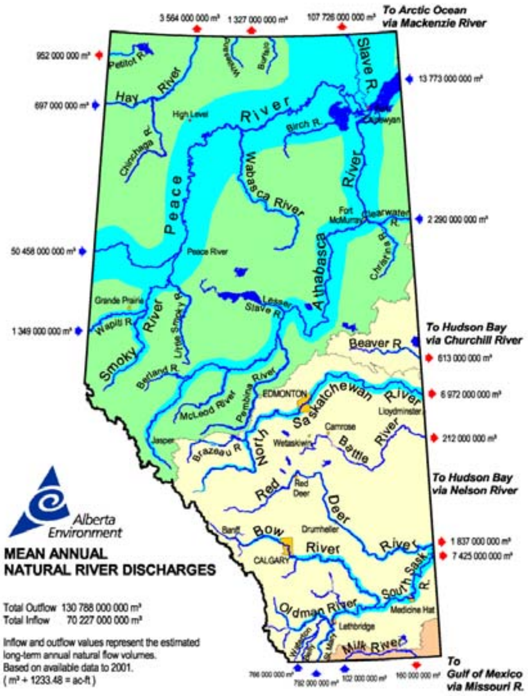
Habitat for sensitive species is limited by periodic low flow events.



Greater protection of low flows is needed to maintain the natural ecosystem productivity, species diversity, and biomass.

There is increased ecosystem sensitivity to water withdrawals at low flows compared to higher flows.

Athabasca River & Oilsands Mines



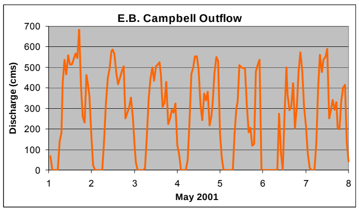
MEAN ANNUAL
NATURAL RIVER DISCHARGES

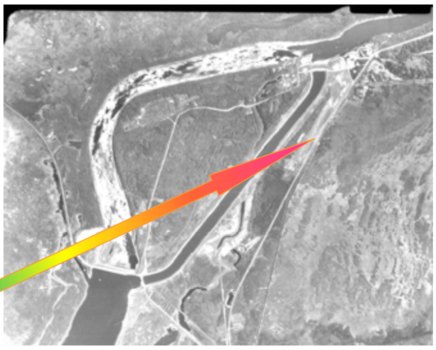
Total Outflow 130 788 000 000 m³
Total Inflow 70 227 000 000 m³

Inflow and outflow values represent the estimated long-term annual natural flow volumes.
Based on available data to 2001.
(m³ + 1233.48 = ac-ft)

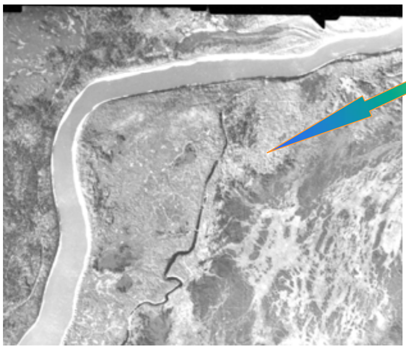
Hydropeaking

Minimum flow provided in 2004 and instream flow study undertaken





River Site in 1986, after E.B. Campbell Hydroelectric Station



Saskatchewan River Site in 1950

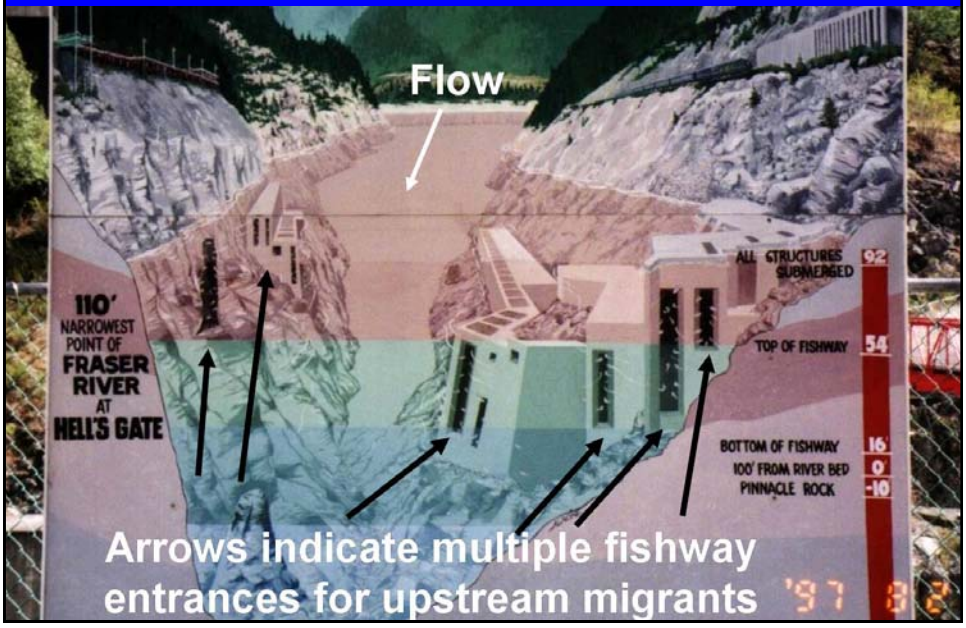
Restoring fish movements – a paradigm for other biota

