Is complex channel behavior predictable? Steady states, thresholds and disturbances

Brett Eaton\textsuperscript{1}

\textsuperscript{1}Geography, University of British Columbia

River Restoration Northwest, 4 February 2015
This presentation would NOT be possible without financial support or our excellent researchers. I would like to specifically acknowledge:

- **Aaron Tamminga** (PhD in progress)
- **Dan McParland** (MSc, now with AECON)
- **David Luzi** (PhD, now with STANTEC)
- **Holly Buehler** (MSc, now with ERM)
- **Jeff Phillips** (MSc, now with Tetra Tech)
- **Lucy MacKenzie** (MSc, now with UBC)
- **Sarah Davidson** (MSc, PhD in progress)
River systems can change...quickly!

(Example: Slesse Creek, British Columbia [see Millar, 2000])
And the results can be devastating . . .

(example: Cougar Creek, Canmore, Alberta)

...affecting private property...

(example: Cougar Creek, Canmore, Alberta)

...and public infrastructure.

(example: Cougar Creek, Canmore, Alberta)

Rivers are influenced by a wide range of processes . . .

Some **Drivers** of Change

- Hydropower, Diversions
- Urbanization, Agriculture, Forestry
- Fire, Flood
...and the effects are scale-dependent.

Wood dominates morphology in some streams

Bedload transport dominates it in others
Downstream Hydraulic Geometry

- Origins: design of stable canals
- \( W = aQ^b \quad d = cQ^f \quad (U = kQ^m) \)

- \( Q \), formative discharge ... a convenient fiction
  - mean annual peak flow
  - bankfull flow
  - effective flow

- Assumption: system at steady state

- Applications: response to flow changes; channel design;
  \((\Delta Q \rightarrow \Delta W, \Delta d)\)
Downstream Hydraulic Geometry

- Origins: design of stable canals
- $W = aQ^b \quad d = cQ^f \quad (U = kQ^m)$

- $Q$, formative discharge ... a convenient fiction
  - mean annual peak flow
  - bankfull flow
  - effective flow

- Assumption: system at steady state
- Applications: response to flow changes; channel design;
  $(\Delta Q \rightarrow \Delta W, \Delta d)$
Downstream Hydraulic Geometry

- Origins: design of stable canals
- $W = aQ^b \quad d = cQ^f \quad (U = kQ^m)$

- $Q$, formative discharge . . . a convenient fiction
  - mean annual peak flow
  - bankfull flow
  - effective flow

- Assumption: system at steady state
- Applications: response to flow changes; channel design; $(\Delta Q \rightarrow \Delta W, \Delta d)$
Downstream Hydraulic Geometry

▶ Origins: design of stable canals

▶ $W = aQ^b \quad d = cQ^f \quad (U = kQ^m)$

▶ $Q$, formative discharge ... a convenient fiction
  ▶ mean annual peak flow
  ▶ bankfull flow
  ▶ effective flow

▶ Assumption: system at steady state

▶ Applications: response to flow changes; channel design;
  $(\Delta Q \rightarrow \Delta W, \Delta d)$
Predicting Steady State in the Field using Empirical Relations

- Predictions based on one variable
- Relation holds over many scales
- Gravel bed & sand bed overlap

\[ W \approx 3Q^{0.5}, \quad d \approx 0.3Q^{0.4} \]

- Most data fall in range \( \bar{X} \pm 50\% \)
Refined Empirical Predictions

- **Addition of other variables:**
  \[ W = 4.05Q^{0.515}S^{-0.035} \] (Bray, 1973)
  \[ W = 3.004Q^{0.426}D^{-0.002}S^{-0.153} \] (Lee and Julien, 2006)

- **Inclusion of bank strength proxies like bank vegetation**
  \[ W = aQ^b \] where \( a \) varies from 4.33 to 2.43 for increasing vegetation density (Hey and Thorne, 1986)

- **Use of non-dimensional variables and indices of vegetation**
  \[ W^* = 3.19Q^{0.482} \] (thick vegetation, Andrews, 1984)
  \[ W^* = 4.94Q^{0.478} \] (thin vegetation, Andrews, 1984)

