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Agricultural Research Service

Channel Width Adjustment: Importance, Mechanics & Assessment

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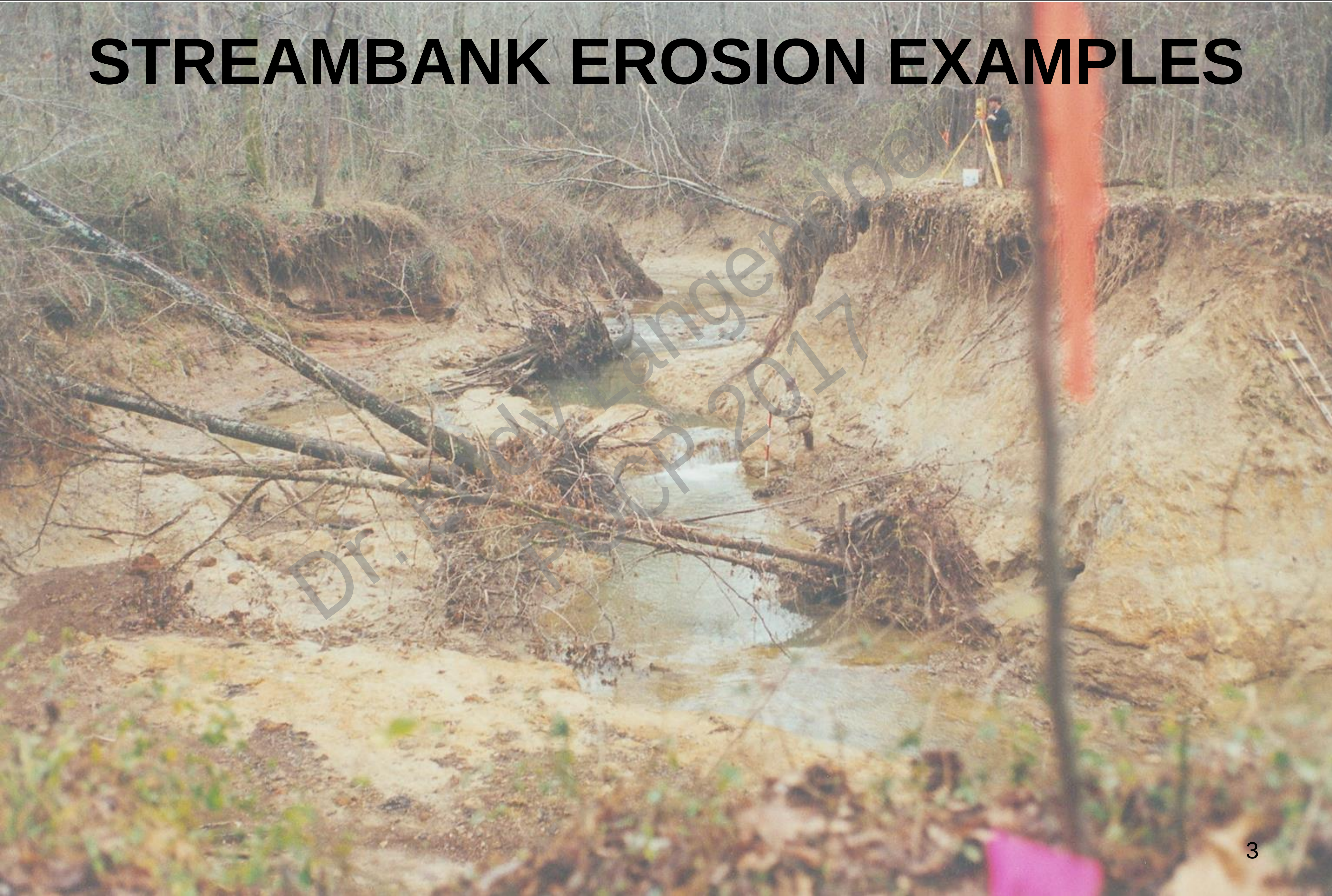
Outline

- Examples of streambank erosion
- Channel dynamics
  - How do channels adjust?
  - Role of streambank erosion
- Streambank erosion processes & analysis
  - Fluvial erosion
  - Mass failure

STREAMBANK EROSION EXAMPLES



WANGMO RIVER – CHINA

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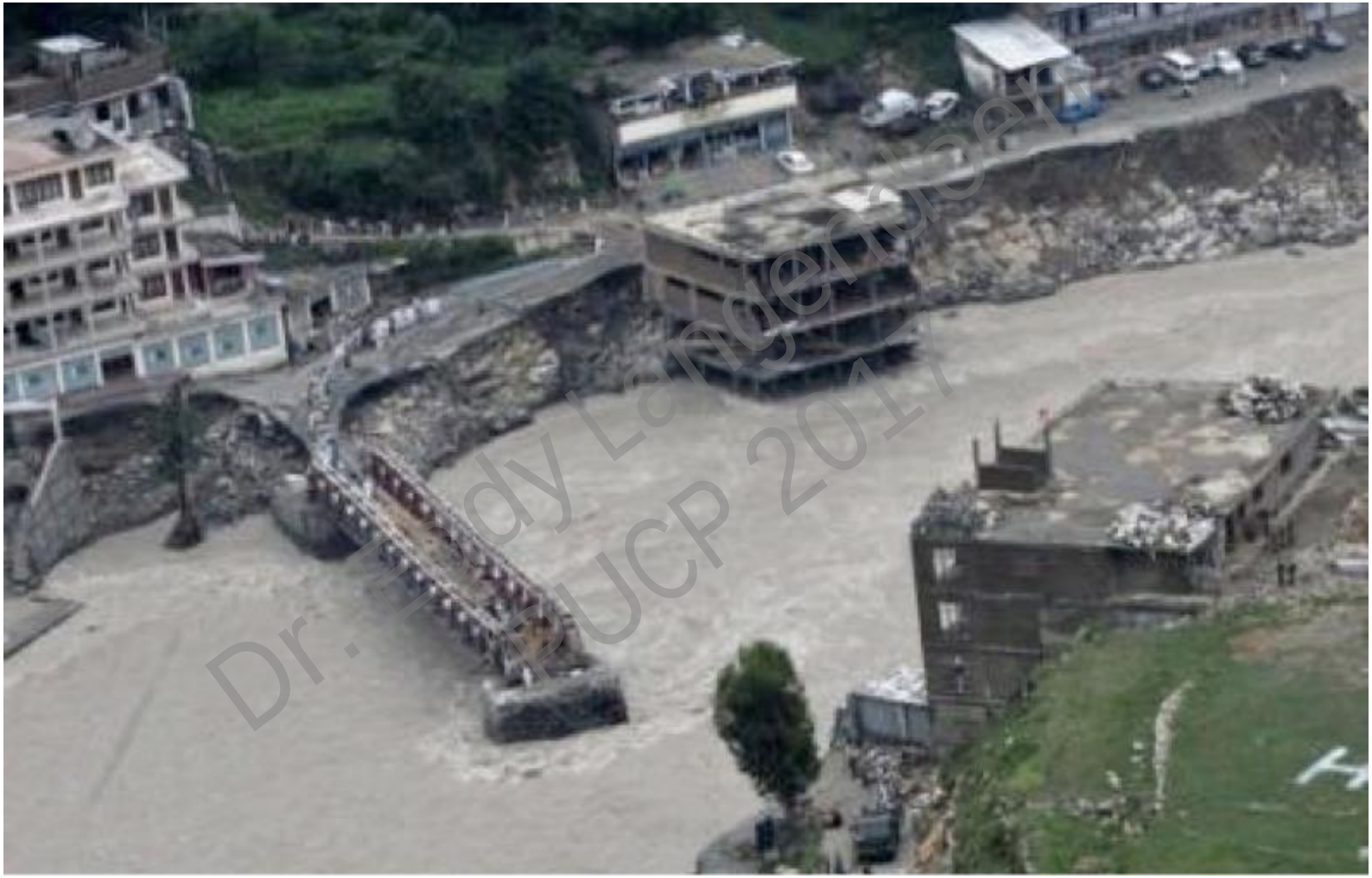

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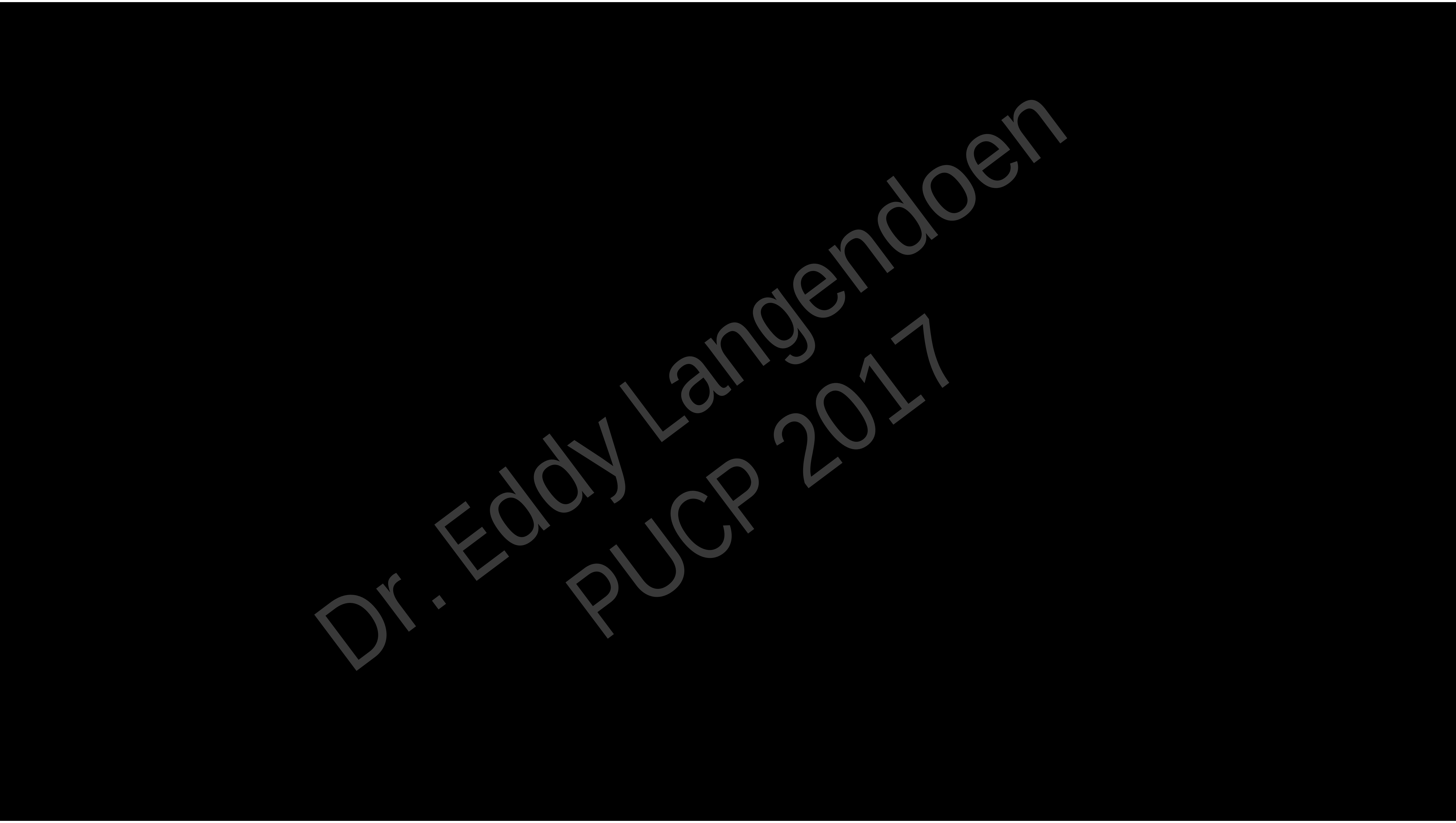
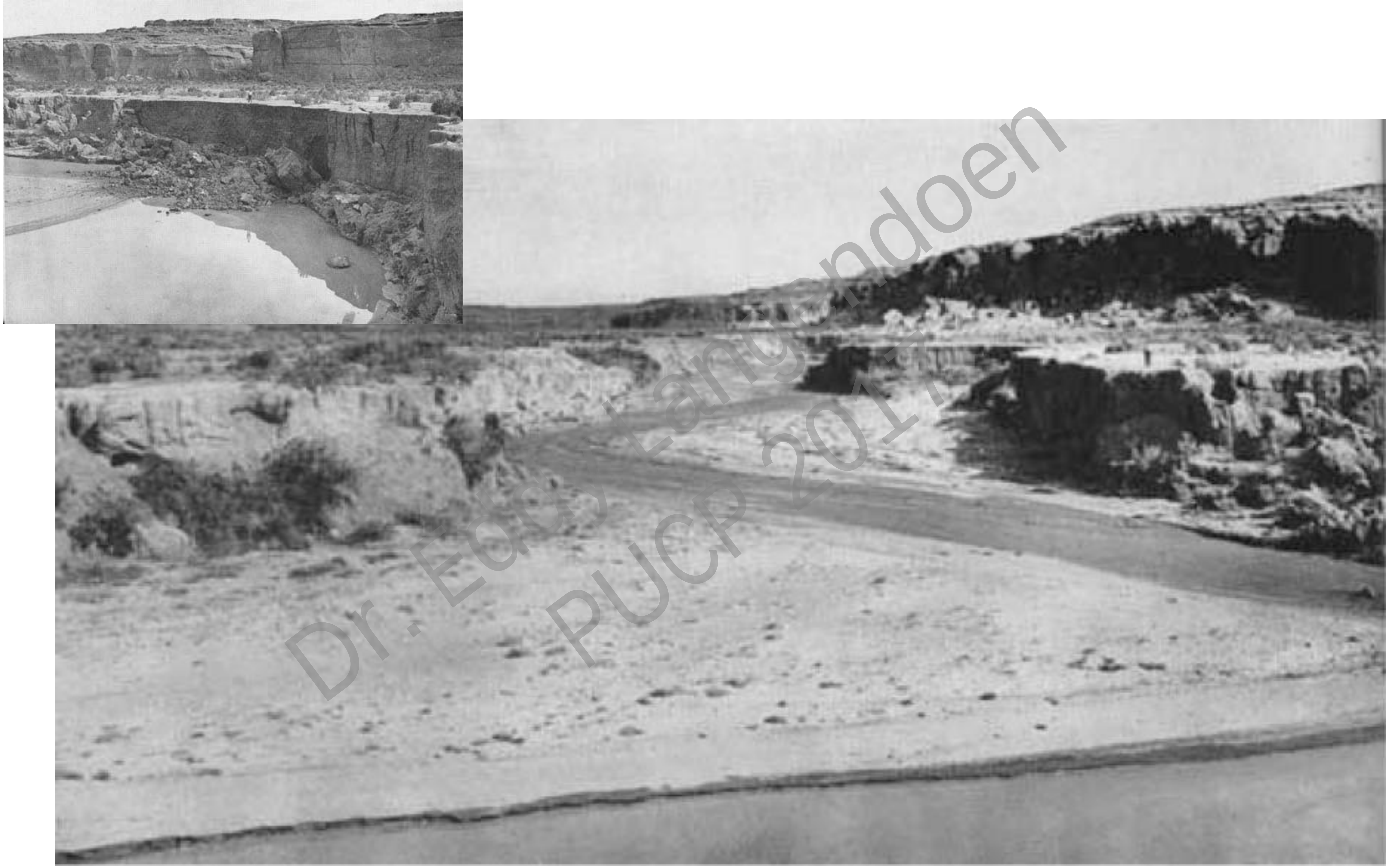


