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Ecohydraulics - Challenges and Opportunities

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Vattendagarna med Fiskmarknad - Karlstad, Sweden, 8 October 2022
"*Remedial measures in regulated rivers*"

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Ecohydraulics & the ecohydraulic trilogy –

Exponential growth in publications since reviews by Katopodis 2005 and Katopodis & Aadland 2006

Movements, swimming abilities, habitat connectivity and passage of aquatic organisms

E-flows for aquatic flora and fauna
(environmental, ecological or instream flow regimes)

Restoration of aquatic habitats and ecosystems,
including nature-based solutions (NBS)
& removal of infrastructure

Energy pathways – Connectivity - Migrations – Passage

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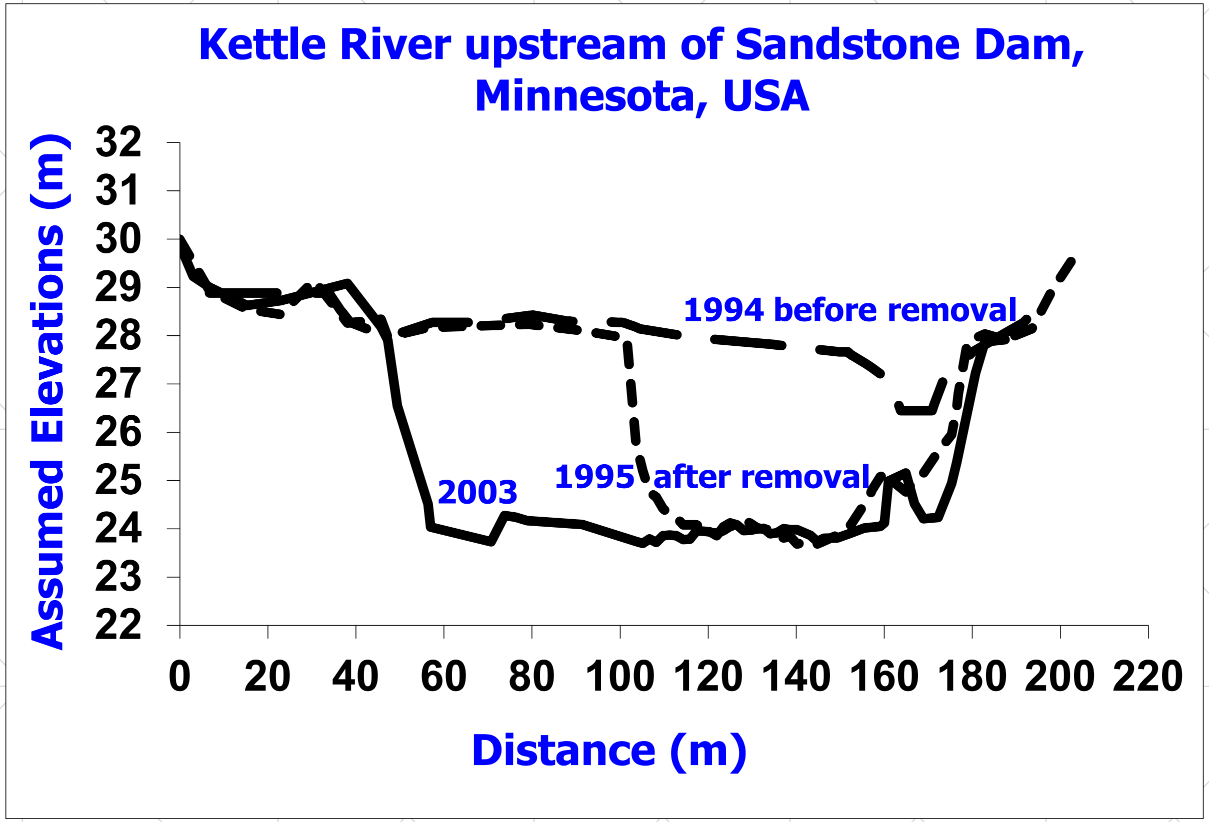
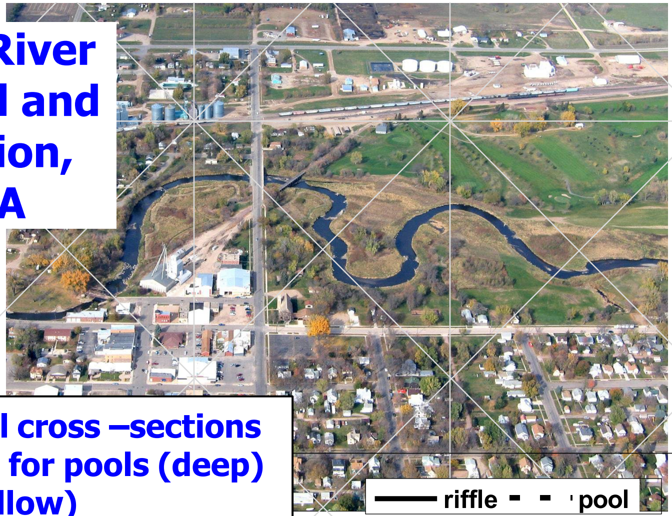
Nature based solutions (NBS)

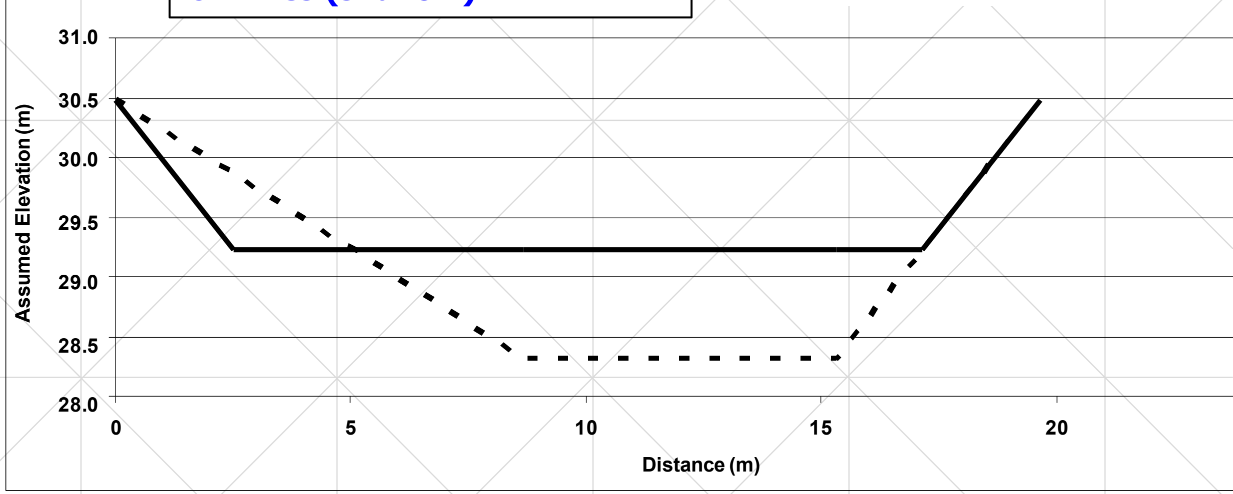
Dam removal & river restoration:

"Let river recover" taking a long time
or pre-design & "speed-up restoration"



Pomme de Terre River after dam removal and channel restoration, Minnesota, USA





Fish responded well to dam removal at Kettle, Pomme de Terre in Minnesota (Katopodis & Aadland 2006) and Elwha rivers in Washington State (Duda, Torgersen et al. 2021)

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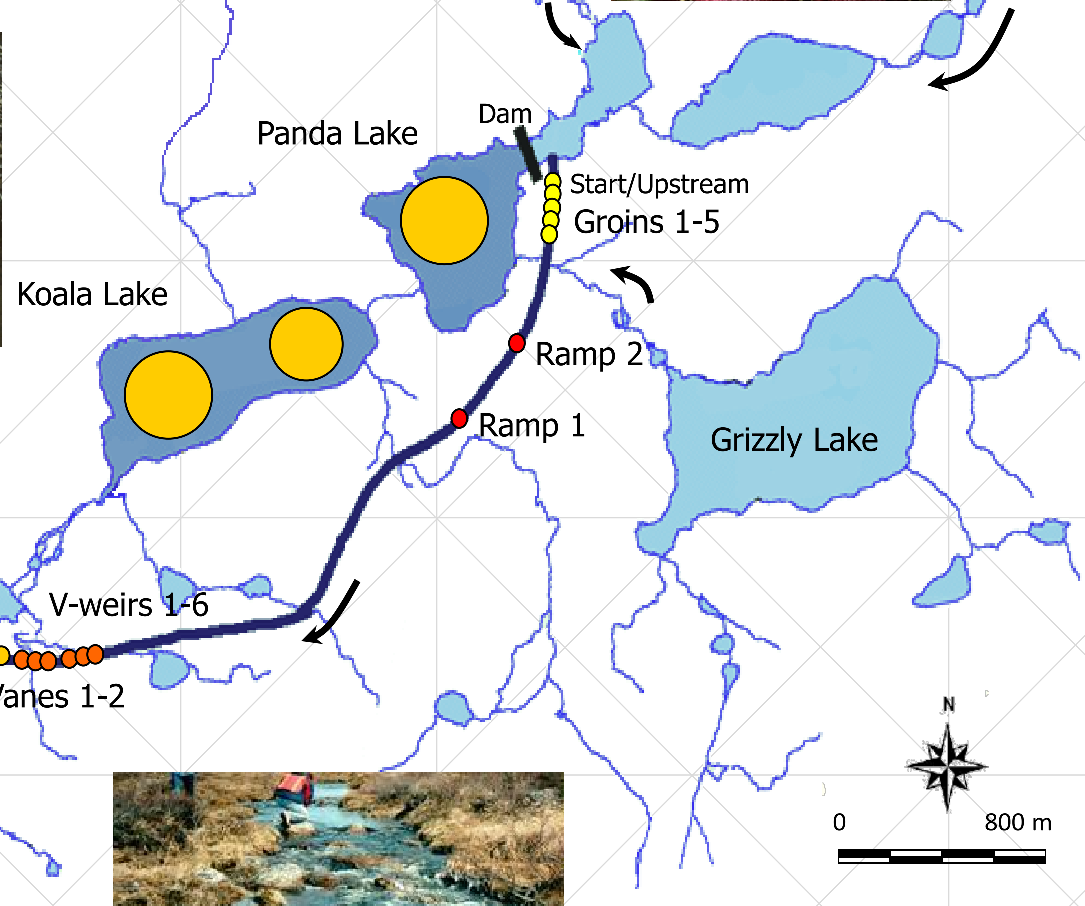
Nature based solutions (NBS) - Habitat replacement

Panda Diversion Channel (PDC), NWT, Canada, above the tree line



Jones, Tonn, Scrimgeour and Katopodis 2003

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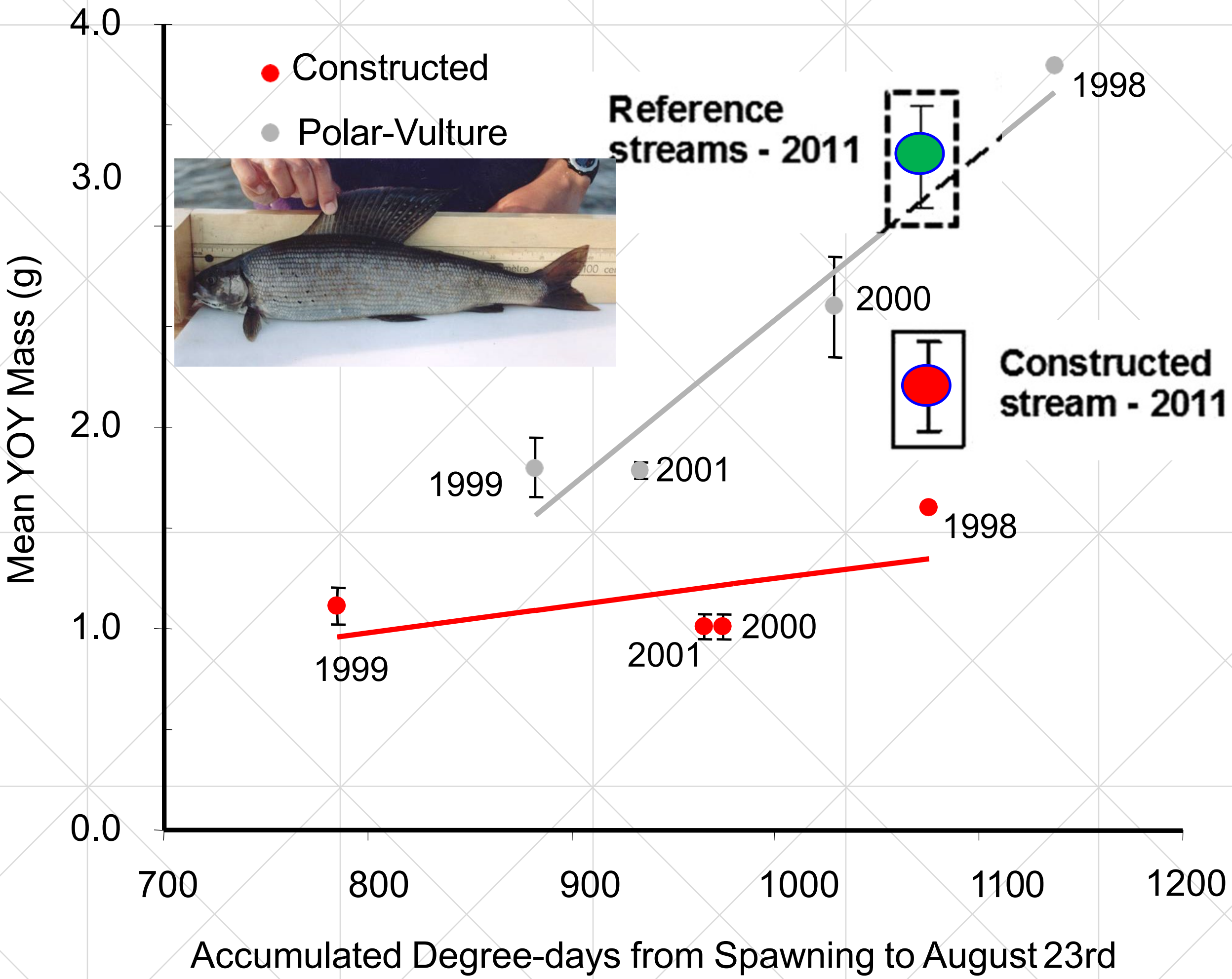
Nature based solutions (NBS) – Panda Diversion

YOY Arctic grayling (*Thymallus arcticus*) **from Panda Diversion 14 years later (2011) were substantially larger than in 1998–2001, yet still smaller than those from natural stream**

Active management over time for more rapid convergence.