- **Result:** most parsimonious equations (for width) consider \( Q \) and bank vegetation (Hey and Thorne, 1986)
Refined Empirical Predictions

- Addition of other variables:
  \[ W = 4.05Q^{0.515}S^{-0.035} \] (Bray, 1973)
  \[ W = 3.004Q^{0.426}D_{50}^{-0.002}S^{-0.153} \] (Lee and Julien, 2006)

- Inclusion of bank strength proxies like bank vegetation
  \[ W = aQ^b \] where \( a \) varies from 4.33 to 2.43 for increasing vegetation density (Hey and Thorne, 1986)

- Use of non-dimensional variables and indices of vegetation
  \[ W^* = 3.19Q^{*0.482} \] (thick vegetation, Andrews, 1984)
  \[ W^* = 4.94Q^{*0.478} \] (thin vegetation, Andrews, 1984)

- Result: most parsimonious equations (for width) consider \( Q \) and bank vegetation (Hey and Thorne, 1986)
Refined Empirical Predictions

- Addition of other variables:
  \[ W = 4.05Q^{0.515}S^{-0.035} \] (Bray, 1973)
  \[ W = 3.004Q^{0.426}D_{50}^{-0.002}S^{-0.153} \] (Lee and Julien, 2006)

- Inclusion of bank strength proxies like bank vegetation
  \[ W = aQ^b \] where \( a \) varies from 4.33 to 2.43 for increasing vegetation density (Hey and Thorne, 1986)

- Use of non-dimensional variables and indices of vegetation
  \[ W^* = 3.19Q^*0.482 \] (thick vegetation, Andrews, 1984)
  \[ W^* = 4.94Q^*0.478 \] (thin vegetation, Andrews, 1984)

- Result: most parsimonious equations (for width) consider \( Q \) and bank vegetation (Hey and Thorne, 1986)
Refined Empirical Predictions

- Addition of other variables:
  \[ W = 4.05Q^{0.515}S^{-0.035} \]  (Bray, 1973)
  \[ W = 3.004Q^{0.426}D_{50}^{-0.002}S^{-0.153} \]  (Lee and Julien, 2006)

- Inclusion of bank strength proxies like bank vegetation
  \[ W = aQ^b \] where \( a \) varies from 4.33 to 2.43 for increasing vegetation density (Hey and Thorne, 1986)

- Use of non-dimensional variables and indices of vegetation
  \[ W^* = 3.19Q^{*0.482} \] (thick vegetation, Andrews, 1984)
  \[ W^* = 4.94Q^{*0.478} \] (thin vegetation, Andrews, 1984)

- Result: most parsimonious equations (for width) consider \( Q \) and bank vegetation (Hey and Thorne, 1986)
Theory-based Prediction of Steady State (part I)

Equations for open channel flow predict that:

\[ W = \alpha_1 Q^{2/5} \quad d = \alpha_2 Q^{2/5} \]

where \( \alpha_1 \) and \( \alpha_2 \) depend on:
- channel geometry \((W/d)\text{ ratio, gradient})
- a flow resistance parameter
- (and some constants)

**key point:** this simple scale effect accounts for most of the success of empirical relations

\[ \alpha_1 = \left( \frac{\sqrt[3]{f(W/d)^{3/2}}}{\sqrt{8gS}} \right)^{2/5} \quad \alpha_2 = \left( \frac{\sqrt{f}}{(W/d)\sqrt{8gS}} \right)^{2/5} \]
Theory-based Prediction of Steady State (part II)

- Channel grade (proposed by Lane, 1955) . . .

\[ \frac{Q_b}{Q} \propto \frac{S}{D} \]

... a qualitative relation based on field observations

- Timescale: $> 10$ yrs, typically

- Flux of water ($Q$), sediment ($Q_b$) $\rightarrow$ channel grade ($S$)
An Indeterminate Interesting Model of Channel Steady State

Combining an equation for predicting $Q_b$ with one for predicting $Q$, yields a complete statement of the graded relation

$$\frac{Q_b}{Q} \propto S^{1+x} \cdot \left[ \frac{d}{D_{50}} \right]^x$$

where $x$ depends on transport intensity!

