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Modelling Sediment Transport and Morphological Changes: Problems and Opportunities

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Sediments and Morphology Matter…

- Channel morphology (and associated sediments) define the river's physical habitat (e.g. deep pools)
- Sedimentation influences flow conveyance and thus flood risk

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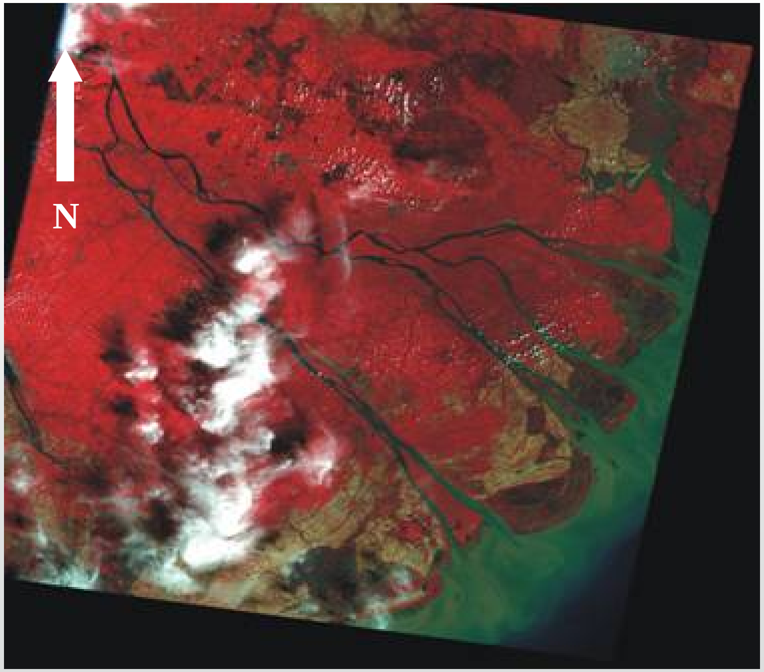
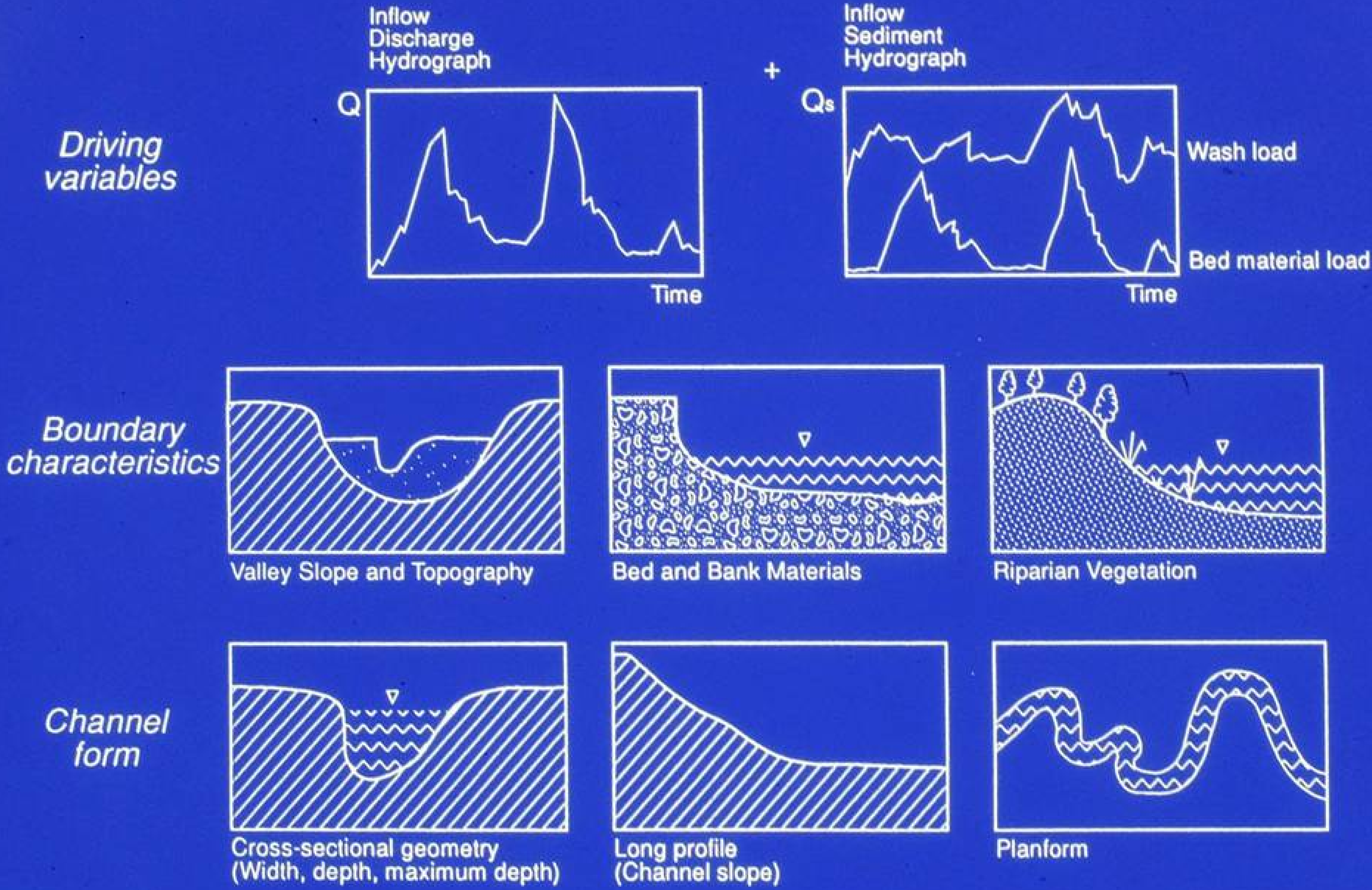
Sediments & Morphology Matter…

