Evaluation of a Hypothesis for How Water Flow Pattern Shapes Fish Trajectories near Infrastructure

ERDC
Engineer Research and Development Center

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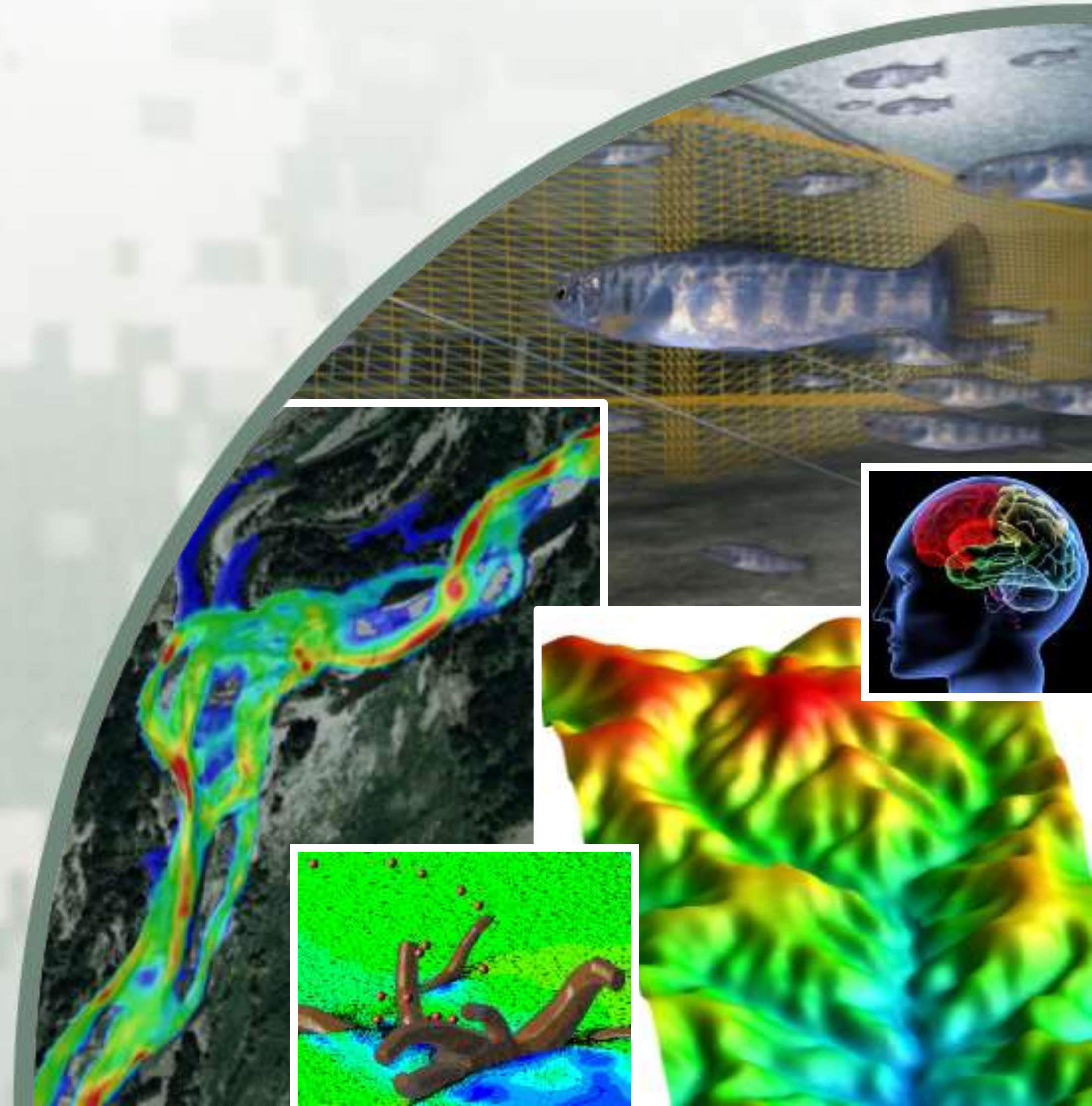

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A lot of infrastructure…and so many species…some context needed

Behavior: depends on many variables, many *will remain* unknown

Premise: stochastic processes dominate moment-to-moment decisions

…but behavior patterns emerge at larger scales

Focus: relate behavior patterns to elements management most directly influences (quantity, quality, and structure of flow)

…at a scale resolution where future environmental pattern might be forecast

…stopping at a level of detail beyond which there is diminishing return

Point of View

<u>Observations</u> ← <u>Factors</u> *<u>(example)</u>*

Fish Movement = *physical* *(mean and turbulent/secondary flows)*

see Jon Burau re: his presentation

\+

behavioral *(Markovian or non-Markovian)*

Past experience does *<u>not</u>* matter.
Environment only at time t matters.

Past experience *<u>does</u>* matter.
Environment at time t, t-1, t-2, etc matters.

<u>Question of:</u>

What is sufficient for management?

is quite different than

What is it theoretically?

<u>Take away</u>

- *No method is complete.*
- *Tradeoffs/approach often reflect researcher preferences.*

Where we fit in…

Sufficient ? + Sufficient ?

Fish Movement = *physical* *(mean and turbulent/secondary flows)*
+
behavioral *(Markovian or non-Markovian)*

+ Sufficient ?

Past experience
does *not* matter.
Environment only at time *t* matters.

Past experience
does matter.
Environment at time *t*, *t*-1, *t*-2, etc matters.

- Most (not all) statistical approaches based on this assumption.
- Sufficient in many (not all) scenarios.

- Our work: *history*, *experience*, or *context* can matter a lot.
- *Hypothesis*: fish modulate their experience in the flow field.

Simple Hypothesis for Navigating *Up*- and *Down*- Water & Wind Currents

- Tested with data on downstream migrating juvenile salmon.
  - at dams, because that's where we had *a lot* of data.
- Simple notion that animals sensitive to gravity are generally also sensitive to other acceleratory and inertial stimuli.
- Work on fish sensitivity to relative water velocity and acceleration fields as well as inertial stimuli, includes:
  - Harden Jones (1956) *Nature*.
  - von Baumgarten et al. (1971) *Space Life Sciences*.
  - Arnold GP (1974) *Biol. Rev*.
  - Kalmijn AJ (1989) Book.
  - Kroese & Schellart (1992) *J. Neurophysiol*.
  - Bleckmann H (1994) Book.
  - Pavlov & Tjurjukov (1995) *J. Fish Biology*.
  - Montgomery et al. (1997) *Nature*.
  - Haro et al. (1998) *Trans. Am. Fish.* Soc.
  - …more

PNAS

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Fish navigation of large dams emerges from their modulation of flow field experience