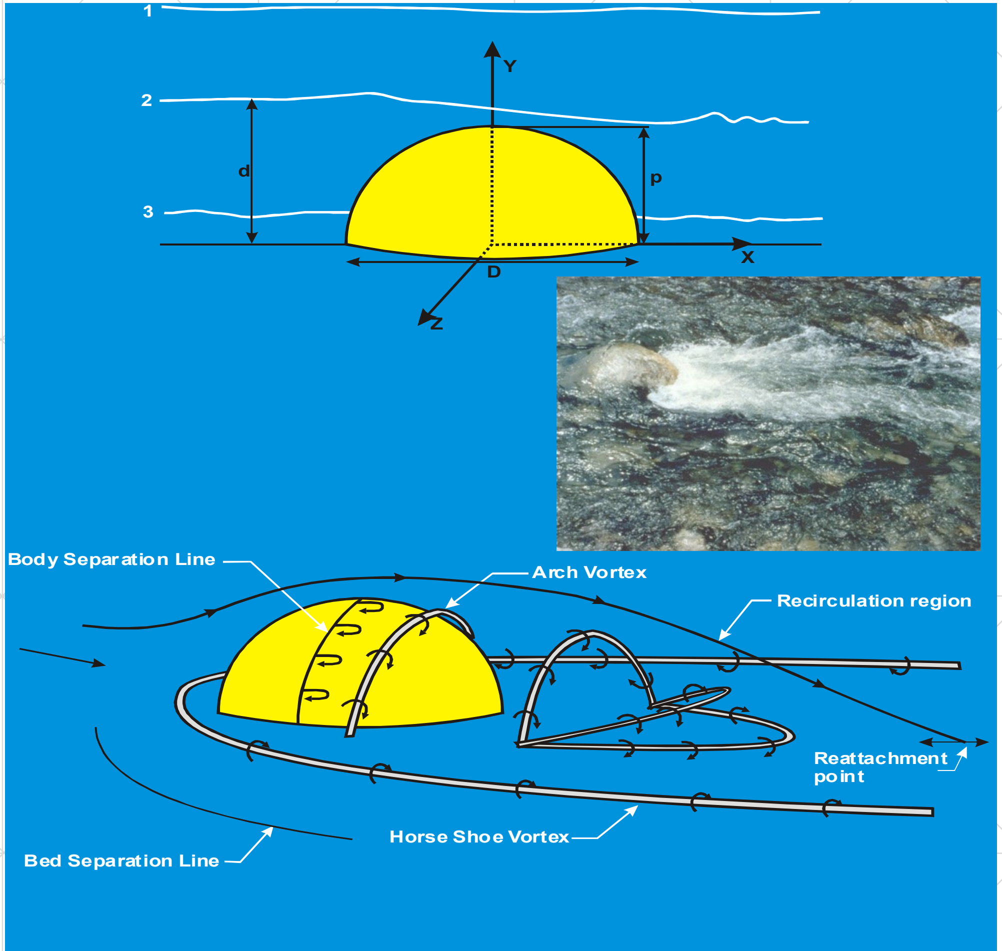


Reference stream: Polar-Vulture stream

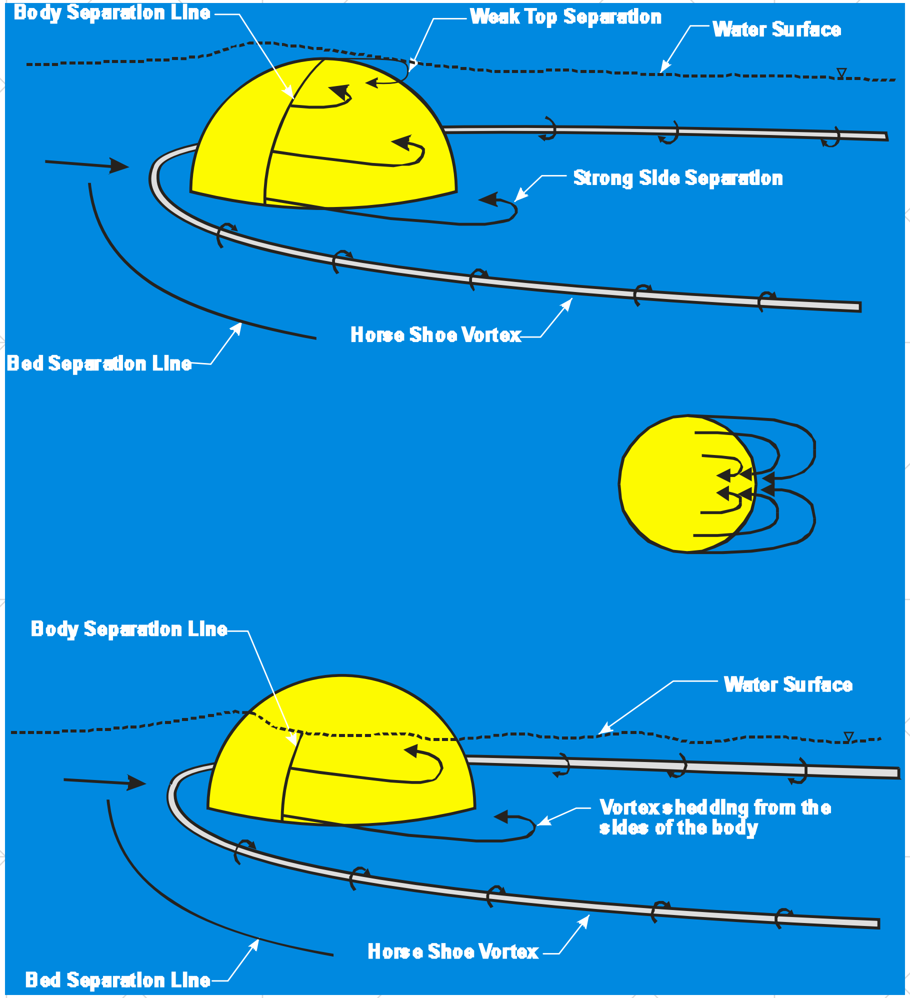
Panda Diversion - Constructed channel

Jones, Tonn, Scrimgeour and Katopodis 2003; Scrimgeour, Tonn, and Jones 2014

Simple habitat structures



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



Shamloo, Rajaratnam and Katopodis 2001

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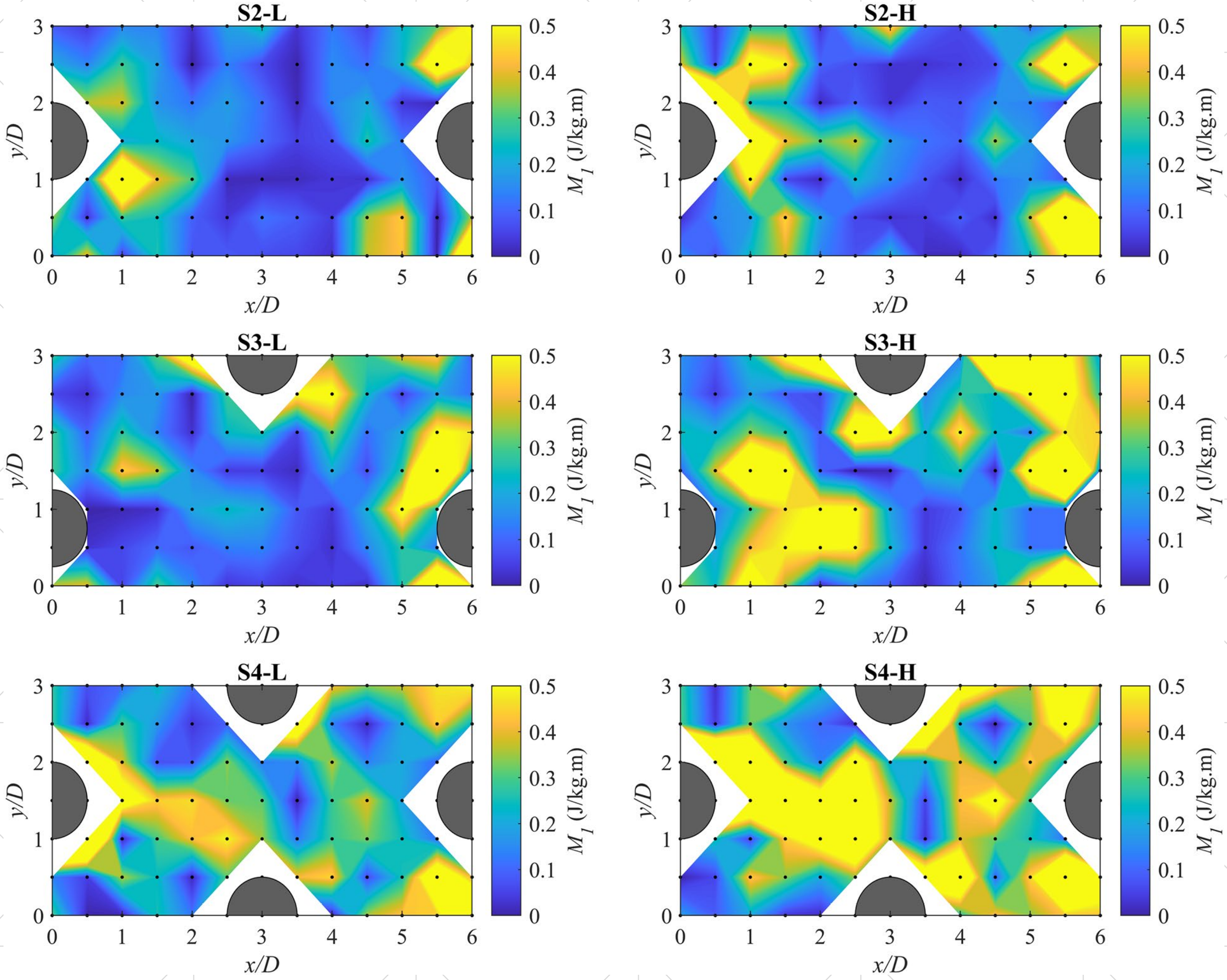
Boulder placement & hydraulic metrics

Contour maps of the kinetic energy gradient metric, *M1*, for different boulder placement.

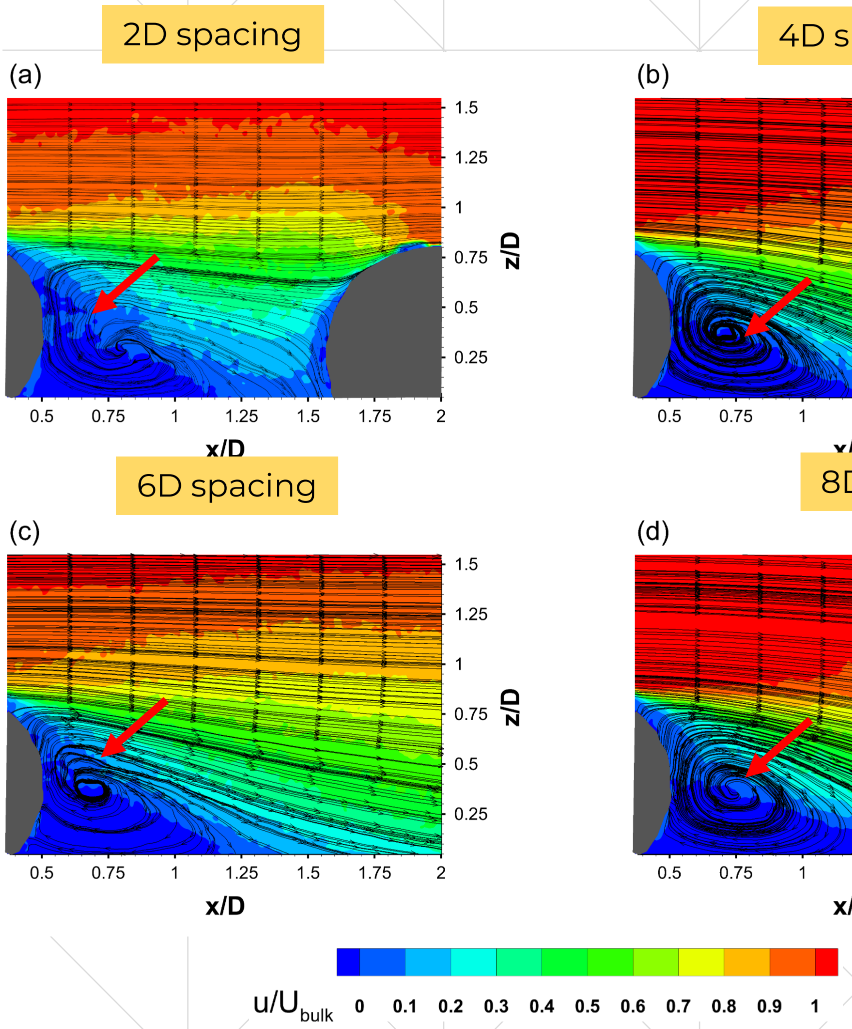
Black dots – measuring locations.
White areas - missing measuring points occupied by boulders.



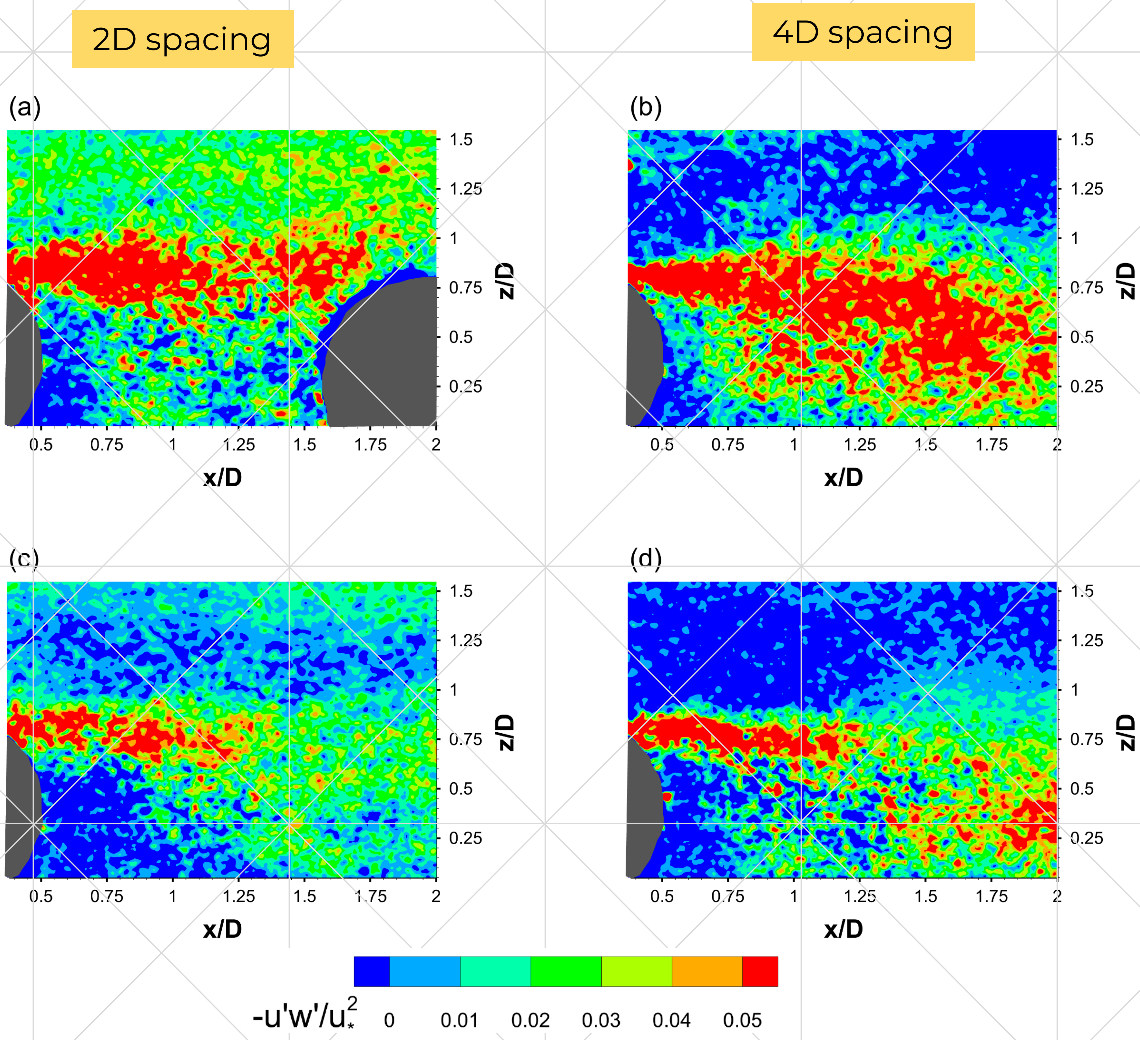
Golpira, Baki, Ghamry, Katopodis, Withers & Minkoff 2022