- Channel morphology (and associated sediments) define the river's physical habitat (e.g. deep pools)
- Sedimentation influences flow conveyance
- River bank erosion and planform change
- Sediment and nutrient transfers
  - Agriculture
  - Aquaculture
  - Coastal erosion





Independent and dependent variables describing channel process and form

The LMB is changing…

Deforestation: MODIS image, 2002

Manwan Dam, PDR China

Spur dikes, Bokeo Province, Lao PDR

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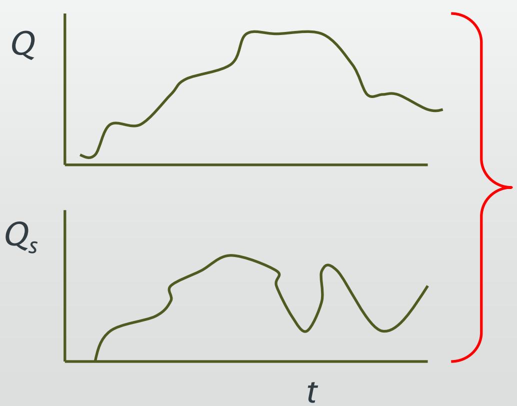
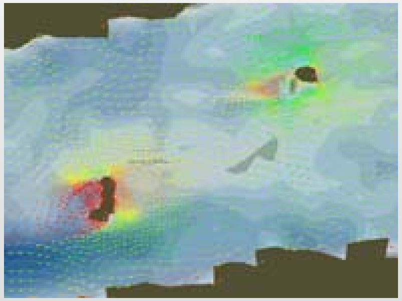
The need for models

- Sustainable management requires knowledge of current **<u>and future</u>** (50-100 yrs) trajectories of change and associated system responses
- **<u>Predictive</u>** approaches are needed
- Predictive morphological models must address the catchment-scale drivers while identifying local responses



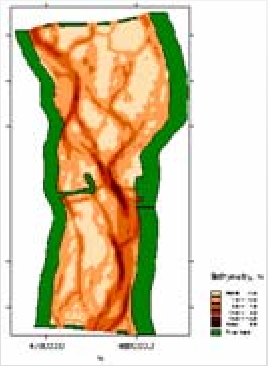


Hydraulics

+

Sediments

+



Morphology

Approach

- Nested modelling to offer strategic, basin-wide, overview of morphological processes and response
  - Empirical/conceptual analyses
  - Numerical morphological models
    - 1D modelling for broad-scale system overview
    - 2/3D modelling in ‘critical’/sensitive reaches
  - Interfacing with **scenario design**, and hydrological and sediment **modelling** and **monitoring** to address changing $Q(t)$, $Q_s(t)$ into the future