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Navigating obstacles is innate to fish in rivers, but fragmentation of the world's rivers by more than 50,000 large dams threatens many of the fish migrations these waterways support. One limitation to mitigating the impacts of dams on fish is that we have a poor understanding of why some fish enter routes engineered for their safe travel around the dam but others pass through more dangerous routes. To understand fish movement through hydropower dam environments, we combine a computational fluid dynamics model of the flow field at a dam and a behavioral model in which simulated fish adjust swim orientation and speed to modulate their experience to water acceleration and pressure (depth). We fit the model to data on the passage of juvenile Pacific salmonids (*Oncorhynchus* spp.) at seven dams in the Columbia/Snake River system. Our findings from reproducing observed fish movement and passage patterns across 47 flow field conditions sampled over 14 y emphasize the role of experience and perception in the decision making of animals that can inform opportunities and limitations in living resources management and engineering design.

fish movement behavior | hydraulic pattern | individual-based model | fish passage | ecohydraulics

Understanding how the design and management of civil infrastructure modifies the outcome of naturally evolved behavior in animals is critical for sustainably using limited environmental resources to spur economic development and maintain native species. The issue is particularly relevant for rivers, which make up only 0.0002% of water on Earth (1) but support more than 40% of the world's human population (2, 3). River regulation to meet society's needs has accelerated in the past two centuries (4), leaving over half of the world's major rivers now fragmented by >50,000 large dams providing water, energy, flood control, and transportation (3, 5, 6). The demand for large hydropower continues, spurred by the need for economic development while limiting carbon use (7). However, dams impede the dispersal and migration of fish, a problem that, along with other factors, has contributed to the loss of populations and entire species (5). These losses have cultural, economic, and geopolitical repercussions (3, 8), because more than 40% of the world's human population lives in internationally shared river basins (9) and declines in fish populations jeopardize the food security of hundreds of millions worldwide (10–12).

In North America, the tension between economic development and living resource conservation is evident in the Columbia River basin. Flowing from Canada to the United States, the river once supported one of the world's largest salmon runs, with annual returns of 10–16 million fish (13) sustaining tribal nations and ecosystems far from the ocean (14). However, years of overharvesting, land-use changes, ocean conditions, and dams have contributed to a decline in the annual return of salmon (15). To reverse the decline, millions of dollars are spent each year seeking a durable hydroelectric strategy to improve annual returns (1–2 million fish). A major emphasis in restoration is ensuring that millions of downstream migrating juvenile salmon reach the ocean where they grow before returning to the river as adults.

Hydropower dams on the river provide three general routes of passage for downstream migrating fish: powerhouse turbines, a spillway, and often a bypass specifically designed for fish. These routes differ in their mortality effects on fish, so an understanding of how fish behavior determines route selection is important for mitigating the impacts of dams on the populations. However, route selection behavior is poorly understood. Not only has it been difficult to explain route passage patterns at one dam, but it has been even more difficult to explain why the pattern may be different at another dam with similar routes.

Assumptions

Monitoring all environmental and internal factors (16–19) that could contribute to fish movement in a large open system is not possible, so the following assumptions underlie our analysis. First, although fish migration between habitats involves many factors (e.g., physiological, life cycle, feeding), over the temporal and spatial scales it takes a fish to transit a dam environment, we assume movement is hydraulically mediated.

Our second assumption stems from the need to describe a fish's perception of hydraulics, which is difficult in open flowing environments because our understanding is still limited (20). One challenge is selecting a stimulus variable, because "hydraulics"

Significance

Whereas adult salmon swimming upstream through a ladder visibly illustrates the challenge a dam presents to fish returning home to spawn, the downstream passage of juveniles swimming toward the ocean is often a greater, although more unseen, challenge to their survival. Decades of work have identified many factors that affect fish behavior near dams, but why downstream passage structures may work well at one dam but not at another is poorly understood. We use a computer model to show that observed downstream passage patterns could result from a generic strategy that fish may use to navigate flow field obstacles. Our findings identify environmental and biological factors warranting further evaluation for sustaining native species amid economic development.

Author contributions: R.A.G., J.M.N., D.H., and L.J.W. designed research; R.A.G. performed research; R.A.G., M.P., J.W.G., J.M.N., J.J.A., E.D., and M.T. contributed new reagents/analytic tools; R.A.G., J.M.N., D.H., L.J.W., E.D., D.L.S., and M.T. analyzed data; and R.A.G. and J.J.A. wrote the paper.

The authors declare no conflict of interest.

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Data deposition: The computational fluid dynamics model and other data reported in this paper are available in the *SI Appendix*.