RÍO RÍMAC, PERÚ

JHIHBEN RIVER, TAIWAN – TYPHOON MORAKOT

WEST PAPILLION CREEK, NEBRASKA

CANE CREEK, TENNESSEE



CHACO CANYON, NEW MEXICO

GULLY EROSION IN ETHIOPIA

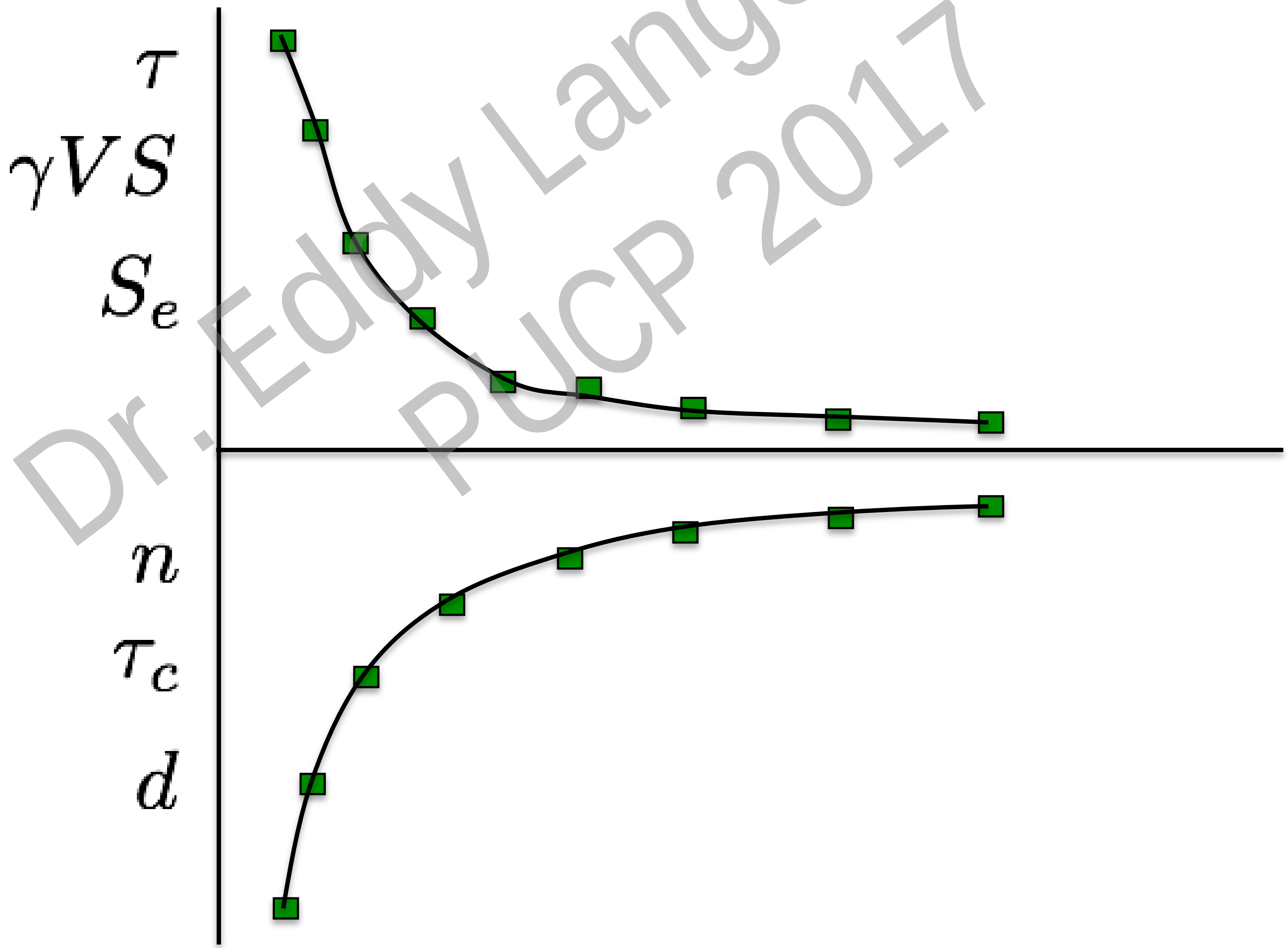
CHANNEL ADJUSTMENT OVERVIEW

Channel Adjustment

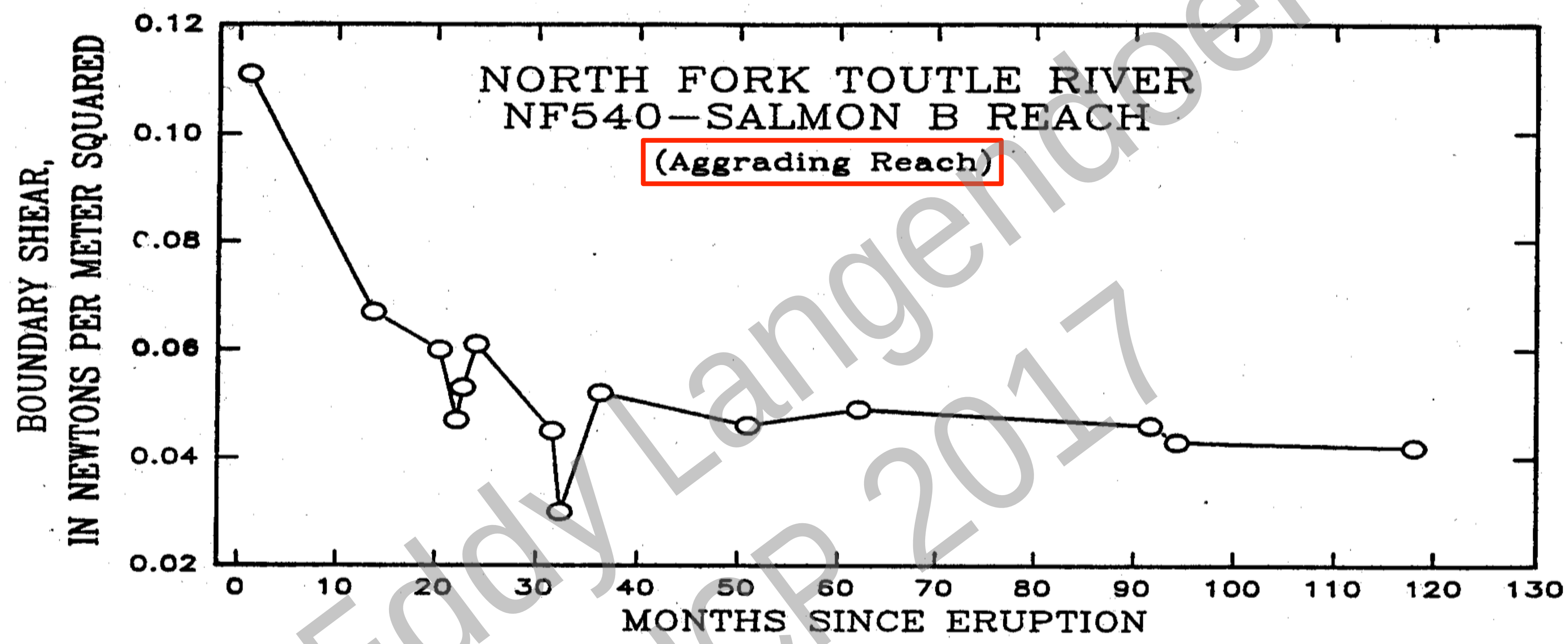
- Longitudinal
  - Long periods of time: Headwater erosion and downstream deposition
  - Short periods of time: Local scour/deposition, degradation, and aggradation
  - Interactions between discharge, sediment supply, and slope
- Lateral, streambank erosion
  - Hydraulic: Fluvial erosion or entrainment
  - Geotechnical: Mass wasting

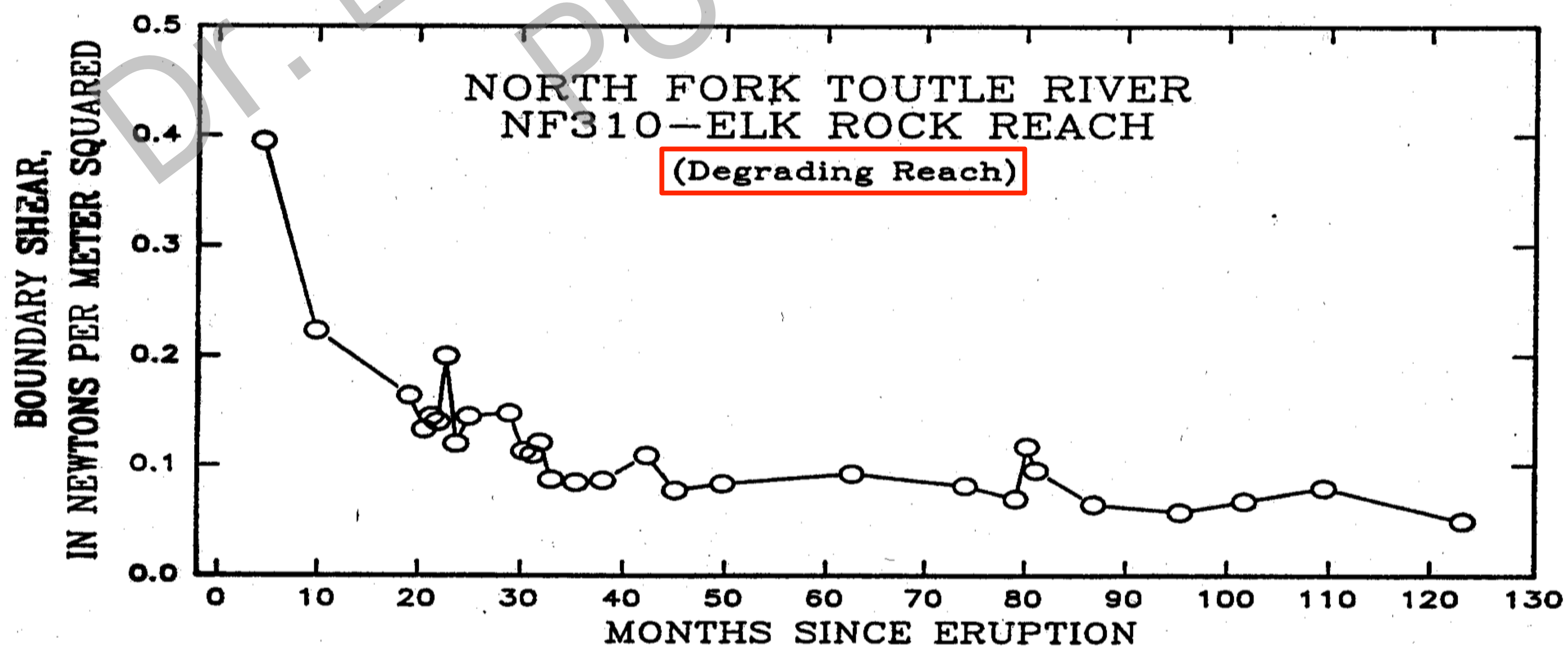
Idealized Adjustment Trends

- For a given discharge (Q)