Spatial and temporal fish movements fulfil basic ecological needs for recruitment, growth and survival; they include movements for:

a) spawning
b) feeding
c) refuge

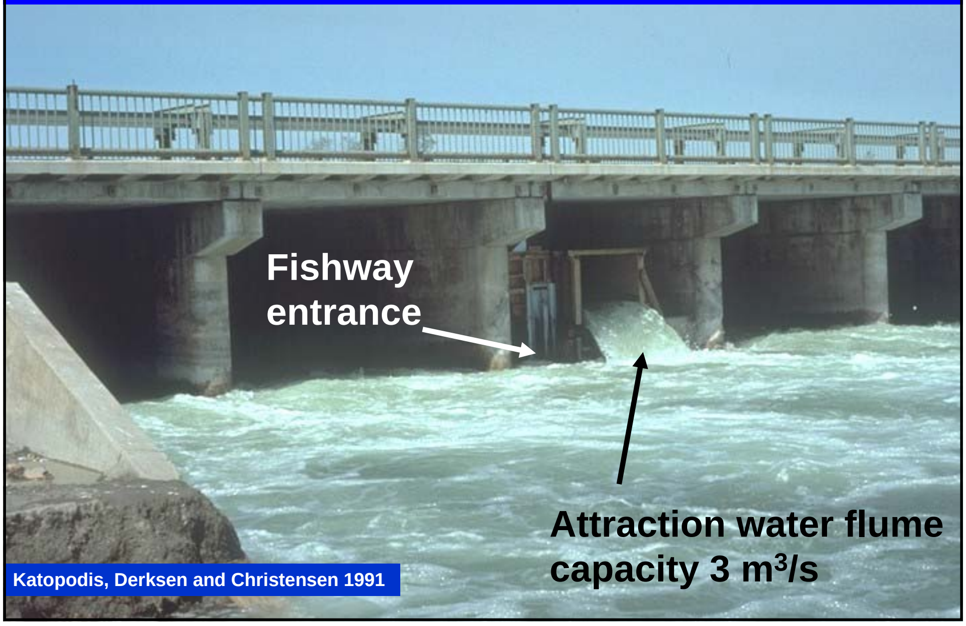
(predator avoidance, usage of refuge habitats during limiting high or low flows, when harmful environmental conditions occur, or for wintering, particularly in ice-covered rivers).

Fish attraction and guidance
Hell's Gate Vertical Slot Fishways, B.C.



Arrows indicate multiple fishway entrances for upstream migrants

Fish attraction and guidance: Fairford Dam Denil fishway, Manitoba

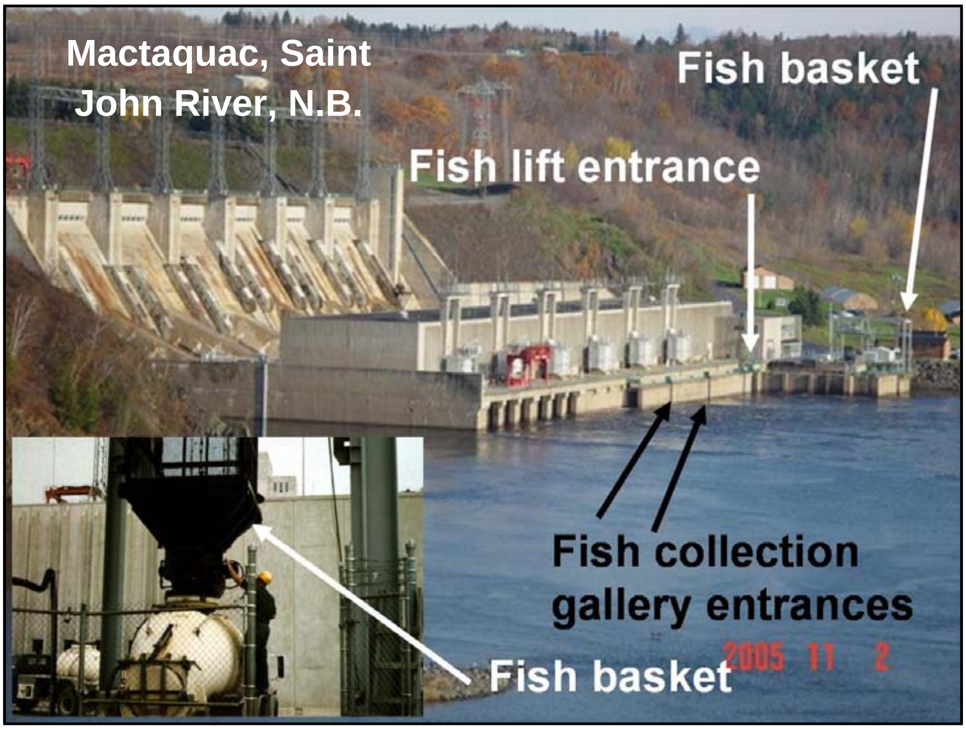


Fishway entrance

Attraction water flume capacity 3 m³/s

Katopodis, Derksen and Christensen 1991

Mactaquac, Saint John River, N.B.



