Accounting for increased flow resistance due to lateral momentum loss in restoration designs using 2-stage channels

Colin R. Thorne  University of Nottingham and Colorado State University
Philip J. Soar  Jeremy Benn and Associates

Outline

- Aim and Objectives
- Definition
- Use of 2-stage channels in stream restoration
- Modelling solution?
- Initial analytical approach
- Curve fitting approach
- Visualisation and nx2 software
- Performance testing
- Demonstration and practical application of the nx2 software
- Questions
**Aim**

Raise awareness of the issue of lateral momentum losses in 2-stage channels and suggest how these might be accounted for in restoration design

**Objectives**

- Define 2-stage channels, explain their use in stream restoration and identify design issues
- Illustrate what can happen if losses are not properly accounted for
- Present an analytical approach for lateral momentum losses (developed by Ron Copeland at Waterways Experiment Station, Vicksburg)
- Present a new approach
- Test the new approach using prototype data
- Demonstrate how the nx2 software could be used in practice
Definition of a 2-stage channel

Use of 2-stage channels in stream restoration

“Modifying about 1 km of straight channel to create a narrow, low flow channel within a much wider flood channel”
But there are warning signs out there

“The pattern of flow in 2 stage channels is complex. The flow velocity in the main channel is greater than on the flood berms and a momentum transfer mechanism is generated in the region of high shear flow between the main channel and the flood berm. This has the effect of reducing local and mean velocities, discharge and boundary shear stress in the main channel.

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And these are recognised in some restoration guides

“Overflow channels and overbank areas usually have hydraulic properties significantly different from those of the main channel. These areas are usually treated as separate subchannels, and the discharge computed for each of them is added to the main channel to compute total discharge. This procedure ignores lateral momentum losses, which could cause n values to be underestimated.”

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Fluvial processes are complex in 2-stage channels

• Velocity differential between the main channel and floodplain flows induces a lateral shear layer between these two regions.
• Secondary circulations, both in plan and within the cross section, carry fast moving fluid from the main channel to the floodplain and visa versa.
• These mechanisms combine to reduce discharge in the main channel and increase it on the floodplain.
• These interactions affect zones of the main channel and floodplain adjacent to the channel bank.

Fluvial processes (continued)

• In narrow channels shear layers may extend across the whole channel.
• The strength of interaction depends mainly on:
  1. Main channel / floodplain depths;
  2. Main channel / floodplain bed roughness, and;
  3. The velocity differential across the shear layer.
Problems have occurred with 2-stage channels in the UK

River Roding at Abridge, Essex
2-stage channel built in 1979
design capacity = 11 m$^3$/s
actual capacity = 7 m$^3$/s
1992 a study of hydraulic performance concluded that:
“the scheme is significantly below design capacity. This is due to a combination of impedance of flow over the berms by reeds and complex eddying associated with the physical geometry.”

Is there a design solution through numerical modelling?

Calculated floodplain velocities 30% lower than measured.
“The model routes more of the flow through the main channel than was the case in the experiment…. over predicts velocity in the main channel and under predicts it on the vegetated floodplain.”

“Flow visualisation revealed large coherent eddies at the interface between the channel and the floodplain….. produced by a shear instability between fast flow in the main channel and the slower jet between the first two rows of cylinders”

(Jason Keane and Jim Dungan Smith, 2004)
**Initial analytical approach (Copeland, 1999)**

The approach set out by Copeland (1999) is to:

1. estimate both a main channel and a floodplain roughness coefficient, ignoring lateral momentum losses, using standard techniques and then

2. apply a roughness multiplier to the channel roughness coefficient to account for increased energy dissipation through lateral momentum loss.

The multiplier is defined as the Manning-$n$ value that accounts for momentum loss divided by the Manning-$n$ value estimated from the main channel boundary only (corresponding to the bankfull stage).

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**Initial analytical approach (Copeland, 1999)**

**Wetted Perimeter Ratio**

\[ \Pi = \frac{P_b + N_{fp}Y_{fp}}{P_b} \]

**Velocity Differential**

\[ \Lambda^* = \frac{V_{ch}^* - V_{fp}^*}{V_{ch}^*} \]

**Roughness ratio**

\[ \Psi^* = \frac{n_{fp}^*}{n_b^*} \]

where:
- $P$ = wetted perimeter (does not include interface between channel and floodplain flows)
- $N_{fp}$ = number of floodplains: 1 or 2
- $n^*$ = assigned Manning $n$ value ignoring lateral momentum loss
- $V^*$ = calculated velocity assuming no lateral momentum loss
- $Y_{fp}$ = water depth in floodplain

**Subscripts:**
- ch = channel
- fp = floodplain
- b = physical surface of the channel
**Initial analytical approach (Copeland, 1999)**

\[
\frac{n_{ch}}{n_b} = \left[ \frac{0.801}{\Psi^*} + 1.087 \left( \Lambda^* \right)^{0.5} + 0.317 \Pi^2 + 0.00064 \left( \Psi^* \right)^5 - 1.152 \right]^{-1}
\]

- **Problems with Initial Analytical Approach**
  - Roughness multiplier is not a linear function.
  - The plot reveals significant scatter.
  - Calculated \( n \) multipliers are conservative at high values.
  - Multiple regression equation includes identical Manning \( n \) values on both sides, indicating significant collinearity.