Boulder placement

Normalized streamwise velocity



Normalized Reynolds shear stress (RSS)



Golpira, Baki, Ghamry, Katopodis, Withers & Minkoff 2022

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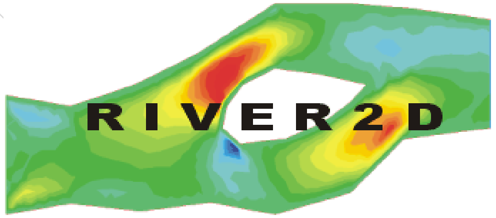
E-flows:

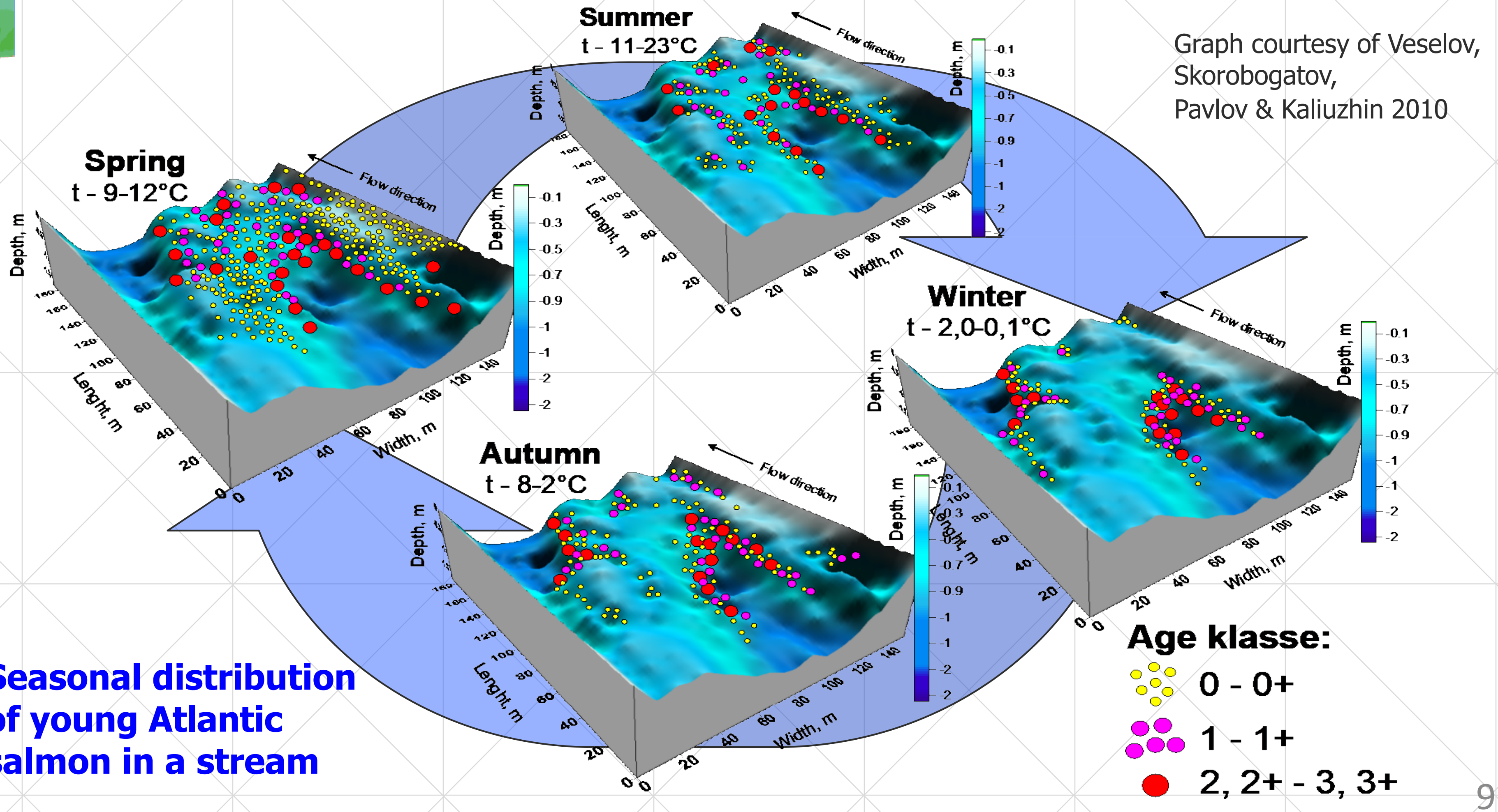
environmental, ecological or instream flow regimes for aquatic flora and fauna



www.river2d.ca

Public domain 2D hydrodynamic and habitat model developed at the University of Alberta, Canada spearheaded by C. Katopodis.

References: Katopodis 2022; Katopodis and Ghamry 2013; Katopodis & Ghamry 2007; Katopodis 2005; Waddle, Steffler, Ghanem, Katopodis & Locke 2000; Ghanem, Steffler, Hicks & Katopodis 1996.



Graph courtesy of Veselov, Skorobogatov, Pavlov & Kaliuzhin 2010

Seasonal distribution of young Atlantic salmon in a stream

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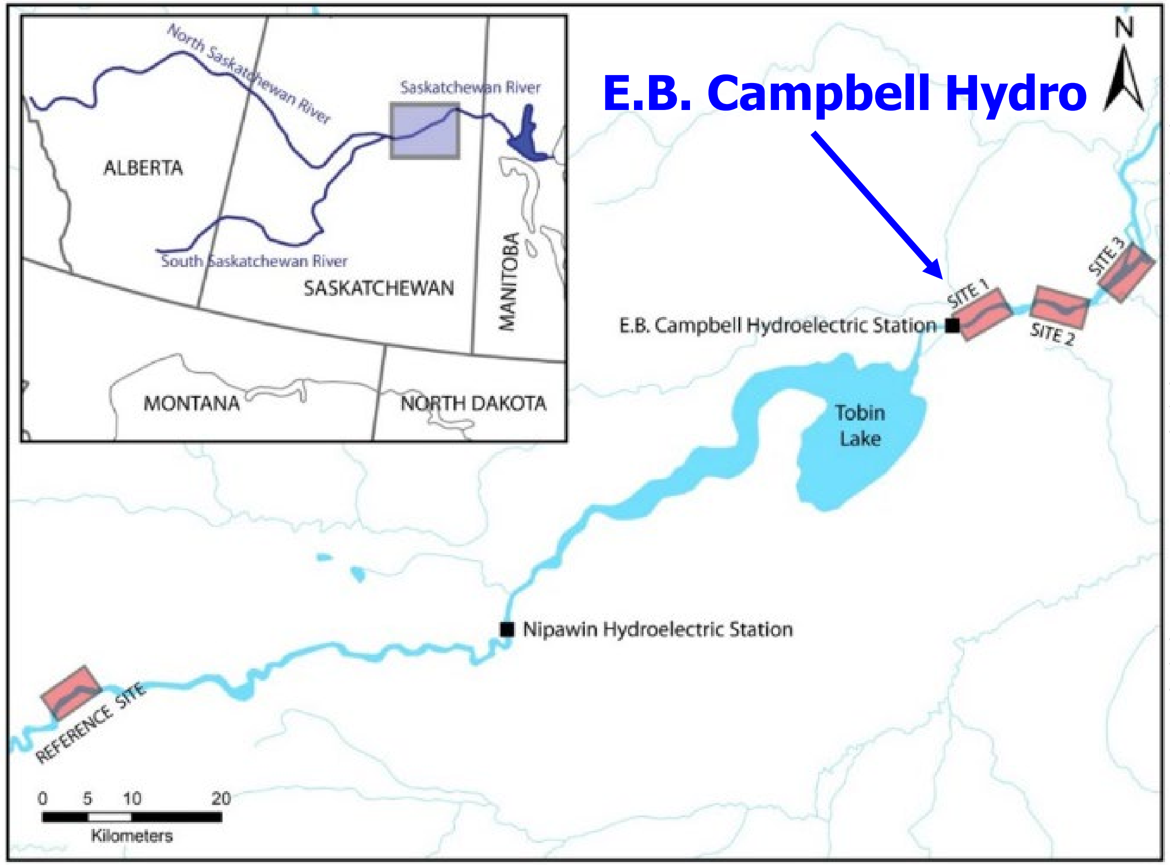
Hydropeaking case study, Sask Power

Lake Sturgeon (*Acipenser fulvescens*)
& many freshwater species

No e-flow: 1986-2004
75 m^3/s min since 2004

Pre-75 m^3/s release

Turbine mortality

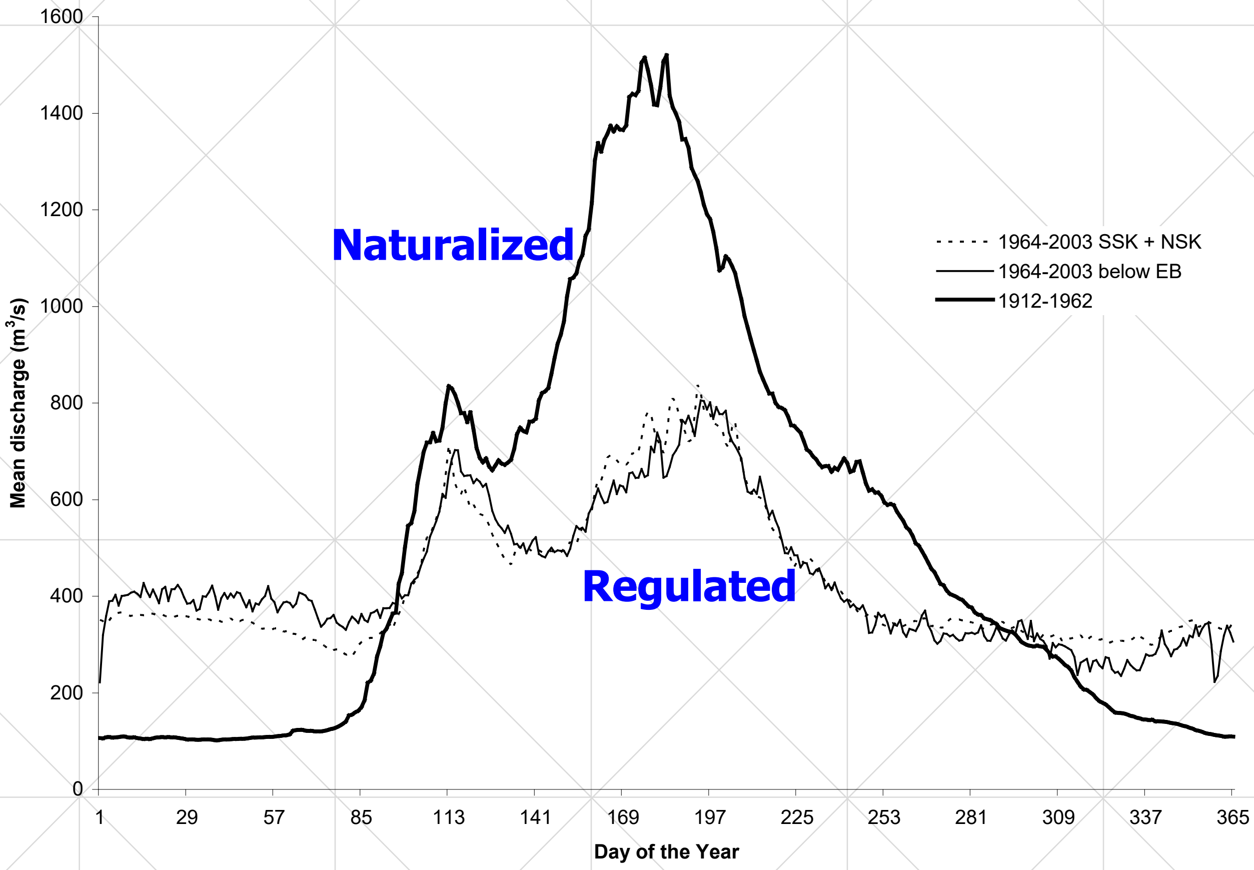


Fish stranding

NOTE: To avoid stranding, it was assumed that adult fish need at least 20 cm in water depth.