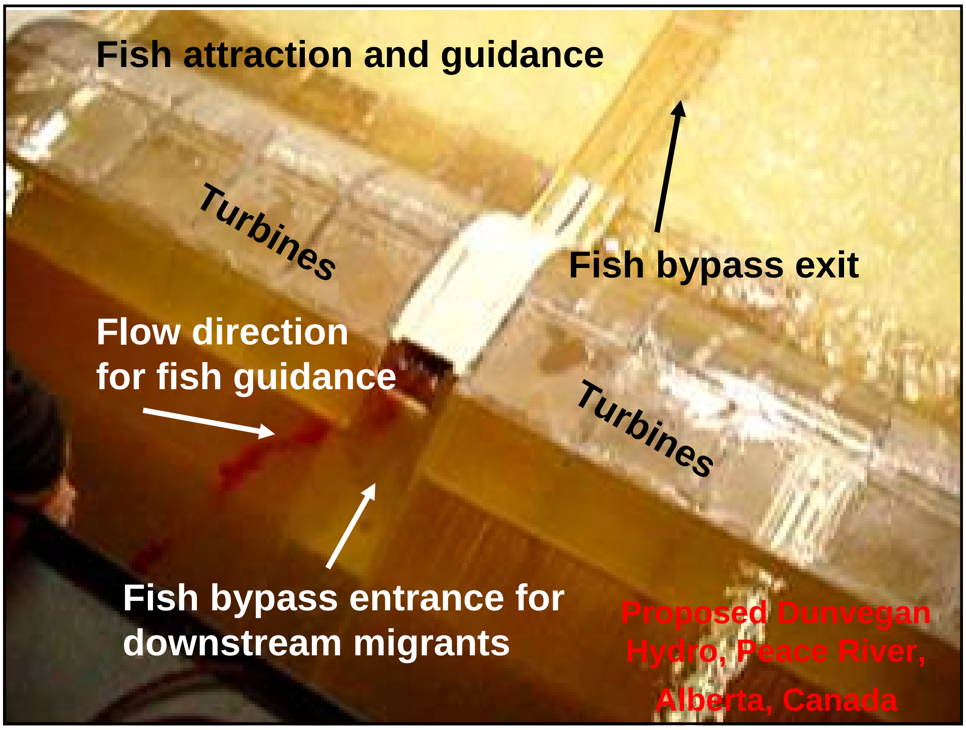
Fish basket

Fish lift entrance

Fish collection gallery entrances

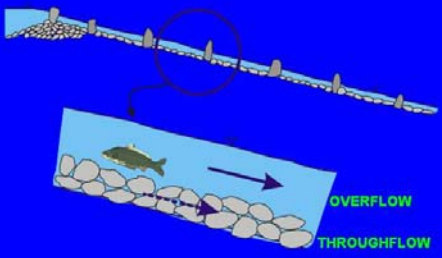
Fish basket

Fish attraction and guidance

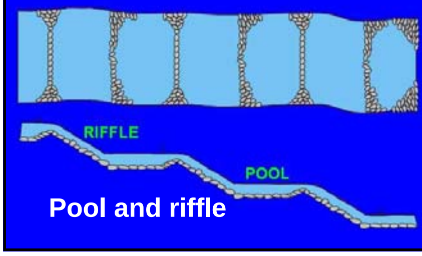


Proposed Dunvegan Hydro, Peace River, Alberta, Canada

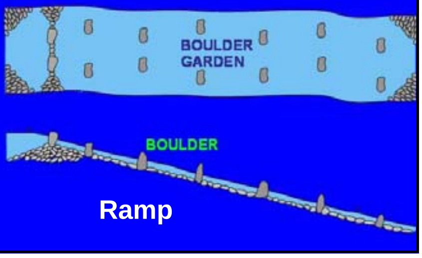
Nature-mimicking fishways



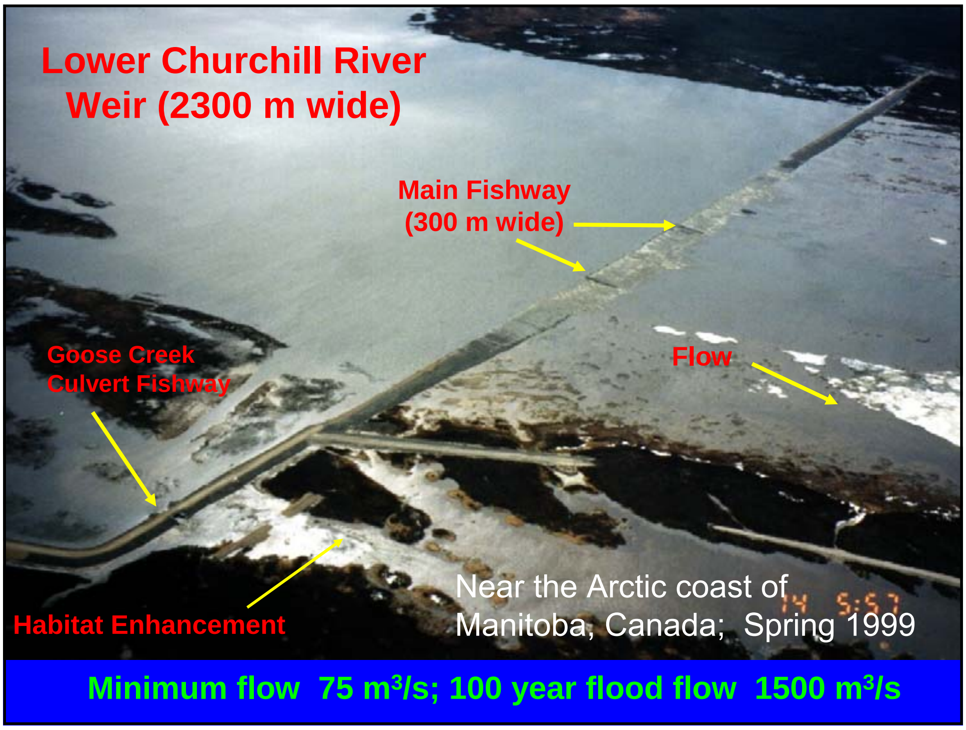
Nature-mimicking fishways attempt to simulate natural channels, use natural materials and are intended to provide suitable passage conditions for a wide variety of species, migration types and stream flow conditions.