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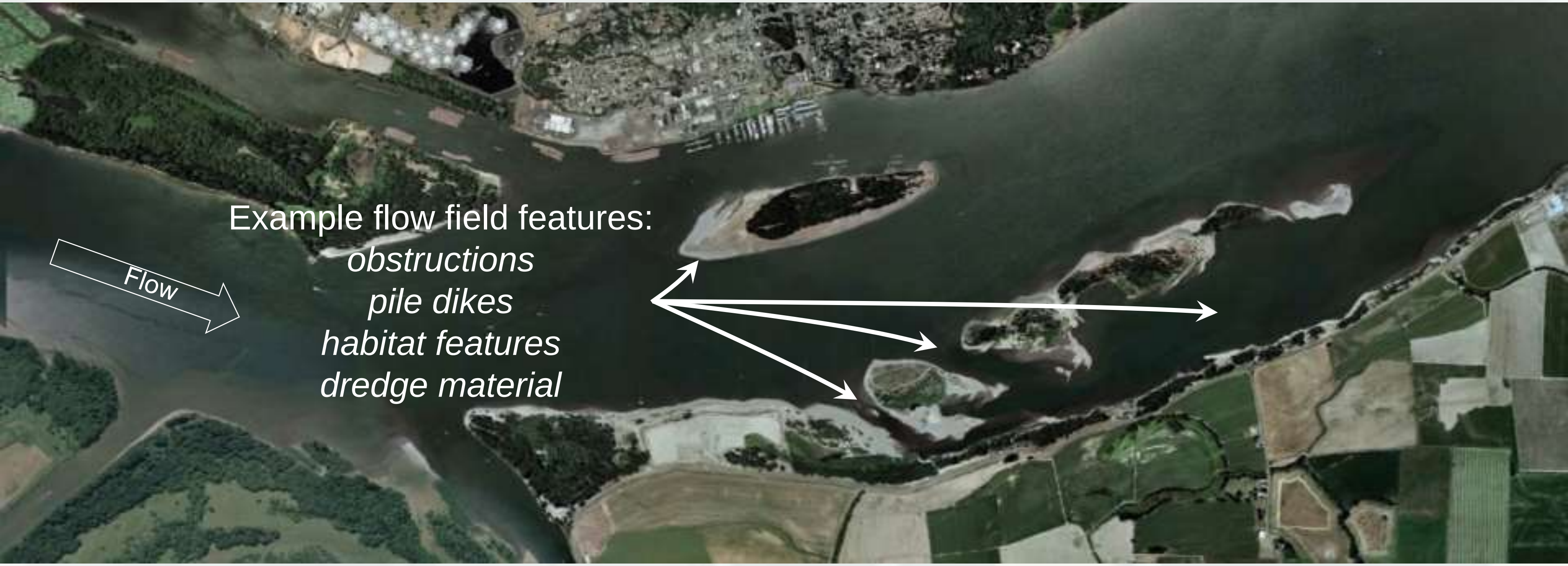
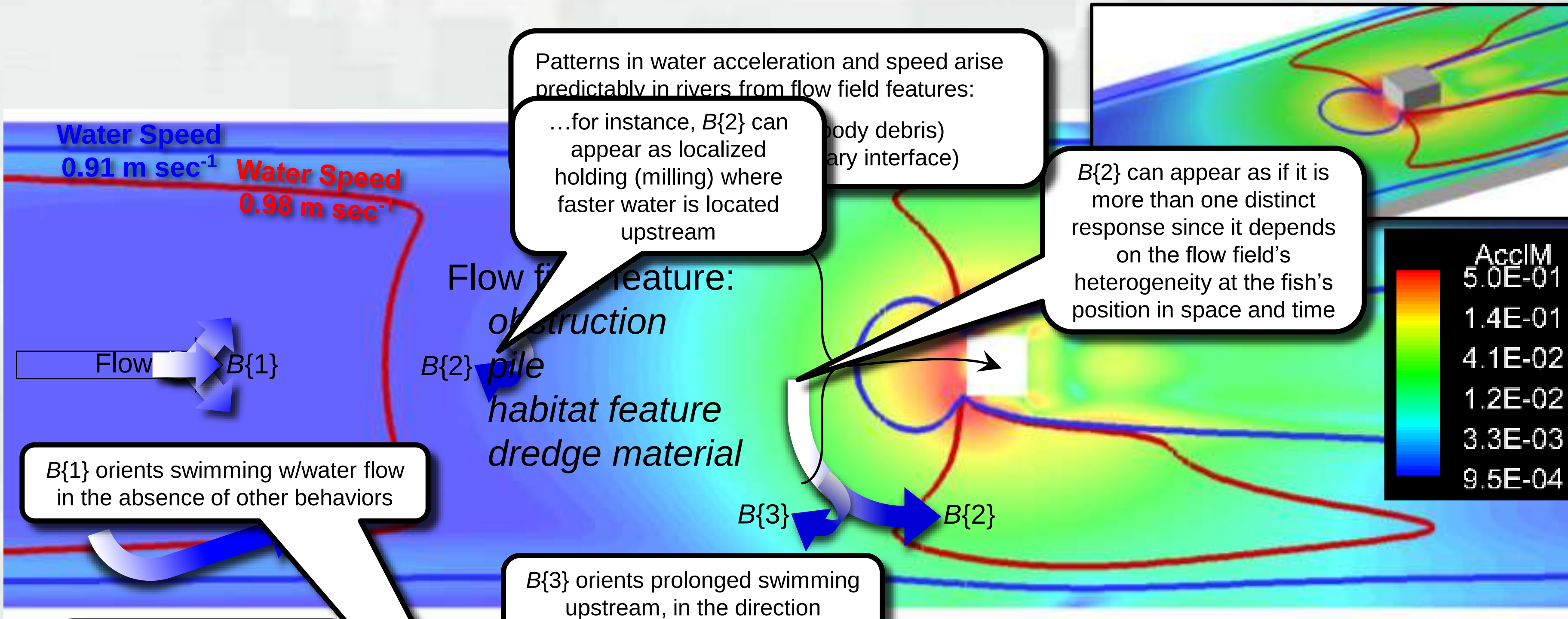
We explored how water acceleration may shape fish movement and identify why fish avoid some flow field regions

Example Setting

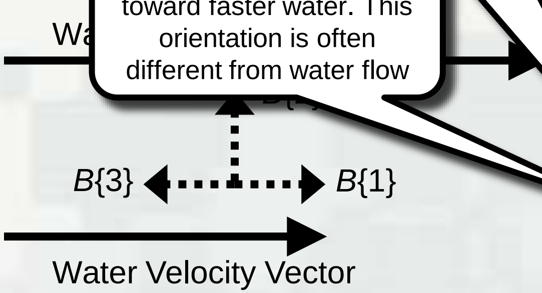


Fish Navigate by Modulating Flow Field Experience

where patterns in water acceleration and water speed arise predictably from river architecture