Katopodis 2022; Watkinson, Ghamry, Franzin & Katopodis 2009

Hydropeaking case study , Sask Power



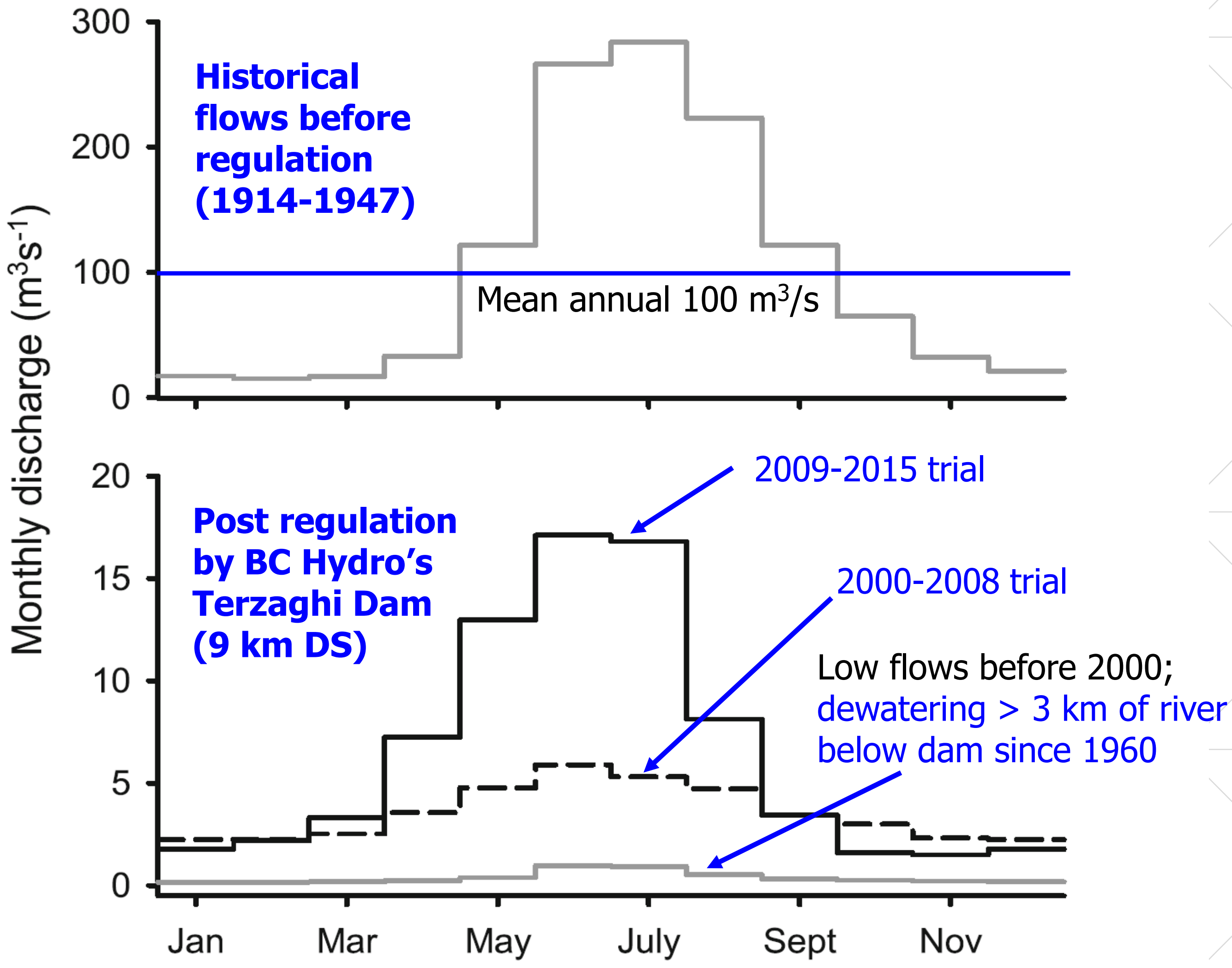
Saskatchewan R naturalized (1912-196) & regulated flows (1964-2003) at E.B. Campbell Hydro Station (EBC)

Katopodis 2022; Watkinson, Ghamry, Franzin & Katopodis 2009

2009 study & 2019 science review e-flow regime	BSP (Biologically Significant Period)			
	Fall & winter spawning	Early spring spawning	Spring spawning	Growing season
	BSP 1 (15 Oct-29 Apr)	BSP 2 (30 Apr-27 May)	BSP 3 (28 May-24 Jun)	BSP 4 (25 Jun-14 Oct)
e-flow exceedance	75 91.5%	300 89%	450 95%	250 95%
Pre-EBC 95%	66	232	459	239
DFO 2019 (science review)	66	232	459 700 sturgeon	239

- e-flow recommendations in m^3/s
- exceedance for BSP based on mean weekly flows
- Releasing >1000 m^3/s when feasible would benefit freshwater Saskatchewan River Delta ~100 km downstream

Bridge River, BC Hydro



Bradford 2022

Field experiments to set e-flows

Adaptive management approach - increased flow releases assessed using abundance of juvenile Pacific salmon *Oncorhynchus* spp. as a metric

Since 2015, BC Hydro has developed **Water Use Plans** for most of its hydroelectric plants to improve e-flows.

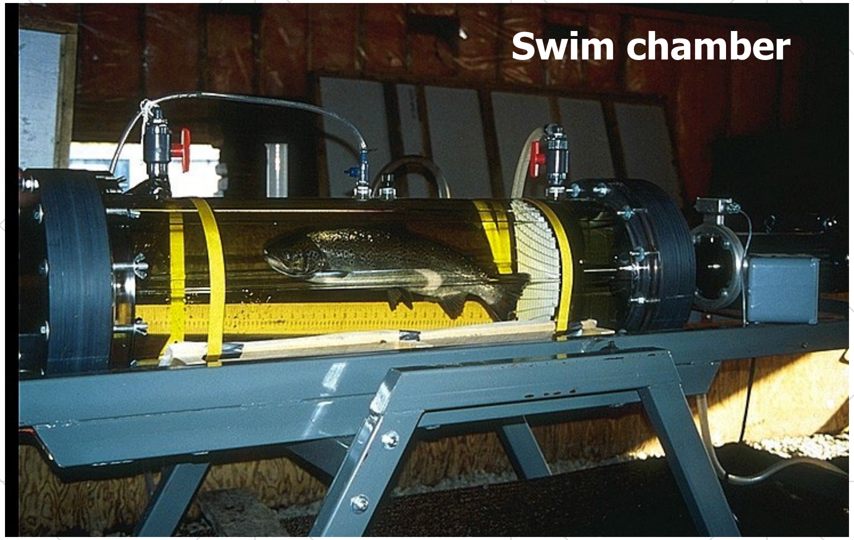
Overall goal to better balance competing uses of water (fish and wildlife, recreation, environmental and social issues).

Site-specific actions:

- adjustments to flow releases and reservoir elevations
- recreation and habitat enhancement
- multiyear environmental monitoring studies to confirm anticipated benefits.

https://www.bchydro.com/toolbar/about/sustainability/conservation/water_use_planning.html.

Fish swimming performance

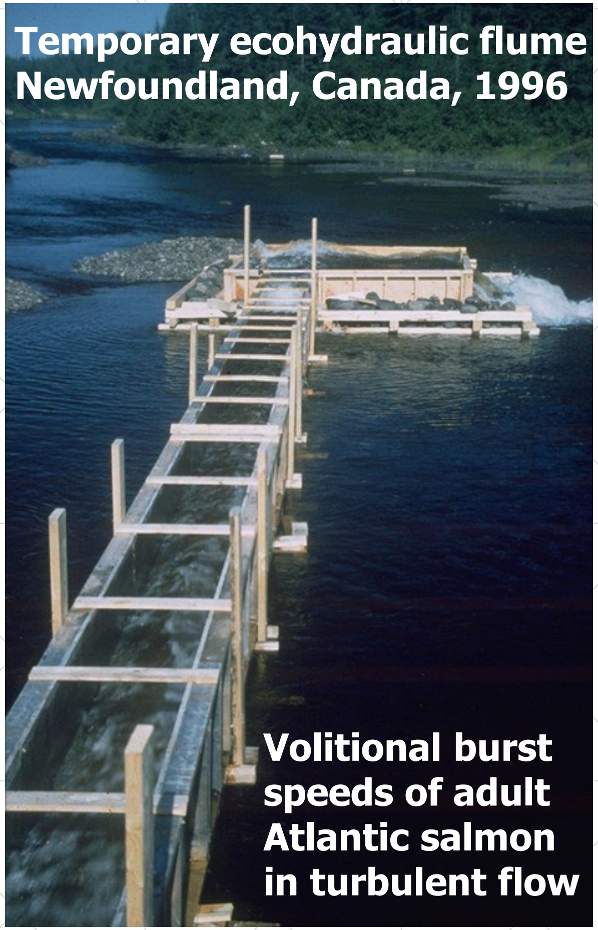


Mainly used for prolonged or sustained swim tests & Ucrit

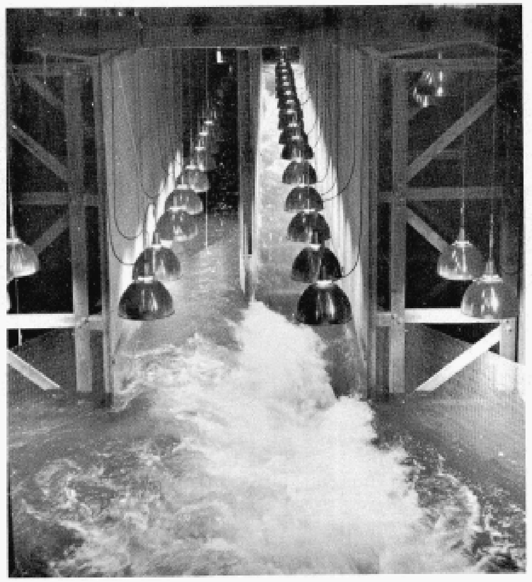
Confinement may limit fish movements or gait transition; uniform flow

Most fish speed and endurance data collected over several decades use this method

Ecohydraulic flumes are used for many studies on hydrodynamics and aquatic flora & fauna.



Colavecchia, Katopodis, Goosney, Scruton and McKinley 1996 & 1998

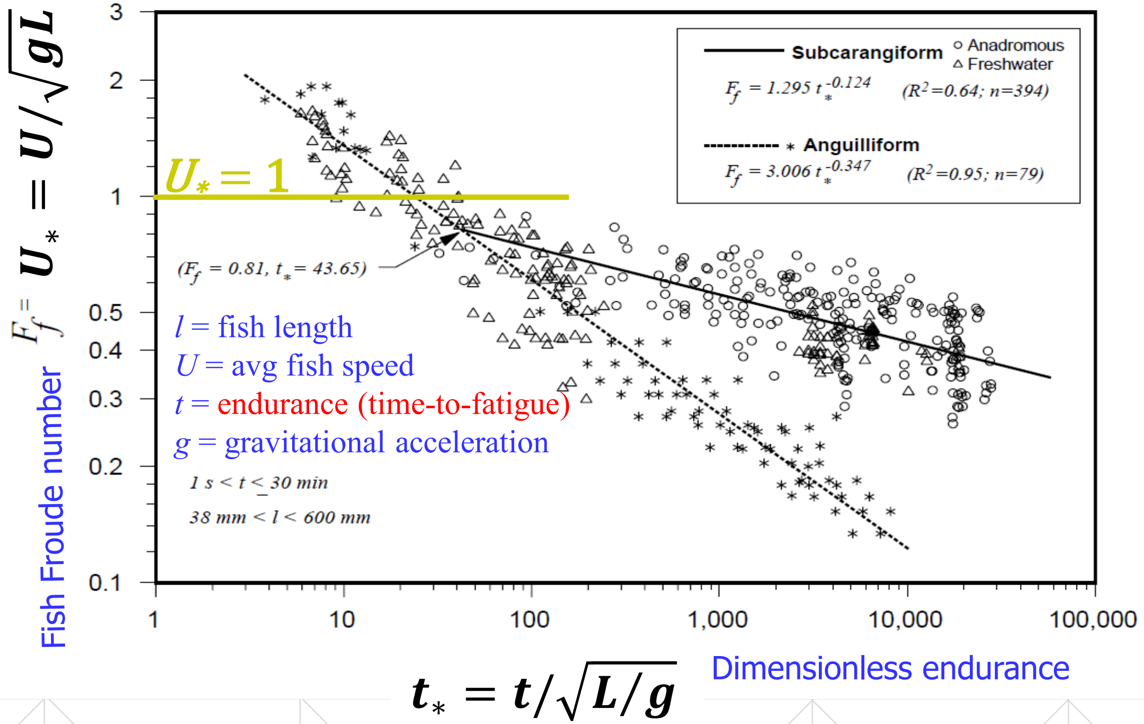


Bonneville Lab Flume Columbia River, USA; Weaver (1963)

- Ecohydraulic flumes used for burst speed swim tests
- Fish less constrained, able to exhibit burst-and-glide behaviour
- More variable velocity & turbulence distributions
- Most data collected recently

Similarity in fish swimming performance

Fixed and increasing velocity tests;
18 subcarangiform & 2 anguilliform species



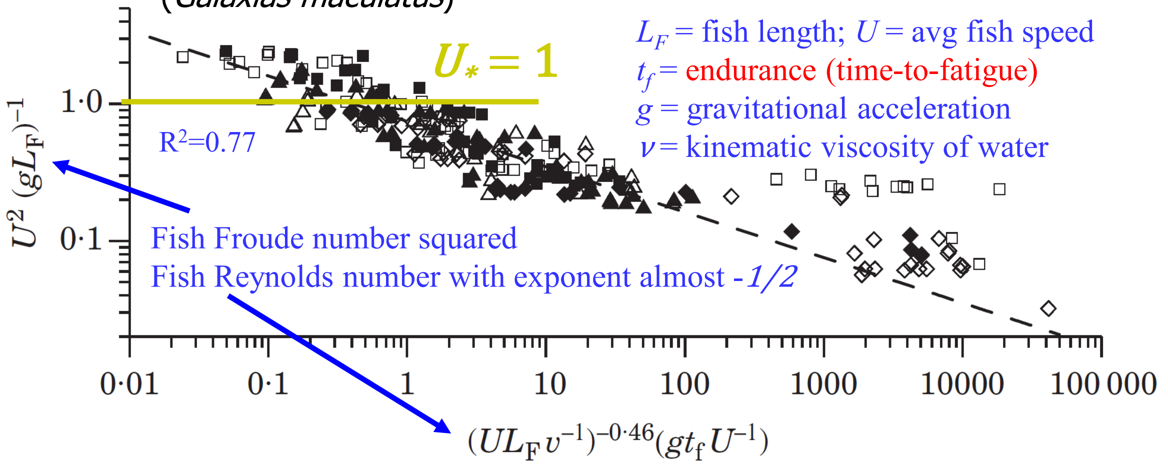
Katopodis 1992

$$U_* \approx \sqrt{\frac{\text{fish inertial forces (momentum)}}{\text{gravitational forces on fish}}}$$

At $U_* = 1$ fish manage to balance gravitational forces

U_*, which includes $\sqrt{L}$ as a scale, provides strong regressions for individual & groups of species displaying similarity in swimming performance

Fixed velocity test: Inanga (*Galaxias maculatus*)