Pool and riffle



Ramp



Lower Churchill River Weir (2300 m wide)

Main Fishway (300 m wide)

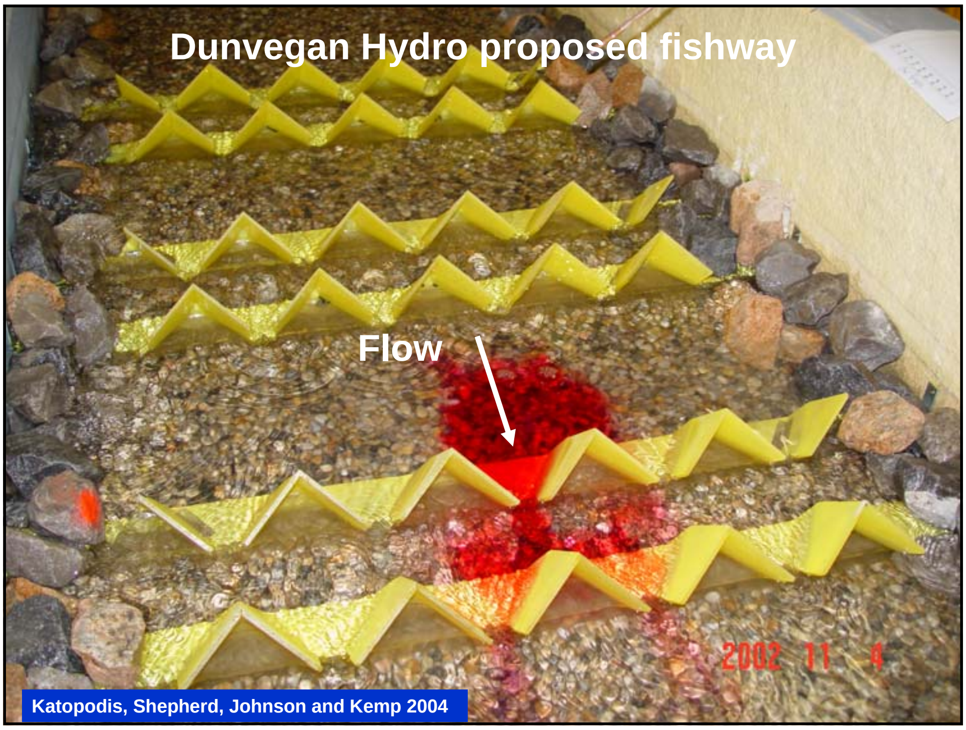
Goose Creek Culvert Fishway

Flow

Habitat Enhancement

Near the Arctic coast of Manitoba, Canada; Spring 1999

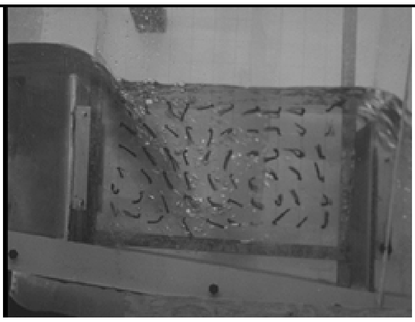
Minimum flow 75 m^3/s; 100 year flood flow 1500 m^3/s

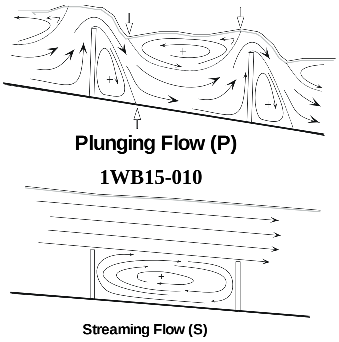


Dunvegan Hydro proposed fishway

Flow

Katopodis, Shepherd, Johnson and Kemp 2004

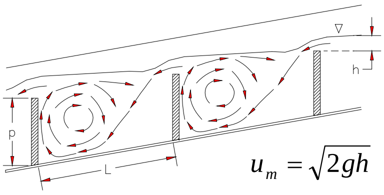
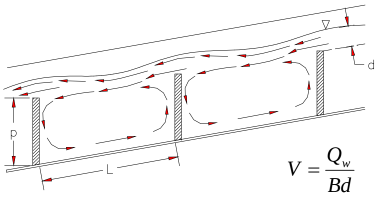