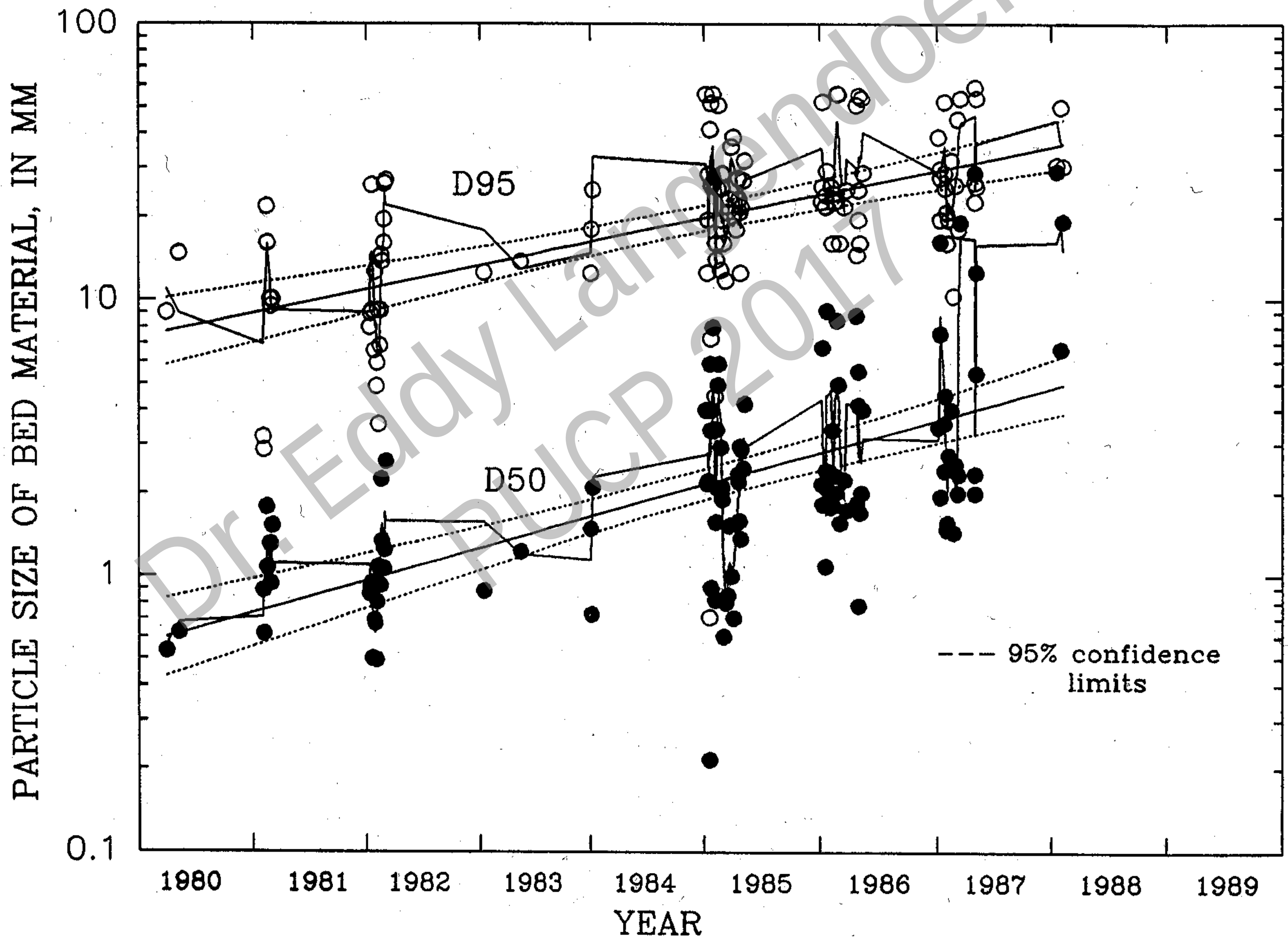


Adjustment: Boundary Shear Stress



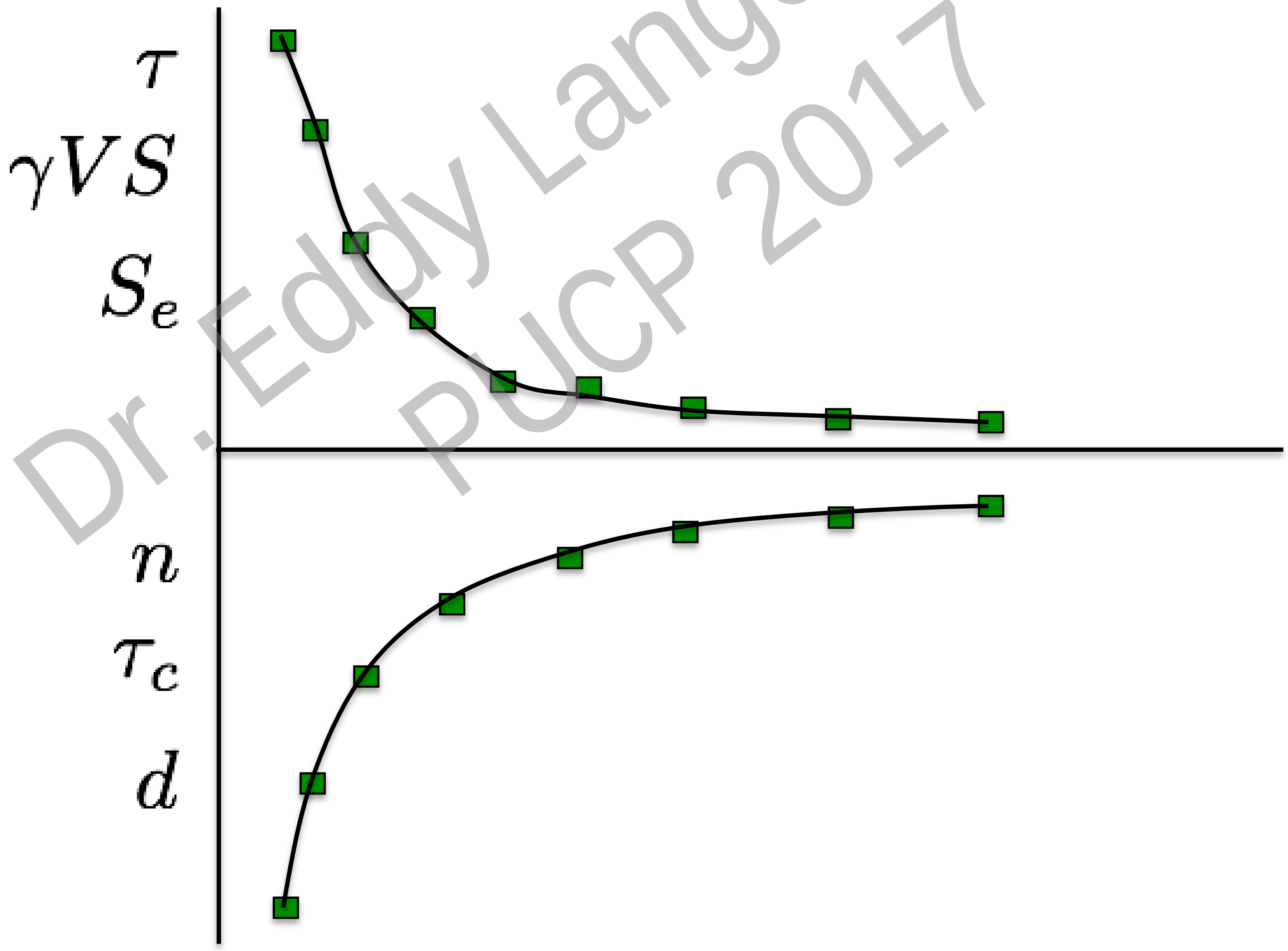


Adjustment: Increasing Resistance



Idealized Adjustment Trends

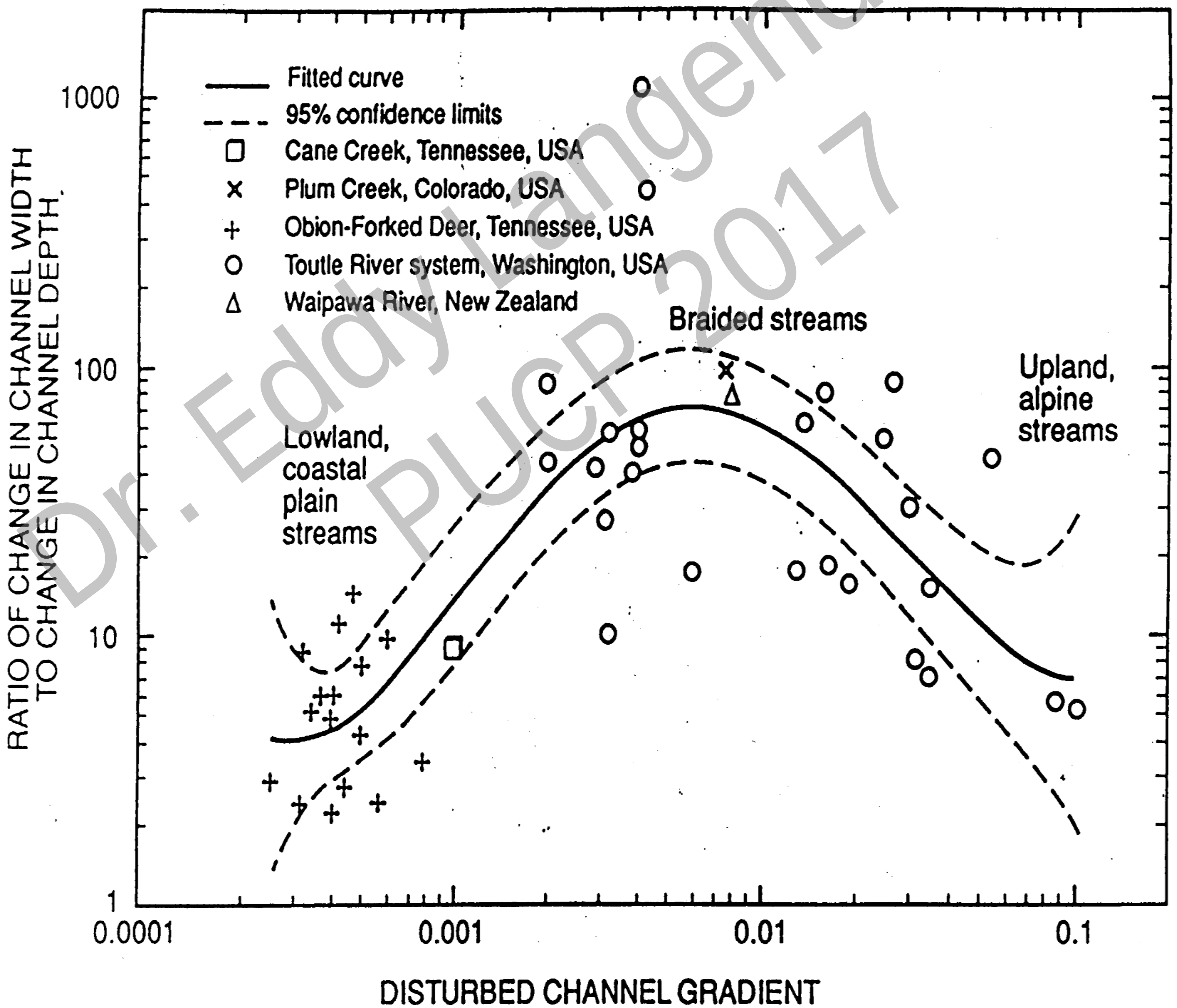
- For a given discharge (Q)



Importance of Widening in Energy Dissipation

- Reduces flow depth (pressure head) for a given flow;
- Increases relative roughness, and therefore,
- Reduces flow velocity (kinetic energy);
- Combined with degradation (potential energy) is the most efficient means of energy reduction because all components of E are reduced;
- Counteracts increase in potential energy from aggradation

Width/Depth Changes During Adjustment



How Much Sediment Comes from Bank Failures?