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Empirical Approaches

- High quality bedload and suspended load data is vital to inform future management
- Acquisition of this data will take at least 5-10 years – can we afford to wait?
- **Retrodiction** of channel changes **for predictive purposes**
  - **Analyse** existing bedload (Conlan) and suspended sediment (e.g. Walling, 2008) data to retrodict channel behaviour in the recent past (last few decades) at the scale of the LMB

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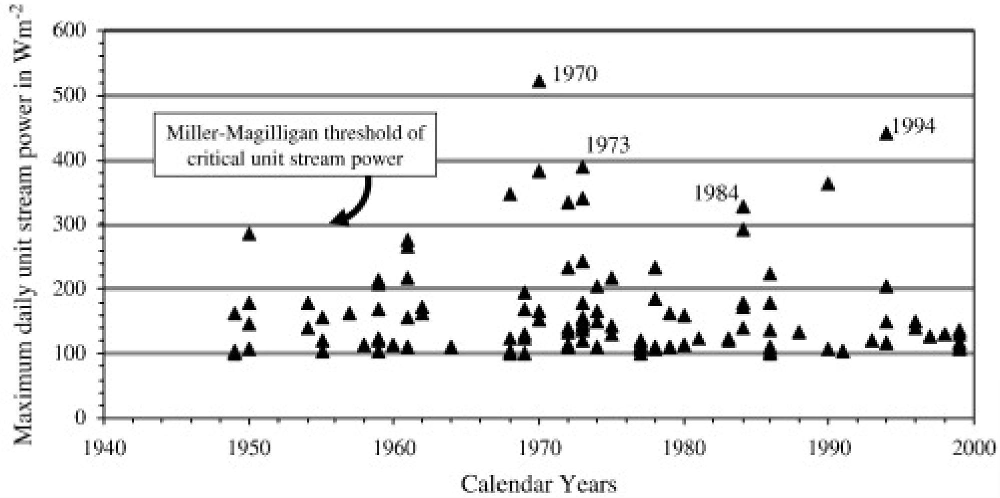
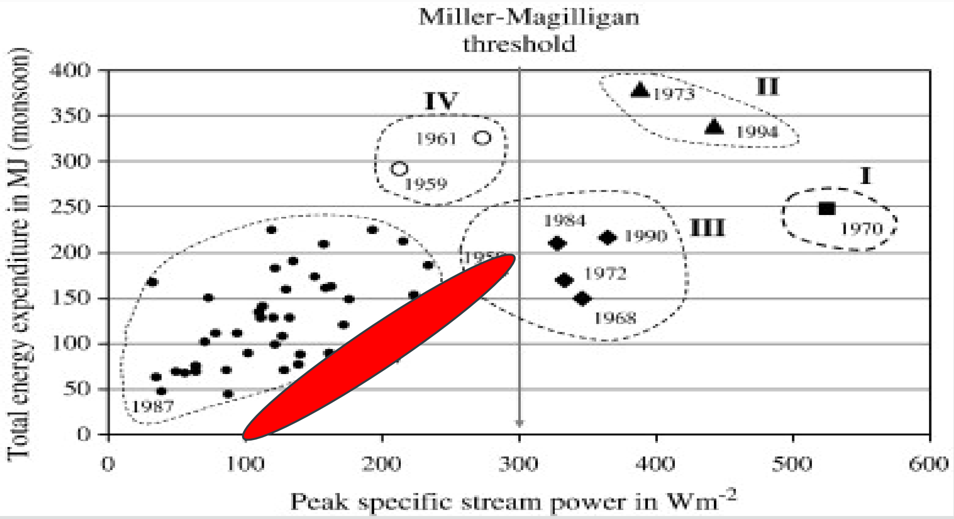
Retrodiction for Prediction: Method

- Use hydrological records (Q) at gauging stations to calculate stream power (Ω) time series (**backwards modelling**)
- Determine key thresholds of morphological change
  - e.g. LMB bank erosion thresholds
  - Miller-Magilligan threshold of catastrophic change
  - Brookes 35 W/m^2 threshold of change
- Analyse historical (stream power) data in terms of threshold exceedances
  - Ascertains channel response from theory and historical observation
- Select future Q and Q_s scenarios: Simulate future stream power time series (**forwards modelling**)