Pool & weir fishways

Ead, Katopodis, Sikora and Rajaratnam 2004

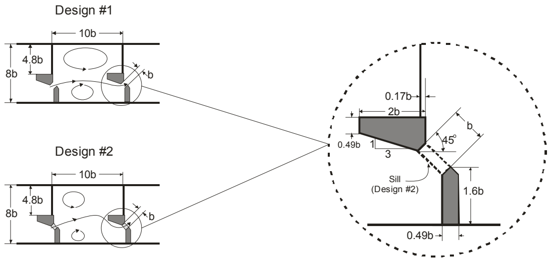
Pool & weir hydraulics

Plunging weir flow  $u_m = \sqrt{2gh}$	**Streaming weir flow**  $V = \frac{Q_w}{Bd}$
$Q_p = \frac{Q_w}{Bh^{1.5}\sqrt{g}} = 0.570 + 0.075\frac{h}{p}$	$Q_s = \frac{Q_w}{Bd^{1.5}\sqrt{gS_o}} = 5.75$
Transition flow $Q_t = \frac{Q_w}{\sqrt{g}BS_oL^{1.5}}$	**L/p=3 and Q_t<0.2 are best to achieve a plunging flow regime, although plunging flows occur for 4>L/p>2 and Q_t<0.1.** **For a streaming flow regime Q_t>2 is needed when L/p=3 or Q_t>4 when L/p=6.**

Twin & single vertical slot fishways

Wu, Rajaratnam and Katopodis 1997; Rajaratnam, Katopodis and Solanki 1992

Vertical slot hydraulics



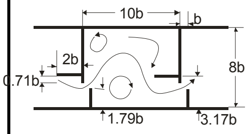
$$Q_* = \frac{Q}{\sqrt{gS_o b_o^{\,5}}}$$

$$u_m = \sqrt{2gh}$$

Design #1 $Q_* = 3.77(y_o/b_o) - 1.11$

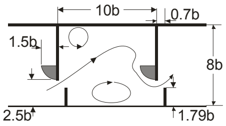
Design #2 $Q_* = 3.75(y_o/b_o) - 3.52$

Design #16



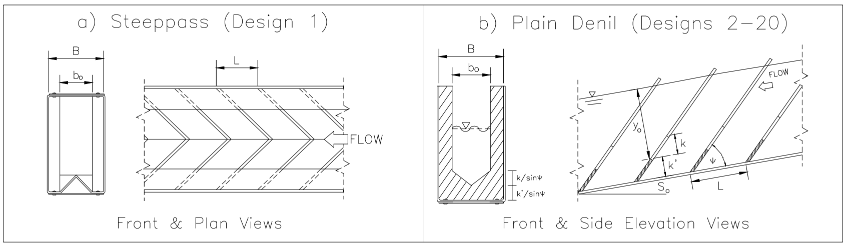
$Q_* = 3.59(y_o/b_o)$

Design #18



$Q_* = 3.75(y_o/b_o)$

Denil fishways

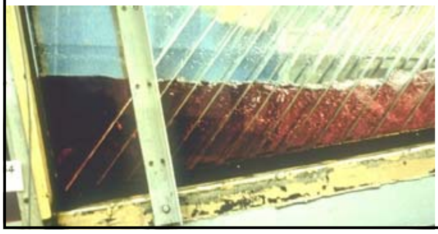


$$Q_* = 0.97\left(y_o / b_o\right)^{1.55} \quad U_* = \frac{u_m}{\sqrt{g b_o S_o}} = 1.43 Q_*^{0.48}$$

Steeppass (Denil 1)

$$Q_* = 1.15\left(y_o / b_o\right)^{1.8} \quad U_* = \frac{u'_m}{\sqrt{g R_h S_o}} = \frac{15 Q_*}{13 + Q_*^{1.25}}$$

Standard Denil (Denil 2)



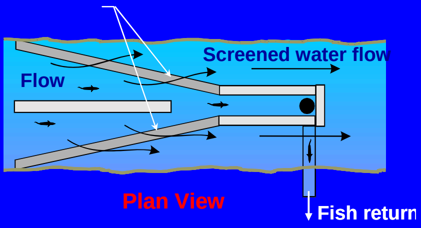
$$Q_* = \frac{Q}{\sqrt{g S_o b_o^5}}$$

Katopodis, Rajaratnam, Wu and Tovell 1997

Fish screens for industrial water intakes

Physical and numerical hydraulic modeling along with experiments & knowledge of fish life history and behaviour.