Eaton and Church, 2012, Earth Surface Processes and Landforms
Overcoming Indeterminacy Using a Numerical Model (UBCRM)

- to overcome the indeterminacy, we apply numerical approximations, to a geometrically idealized river
Concept Diagram of the UBCRM

Key Points:
- trapezoidal geometry
- open channel hydraulics, transport law
- bank stability constraint
- NOT A REAL RIVER
Predicting the Geometry of Experimental Streams

In the lab $Q, Q_b \rightarrow S$, but **Thresholds exist!**

(Eaton and Church, 2004, Journal of Geophysical Research - Earth Surface)
Beyond the Laboratory: Including Bank Strength


- and can be related to bed sediment and riparian vegetation rooting depth (Eaton 2006, Earth Surface Processes and Landforms)
Estimating Bank Strength due to Vegetation

Applying UBCRM to existing dataset (Hey and Thorne, 1986) produces estimates of bank strength

<table>
<thead>
<tr>
<th>Type</th>
<th>Rooting depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>grass</td>
<td>0.36</td>
</tr>
<tr>
<td>1-5% tree/shrub</td>
<td>0.53</td>
</tr>
<tr>
<td>5-50% tree/shrub</td>
<td>0.89</td>
</tr>
<tr>
<td>&gt;50% tree/shrub</td>
<td>1.07</td>
</tr>
</tbody>
</table>

(Eaton, 2006, Earth Surface Processes and landforms)
Predictions: Salmon River, Idaho

\[ C' = 3.0 \text{ kPa} \]

- single bank strength value (calibrated)
- estimates of \( Q, S \) and \( D \) (from Emmett, 1975)

(Eaton and Church, 2007, Journal of Geophysical Research - Earth Surface)
Predictions: A Range of River Systems

Table: Width predictions: UBCRM vs. empirical hydraulic geometry

<table>
<thead>
<tr>
<th></th>
<th>Root Mean Squared Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UBCRM</strong></td>
<td><strong>Empirical Equation</strong></td>
</tr>
<tr>
<td><em>Colorado R.</em></td>
<td>15.9</td>
</tr>
<tr>
<td><em>Fraser R.</em></td>
<td>19.3</td>
</tr>
<tr>
<td><em>Columbia R.</em></td>
<td>20.3</td>
</tr>
<tr>
<td><em>Danube Delta</em></td>
<td>36.0</td>
</tr>
<tr>
<td><em>Laitaure Delta</em></td>
<td>36.2</td>
</tr>
<tr>
<td><em>Salmon R. (1)</em></td>
<td>22.3</td>
</tr>
<tr>
<td><em>Salmon R. (2)</em></td>
<td>12.9</td>
</tr>
</tbody>
</table>

But, while empirical results are constrained by the data, physically based models are generalizable, so long as the physics is appropriately represented.
Predicting Channel Pattern

- UBCRM predicts onset of mid-channel bars
- Three zones:
  1. meandering;
  2. veg.-dep.; and
  3. braided
Validating the channel pattern model: single thread channels

- weak banks → zone (1)
- stronger banks → zones (1) and (2)

(Eaton and Giles, 2010, Earth Surface Processes and Landforms)
Validating the channel pattern model: multi thread channels

- braided channels → zones (2) and (3)

(Eaton and Giles, 2010, Earth Surface Processes and Landforms)
1996 Saguenay Flood . . . a Story of Stability

St. Marguerite R.
Saguenay Region
Quebec, Canada

Event 1: 150 m³/s $Q_{10}$ (April 1996)

Event 2: 250 m³/s $Q_{100}$ (July 1996)

Q_{b2} \approx 10 \cdot Q_{b1}

(Eaton and Lapointe, 2001, Geomorphology)
Morphologic Changes → Stable Channel

(Eaton and Lapointe, 2001, Geomorphology)
2013 Flood in SW Alberta . . . a Different Story

(Tamminga et al, in press, River Research and Applications)
(Tamminga et al, revisions requested, Earth Surface Processes and Landforms)
DEM Before and After an Extreme Flood: Unstable Channel

2012 DEM

2013 DEM
Thresholds for Pattern Instability: Mobility of Large Grains

2D flow models $\rightarrow$ local shear stress

Light grey $= 2013$ morphology

black $= 2012$ morphology

red $=$ immobile; yellow $=$ partially mobile; green $=$ fully mobile

Morphologic adjustments $\rightarrow$ stability of large grains (?)
Experimental Measurements: Bank Erosion Threshold