Water flow field contours:
Fill ⟶ Acceleration
Lines ⟶ Speed



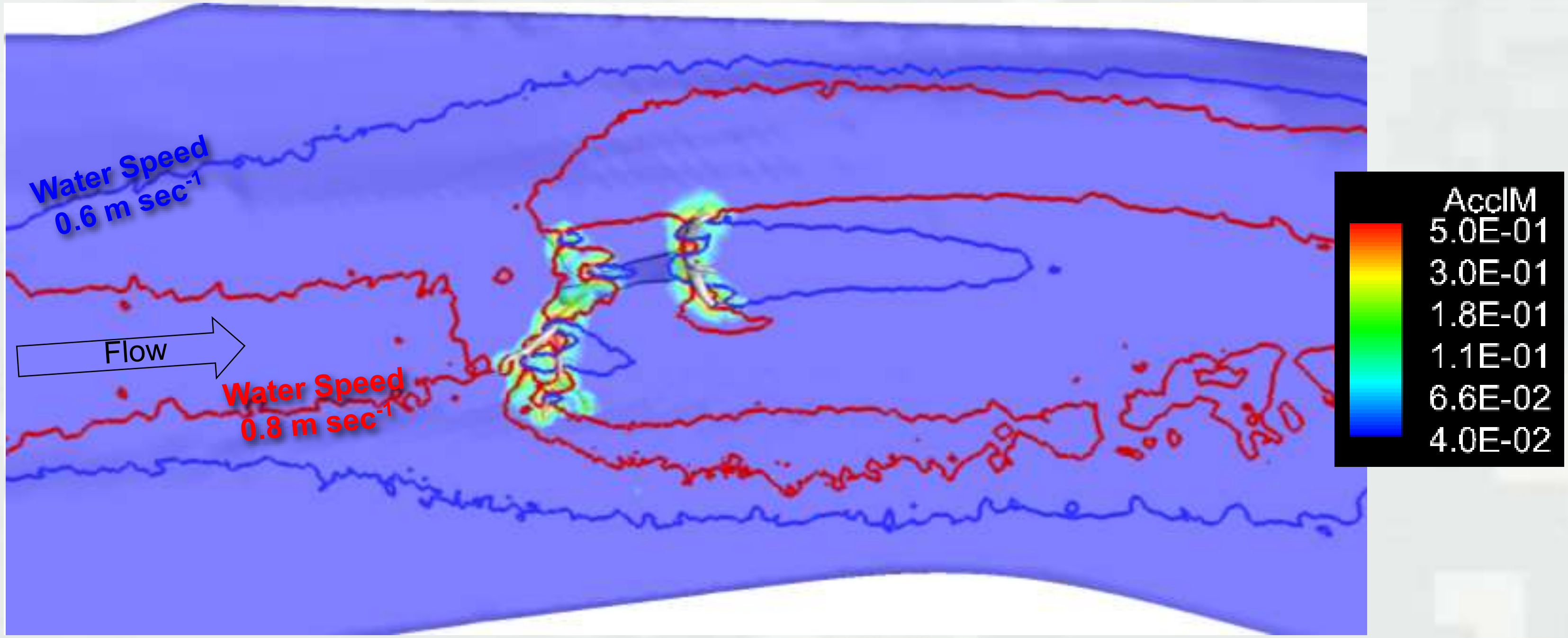
...nstream Navigation Strategy

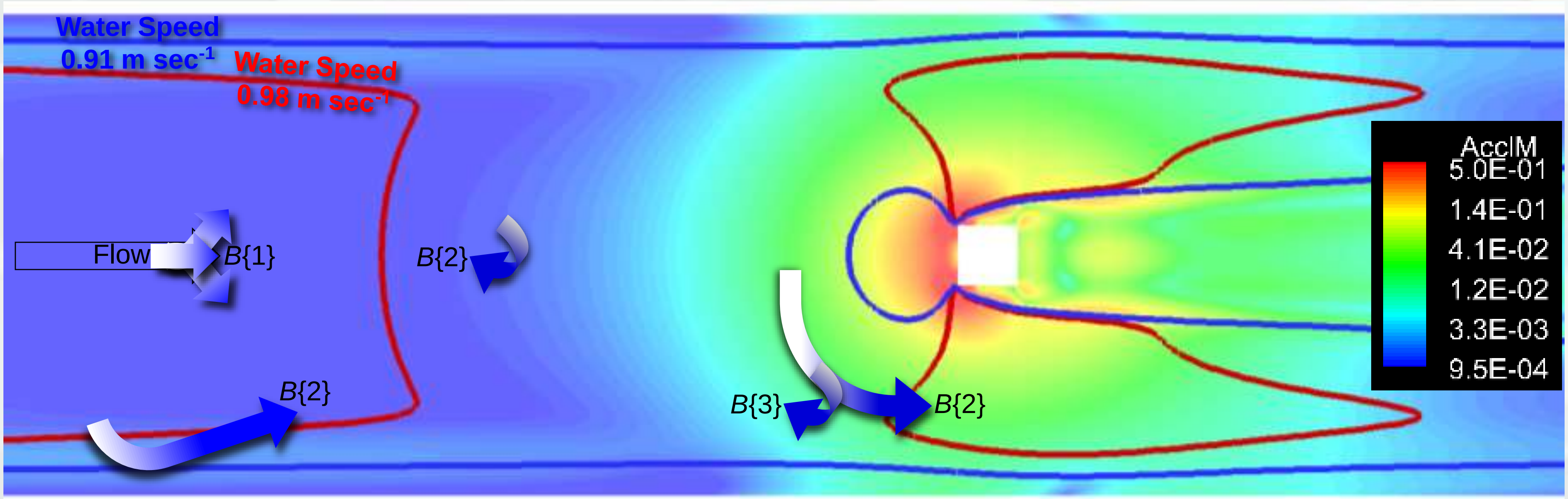
via at... ...on and repulsion responses triggered by perce... changes in water acceleration (contour fill)

- *B*{1} ➡ **correlated random walk** biased (BCRW) in direction of water flow
- *B*{2} ➡ **velocity attraction** triggered by *change in water acceleration*
- *B*{3} ➡ **flow repulsion** *water acceleration*
- *B*{4} ➡ **vertical movement** *water pressure (depth)*

Fish Navigate by Modulating Flow Field Experience

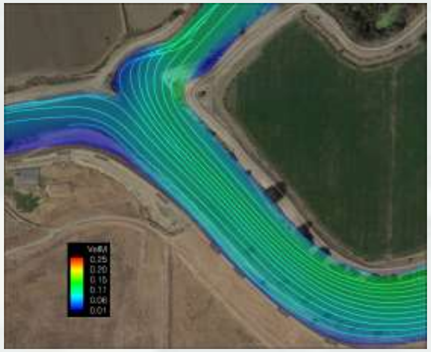
where patterns in water acceleration and water speed arise predictably from river architecture

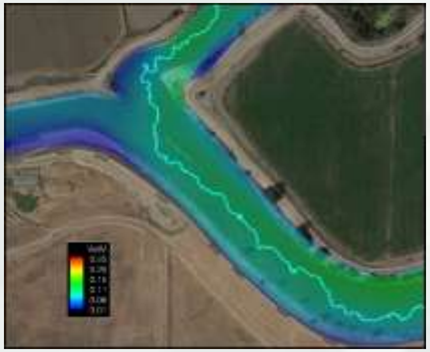


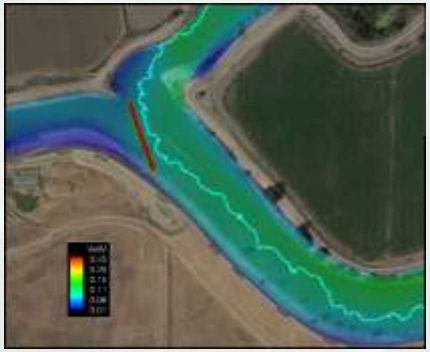


Head of Old River Bifurcation: Simulated & Real Fish

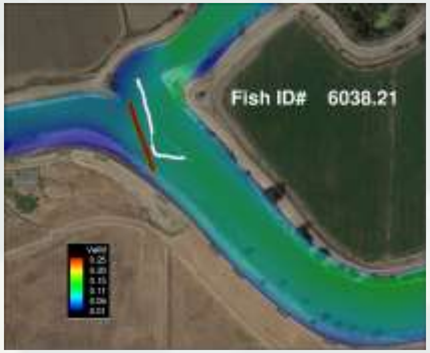
…may have apparent non-physical barrier guidance when it is not.