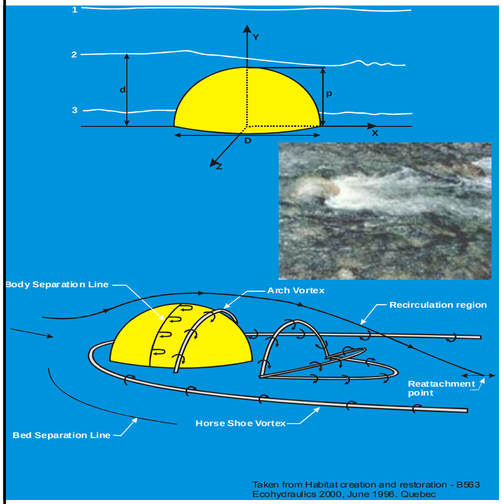
High velocity fish screens for irrigation canals



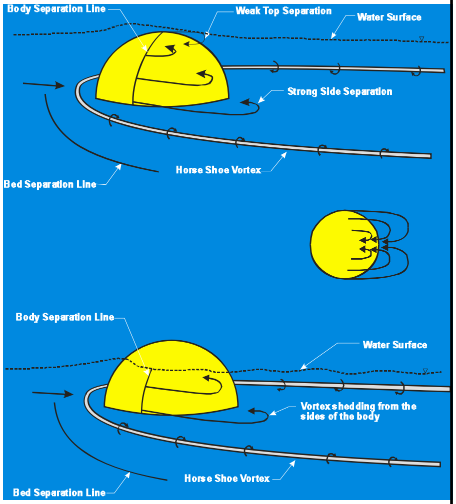
Katopodis, Ead, Standen and Rajaratnam 2005; Katopodis 2005

Turbines with trash racks of narrow spacing to prevent fish entry and lead them to the bypass

Hydraulics of simple habitat structures

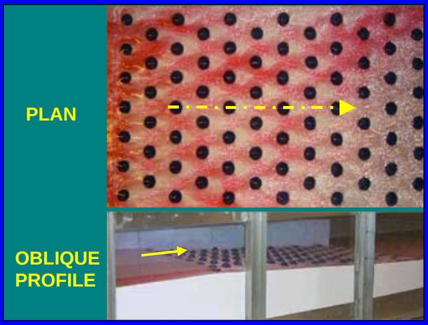


Taken from Habitat creation and restoration - B563 Ecohydraulics 2000, June 1996. Quebec

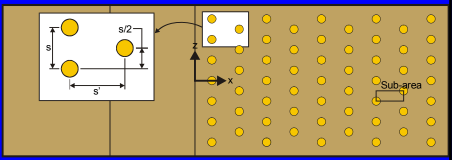


Shamloo, Rajaratnam and Katopodis 2001

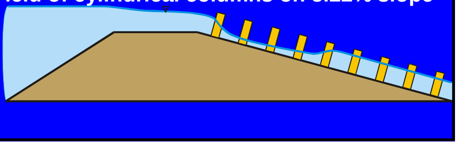
Hydraulics of ramps with regularly spaced objects



Field of hemispheres on 5% slope



Field of cylindrical columns on 5.22% slope



McKinnon and Hnytka 1985

“Stream simulation”

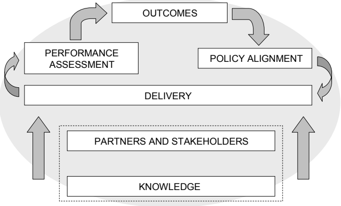
We introduced an early version of physiomimesis or mimicking nature in the late 1970’s for fish passage through culvert crossings on the Liard Highway in the Canadian Arctic.

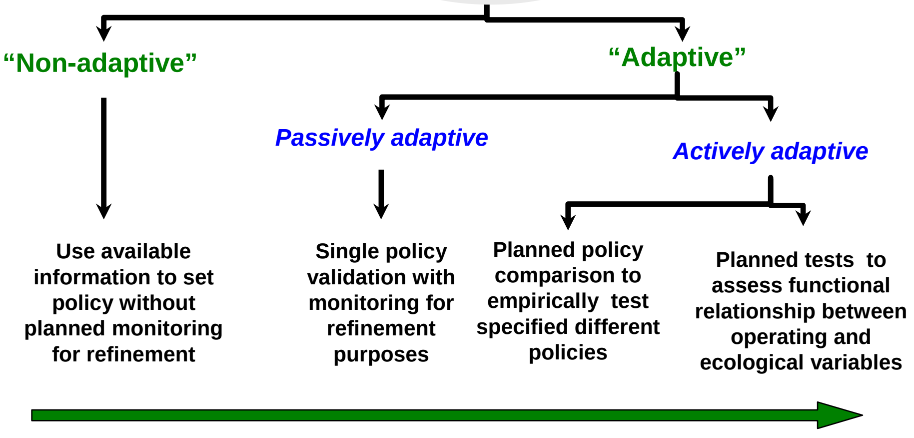
Natural stream width and slope were used to size and set culvert slope respectively. Large riprap, resembling passable natural rapids, placed in culvert barrels and sized for stability at the design discharge.