- Widening rates of up to 100 m/yr
- Up to 90% of the sediment emanating from eroding channels
- Often, more than 50% of the sediment emanating from a watershed
- One 1-m failure along a 5-m high bank along a 100-m reach equals 400 metric tons or about 26 dump trucks

Little Blue River, Kansas

STREAMBANK EROSION PROCESSES

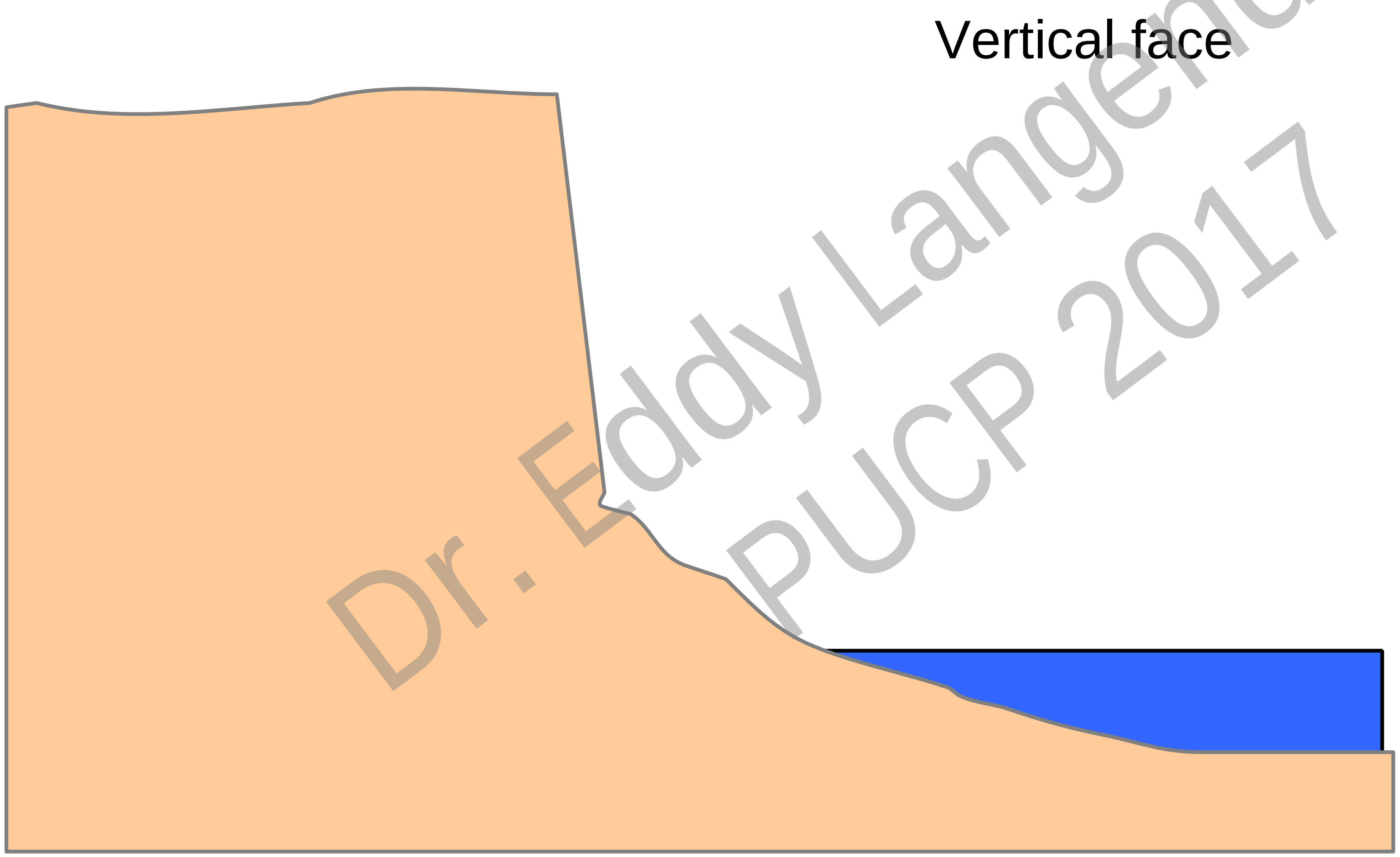
Streambank Erosion – I

- Hydraulic processes
  - Erosive force applied by the flow exceeds the resisting force mobilized by the bank materials
  - Resisting forces are different for cohesionless and cohesive materials:
    - Cohesionless: grain size
    - Cohesive: electrochemical bonding between soil particles

Streambank Erosion – II

- Geotechnical processes
  - Mass instability
  - Gravitational force exceed resisting force
    - Weight of soils vs. cohesion and friction
- Interplay between fluvial erosion and mass wasting
  - Fluvial erosion may promote mass wasting
  - Mass wasting may prevent fluvial erosion

Bank Retreat Processes



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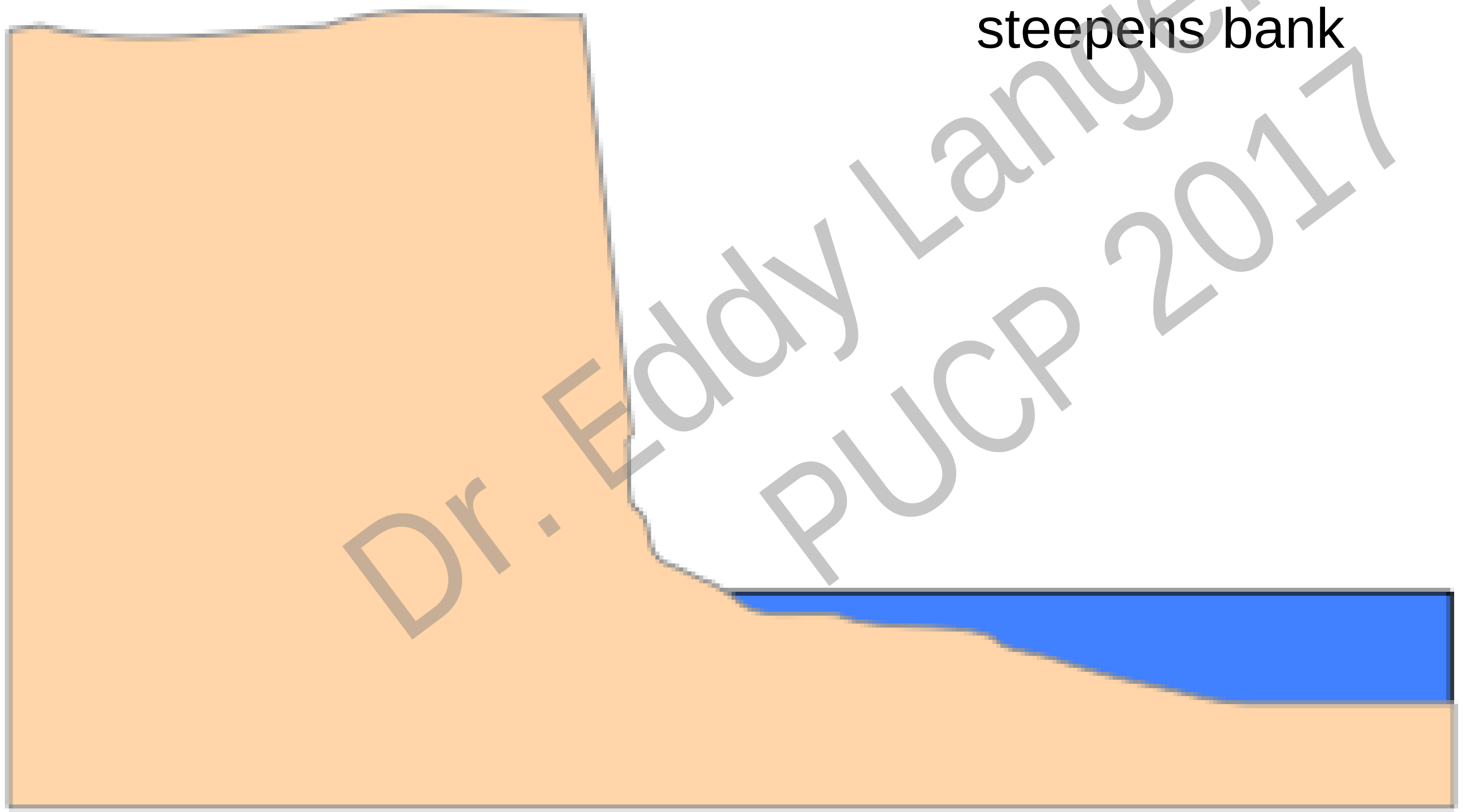
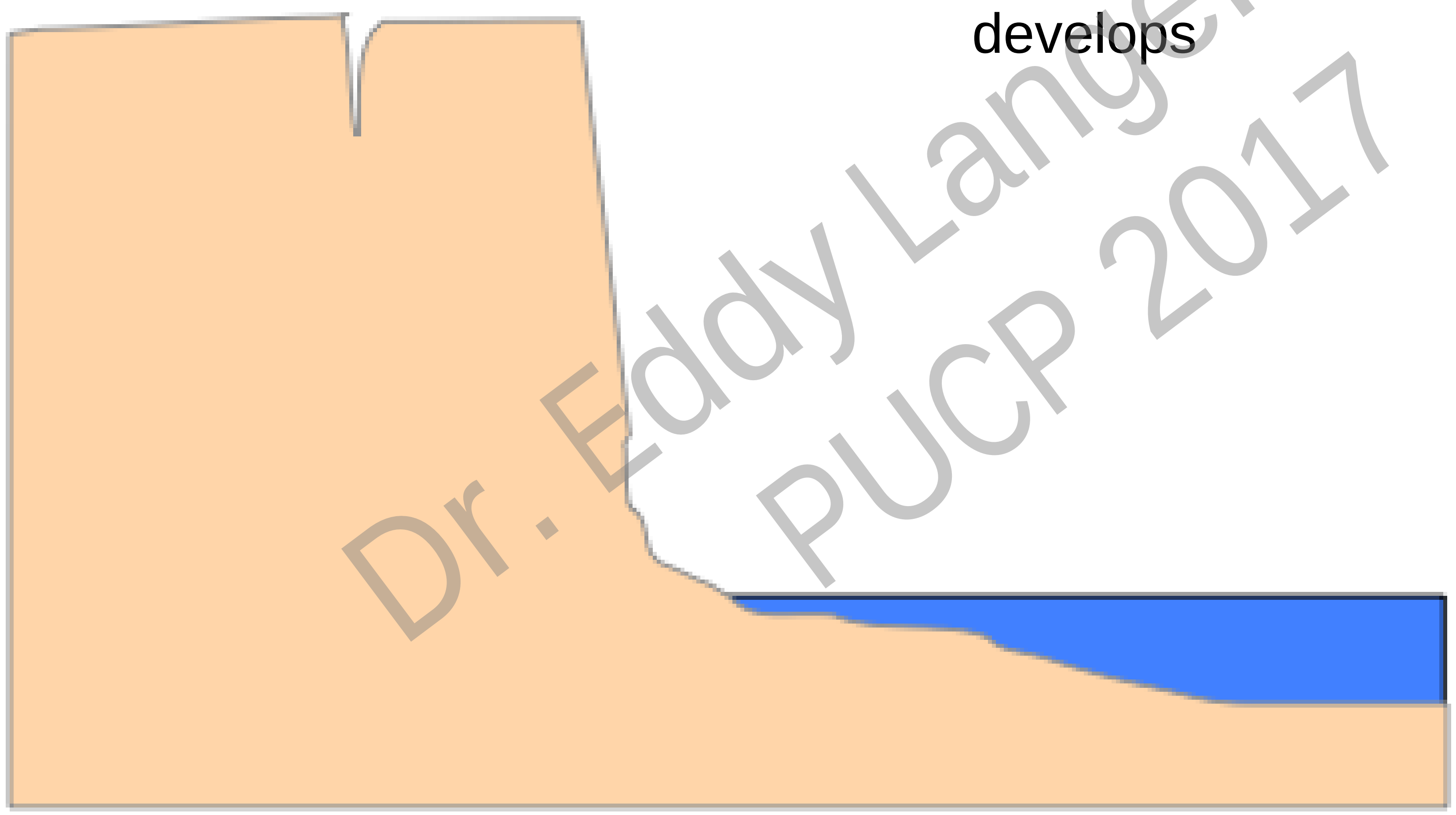
Bank Retreat Processes