Scale Model (1:30)

particle mobility → bank erosion
Steady State Morphology: Laterally Stable

0.37 L/s or 2.2 m3/s

0.41 L/s or 2.4 m3/s

0.45 L/s or 2.6 m3/s
Steady State Morphology: Laterally Active

0.62 L/s or 3.6 m³/s

0.73 L/s or 4.3 m³/s

0.89 L/s or 5.2 m³/s
Particle Mobility: All Grain Sizes, Stable Channel

0.33 L/s or 1.9 m³/s

Proportion in Size Class

- Subsurface
- Hour 0
- Hour 1
- Hour 2
- Equilibrium

Particle Size (mm)
Particle Mobility: All Grain Sizes, Unstable Channel

0.89 L/s or 5.2 m3/s

Proportion in Size Class

- Subsurface
- Hour 0
- Hour 1
- Hour 2
- Hour 3
- Hour 4
- Equilibrium

Particle Size (mm)
Particle Mobility: Largest Grains, All Experiments

- 1:1 Line
- 30% Total Run Time
- Equilibrium

Discharge (m³/s)

Discharge (L/s)
Thresholds in Another Flume (post-hoc evidence)

(Laterally active)

Previous **threshold** bounding graded channels $\rightarrow$ full mobility!

(Eaton and Church, 2004, Journal of Geophysical Research - Earth Surface)

February 2015: River Restoration Northwest

Steady States, Thresholds, Disturbances
Reach-Scale Channel Simulator (RSCS): a Stochastic Model

Module 1: Riparian Forest Inputs
Module 2: Small Wood Advection
Module 3: Key Piece Identification
Module 4: LW Movement and Jam Growth
Module 5: Bed Material Sediment Storage
Module 6: LW Decay
Disturbances: Wildfire and Riparian Harvesting

![Graph showing total wood load over time for different scenarios.](image)

Davidson and Eaton, submitted, Water Resources Research

February 2015: River Restoration Northwest
The influence of wildfire: the effects of scale

Davidson and Eaton, submitted, Water Resources Research
The influence of wildfire: channel dynamics

Davidson and Eaton, submitted, Water Resources Research
The influence of wildfire: habitat values

Davidson and Eaton, submitted, Water Resources Research
The influence of riparian forest harvesting

Davidson and Eaton, submitted, Water Resources Research

February 2015: River Restoration Northwest
Concluding Remarks: Application to Restoration

- **Empirical** equations $\rightarrow$ hydraulic geometry
  (used to approximate channel response to changes in $Q$)

- **Deterministic** models (e.g. UBCRM) $\rightarrow$ hydraulic geometry, channel pattern, transport capacity
  (used to estimate long-term stream response to changes in $Q$, $Q_b$, $S$, bank vegetation)

- **Physical** models $\rightarrow$ controlled experiments
  (used to estimate bank migration thresholds, assess channel response to well defined environmental change, evaluate potential restoration options)

- **Stochastic** models (e.g. RSCS) $\rightarrow$ range of channel conditions
  (used to estimate reference conditions against which to compare disturbed streams, set restoration goals)
Concluding Remarks: Application to Restoration

- **Empirical** equations → hydraulic geometry (used to approximate channel response to changes in $Q$)

- **Deterministic** models (e.g. UBCRM) → hydraulic geometry, channel pattern, transport capacity (used to estimate long-term stream response to changes in $Q$, $Q_b$, $S$, bank vegetation)

- **Physical** models → controlled experiments (used to estimate bank migration thresholds, assess channel response to well defined environmental change, evaluate potential restoration options)

- **Stochastic** models (e.g. RSCS) → range of channel conditions (used to estimate reference conditions against which to compare disturbed streams, set restoration goals)
Concluding Remarks: Application to Restoration

- **Empirical** equations → hydraulic geometry (used to approximate channel response to changes in $Q$)

- **Deterministic** models (e.g. UBCRM) → hydraulic geometry, channel pattern, transport capacity (used to estimate long-term stream response to changes in $Q$, $Q_b$, $S$, bank vegetation)