Nature-mimicking approaches

- **Natural analogues or mimics offer guidance in developing softer environmental solutions and an adaptive management philosophy.**
- **Mimicking natural hydrographs (e.g. natural flow paradigm)**
- **Mimicking natural rivers or streams in restoration projects (e.g. pool and riffle sequences; re-meandering)**
- **Nature-like fish passage facilities**
- **Holistic, expert based approaches based on natural processes**

Adaptive management approaches





“Non-adaptive”

“Adaptive”

Passively adaptive

Actively adaptive

Use available information to set policy without planned monitoring for refinement

Single policy validation with monitoring for refinement purposes

Planned policy comparison to empirically test specified different policies

Planned tests to assess functional relationship between operating and ecological variables

Increasing cost, risk and improvement in scientific understanding

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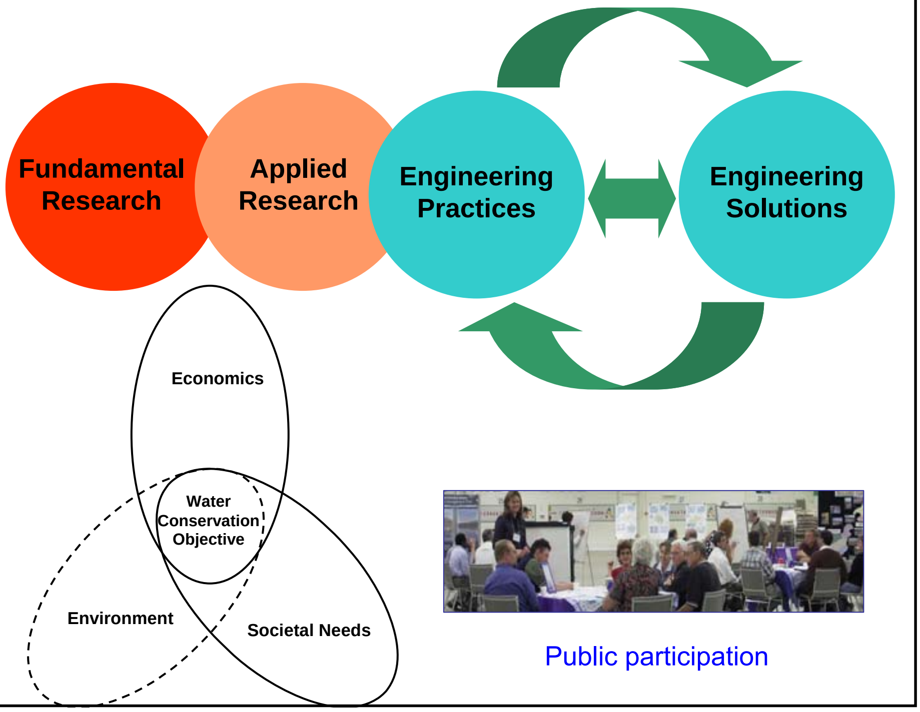
Science-based monitoring

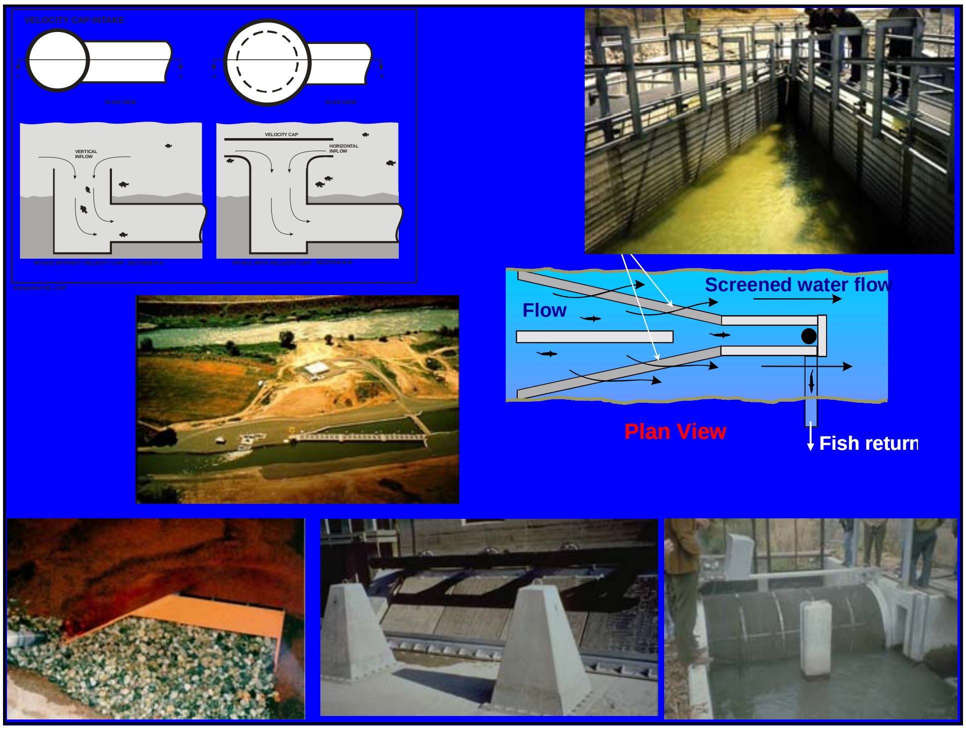
Ecological variables, such as habitat suitability curves, aquatic biota behaviour and mobility, bioenergetic constraints, ecosystem base flow and degree of deviation from natural flow regimes, introduce uncertainties which make scientific monitoring imperative; yet, such monitoring is rarely developed and implemented successfully.