  **In light of these limitations, an alternative method is required.**

  - New approach may be applied to a compound channel in which there is a distinct over-bank area on one or both sides of the main channel.
  - It can also be applied to the case of a channel and floodplain as no distinction is made between over-bank surfaces in a compound channel configuration and a floodplain.
New approach rests on application of curve-fitting software to:

- better represent the non-linear relationships between the roughness multiplier and the two main dimensionless parameters
- account for various levels of risk and uncertainty in the application.

Approach predicts the likely maximum $n$ multiplier for a specified confidence level (50, 75, 85, 95%), rather than some average value (as in regression analysis).

\[
Y = Y_0 + A \left[ 1 + \left( \frac{W_2 + W_3 - 2}{W_1(W_2 - 1)} \right) (X - X_c) \right]^{W_2-1} \left[ 1 - \left( \frac{W_2 + W_3 - 2}{W_1(W_3 - 1)} \right) (X - X_c) \right]^{W_3-1}
\]

$Y$ = dependent variable  $X$ = independent variable
$Y_0$ = $Y$- offset  $X_c$ = mode (at $Y=Y_0+A$)
$W_1$, $W_2$, $W_3$ = shape parameters  $A$ = amplitude
Curve fitting results

For parameters in Equation 1 for given confidence limits applied to the $n$ multiplier ($Y$) as a function of:

i) Wetted Perimeter Ratio ($P$)

ii) Velocity Differential ($L^*$)

iii) Floodplain type, where: $s = $ smooth floodplain; $r = $ rough floodplain.

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<th>$X_c$</th>
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<th>$W_2$</th>
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Single parameter curvilinear plots

Wetted perimeter ratio (smooth and rough floodplains)

Velocity ratio (upper = smooth floodplains, lower = rough floodplains)
Multi-parameter approach (Thorne and Soar, 2001)

- Curve fitting approach treats the two dimensionless variables in isolation of each other.
- Actually, the value of the $n$ multiplier is the net result of the combined influence of both parameters.
- This can be analysed using a matrix representation of the data, with the $n$ multiplier (z-axis) a result of both the Wetted Perimeter Ratio (y-axis) and the Velocity Differential (x-axis) and fitting 3-D surfaces to the data for different levels of confidence.
- Therefore a multi-parameter approach was developed.

Multi-parameter analysis (Thorne and Soar, 2001)

The method adopted to develop the 3-D plots involved 5 steps:

i) Subdivide data according to floodplain roughness;
ii) Convert raw vector data into a low-resolution matrix;
iii) Resample the matrix to improve resolution;
iv) Develop matrices for different levels of confidence;
v) Develop end-user data visualisation software.
2-D plots allow comparison with Initial method

Smooth Floodplains       Rough Floodplains

Visualisation of Manning-n Multiplier Plots

• Three-dimensional plots provide a way to examine the interplay between bivariate data and have been used previously in river habitat models.
• For example, to provide a simple means of assessing instream habitat response to the effects of flow alterations, Peters et al. (1995) developed the Riverine Community Habitat Assessment and Restoration Concept (RCHARC).
• Output from RCHARC is a 3-dimensional plot of depth (x-axis) versus velocity (y-axis) versus percent occurrence in each study reach (z-axis).
**Nx2 Mannings-\(n\) Multiplier Software**

- Enables end users to view (and revolve) the 3-D plots and matrix data.
- Enables end-users to calculate Mannings-\(n\) multipliers for specified values of Wetted Perimeter Ratio, Velocity Differential and Floodplain type at selected levels of confidence.
- nx2 software follows uses smoothed 3-D surfaces.
- Software is available from the authors on request on a CD-ROM.
- User Guide is included as a help file.
- It is planned to post the software on Colin Thorne’s homepage at the School of Geography, University of Nottingham website:

  [http://www.geog.nottingham.ac.uk/](http://www.geog.nottingham.ac.uk/)