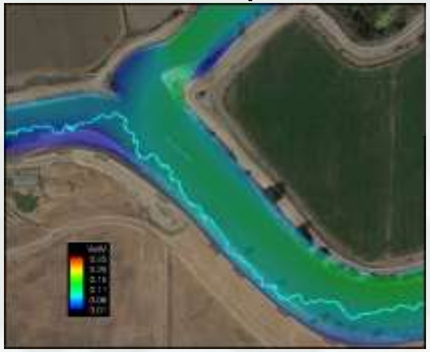


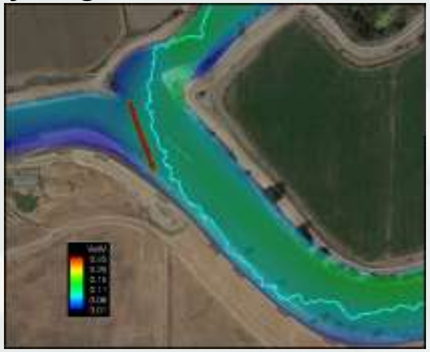


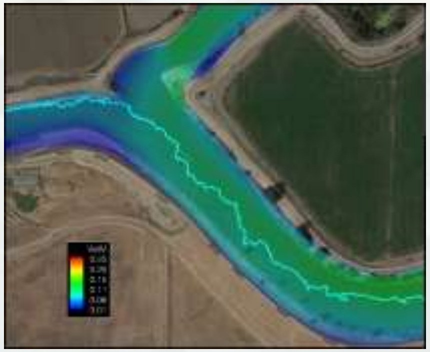


…small changes in advective/exploratory processes may play big role

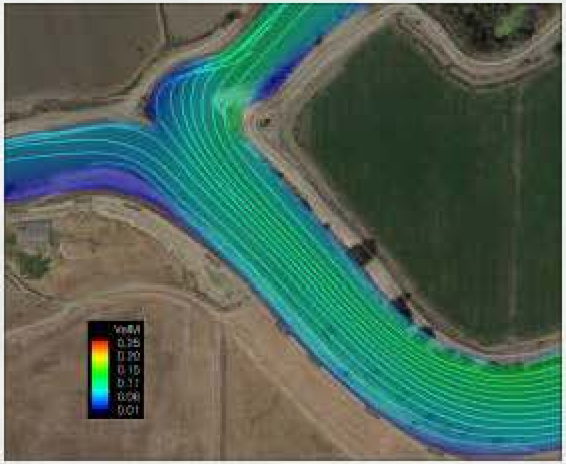


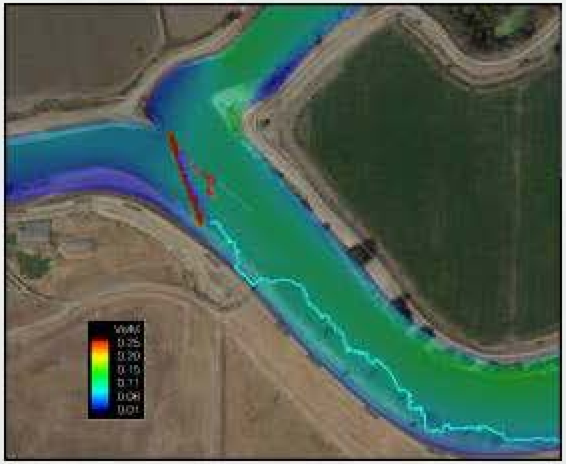


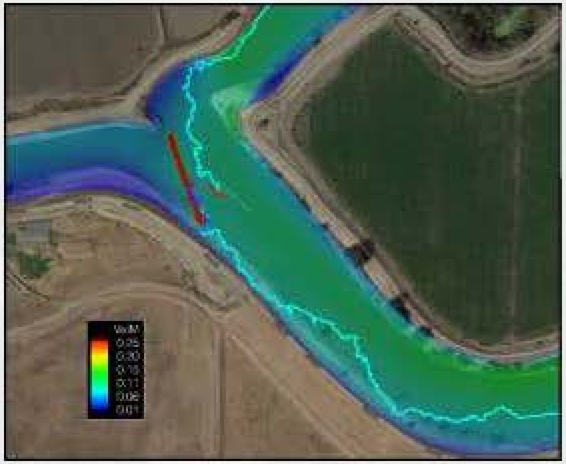




Head of Old River Bifurcation: Simulated & Real Fish







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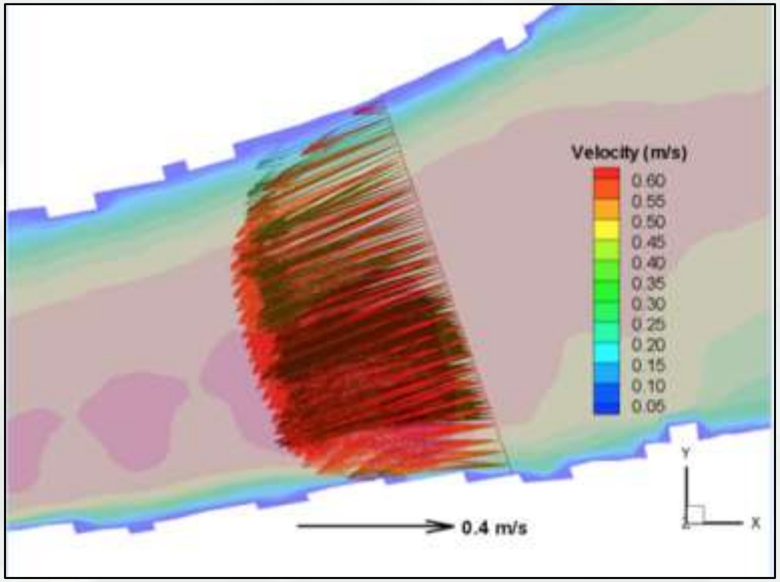