Toe erosion
steepens bank

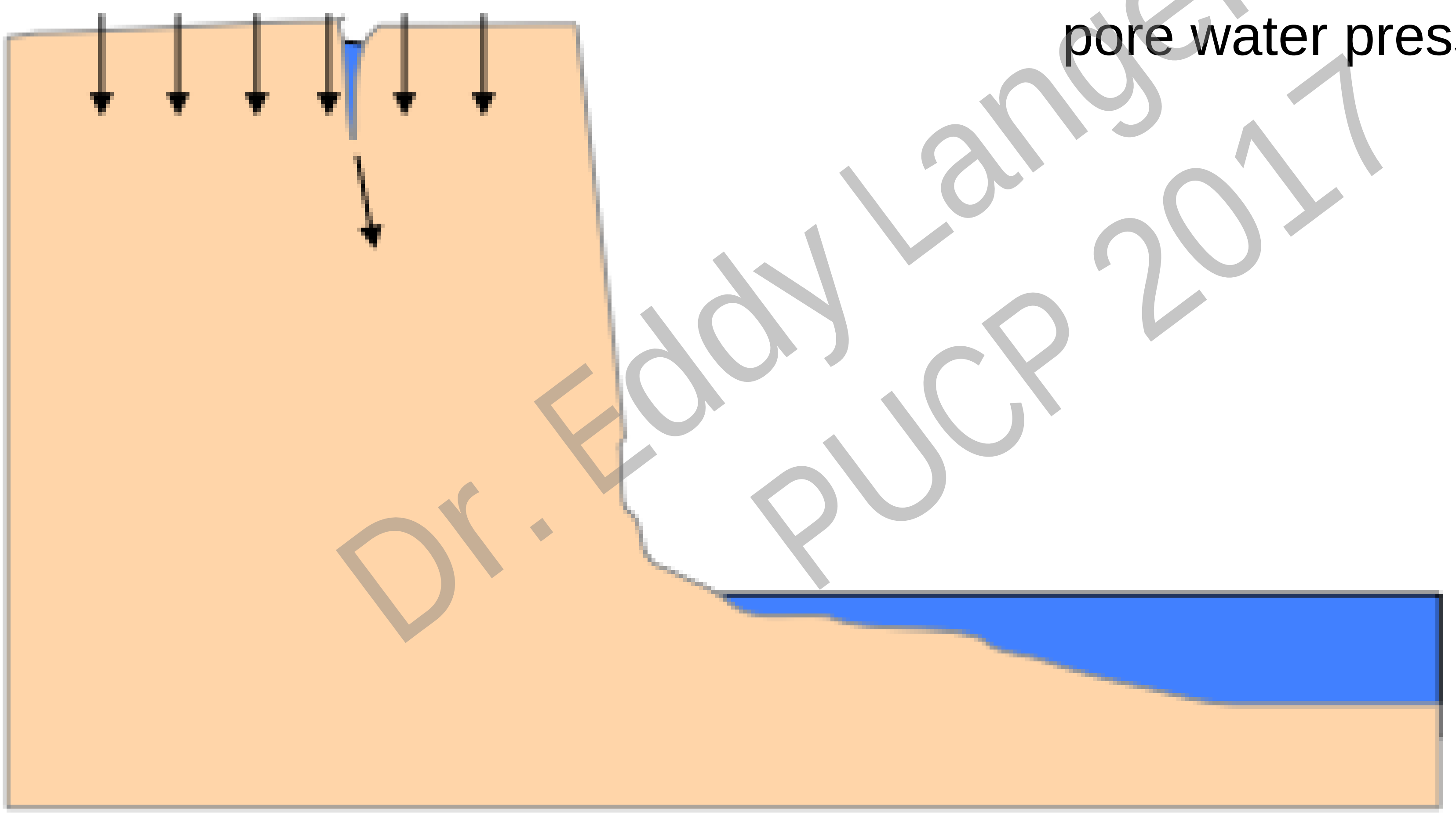
Bank Retreat Processes

Tension crack
develops



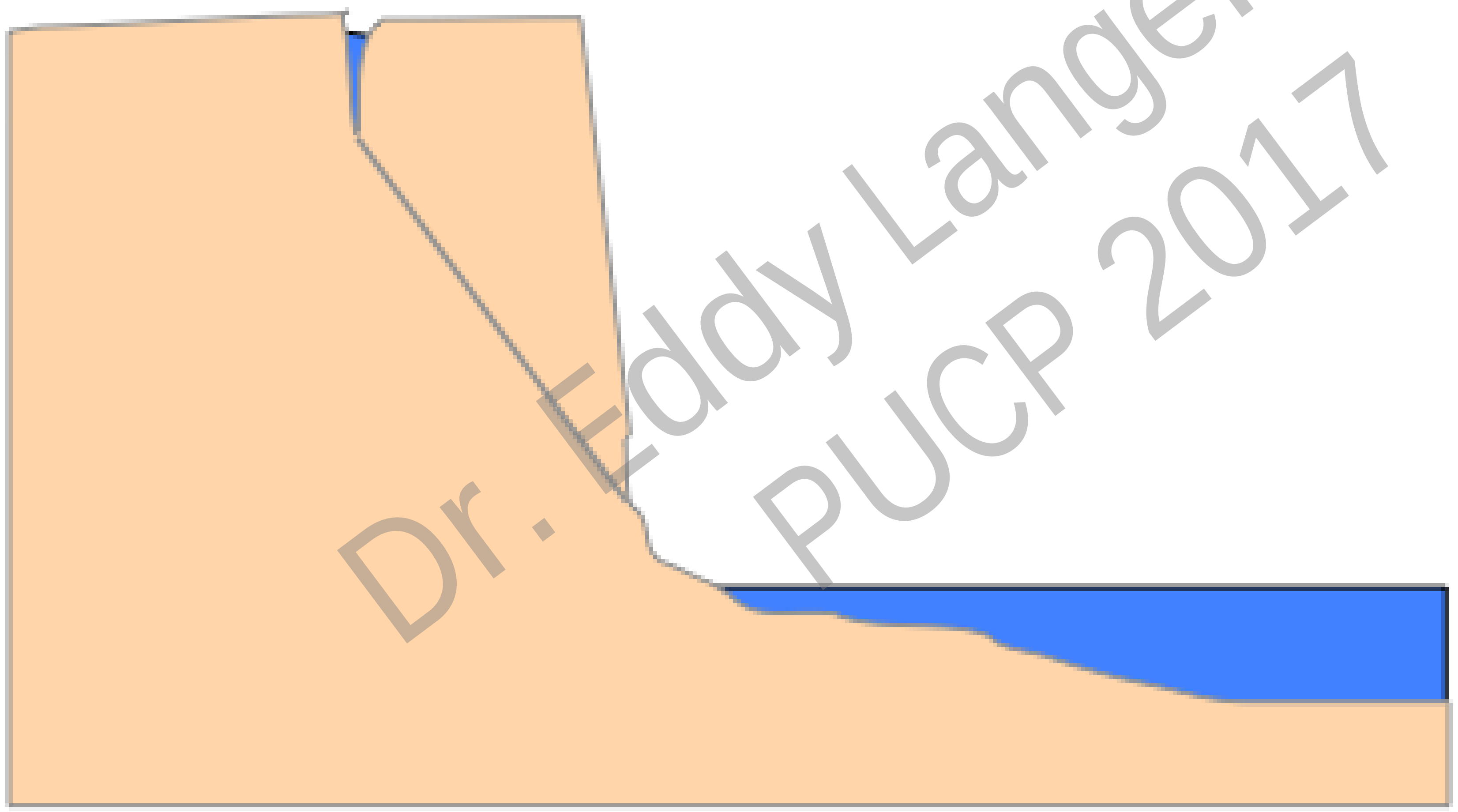
Bank Retreat Processes

Infiltration raises
pore water pressure



Bank Retreat Processes

Shearing starts



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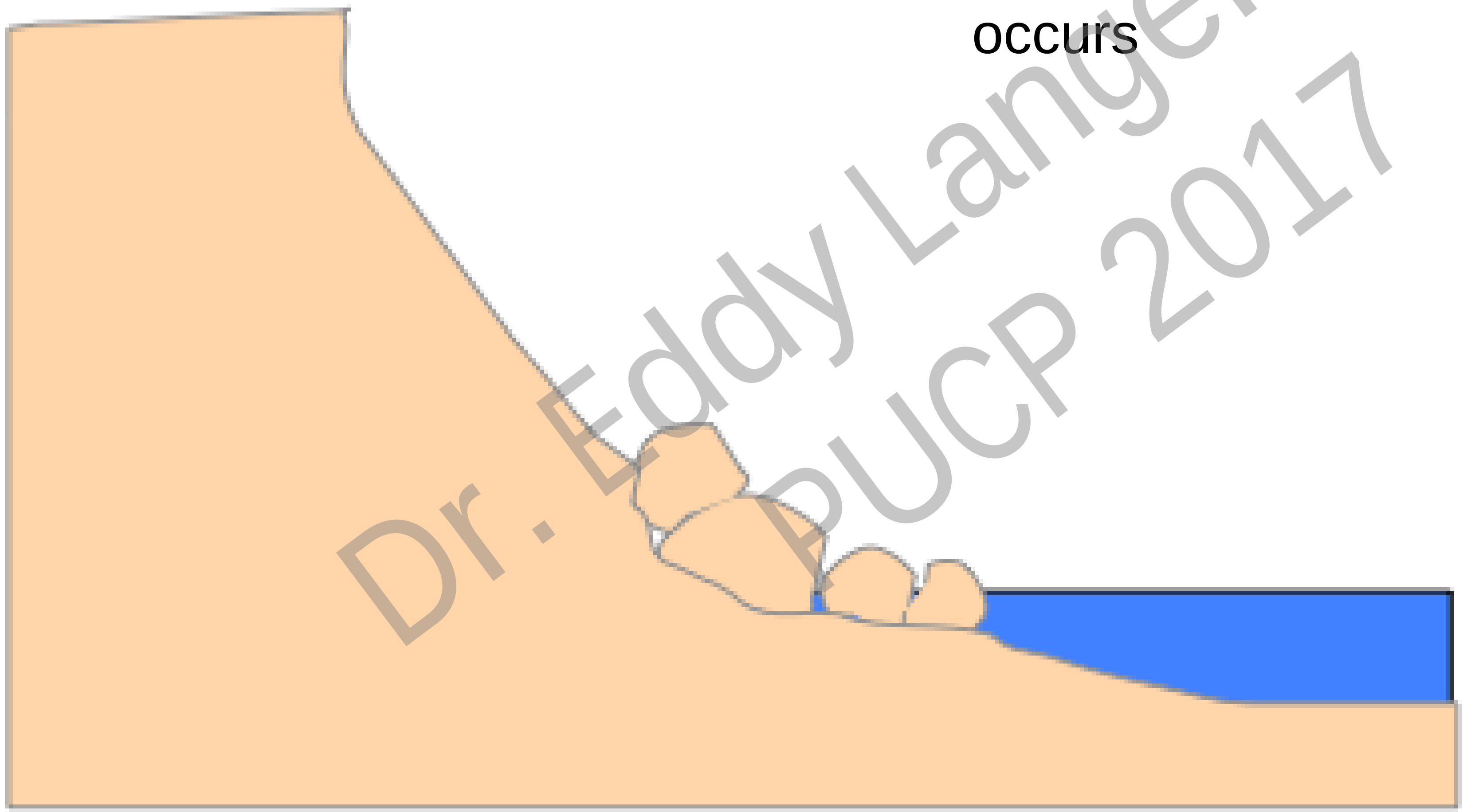
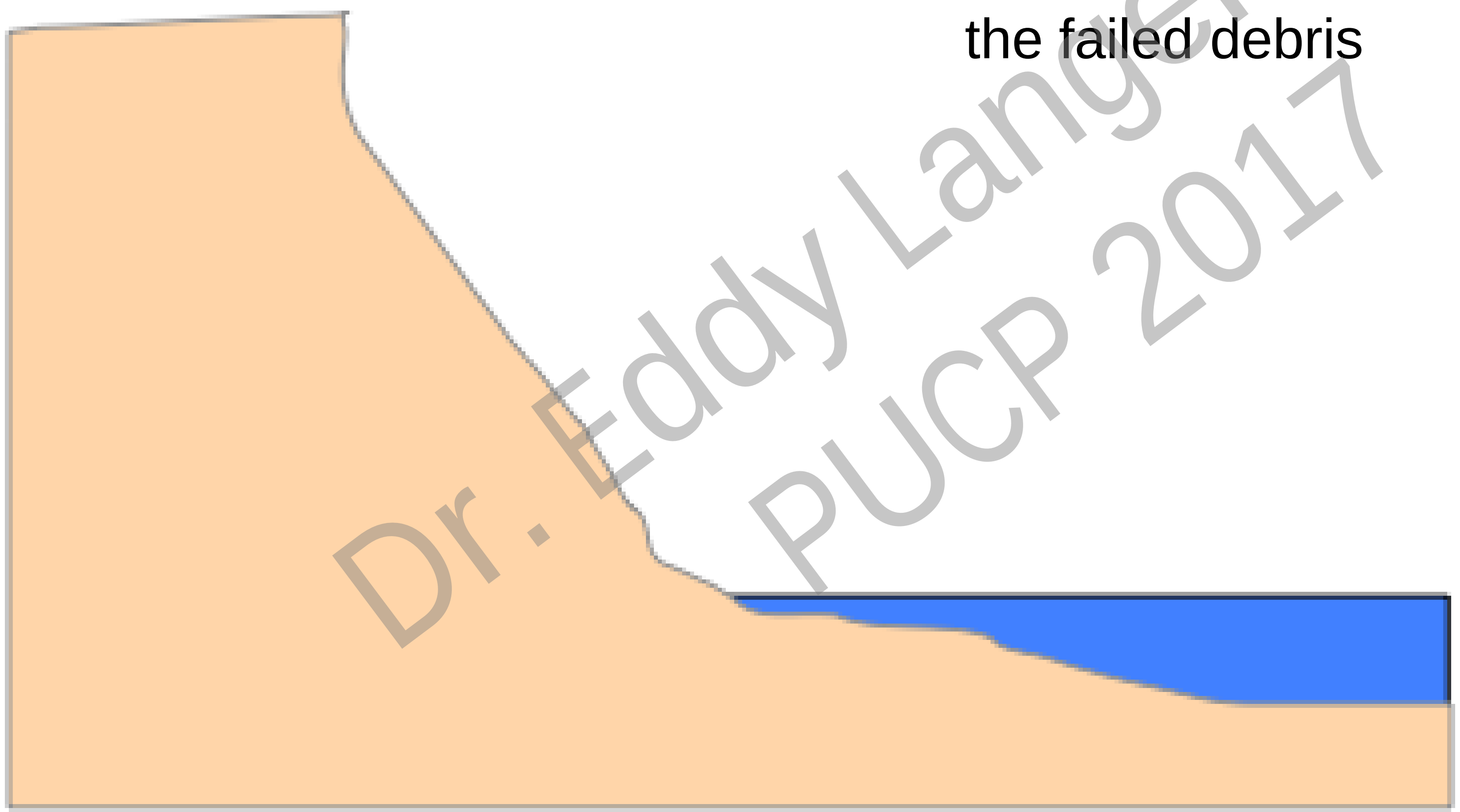
Bank Retreat Processes