Science-based monitoring

- The challenge to managers, engineers and scientists is to develop, implement and interpret science-based long term monitoring at least for significant flow regime changes.
- Scientific monitoring is an essential part to validate assessments, models, and assumptions, as well as a critical instrument to provide insights for improving approaches, analogs, models, and analyses for estimating ecological flow regimes.

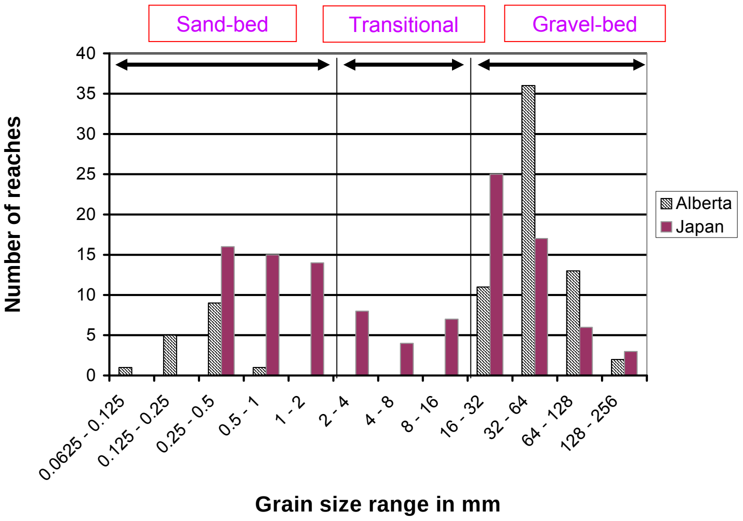


Public participation



Gravel-bed and sand-bed rivers

frequency of river reaches with various grain sizes



Courtesy: Gary Parker

Bankfull geometry comparisons

Gravel-bed rivers

$$H_{bf} = 0.3785 \frac{Q_{bf}^{2/5}}{g^{1/5}}$$

$H_{bf} \sim Q_{bf}^{0.4}$

Gravel-bed rivers have larger grain size and higher slopes than sand-bed rivers

$$B_{bf} = 4.698 \frac{Q_{bf}^{2/5}}{g^{1/5}} \left(\frac{Q_{bf}}{\sqrt{gD_{s50}}\, D_{s50}^{2}} \right)^{0.0661}$$

$B_{bf} \sim Q_{bf}^{0.466}$

$$S = 0.1003 \left(\frac{Q_{bf}}{\sqrt{gD_{s50}}\, D_{s50}^{2}} \right)^{-0.3438}$$

$S \sim Q_{bf}^{-0.344}$

Sand-bed rivers

$$H_{bf} = 2.52 \frac{Q_{bf}^{2/5}}{g^{1/5}} \left(\frac{Q_{bf}}{\sqrt{gD_{50}}\, D_{50}^{2}} \right)^{-0.063} \sim Q_{bf}^{0.337}$$

$$B_{bf} = 0.280 \frac{Q_{bf}^{2/5}}{g^{1/5}} \left(\frac{Q_{bf}}{\sqrt{gD_{50}}\, D_{50}^{2}} \right)^{0.153} \sim Q_{bf}^{0.553}$$

$$S = 2.13 \left(\frac{Q_{bf}}{\sqrt{gD_{50}}\, D_{50}^{2}} \right)^{-0.357} \sim Q_{bf}^{-0.357}$$

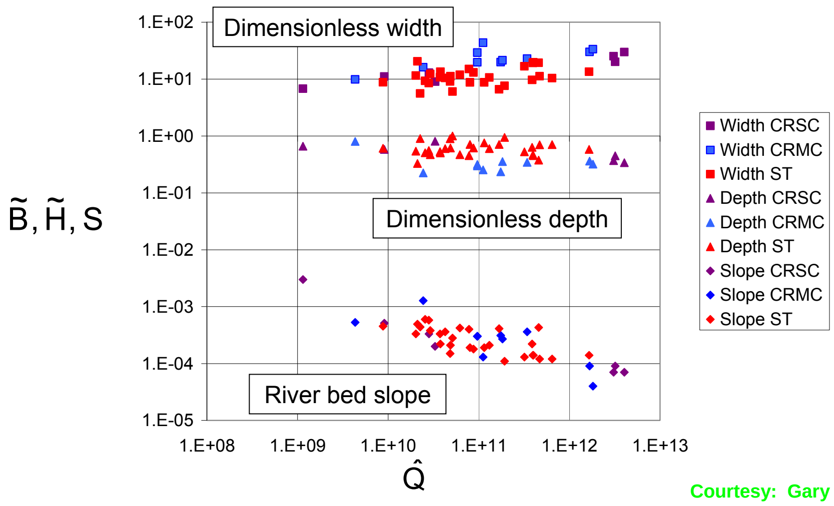
Dimensionless relationships for both gravel- and sand-bed rivers comparable to:

$$B_{bf} \sim Q_{bf}^{0.5}$$
$$H_{bf} \sim Q_{bf}^{0.4}$$
$$S \sim Q_{bf}^{-0.3}$$

Modified from Gary Parker

Bankfull geometry: sand-bed rivers

The four data sets are consistent for bankfull channel characteristics



Courtesy: Gary Parker