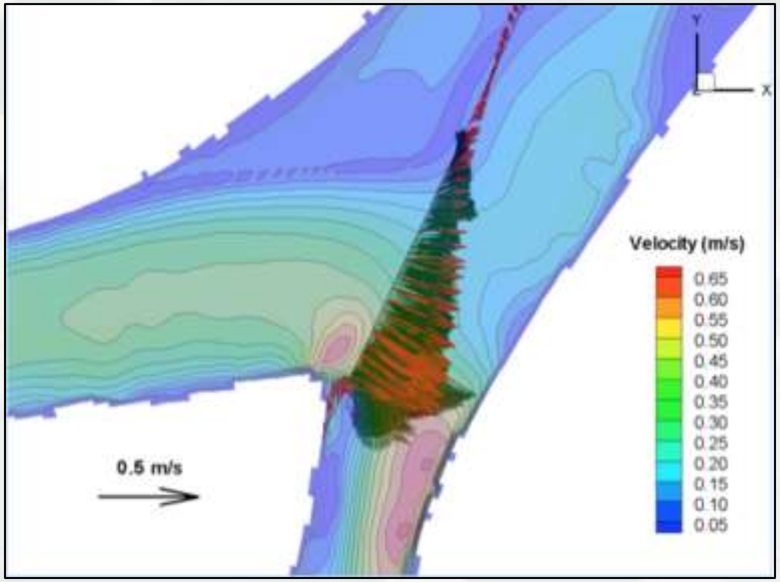

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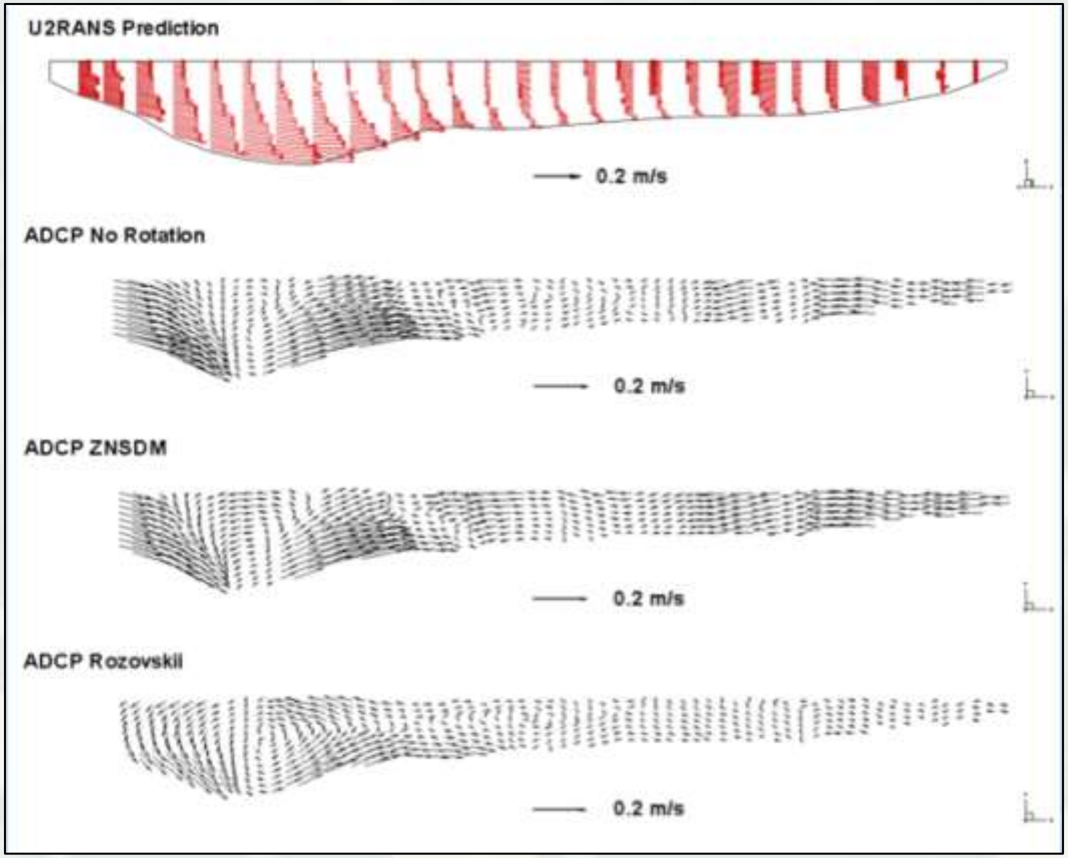

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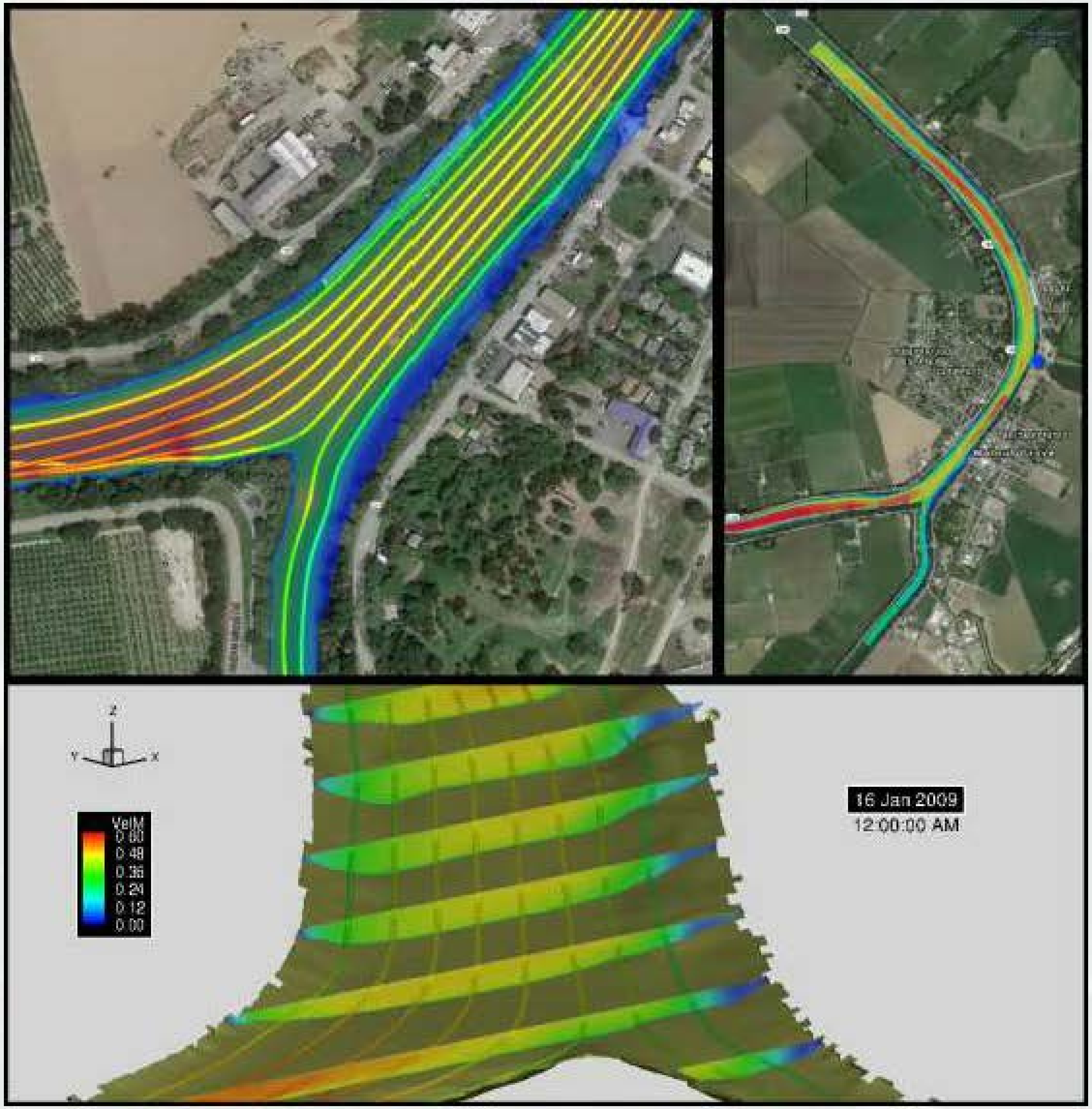