Bank failure occurs



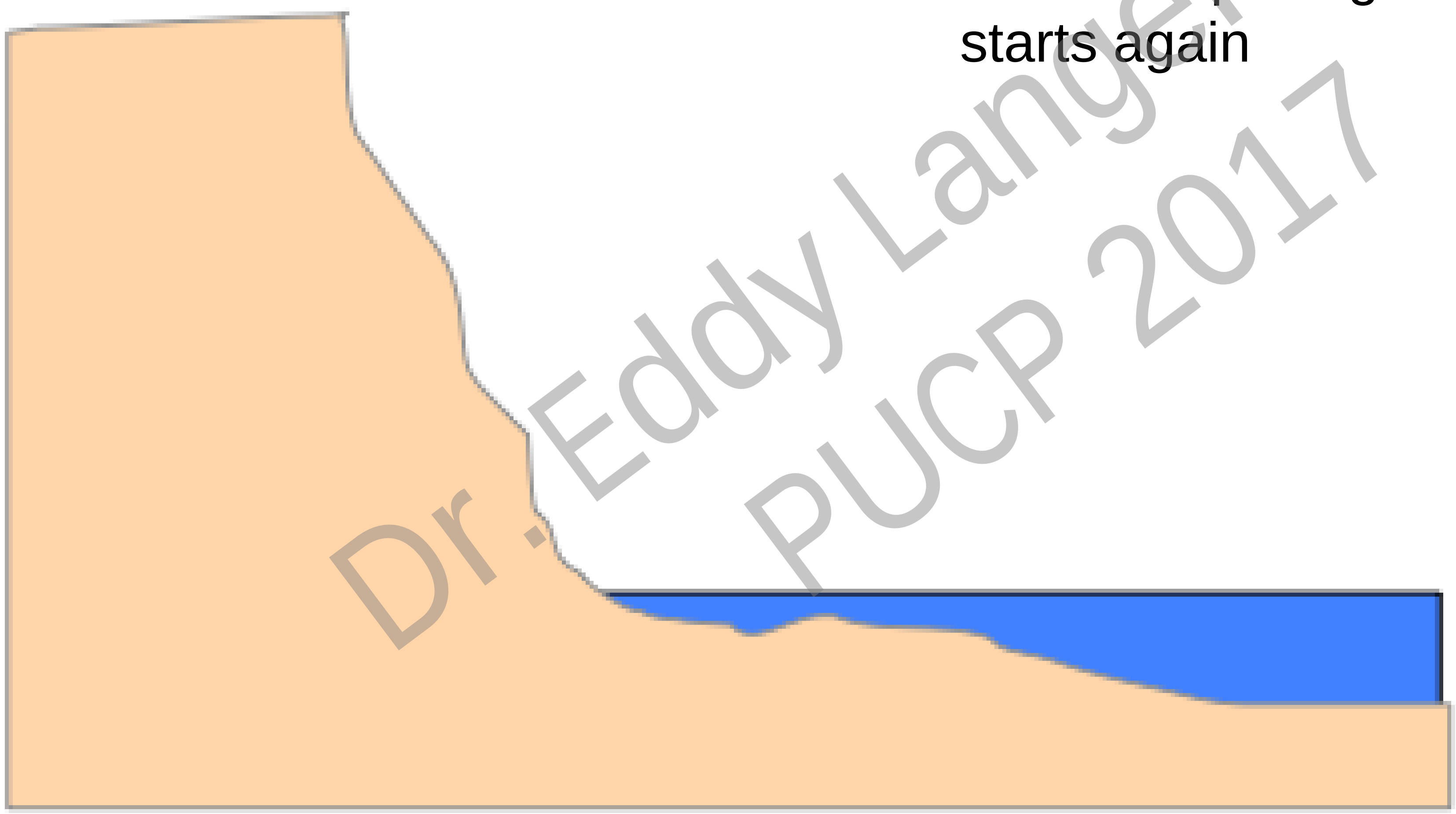
Bank Retreat Processes

Erosion removes
the failed debris

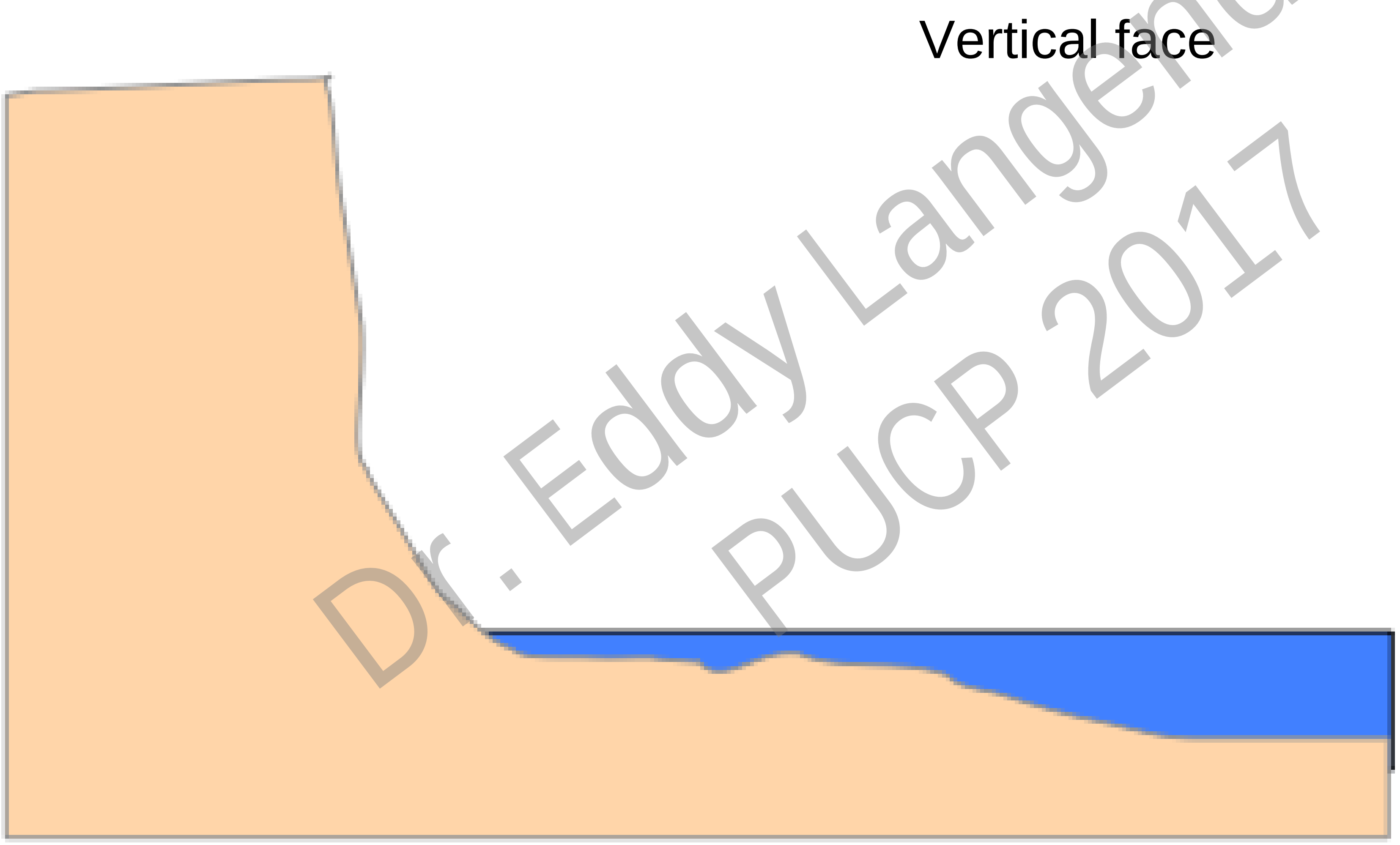


Bank Retreat Processes

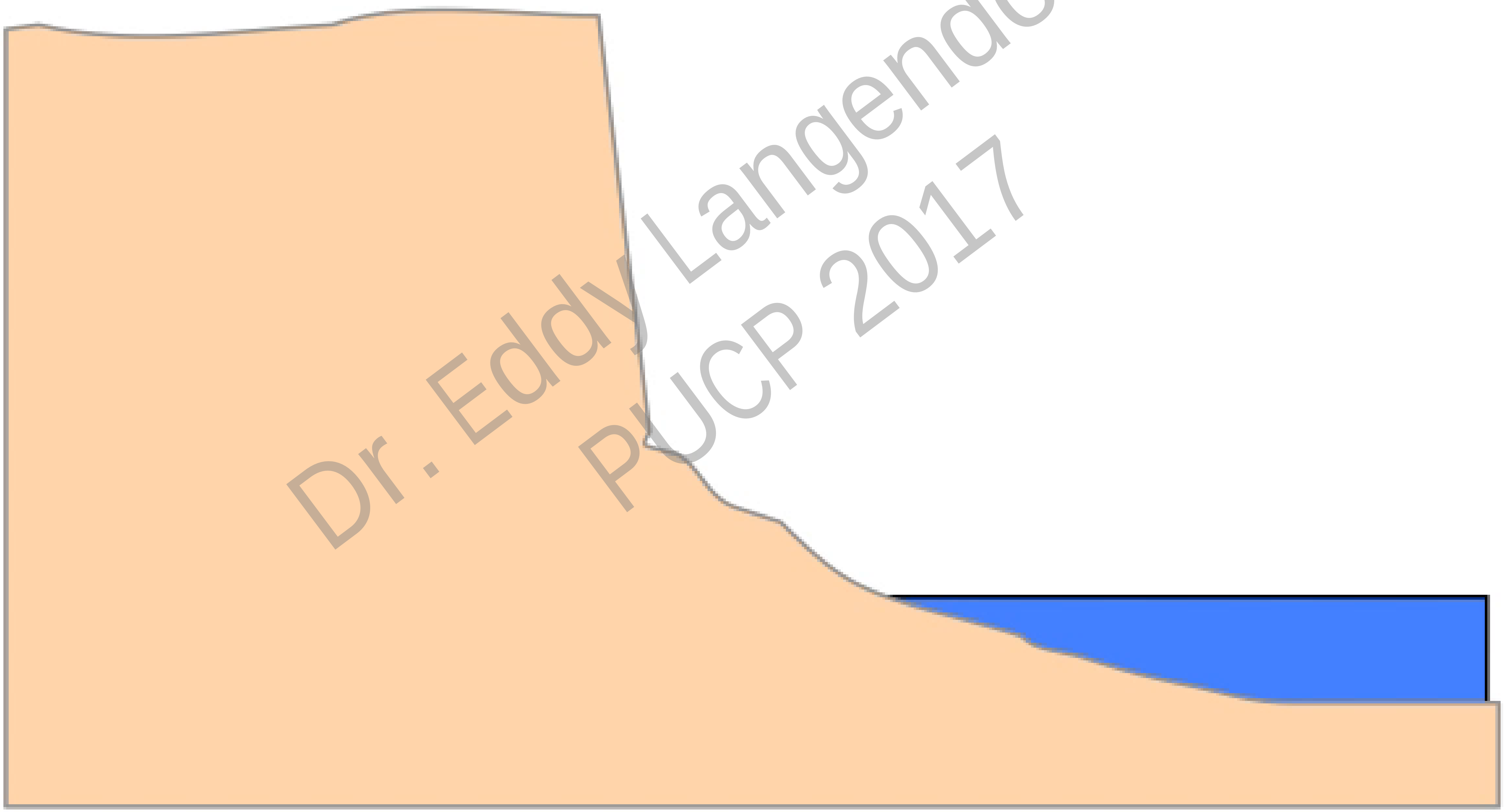
Bank steepening
starts again



Bank Retreat Processes



Vertical face



Fluvial erosion

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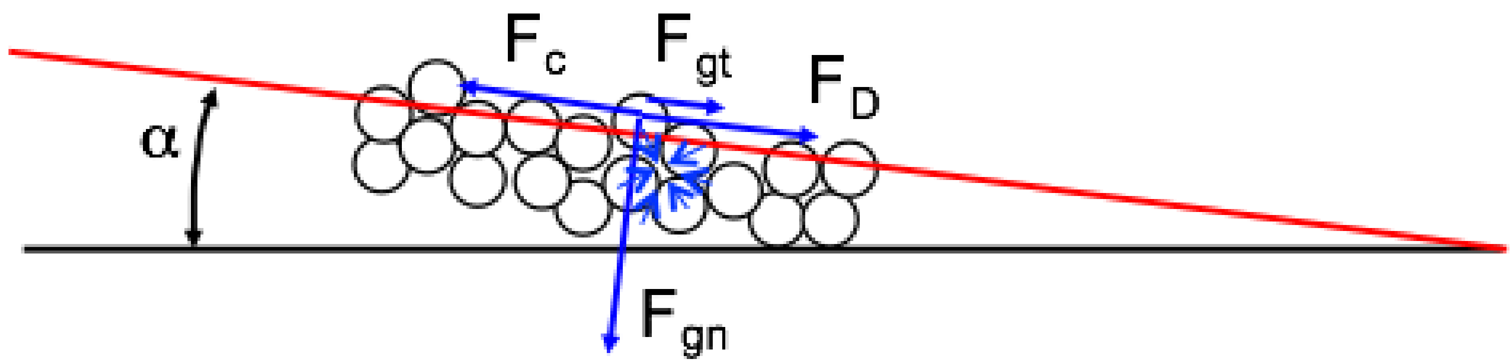
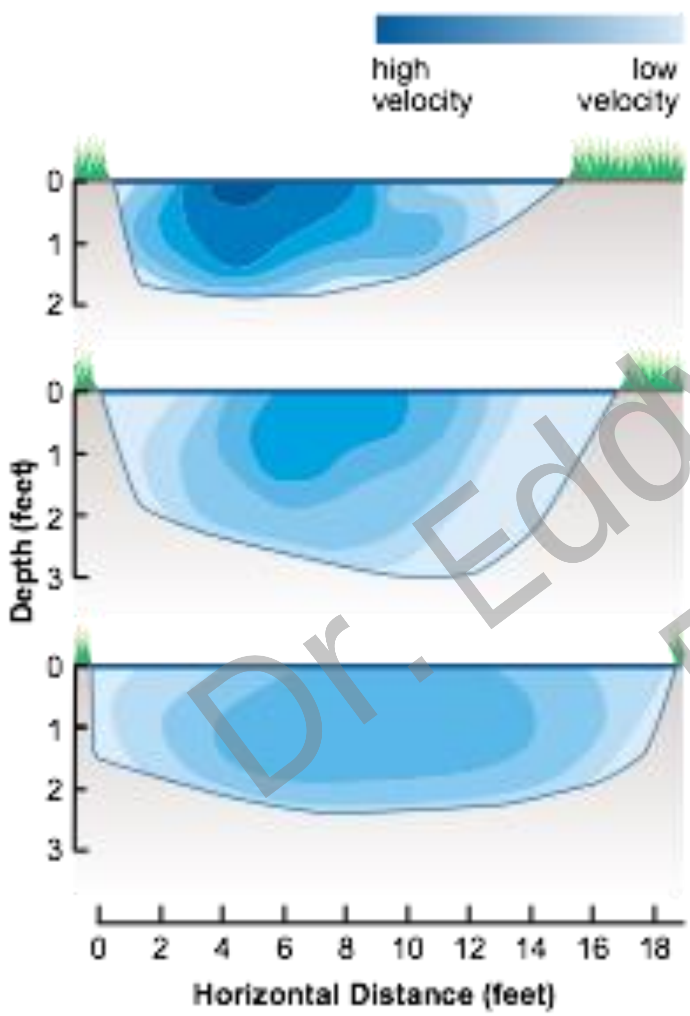
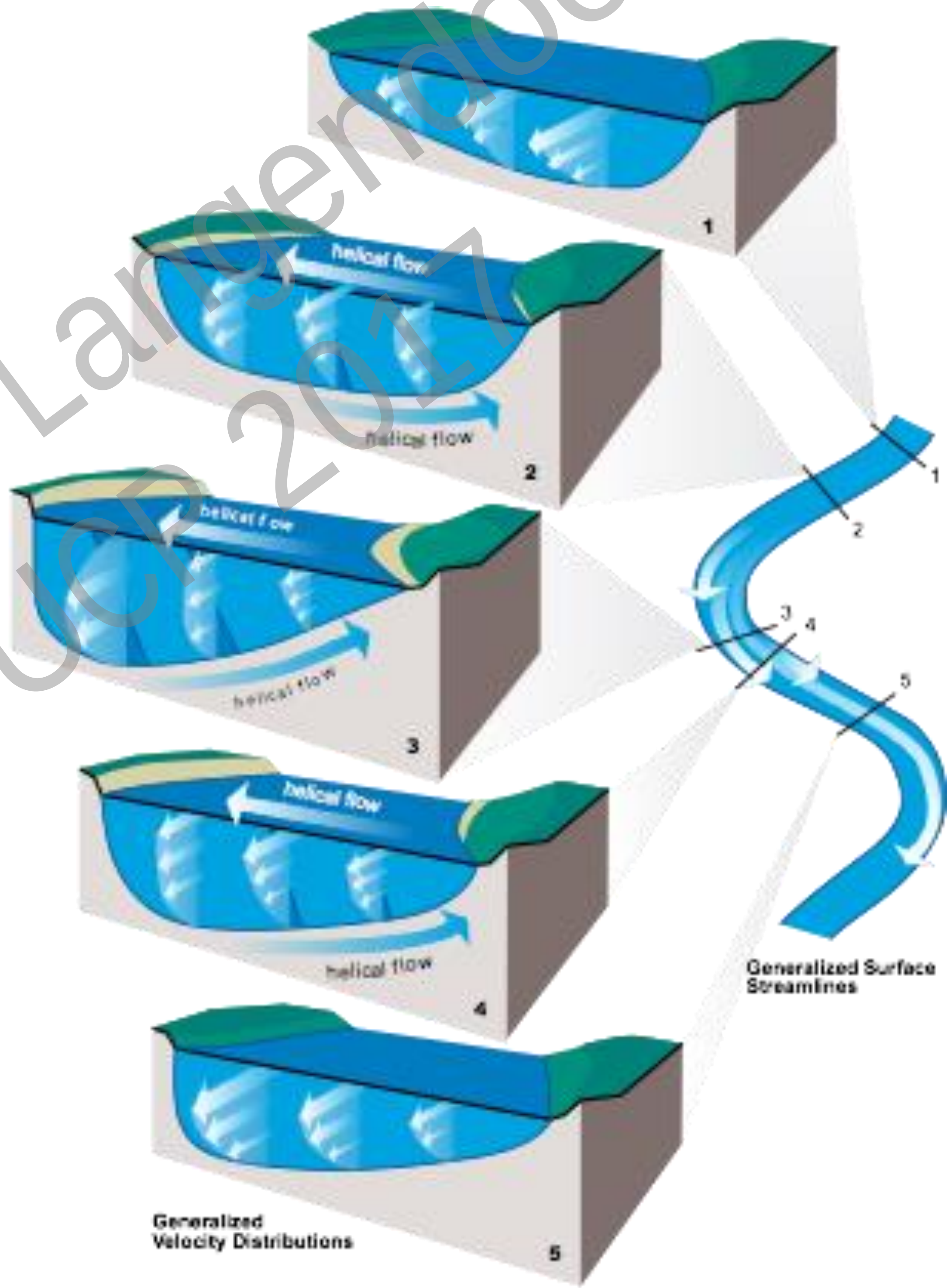
Fluvial Erosion