Nikora, Aberle, Biggs, Jowett & Sykes 2003

Empirical relationships

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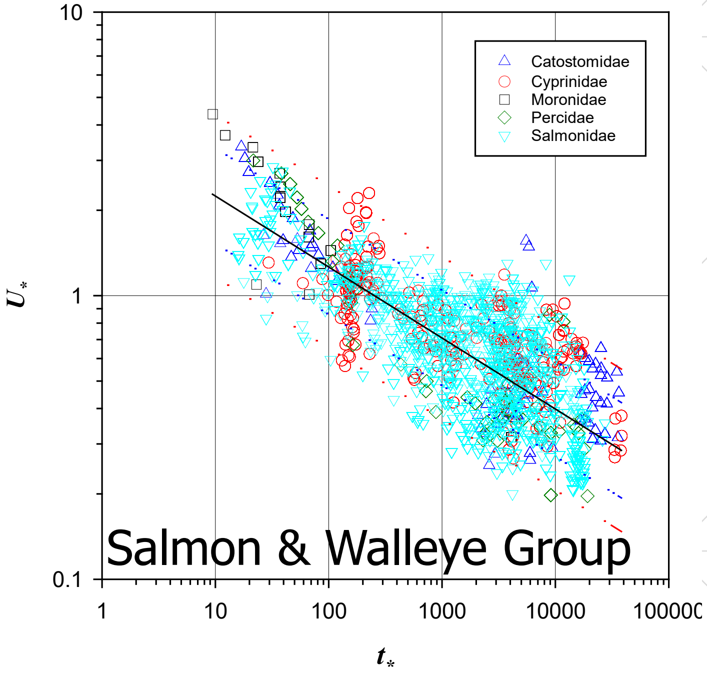
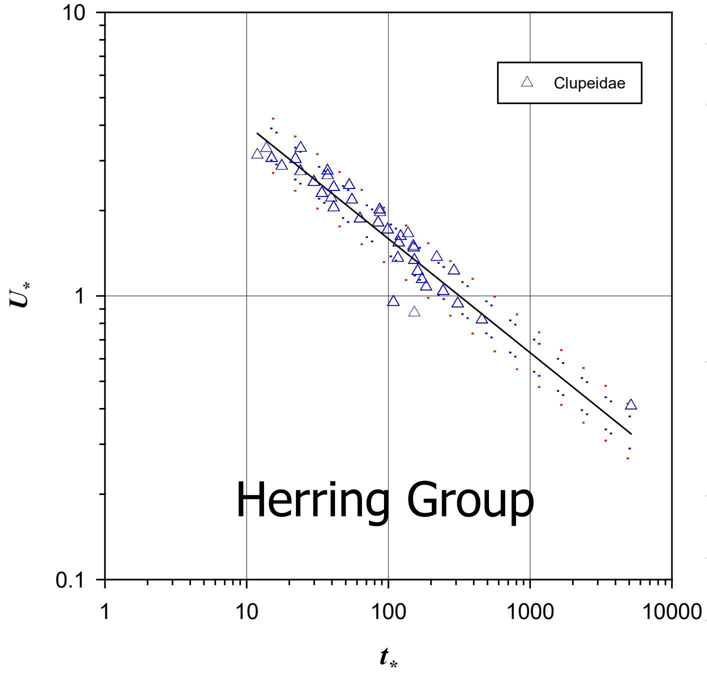
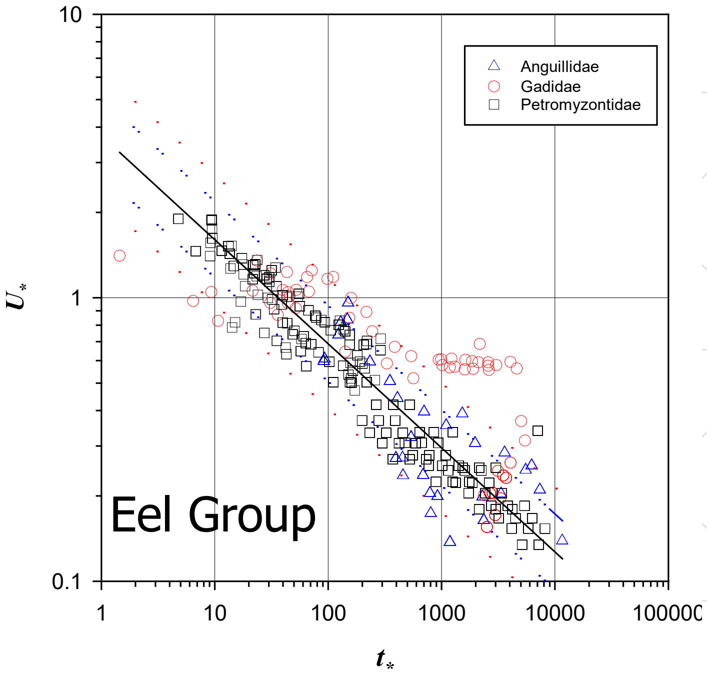
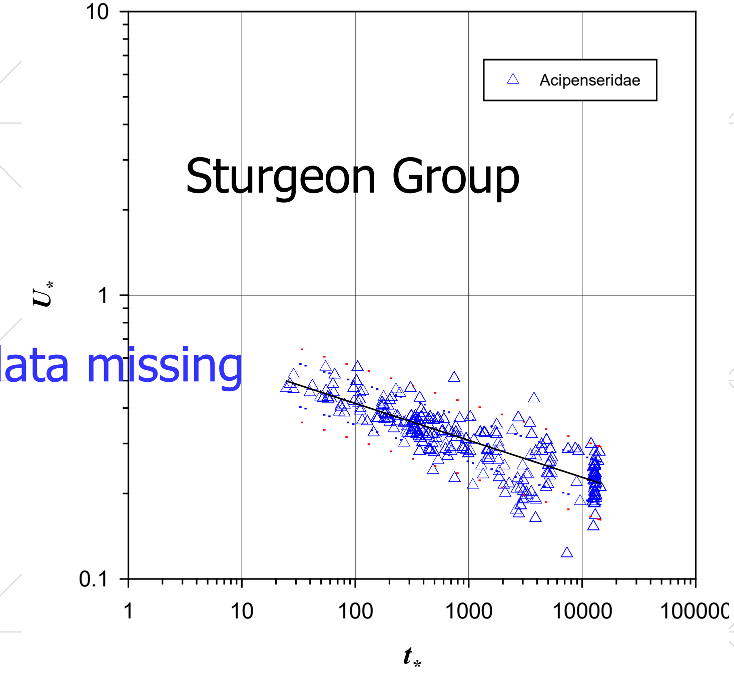




Lower prolonged data missing





Burst data missing

Based on Katopodis and Gervais 2016

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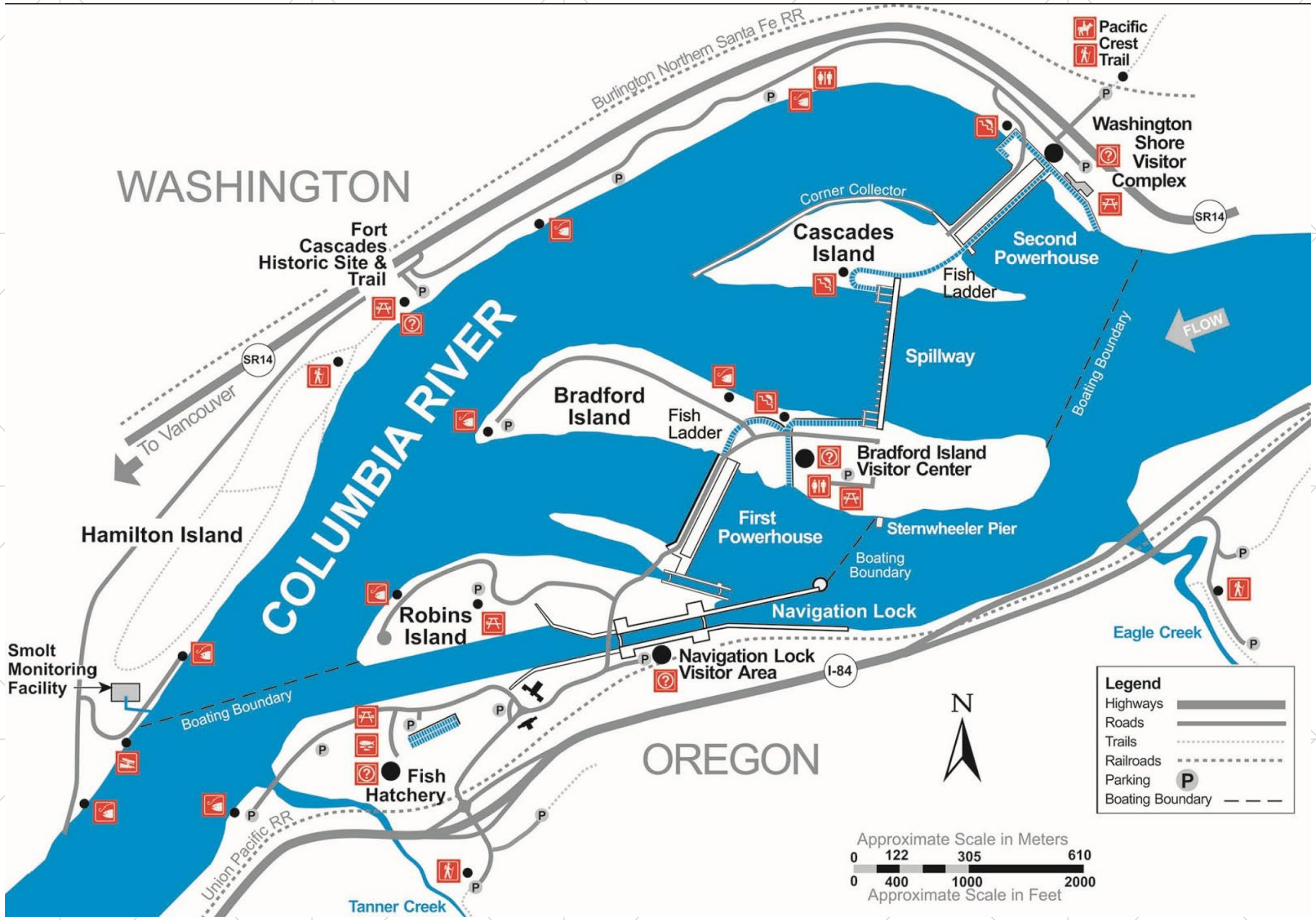
Chinook salmon seeking fishway entrances in tailrace of Bonneville Lock and Dam

- Adult spring Chinook salmon *Oncorhynchus tshawytscha* with mean FL=760 mm tracked migrating through the physically and hydrodynamically complex tailrace area
- The highest speed Chinook salmon swam at was 1.19 m/s or mean $U_* = 0.44$.
- U_{crit} = 1.55 m/s for 755 mm Chinook measured previously in swim chamber tests or U_* =0.57, aerobic physiological limit
- Chinook 74% of the time preferred to maintain aerobic swimming, which was close to $U_* = 0.5$.

Brown, Geist & Mesa 2006



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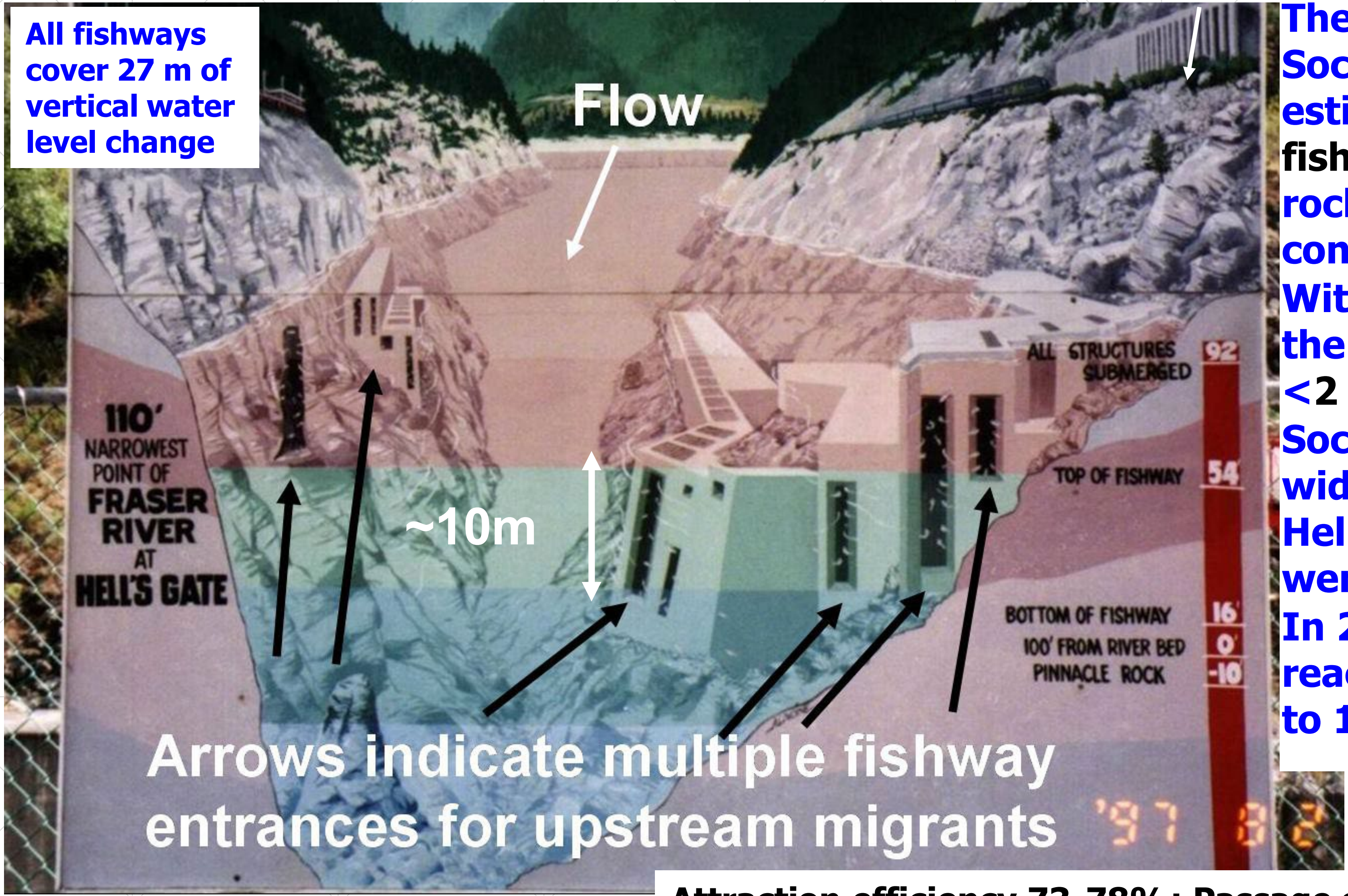
Hell's Gate, BC, Canada - Sockeye salmon *Oncorhynchus nerka*



The 1913 Fraser River Sockeye salmon run, estimated at 39 million fish, was blocked by a rockslide during railway construction

Within a few life cycles, the run was reduced to <2 million fish

Sockeye runs have varied widely since the first two Hell's Gate fishways were built in 1947

In 2010, the Sockeye run reached numbers similar to 1913

Attraction efficiency 73-78%; Passage efficiency ~100%

Review by Katopodis & Williams 2012; Hinch and Bratty 2000

Hell's Gate, BC, Canada - Sockeye salmon *Oncorhynchus nerka*

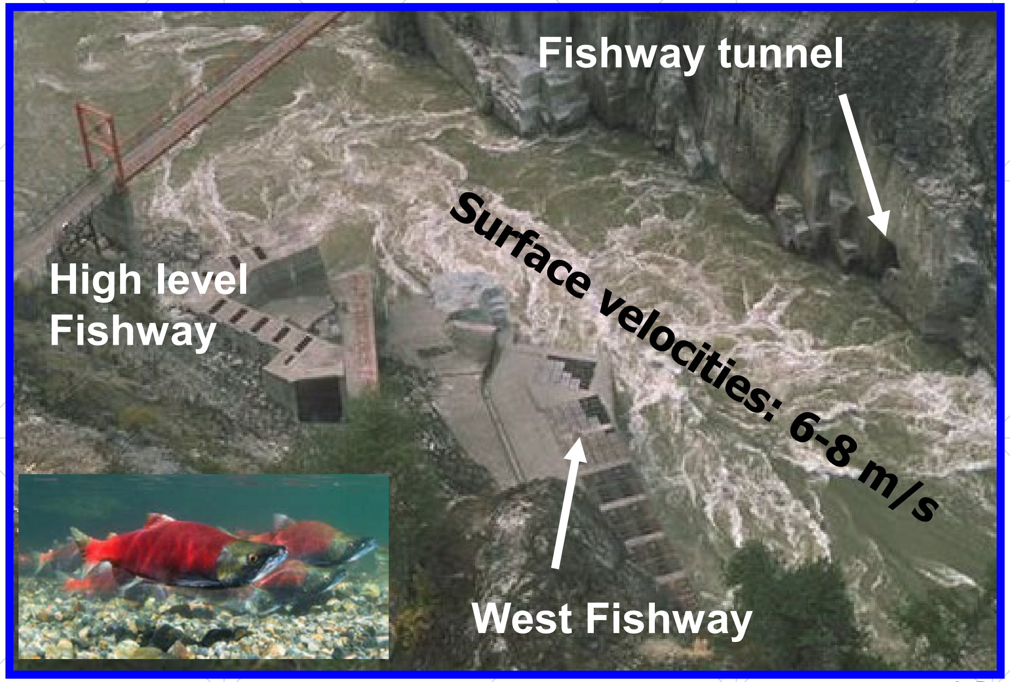
Sockeye 550–630 mm: U_{crit} = 1.2 m/s or 2.3 BL/s (Brett and Glass 1973) or U_***=0.5**, aerobic limit

