Detailed observations of fish swimming in a turbulent stream environment

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Flow speed affects aquatic habitat

- Increased flow speed results in more drag, which requires more energy expenditure to overcome

Turbulence

- Ubiquitous in rivers and streams
- Time-varying coherent structures (eddies)
  - Size characteristic of length scale of shear that produces them

Turbulence from banks


Turbulence from boulder

Van Dyke. 1982. An Album of Fluid Motion.
Measuring turbulence

<table>
<thead>
<tr>
<th>Velocity</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>Laminar flow</td>
<td>Turbulent flow</td>
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<td>$U$</td>
<td>$\bar{U}$</td>
<td>$\bar{U}$</td>
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<table>
<thead>
<tr>
<th>Transport</th>
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<tbody>
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<td>dye trace</td>
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Turbulent flow compared to laminar flow in terms of velocity and transport.
Turbulence creates fluctuations over time
Effect of turbulence on organisms


(measure of turbulence)
Sorry to interrupt you, folks, but we've just had a report of some turbulence ahead, so please stay in your seats a little while.

Ready?...One, two, three!

Well, folks, guess we're through the worst of it and... oh! wait! wait!...Looks like we're coming in to some more turbulence!
Turbulence can destabilize fish

Small eddies will not affect stability

Eddies similar in size to the fish can destabilize it

Eddies much larger than the fish may move it, but they won’t destabilize it

See work by Paul Webb and Aline Cotel, U. Michigan
River restoration structures create turbulence

Shingle Creek, Brooklyn Park, MN

What is the effect of stream restoration structures on fish swimming behavior?
Experimental area
Experimental setup

- Screened inlet from river
- Stilling basin
- Discharge measurement
- Weir
- Inlet pipes
- Net pens
- Rock vane
- Sediment feed
- Settling basin
- Sediment return
- Outlet to river
- North
- Scale (m)
- St. Anthony Falls Laboratory building
Topography adjacent to single rock vane

Average stream width increase = 33 ± 7 cm

Average depth increase = 6.2 ± 0.6 cm
Fish species

Hornyhead chub (*Nocomis biguttatus*)
Habitat: warm rivers and creeks, relatively fast-moving water

Brown bullhead (*Ameiurus nebulosus*)
Habitat: shallow bays and warm quiescent water

Like fast flow

Like slow flow

(Krafte et al. 2006).
Fish preparation

- Fish acclimatized in cages within experimental stream for ≥ 7 days
- Surgery to attach a monofilament loop and up to three orange beads to dorsal musculature
- Fishes attached to ≥ 3 m length of monofilament and tethered adjacent to rock structure
  - Line was slack during testing and appeared to have no effect on fish swimming or local flow field; served only to prevent escape
Color used to separate fish & flow data

Spatially registered full-color image (1 s of data)

Monofilament line attached to fish

Scale bar

Frame 100

Blue pixels (flow)

Red pixels (fish)
Fish microhabitat choice
Depth-averaged velocity profiles

(a) No structure
(b) With rock vane

Measurement location

ADV
Surface flow from particle image velocimetry (PIV)

Low flow

High flow

Acoustic Doppler velocimetry (ADV) profile
Comparison between PIV and ADV

ADV profiles obtained at positions chosen by chub at each flow rate

Chub position at low flow

Chub position at high flow

University of New Hampshire
## Microhabitat consistent for each species

<table>
<thead>
<tr>
<th></th>
<th>Stream flow rate (L/s)</th>
<th>Water depth at position of fish (cm)</th>
<th>Flow speed at position of fish (cm/s)</th>
<th>Turbulence intensity at position of fish</th>
<th>Fish-scale Reynolds number</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bullhead</strong></td>
<td>45 ± 5</td>
<td>29 ± 4</td>
<td>6 ± 3</td>
<td>0.43 ± 0.16</td>
<td>11,000 ± 5,000</td>
</tr>
<tr>
<td></td>
<td>150 ± 10</td>
<td>25 ± 3</td>
<td>6 ± 2</td>
<td>0.44 ± 0.12</td>
<td>11,000 ± 3,000</td>
</tr>
<tr>
<td><strong>Chub</strong></td>
<td>45 ± 5</td>
<td>33 ± 1</td>
<td>10 ± 1</td>
<td>0.32 ± 0.08</td>
<td>14,000 ± 1,000</td>
</tr>
<tr>
<td></td>
<td>150 ± 10</td>
<td>18 ± 1</td>
<td>10 ± 4</td>
<td>0.46 ± 0.07</td>
<td>14,000 ± 6,000</td>
</tr>
</tbody>
</table>
Simultaneous data on surface flow & fish position
Fish kinematics

- Tail beat amplitude angle, $\theta$ 
- $1/frequency, f$
- Tail offset angle
- Body angle
- Relative tail angle
- Body angle

Longitudinal position, $x$

Lateral position, $y$

Angle (°)

Time (s)
Correlations between flow & fish kinematics

83% of comparisons between flow & fish variables showed significant correlation. For example:

![Graph showing comparisons between flow and fish kinematics.](image)
Efficiency for flying and swimming animals

- Optimal propulsion produced when frequency of flapping allows each stroke to complement last (resonance)
Tradeoff between tail beat amplitude & frequency

To swim faster:

- Increase amplitude
- Increase frequency

Graph showing the product of tail beat frequency and amplitude vs. flow speed.
Strouhal number

- Optimal frequency depends on body size and flow speed

- Strouhal number:
  $$St = \frac{\text{tail frequency} \times \text{tail amplitude}}{\text{flow speed}}$$

- Optimal when Strouhal number between 0.2 and 0.4


Simulation of wake behind swimming mackerel, I. Borazjani and F. Sotiropoulos
Many species exhibit similar Strouhal number

Observed Strouhal number

\[ St = 0.3 \text{ (optimum)} \]
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