- Applied force vs. resisting force
- Applied drag force: boundary shear stress
  - Near-bank flow field
    - Discharge, flow depth, slope, channel form, secondary flow, turbulence, etc.
  - Bank roughness
    - Topographic variability, grain size, vegetation
- Resisting: Erosion resistance
  - Grain size
  - Cohesivity
  - Water content
  - Below-ground organics



Near-Bank Flow Field





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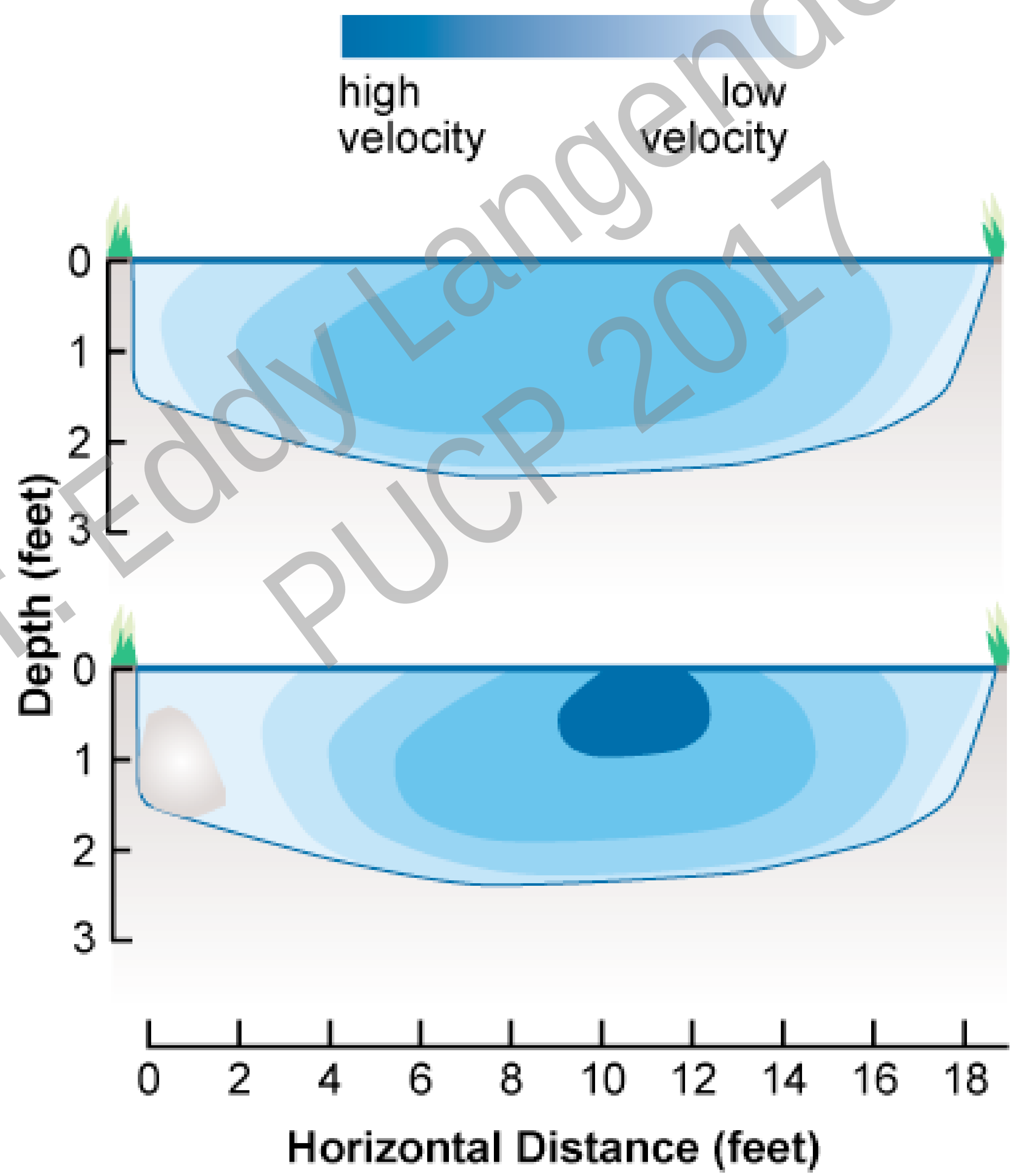
Near-Bank Flow Field /w Roughness & Cover