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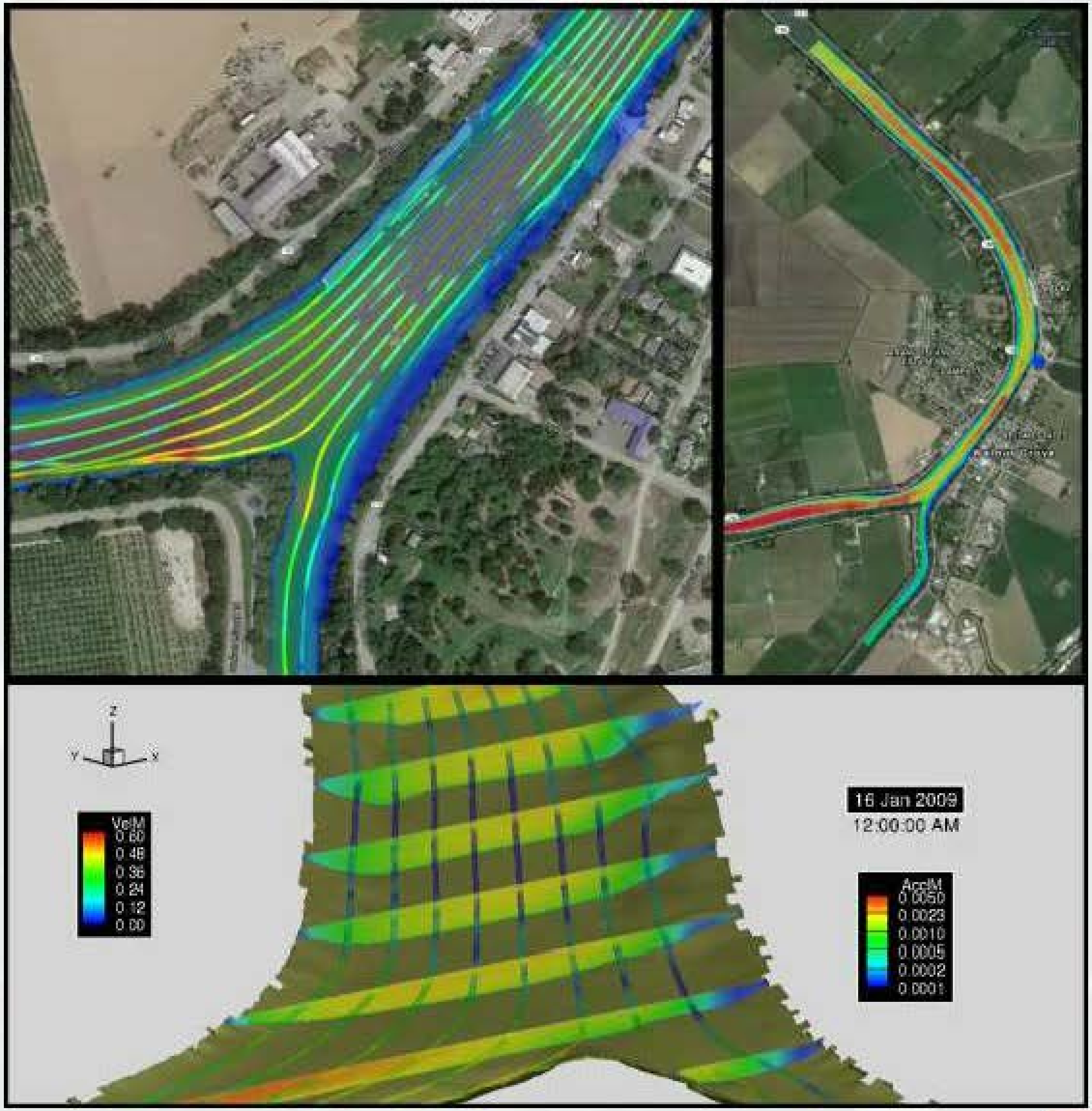