**Performance testing: River Blackwater, Hampshire, UK**

- Objective: to evaluate the new analysis using hydraulic data from a real case study of a 2 stage channel.
- Two approaches were adopted:
  i) **direct comparison between the predicted \(n\) multipliers and those back-calculated from observed data**;
  ii) **using the observed data to compare the \(n\) multipliers predicted by the new analysis and those predicted by an established methodology**.
- Data for a 2-stage reach of the River Blackwater was made available by Robert Sellin (Department of Civil Engineering, University of Bristol, UK).
River Blackwater

2-stage channel reach ~3 km long.
5 water level monitoring stations along 315 m of channel length.
Inner channel width = 6 m
Depth of inner channel = 0.75 m
Outer channel width = 16 m
Bed slope = 0.0009
Sinuosity = 1.0 to 1.25.
Characterized by very significant seasonal variation in the type and density of vegetation, with occasional cutting of vegetation for flood control.

River Blackwater - seasonal variability in roughness

Seasonal vegetation variability markedly affects the boundary roughness in the compound channel.

At the bankfull level in the inner channel in 1999:
Winter Mannings-$n$ = 0.014
Summer Mannings-$n$ = 0.157

This corresponds to a variation in discharge capacity between 5.67 m$^3$ s$^{-1}$ and 0.51 m$^3$ s$^{-1}$.
HR Wallingford Flood Channel Facility - Phase A Method

- Detailed results described by Ackers (1991) and Wark et al. (1994).
- Compound channel is subdivided into main channel and left and right floodplains separated by vertical division lines.
- Computes the 'basic discharges' for the main channel, floodplains and the whole section for a specified water level using conventional flow resistance equations.
- Adjusts basic discharges to account for lateral momentum loss. The adjustment is a function of the characteristics of the channel and also varies with stage and flow interaction type.
- Calculates the adjusted discharges for the main channel and floodplain areas then totals these for the whole compound channel.

Results for 30 October 2000 (peak Q = 4.27 m³s⁻¹)

- $n$ multiplier values for the 95% level of confidence are very close to the calculated values at low values of floodplain roughness.
- As the floodplain roughness increases, 95% line provides a suitable factor of safety: 2-stage channel would have some freeboard.
- FCFA method underestimates the $n$ multiplier, corresponding to an overestimation of discharge conveyance capacity.
nx2: Demonstration and Application

Demonstration and practical application of the nx2 software

nx2: Demonstration and Application

nx2 Software:
  • Visualisation tool - Front end to the 3D n-multiplier distributions
  • Interpolation tool – Estimate n-multiplier values
  • Compare values for different levels of uncertainty

nx2 Demonstration

nx2 Application:
  • River Stour Floodplain Rehabilitation

nx2 Limitations
nx2 Application

nx2 Application: River Stour Floodplain Rehabilitation

Not a compound channel but a river in a very wide floodplain.
**nx2 Application**

**River Stour:** Flooding of Sturminster Marshall, 2000

[Image: Aerial view of flooded area with marked 1992 Defenses]

**nx2 Application**

**River Stour:** Flooding of Sturminster Marshall, 2000

[Image: Aerial view of flooded area with marked 1992 Defenses]
nx2 Application

River Stour Floodplain Rehabilitation

nx2 Application

Other Development on Edge of Floodplain

Objective

- Estimate the existing 1% (1 in 100-yr) flood level
- No hydraulic model is available
- Flow is available from Flood Estimation Handbook
- Hand calculation approach is required
**nx2 Application**

**Conventional approach: stage-discharge relationship**

- Graph showing discharge (m³/s) against elevation AOD (m)
- Line indicating no lateral momentum loss
- Dashed line marking 255 m³/s as 1 in 100-yr flow at elevation 22.65 m

**nx2 Application**

**n-multiplier approach**

- Graph displaying Wetted Perimeter Ratio and Velocity Differential against elevation AOD (m)
- Wetted Perimeter Ratio line is generally decreasing, while Velocity Differential line is increasing
**nx2 Application**

**n-multiplier approach: 95% confidence**

![Diagram showing Velocity Differential vs Wetted Perimeter Ratio with 95% confidence range outlined.]

**nx2 Application**

**n-multiplier approach: 75% confidence**

![Diagram showing Velocity Differential vs Wetted Perimeter Ratio with 75% confidence range outlined.]

Range of values indicated.
**nx2 Application**

**Range of n-multiplier values**

- **95%**
- **75%**

**nx2 Application**

**Underestimation of flood level and freeboard!**

- **no lateral momentum loss**
- **n multiplier at 95% probability**
- **n multiplier at 75% probability**

- **255 m³/s = 1 in 100-yr flow**
- **0.23m**

22.65 m to 22.88 m
nx2 Limitations:

- Dataset is based on physical models
- The approach has not been applied widely
- Applicable to straight channels only
- Results should be treated as a guide only

but...
- Lateral momentum loss can be significant and should not be ignored