Example: Narmada River, India

- Kale (2008, Catena, 75, 154-163)
- Historic stream power time series isolates historic flood maxima that were ‘significant’
- Identify years with similar peak power and total energy expenditures. Clustering of floods can be interpreted in terms of channel behavioural response
- Future flow scenarios (regulated/climate change) can then be added as a means of estimating the impact on channel stability





Morphodynamic modelling

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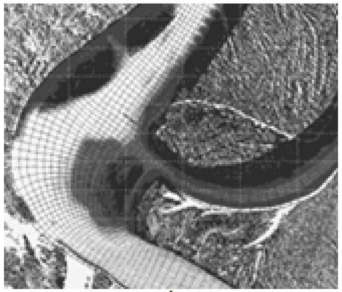
Discretise channel onto computational mesh



DATA INPUTS

Flow Hydraulics Model

Sediment Transport Model

Bank Erosion Model

Process Sub-models

Sediment Continuity Equation

$$(1-\lambda)\frac{\partial Z}{\partial t}+\left(\frac{\partial S_x}{\partial x}+\frac{\partial S_y}{\partial y}\right)=S.T.$$

T = T + ΔT; Update Z (x, y)

T = END

Channel surveys

INITIAL CONDITIONS

(i) Channel morphology
(ii) Bed & bank materials

BOUNDARY CONDITIONS

(i) Flow Discharge; $Q(t)$
(ii) Sediment inflow; $Q_s(t)$

Predictive mode: Basin-scale modelling
Retrodiction/validation mode: Monitoring

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Morphodynamic Models

- A wide range of software packages are available
- These software tools differ primarily in their
  - **Scale:** The **spatial extent** over which they can be applied and the **spatial resolution** of their outputs (e.g. 1D versus 2D models)
  - **Scope:** The range of relevant process sub-models included
  - **Science:** The specific 'laws' used in the process sub-models
- I am not reviewing the process 'laws' here, as (i) most software tools offer a menu of choices and (ii) errors are in any case usually minimised by **calibration**
  - This again highlights the need for **high quality data**

Features of Reviewed Models

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Model	Category	Commercial?	Planform
FLUVIAL-12	1D	☺	Single-Thread
HEC-6	1D	☺ (freeware)	Single-Thread
CONCEPTS	1D	☺ (freeware)	Single-Thread
ISIS	1-2D	☺	Any
Darby-Thorne	1D	Research	Straight
RIPA	2D	Research	Single-Thread
MRIPA	2D	Research	Single-Thread
DELFT3d	2-3D	☺	Any
MIKE 21C	3D	☺	Any

Flow Process Representation

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Model	Unsteady Flow	Secondary Flow	Friction Factor
FLUVIAL-12	Yes	Yes	Time-space variable
HEC-6	Yes (SH)	No	Time-space variable
CONCEPTS	Yes (SH)	No	Time-space variable
ISIS	Yes	Limited	Time-space variable
Darby-Thorne	Yes (SH)	No	Constant
RIPA	Yes (SH)	Yes (but crude)	Constant
MRIPA	Yes (SH)	Yes (but crude)	Constant
DELFT3d	Yes	Yes	Time-space variable
MIKE 21C	Yes	Yes	Time-space variable

Sediment Transport Models

Model	Load (BL/SL)	Sorting?	Bed-Material
FLUVIAL-12	BL + SL	Yes	Any non-cohesive
HEC-6	BL + SL	Yes	Any non-cohesive
CONCEPTS	BL only	Yes	Any non-cohesive
ISIS	BL+ SL	Yes	Any non-cohesive
Darby-Thorne	BL only	No	Sand
RIPA	BL only	No	Sand or Gravel
MRIPA	BL only	No	Sand or Gravel
DELFT3d	BL + SL	Yes	Any non-cohesive
MIKE 21C	BL + SL	Yes	Any non-cohesive

Bank Erosion Predictors

Model	Deposition	Fluvial Erosion	Mass-Wasting
FLUVIAL-12	not applicable	not applicable	not applicable
HEC-6	No	No	No
CONCEPTS	No	Yes	Yes
ISIS	No	No	No
Darby-Thorne	No	Yes	Yes
RIPA	No	Yes	Yes
MRIPA	No	Yes	Yes
DELFT3d	Yes	In development	In development
MIKE 21C	Yes	Yes	No