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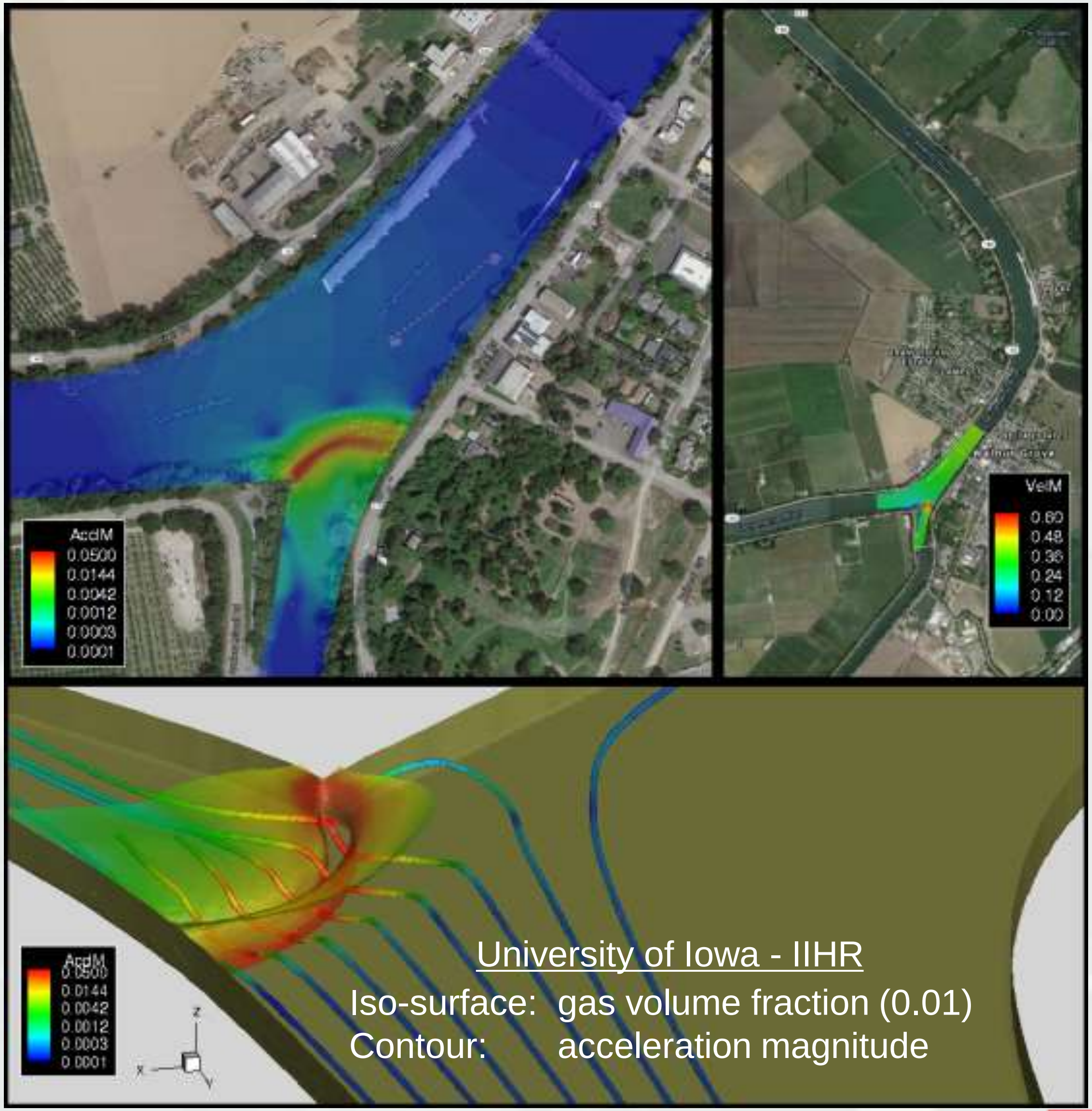
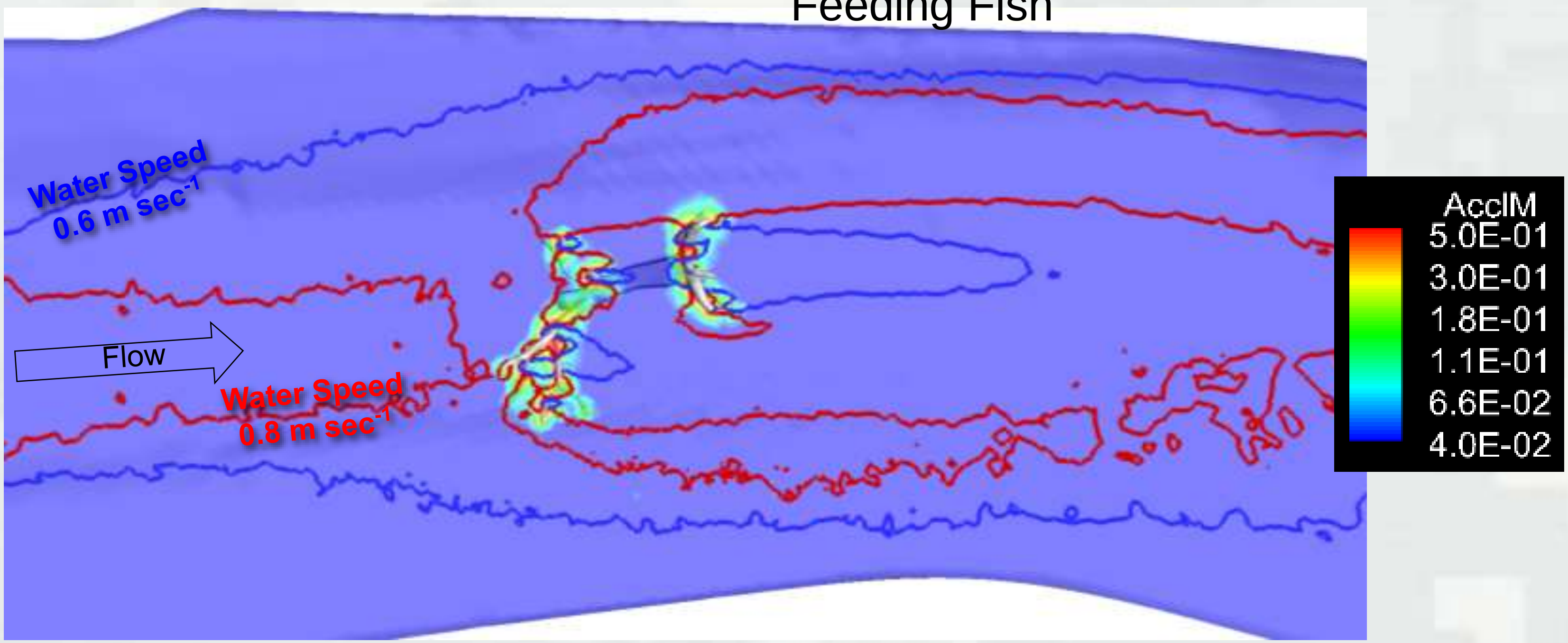
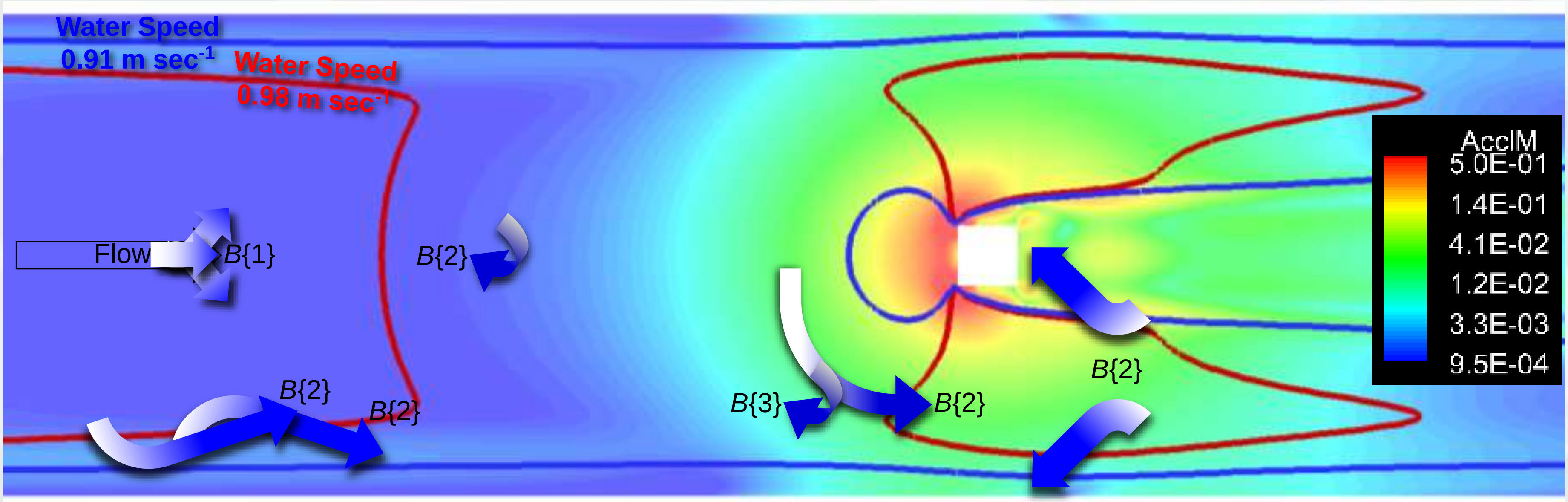


Hypothesis Reversal for: Upstream-migrating Fish
Resident Fish
Feeding Fish





Questions / Comments / Criticisms ???