Sockeye that successfully reached and entered the fishways (75%):

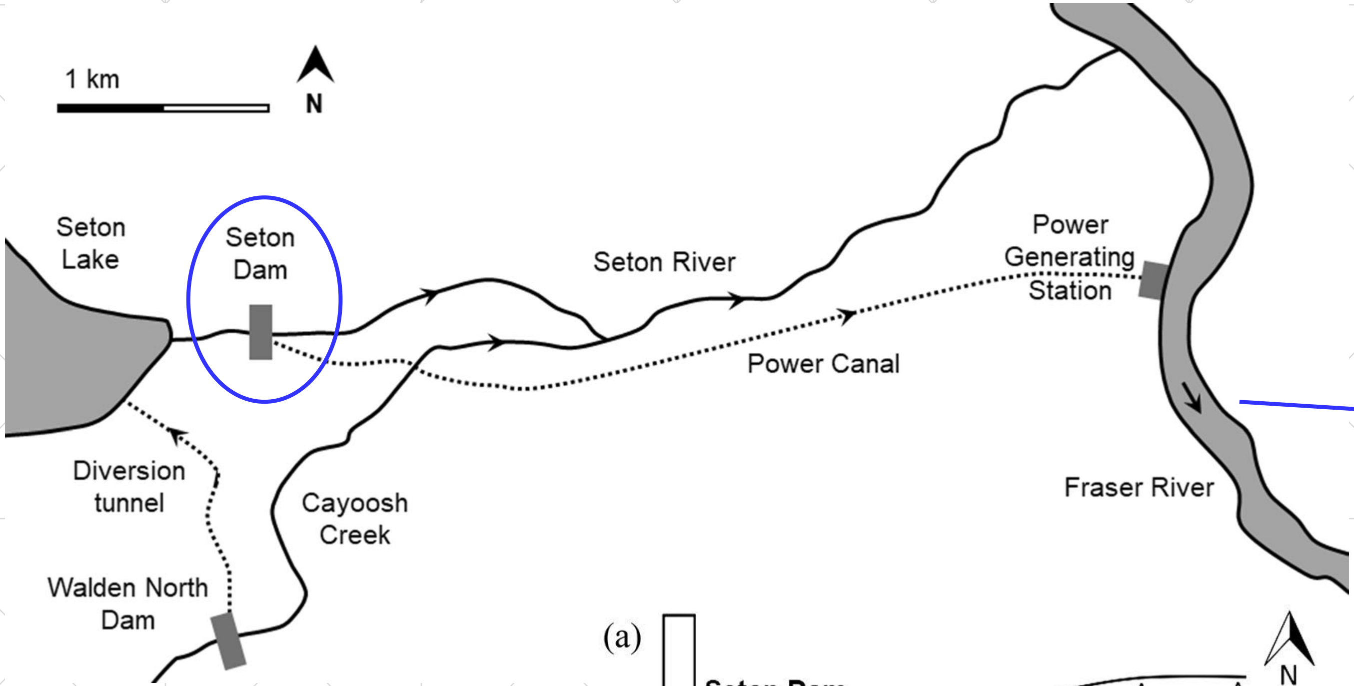
- alternated between relatively fast and slow speeds;
- used shorter average endurance & slower avg speed: 1.85 BL/s or 0.8U_{crit} and U_***=0.4**;
- had lower avg maximum speed: 5.81 BL/s or 2.5U_{crit} and U_***= 1.4, i.e. anaerobic**;
- used high speeds very infrequently and never attained burst speeds;
- used mostly aerobic activity.

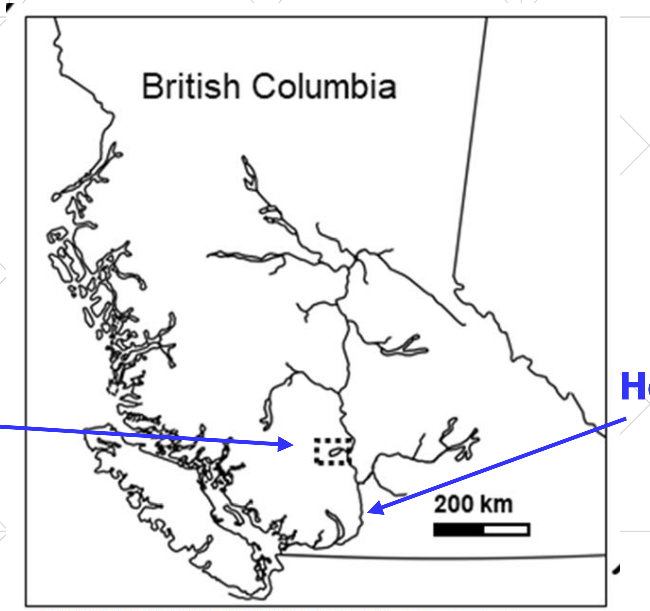
Sockeye that failed to reach the fishways (25%):

- used avg speed: 4.23 BL/s or 1.8U_{crit} and U_***=1.0, i.e. anaerobic**;
- used twice the avg maximum speed: 11.49 BL/s or 5U_{crit} and U_***= 2.7**;
- swam 2.2x as fast & 50 times longer;
- frequently alternated between burst and U_{crit} i.e. used mostly anaerobic activity.

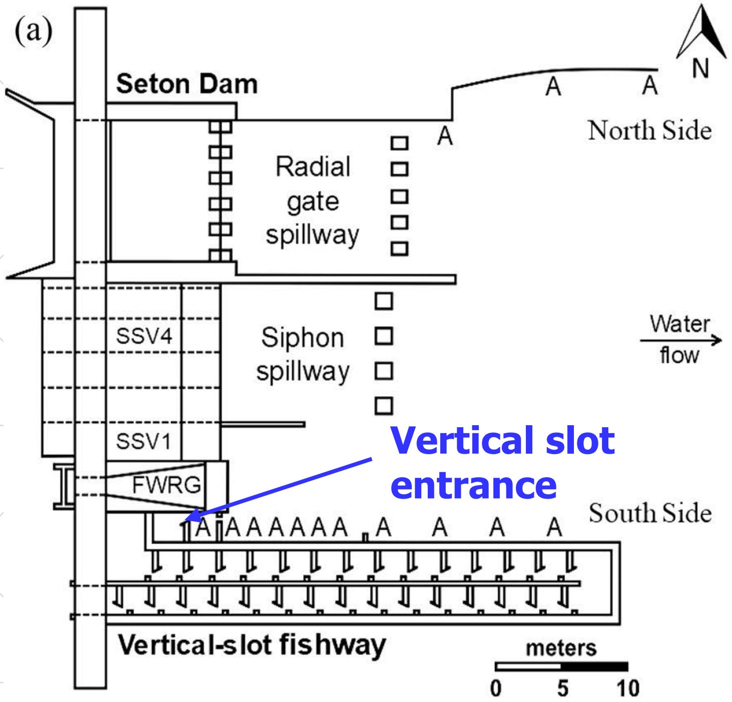


Hinch and Bratty 2000





Hell's Gate



Vertical slot entrance

(a) Plan view; acoustic receivers marked by A

(b) (b–c) Attraction flow Scenarios 1 and 2 released from SSV1 and SSV4 respectively

Seton Dam, B.C.

Li P, Zhang, Burnett, Zhu, Casselman & Hinch 2021

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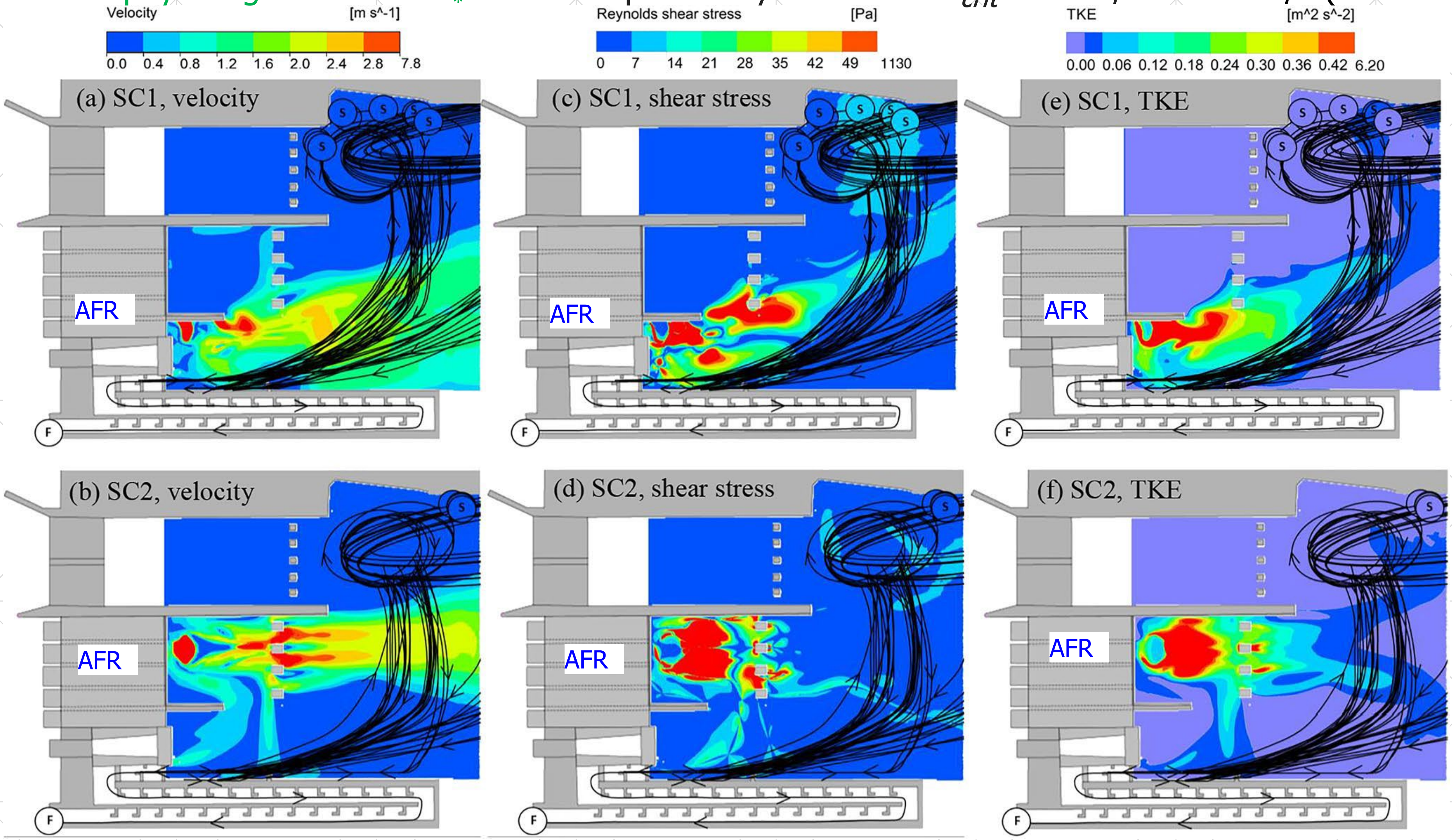
Seton Dam, B.C. field study & CFD

Adult sockeye salmon, avoided areas:>2.4 m/s, $2U_{crit}$, 4 BL/s or $U_* = 1$, RSS >21 N/m² & TKE >0.12 m²/s²

aerobic physiological limit of $U_* = 0.50$ at previously measured U_{crit} =1.2 m/s or 2.3 BL/s (Brett and Glass 1973)



Sockeye salmon
Oncorhynchus nerka
FL=593 mm (510-665)

(a, b) Mean velocity field

(c, d) RSS

(e, f) TKE

at plane 0.5 m below water surface

AFR – attraction flow release

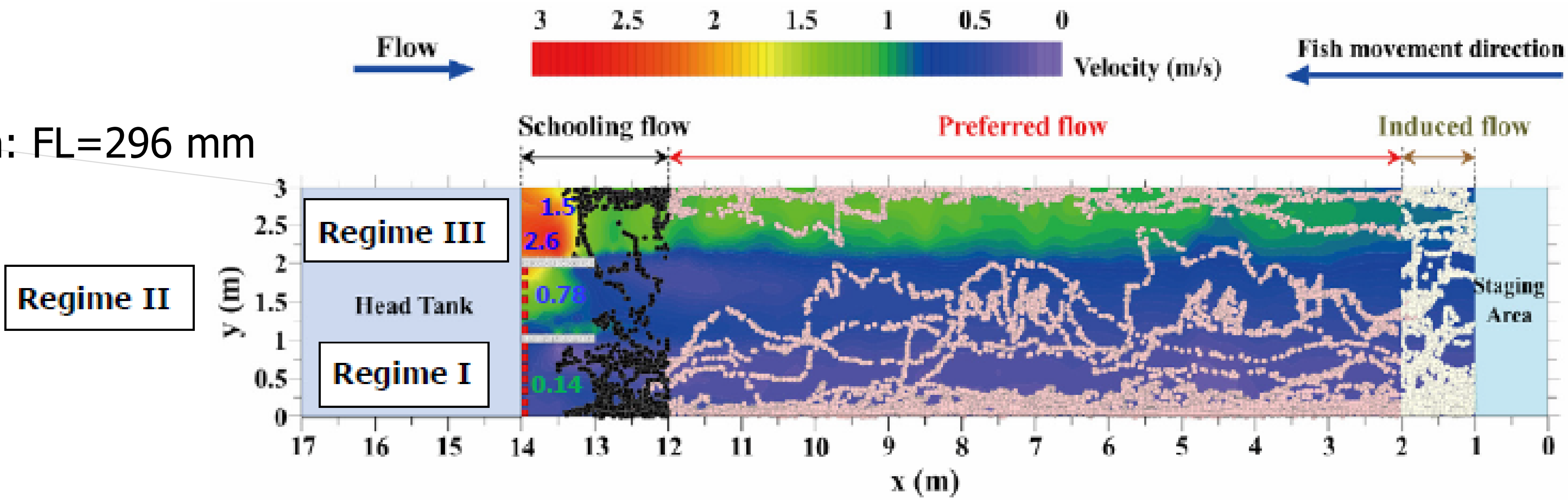
"S" location of first detection & "F" fishway exit

Li P, Zhang, Burnett, Zhu, Casselman & Hinch 2021

Cyprinid in turbulent flow - Ya-fish *Schizothorax prenanti*, lab study

290 mm Ya-fish: U_{crit} = 0.87 m/s or U_* = 0.52

Tested Ya-fish: FL=296 mm



Ya-fish avg speeds:

- 1.18 m/s and U_* = 0.69 in Regime I
- 1.49 m/s and U_* = 0.87, in Regime II
- 2.63 m/s and U_* = 1.54, in Regime III

Ya-fish:

- used mainly areas with TKE < 0.05 m^2/s^2
- "avoided" high TKE flows of 0.05 to 0.25 m^2/s^2
- "preferred" flow areas with RSS of -5 to 5 N/m^2
- "avoided" flow areas with RSS of -14 to 31 N/m^2 (horizontal component)

Li M, An, Chen, Li J 2022

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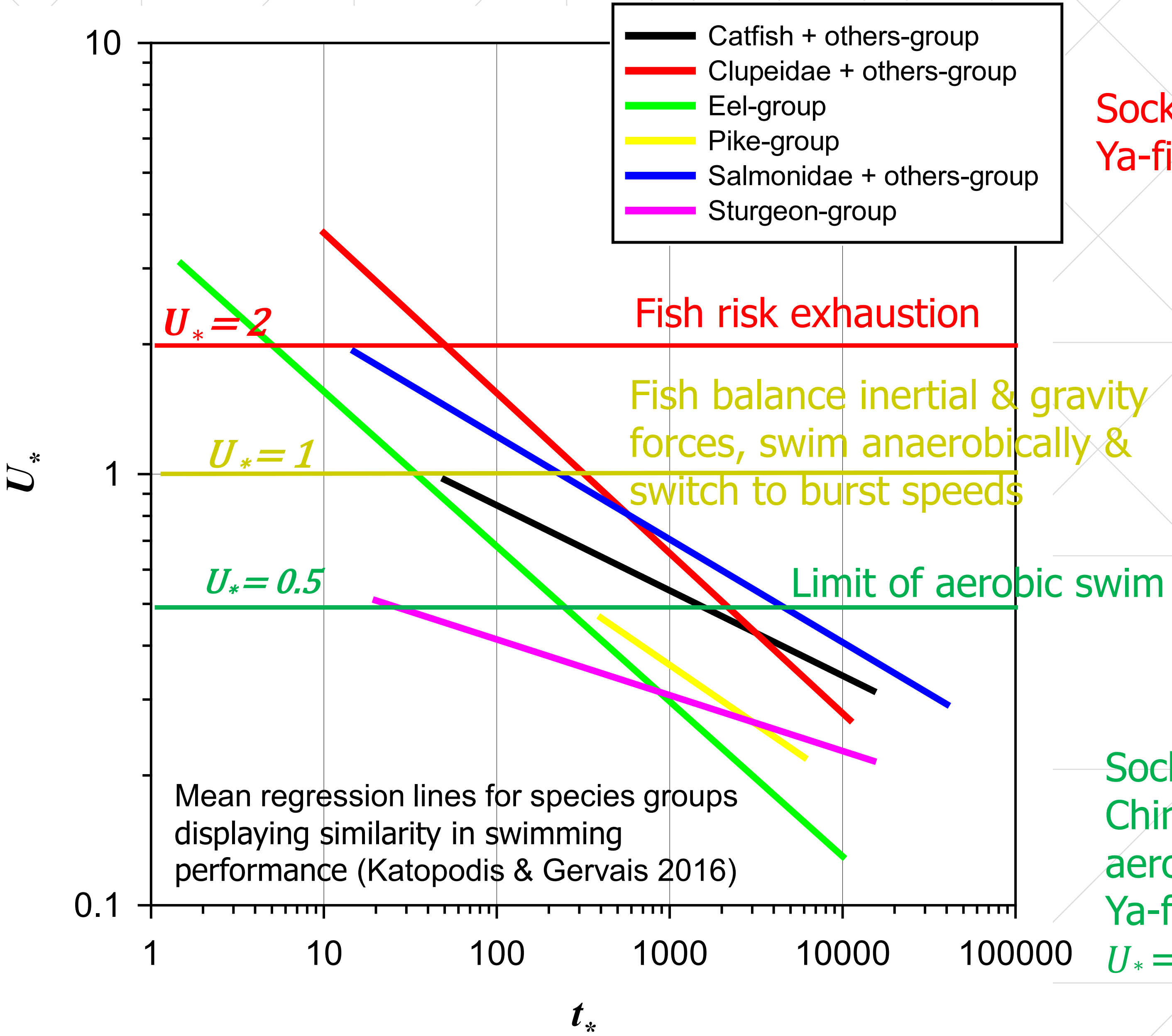
This is where physics meets physiology



$$U_* \approx \sqrt{\frac{fish\ inertial\ forces\ (momentum)}{gravitational\ forces\ on\ fish}}$$

Sockeye salmon, $U_* = 2.7$ at Hell's Gate
Ya-fish, $U_* = 1.54$ in Regime III

Atlantic sturgeon *Acipencer oxyrinchus* surfacing in Bay of Funday, Canada: $U_* \leq 1$ for highest recorded U with FL=1.68 & 1.76 m (Katopodis, Cai & Gervais 2019; data from Logan-Chesney 2017)

Sockeye salmon, $U_* = 1$, Seton Dam
$U_* < 1.4$, anaerobic at Hell's Gate
Ya-fish, $U_* = 0.87$ in Regime II

Sockeye salmon, $U_* = 0.50$ aerobic
Chinook salmon, $U_* = 0.4$, $U_* = 0.57$ aerobic, Bonneville Dam
Ya-fish, $U_* = 0.52$ aerobic, $U_* = 0.69$ in Regime I

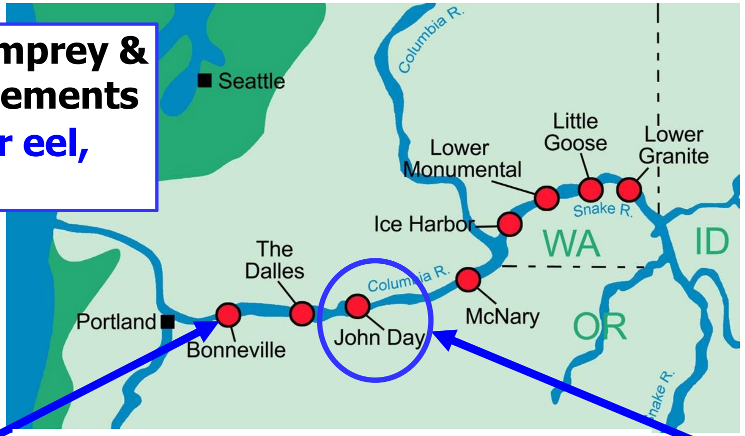
Pool-Weir-Orifice Fishways, Columbia River, USA

Depending on fishway discharge **plunging or streaming flow** regimes can be generated in either design

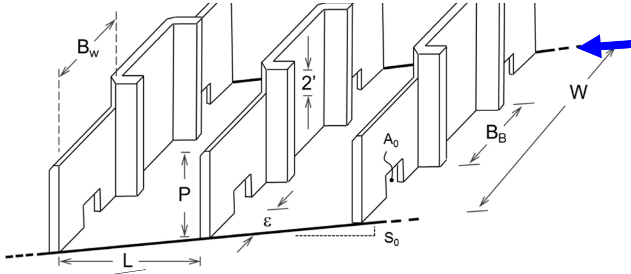
Efficient for salmon, but not for Pacific lamprey & White sturgeon that have different requirements
Special fishways developed or adapted for eel, lamprey & sturgeon

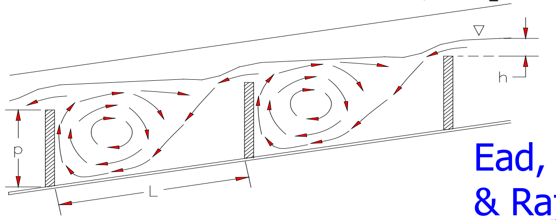
Sockeye salmon (*Oncorhynchus nerka*)
passage effectiveness at each of 9 dams: 94-98%
Cumulative passage:
81% through first **6 dams**
75% through **9 dams**

Williams & Katopodis 2016



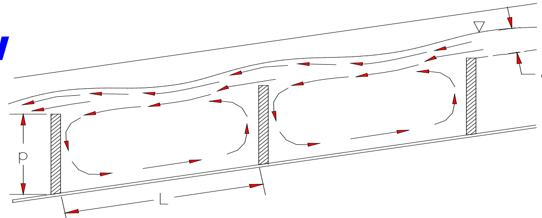
Adapted from USACE, BPA 2010 & USFWS (Northeast Region R5) 2019





Plunging flow

Ead, Katopodis, Sikora & Rajaratnam 2004



Streaming flow

At first operation of John Day Dam (1968), introduced **American shad** (*Alosa sapidissima*) did not pass through the upper part of the two new fishways that had plunging flow, while Pacific salmon did.

Ice Harbor design – flow divided by pillar

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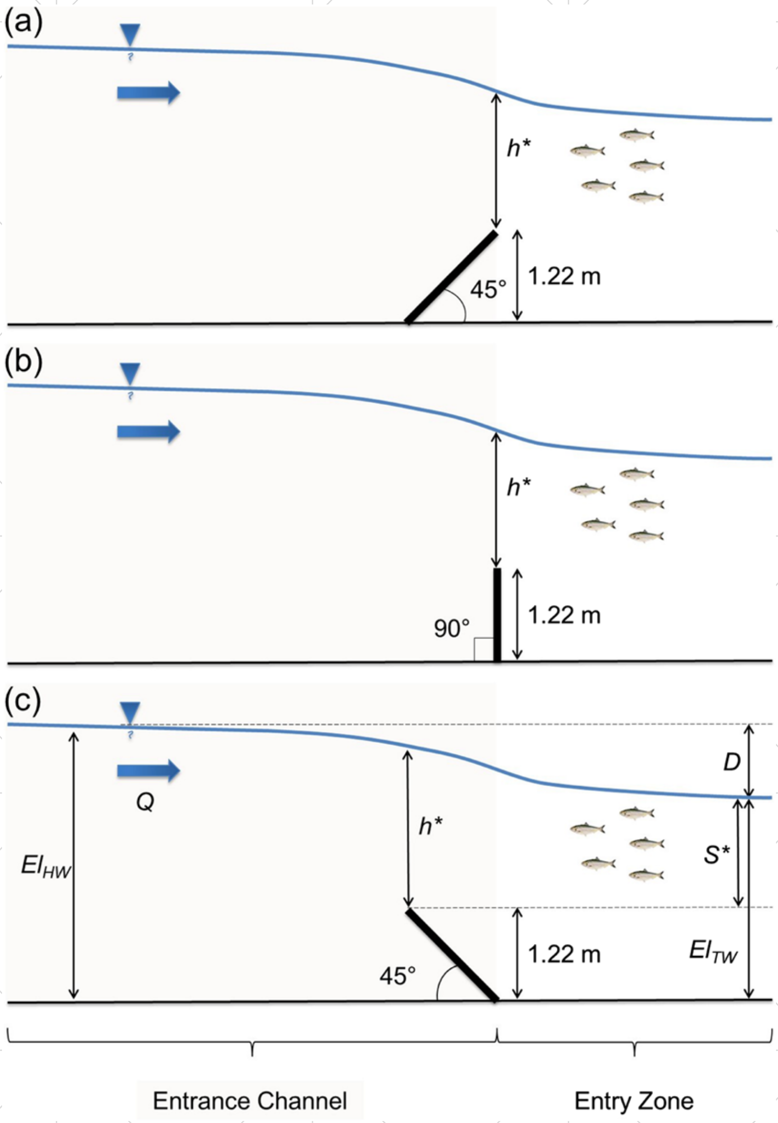

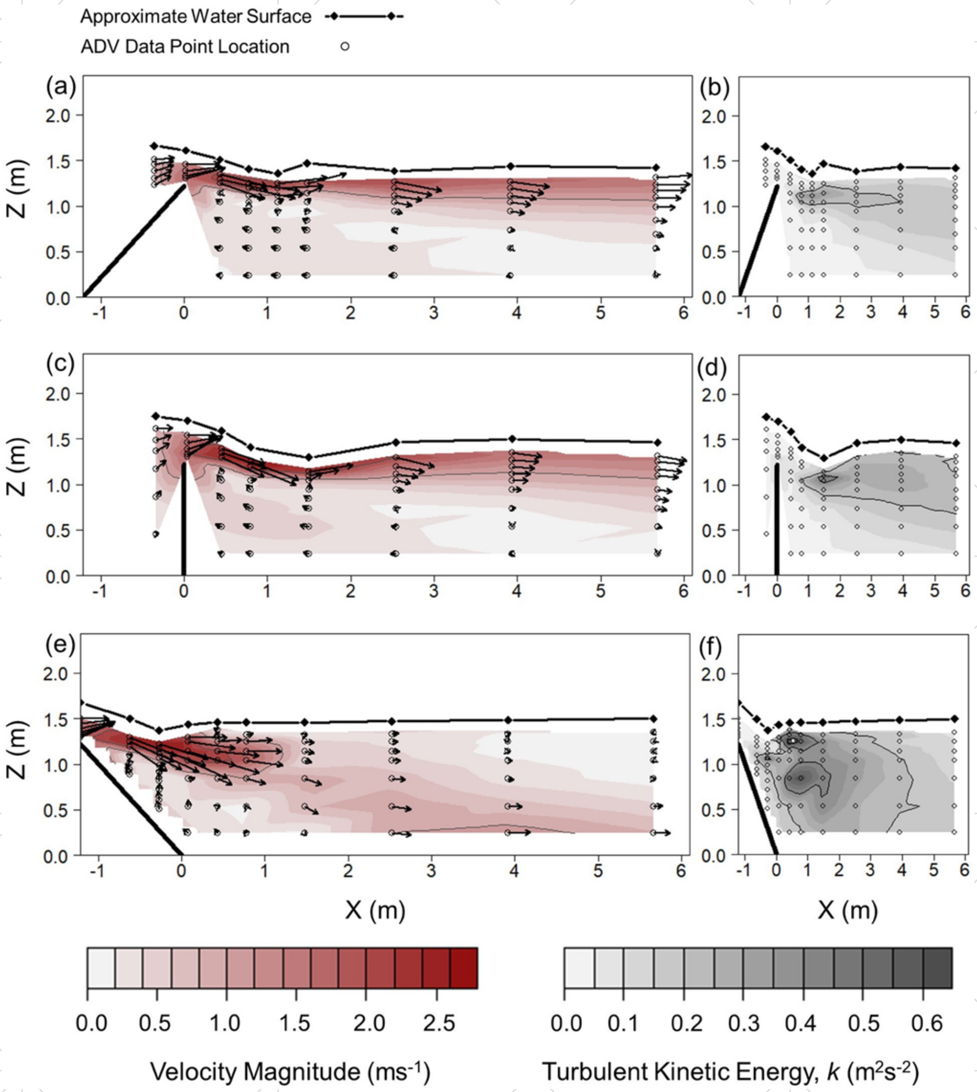

Side views of gates tested with velocity and TKE contours generated

Tests with **adult American shad**. Left: side view of the ecohydraulic flume and geometry of overshot (a), vertical (b) or reversed overshot (c) gates tested with different submergence (S*). Right: Velocity and TKE patterns along the longitudinal centerline of the flume for a submergence S* = 30.5 cm. Contour lines for velocity are at 1.0 and 2.0 m/s and TKE at 0.2, 0.4, and 0.6 m^2/s^2– adapted from Mulligan, Haro, Towler, Sojkowski & Noreika (2019).