- **Physical** models → controlled experiments (used to estimate bank migration thresholds, assess channel response to well defined environmental change, evaluate potential restoration options)

- **Stochastic** models (e.g. RSCS) → range of channel conditions (used to estimate reference conditions against which to compare disturbed streams, set restoration goals)
Concluding Remarks: Application to Restoration

- **Empirical** equations $\rightarrow$ hydraulic geometry
  (used to approximate channel response to changes in $Q$)

- **Deterministic** models (e.g. UBCRM) $\rightarrow$ hydraulic geometry,
  channel pattern, transport capacity (used to estimate
  long-term stream response to changes in $Q$, $Q_b$, $S$, bank
  vegetation)

- **Physical** models $\rightarrow$ controlled experiments
  (used to estimate bank migration thresholds, assess channel
  response to well defined environmental change, evaluate
  potential restoration options)

- **Stochastic** models (e.g. RSCS) $\rightarrow$ range of channel conditions
  (used to estimate reference conditions against which to
  compare disturbed streams, set restoration goals)
DOD for an Extreme Flood: Unstable Channel
Effect of Initial Conditions: Lateral Activity

0.73 L/s

0.25 m initial width

0.33 m initial width

0.89 L/s

0.25 m initial width

0.40 m initial width
The influence of wildfire: sediment storage

Davidson and Eaton, submitted, Water Resources Research
Variables in the RSCS

- LW pieces (dimensions, orientation, function, sediment)
- spanning jams (volume of wood, sediment storage, avulsions)
- Study reach (wood load, sediment load)
Data from a single run

- Wood Load (m$^3$/m$^2$)
- Sediment Volume (m$^3$)

Time (yrs):
- 0 200 400 600 800

Wood Load:
- 0.008
- 0.014

Sediment Volume:
- 100
- 300

February 2015: River Restoration Northwest

Steady States, Thresholds, Disturbances
Data from a single run

Pool Area (m²)

No. Side Channels

Time

February 2015: River Restoration Northwest

Steady States, Thresholds, Disturbances
Wood load distribution across scales

- Spanning wood
- Wood export
- Channel size

(Eaton and Hassan, 2013, JGR - Earth Surface)
Frequency of jam formation

- Maximum (≈ 10 m³/s)
- Spanning LW (< 10 m³/s)
- Mobile LW (> 10 m³/s)
Jam size per unit channel width

- Minimum (≈ 5 m³/s)
- Maximum (20 - 30 m³/s)
- Piece mobility vs. key member stability
Reach-average sediment storage

- Normalized by channel volume
- Declining median with $Q$
- Declining range with $Q$
- Maximum (5 to 10 m$^3$/s)
Reach-average significance of jams

- $Q < 15 \text{ m}^3/\text{s}$: jams store 40 to 90% of sediment
- $Q > 40 \text{ m}^3/\text{s}$: jams store very little sediment
- $20 < Q < 30 \text{ m}^3/\text{s}$: jam influence is variable
Storage behind individual jams

- Normalized by $d \cdot W^2$
- Stable jams vs. mobile jams
- Largest jams form in transition (20 to 30 m$^3$/s)
Key factor: functional wood load
- abundant in smaller channels
- limited in larger channels

Cover provided by wood

[Graph showing the relationship between Q (m³/s) and Cover (m²/m²)]
Area of pools formed by jams

- Key factor: jam height
- Critical in smaller channels
- (Absent in larger channels)

Graph showing the relationship between pool area and discharge, with key features:

- 99th percentile
- 50th percentile
- 1st percentile

Key points:
- February 2015: River Restoration Northwest
- Steady States, Thresholds, Disturbances
Area of LW-induced deposition

Key factors: sed. supply, jam size, age

- $Q \sim 10$ to $15 \text{ m}^3/\text{s}$: LW-induced deposition dom.
Active side-channel frequency

- Key factors: number, size and longevity of jams
- Maximum $\sim 15$ to $20$ m$^3$/s
- $Q > 30$ m$^3$/s: jams unlikely to create side channels
Depends on stored sediment, energy gradient modification

- \( Q \sim 20 \text{ m}^3/\text{s} \): greatest potential effect
- Little textural modification in small channels