Scope of Morphodynamic Modelling

- Available modelling tools may be limited in respect of key physical processes and associated issues on the LMB
  - Flow processes
  - Multi-thread channels
  - Sediment sorting
  - **Bank erosion**

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Simulation of Bank Erosion

- A widely accepted model of fluvial bank erosion already exists:
  - $\varepsilon = k\,(\tau - \tau_c)$
- At Southampton, we have been focusing on the methods used to estimate τ, τ_c and k
  - Novel measurements of bank material characteristics
  - Application of new bank shear stress partitioning model
  - Utilising **existing flow models and measurements** to estimate necessary boundary conditions
    - Collaboration with Finns, Iwona Conlan, etc.

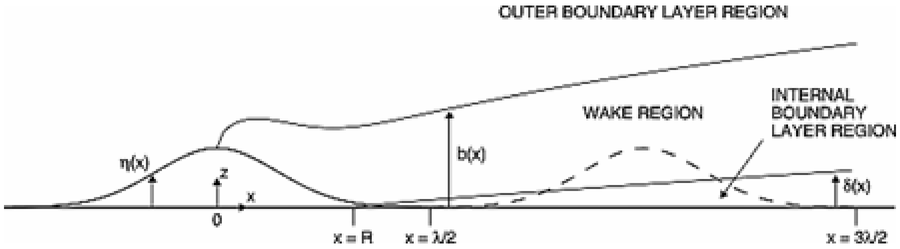
Mekong near Pakse; October 2006

Shear Stress Partitioning

- Shear stress partitioning [Kean and Smith, 2006 a,b]:

$$\tau = \rho \langle u_{*IBL} \rangle^2 + \frac{1}{2} \rho C_D \frac{H}{\lambda} u_{ref}^2$$

Skin drag   Form drag



Source: Fig. 2 of Kean and Smith [2006a]

- U_{ref} is controlled primarily by wakes generated by roughness elements upstream
- H, λ and C_d are functions of the geometry of the bank topography
  - H = protrusion height of roughness element
  - λ = spacing of roughness elements
  - C_d = drag coefficient
- The roughness elements are modelled as Gaussian shapes

River Mekong at Ban Hom (near Vientiane), Laos; May 2007

Bank Roughness Estimation

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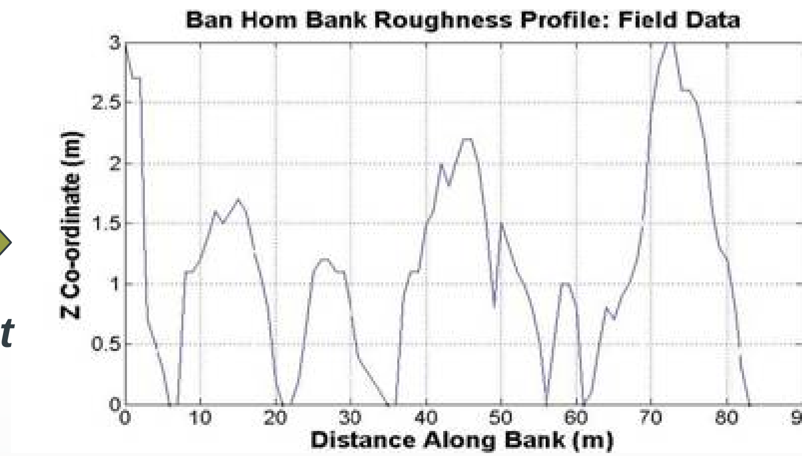
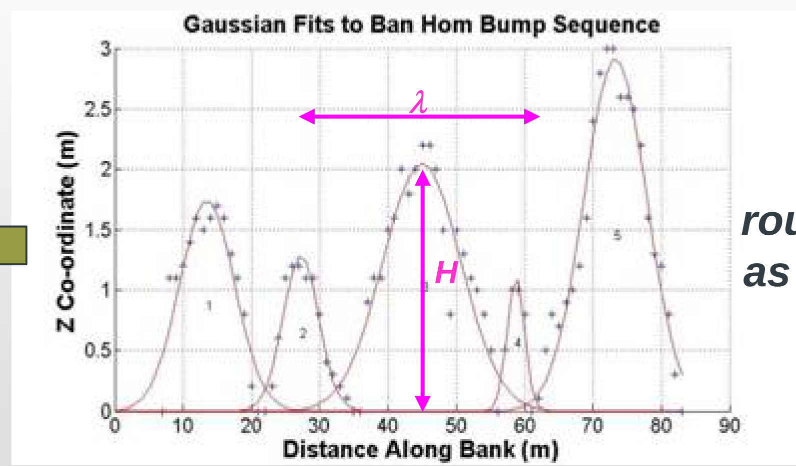
1. *Field survey*