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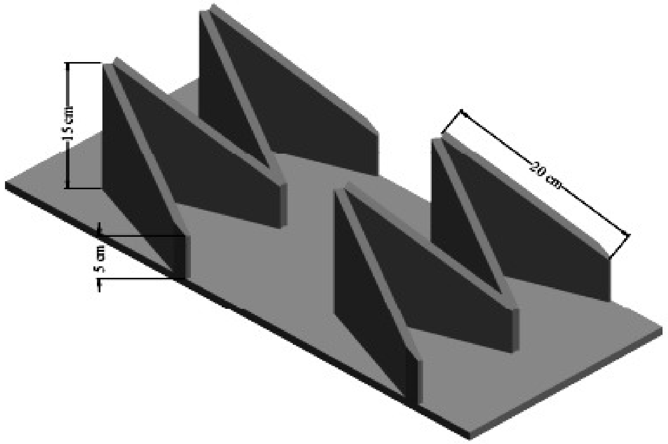
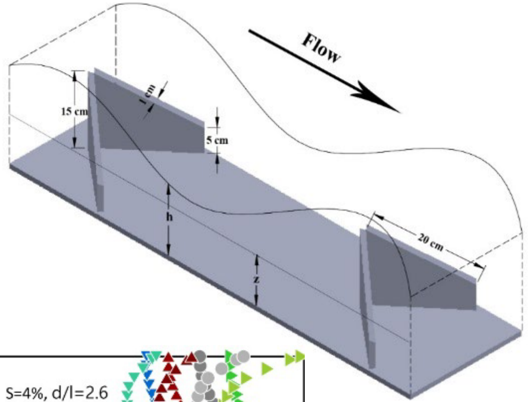
Does turbulence stress fish?

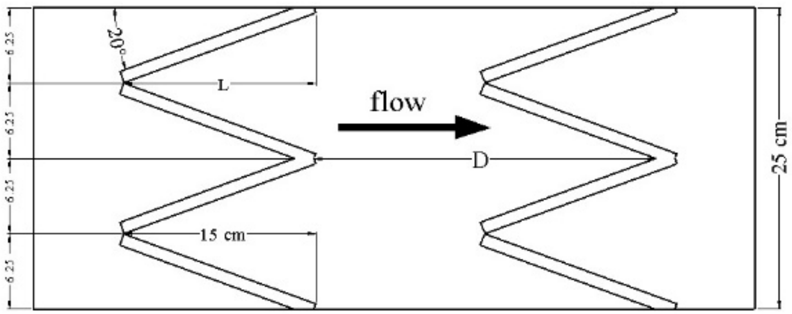
Many laboratory and a few field studies provide fish responses to different levels of TKE and RSS. Congruent results can assist in setting limits.

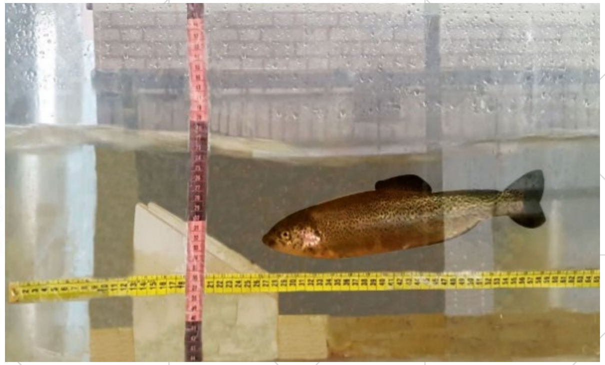


Study integrated hydrodynamics & turbulence metrics with physiological parameters:

- hematological (heparin sodium, haematocrit), immunological (lysozyme serum)
- Stress (glucose & cortisol)

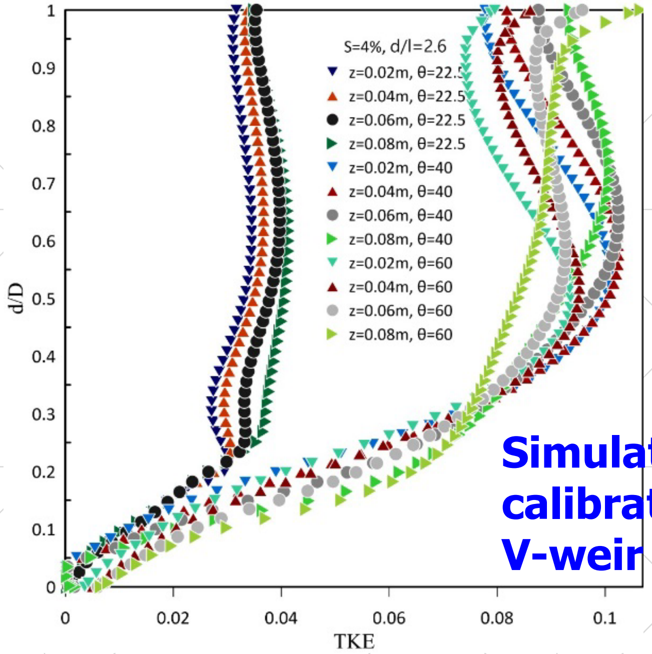






Fish stress comparable to control group with 4% slope & weir spacing ratio D/L = 6
Slopes tested: 4, 7 & 10%
Tested weir spacing ratios: D/L = 2, 4 & 6

Tested rainbow trout (*Oncorhynchus mykiss*) mean TL=15 cm



Simulations with calibrated CFD of V-weir fishway

Fish not stressed when:

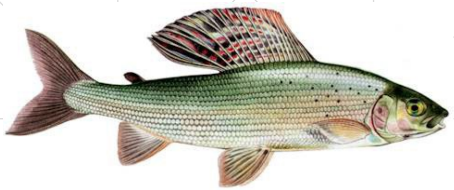
- TKE < 0.063 (m^2/s^2)
- TI < 55.55

Shahabi, Ghomeshi, Ahadiyan, Mohammadian & Katopodis 2021

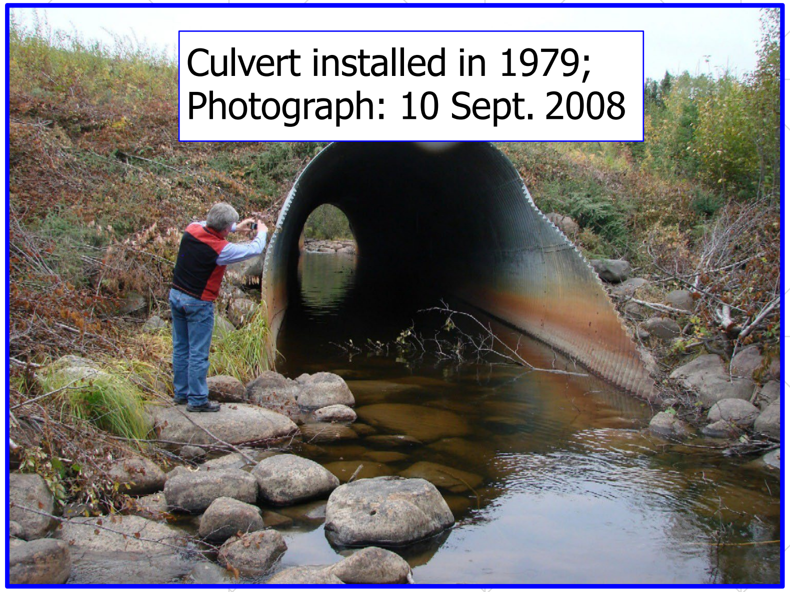
Shahabi, Ahadiyan, Ghomeshi, Narimousa, Katopodis & Nadian 2022

Nature based solutions (NBS) - Nature-like fishways

"Stream simulation"
Liard Highway, Northwest Territories, Canada



Arctic grayling *Thymallus arcticus*



Beaver River, Ontario, Canada

Merikoski, Finland

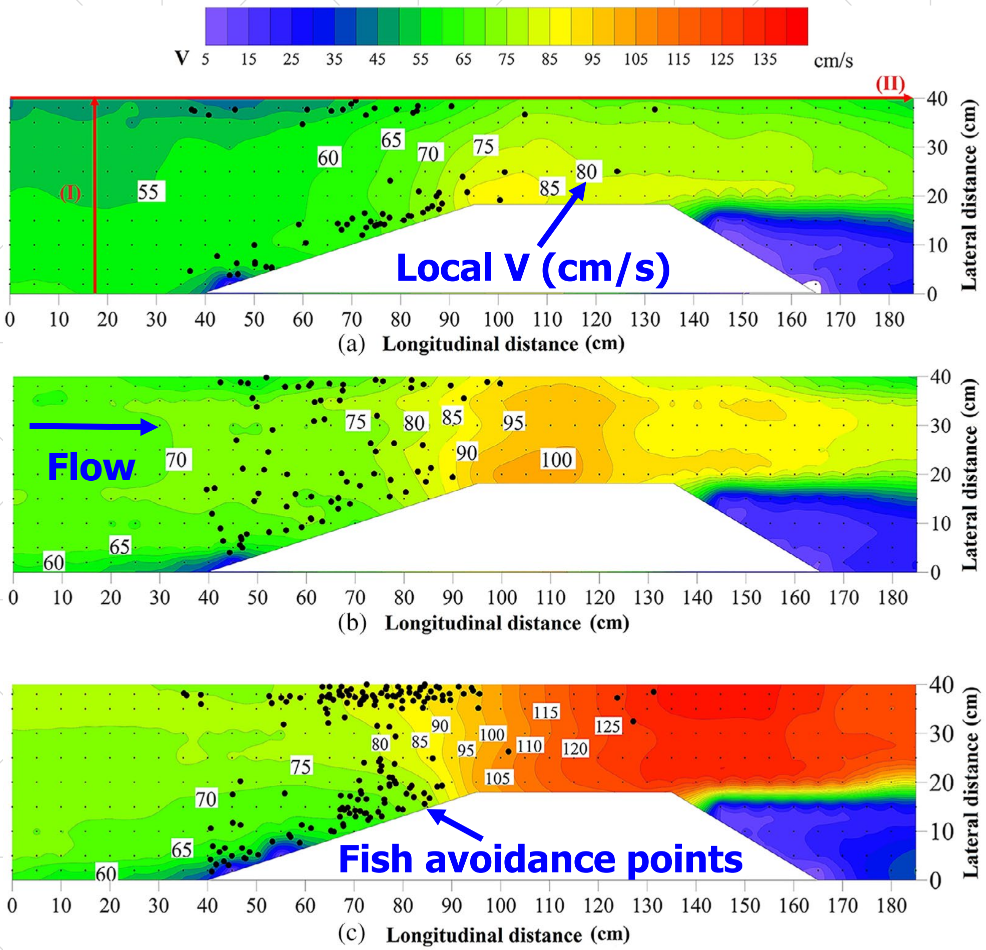
Fish Migration River (FMR) The Netherlands

Fish species include:
Sea trout, Sturgeon, Atlantic Salmon, European Eel, Anchovy, Flounder & Smelt, Atlantic Herring, Houting, Allis Shad, lamprey, stickleback

Katopodis Ecohydraulics Ltd.

Accelerating flows - downstream migrating Tibetan Plateau rheophilic cyprinid

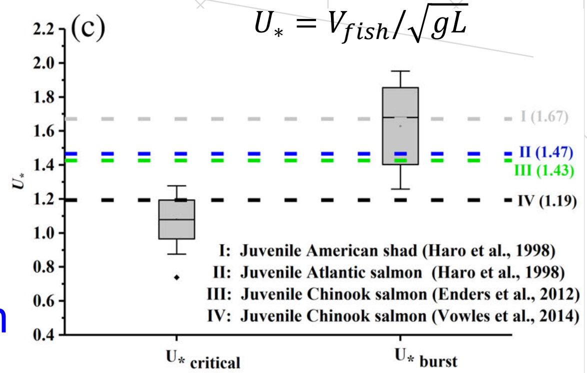
Lhasa naked carp *(Schizopygopsis younghusbandi)*



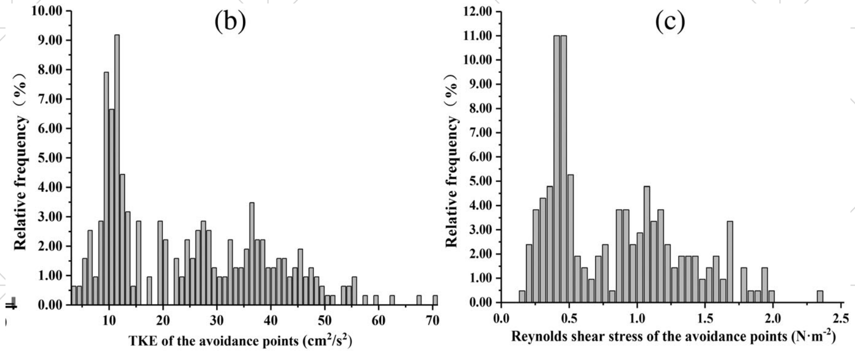
Velocity (V) contour plots: low (a), medium (b), high (c)

Li M, Shi, Jin, Ke, Lin, An, Li J & Katopodis 2021

Average fish speeds close to
U_{crit} =1.1 m/s, 10.4 BL/s or
$\boldsymbol{U_*}$ **=1.1**
U_{burst} =1.7 m/s, 15.0 BL/s or
$\boldsymbol{U_*}$ **=1.6**
fish mean length: 107-112 mm



Summarized previous studies indicating **spatial acceleration of 1 m/s/m distance** best for juvenile fish to move downstream



Fish generally responded to a discrete range of
TKE < 50 cm²/s² and RSSxy < 2 N/m²
(ADV measurements closer to flume floor, small velocity fluctuations)

Concluding remarks

- Ecohydraulics studies aquatic habitat, including fish movements in turbulent flow, and can integrate interdisciplinary knowledge, leading to innovative and practical applications towards sustainable and ecologically sensible water infrastructure

- There are tremendous challenges as well as opportunities for "Archimedean eureka" moments and pioneering research towards knowledge-based applications in the ecohydraulic trilogy topics of fish passage, environmental flows and habitat restoration, including nature-based and climate change solutions

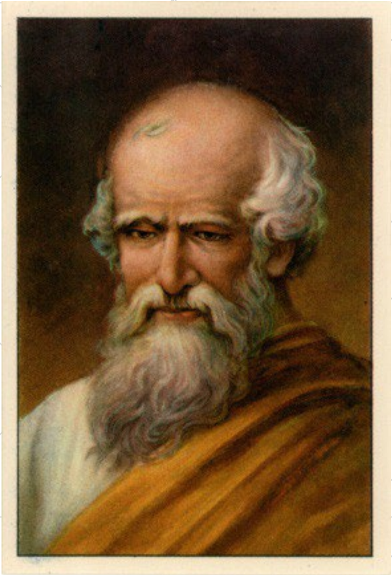
- Best solutions are found by considering ecological aspects as an integral part in designing and operating a new water project or modifying an existing one, as well as integrating efficiencies and synergies resulting from interdisciplinary and transdisciplinary science

Classical Hellenic thinking -
Solon the Athenian (640-560 B.C.):

«Γηράσκω δ′ αιεί πολλά διδασκόμενος»

"I grow older ever ready to be educated on many things"

i.e. life-long learning



Father of Ecohydraulics
Archimedes and his helical pump

Thank you!

I wish all PhD & other students, as well as the hydro industry and those negotiating on behalf of fish to have their own "eureka" moments in discovering innovative and well-balanced solutions!