2. Transect



3. Model bank roughness elements as Gaussian shapes



4. Provides a statistical model of bank roughness in terms of *H, λ, C_d*

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Application to the Mekong

- Two sites near Vientiane, Laos
  - Ban Hom
  - Friendship Bridge
- Bank roughness and CSM survey define H, λ, C_d, τ_c, k directly
- Secondary data was used to estimate the reference flow velocity (u_{ref})
  - CFD simulations of the Vientiane reach
  - aDcp data
  - Note: any simple flow estimates are OK

Ban Hom

Friendship Bridge

Results

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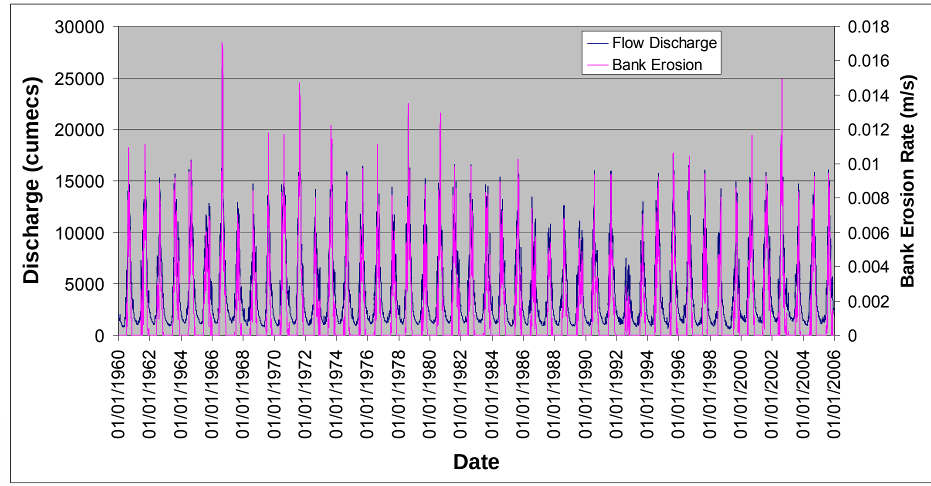
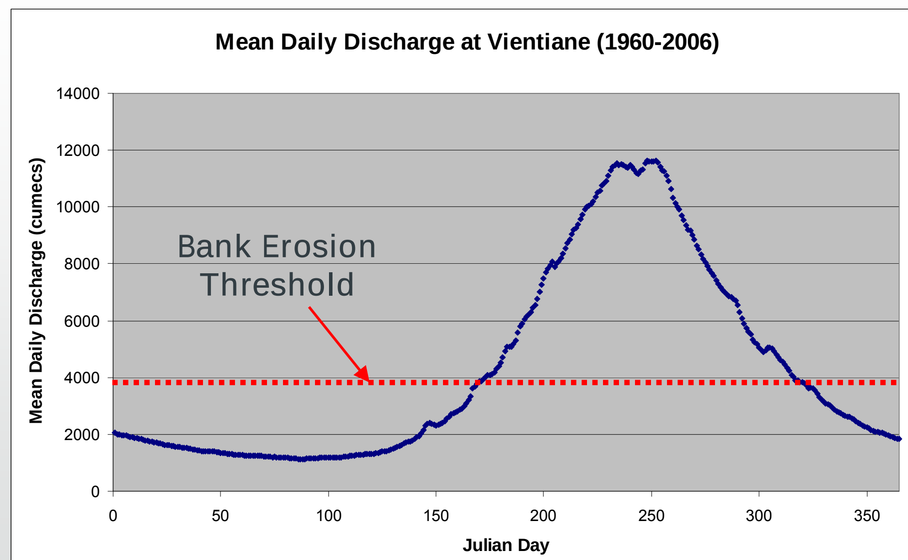
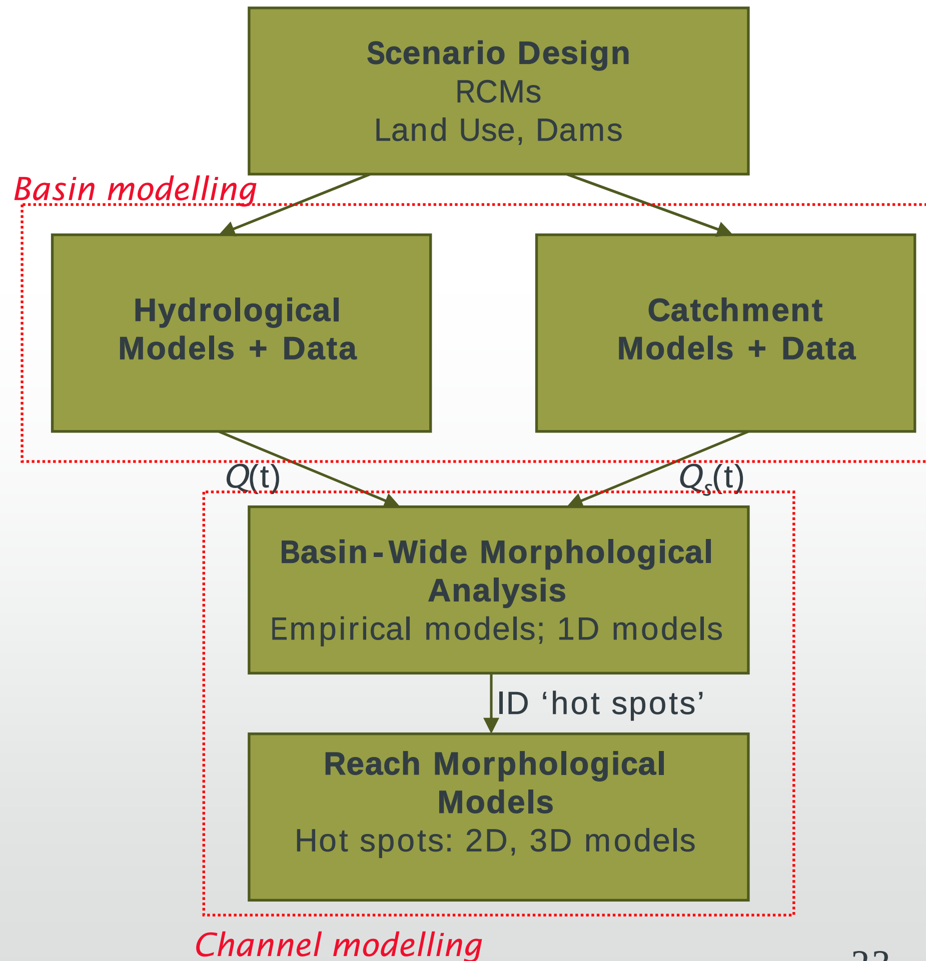
- Multiple analyses were used to link τ to a range of flow discharges
- Daily flow discharge data were then used to estimate ε for 1960-2005
  - Ban Hom
    - 1960-2005 (0.5 m/yr; 0.8 ± 0.1 m/yr)
- Threshold Q for onset of bank erosion:
  - $Q_c \approx 4000\ m^3/s$





Summary: Possible Ways Forward

- Nested modelling to identify morphologic response across the LMB
  - Basin-wide empirical analyses
  - 1D modelling (linked to bank erosion prediction)
  - Detailed 2D and 3D modelling in identified 'hot spots' (again linked to bank erosion prediction)
- To be useful, modelling scenarios must be devised based on realistic future conditions that reflect changing system drivers
- Regional Climate Models (RCMs) linked to (e.g. grid-based) hydrological modelling are needed to give improved $Q(t)$ scenarios
- Catchment-scale sediment models are needed to evaluate $Q_s(t)$ for a range of key grain sizes (gravel, sand, silt, clay)



Basin-Scale Modelling

- Fully process-based catchment models are available, but tend to be limited to small basins (< 2500 km^2)
- Alternative approaches:
  - Landscape Evolution Models (LEMs), e.g. CAESAR
  - Linking grid-based hydrological (G2G) and surface erosion models
  - Reduced Complexity Models
    - HYDROTREND
    - RIVER3

} Syvitski et al. (2008)