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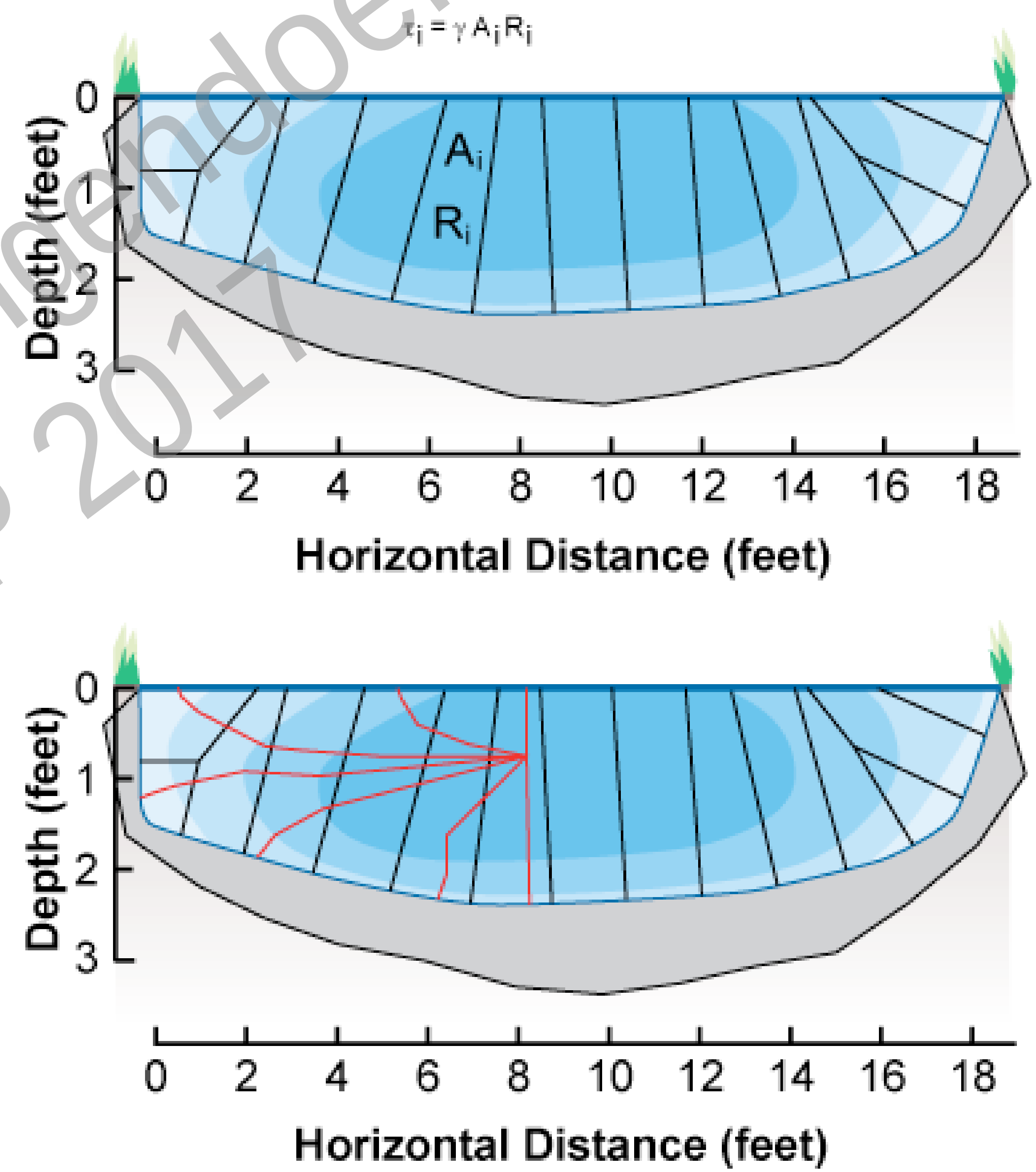
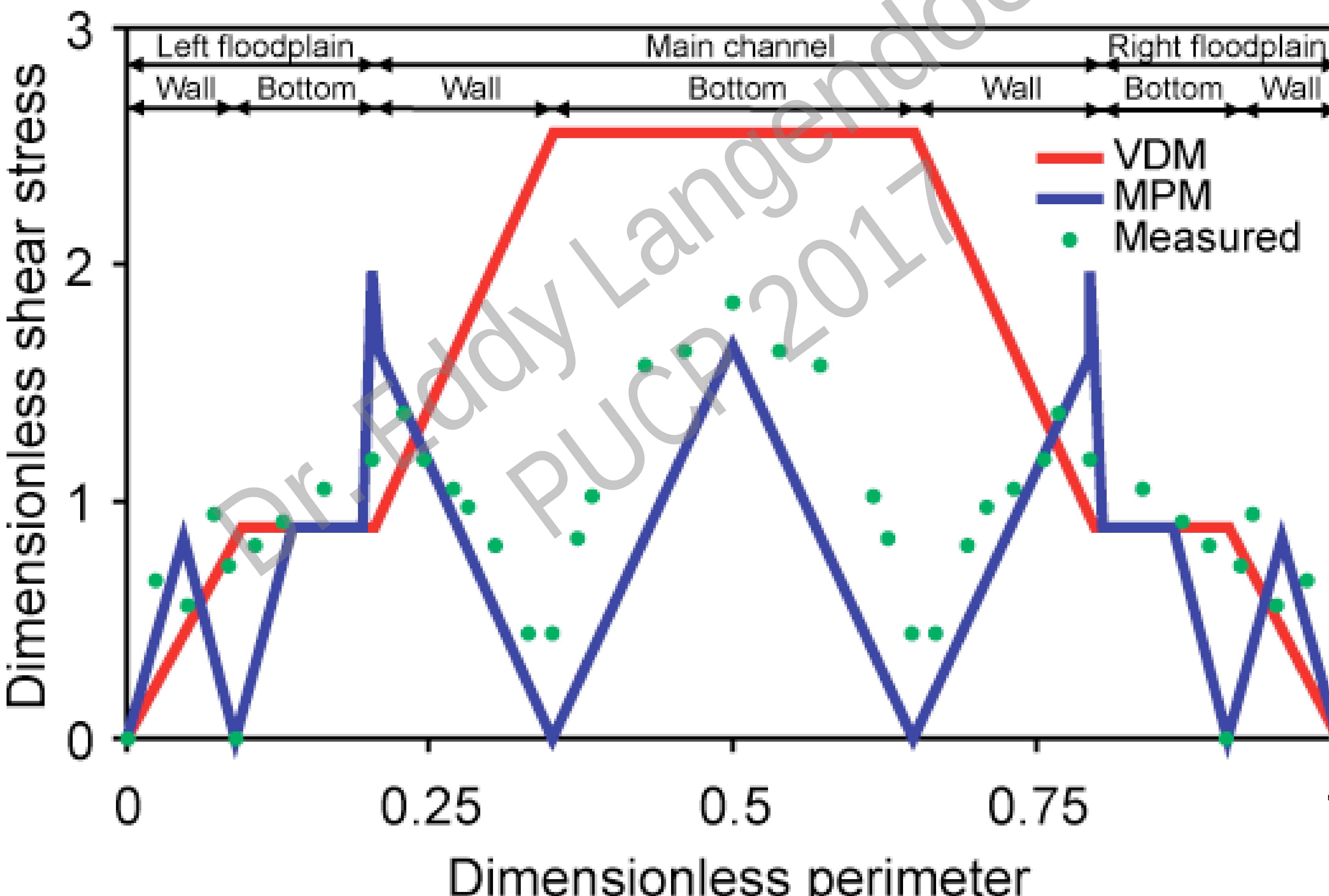
Bank Shear Stress Estimation – I

- Divided Channel Methods
  - Vertical depth/area
  - Normal depth/area
  - Merged perpendicular method
- Can have significant error for more complex flow fields



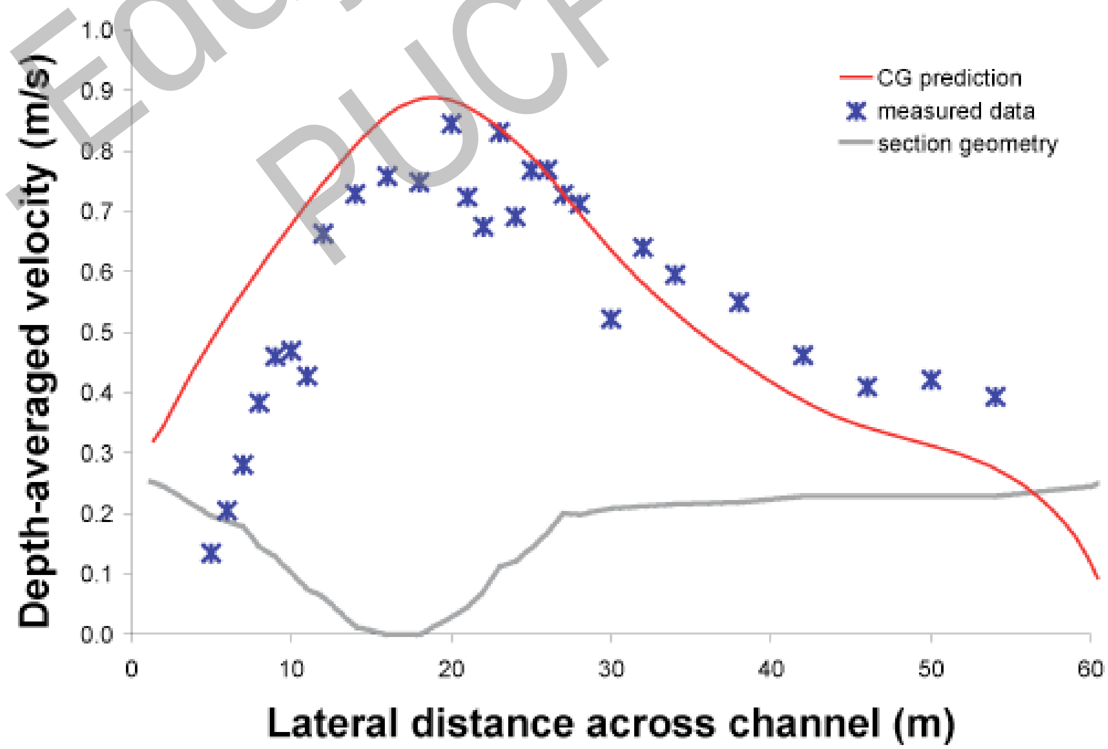
Bank Shear Stress Estimation – Ia



Bank Shear Stress Estimation – III

- Simplified momentum equation – Shiono & Knight method extended by Ervine

$$\underbrace{gHS}_{\text{pressure}} - \underbrace{\frac{f\beta q^2}{8H^2}}_{\text{boundary friction}} + \underbrace{\frac{\partial}{\partial y}\left[\lambda H\sqrt{f/8}\,q\frac{\partial}{\partial y}\left(\frac{q}{H}\right)\right]}_{\text{lateral shear}} = \underbrace{C_{uv}\frac{\partial}{\partial y}\left(\frac{q^2}{H}\right)}_{\text{secondary currents}}$$



River Severn upstream of Shrewsbury

Bank Shear Stress Estimation – IV

- 2D models
- 3D models

Cohesionless Bank Material Resistance & Transport

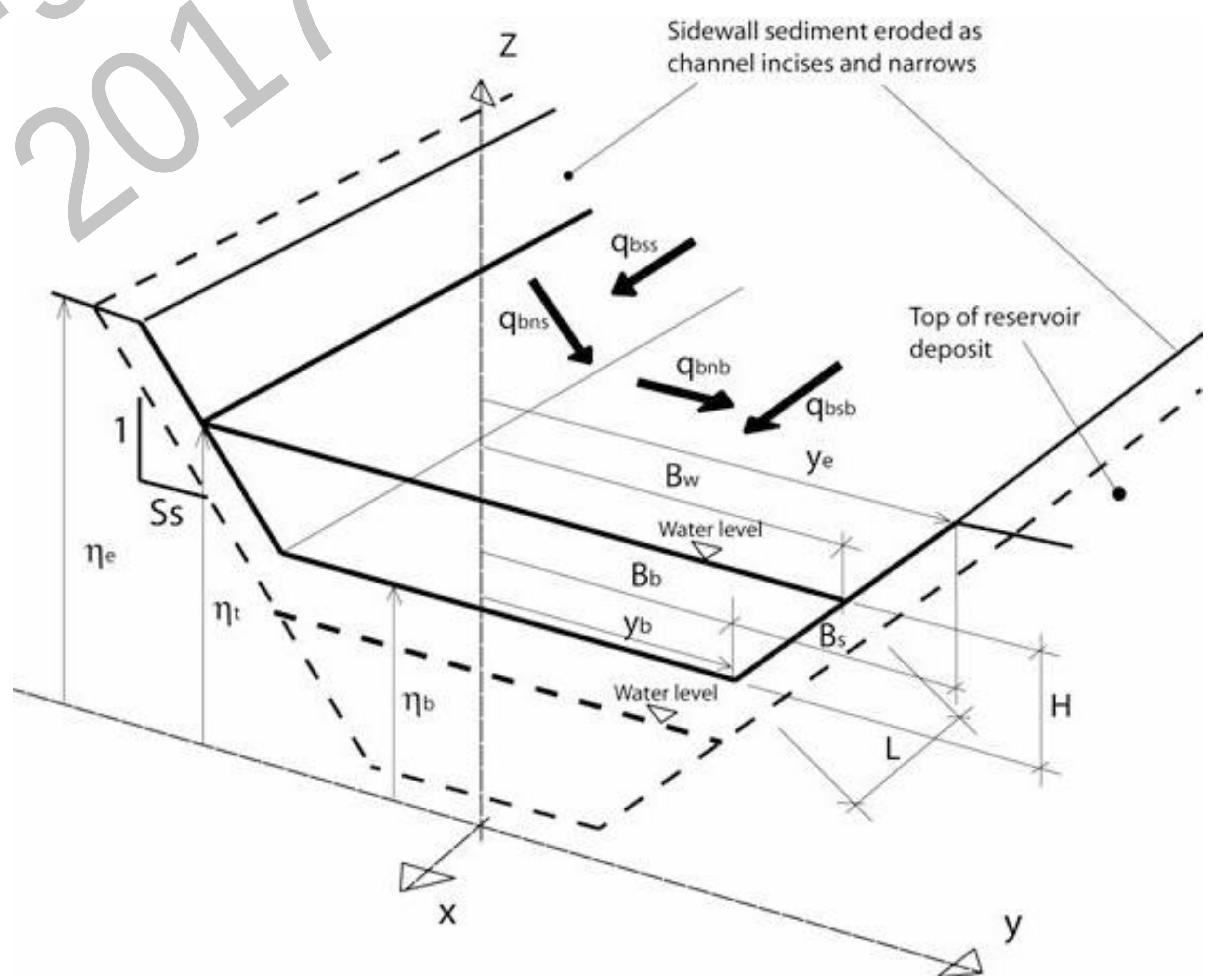
- Grain-size dependent
- Sediment transport dependent
- Cantelli and Parker (2004)

$$\tau_s = \phi \tau_b \quad (\phi = 0.4 - 0.8)$$

$$q_{bss} = F(\tau_s)$$

$$\frac{q_{bns}}{q_{bss}} = \frac{\tau_{ss}}{\tau_{ns}} - 2.65\sqrt{\frac{\theta_c}{\theta_s}} S_s$$

$$(1-\lambda)\frac{\partial \eta}{\partial t} = -\frac{\partial q_{bs}}{\partial s} - \frac{\partial q_{bn}}{\partial n}$$



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Cohesive Bank Material Resistance to Erosion

- Transport, deposition, and erosion of cohesive sediments are extremely complex
- Erosion resisting forces vary according to grain size and electrochemical bonding between particles
- Bonding is also affected by local history of soil development and antecedent soil moisture conditions
- Commonly it are aggregates that are eroded, disintegrating rapidly once entrained

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Cohesive Bank Material Resistance to Erosion (cont.)

- Weathering, cycles of wetting and drying can significantly increase erodibility
- Vegetation can increase erosion resistance by
  - Binding the soil through their roots introducing an added cohesion
  - Reducing pore-water pressures in the streambank

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Cohesive Streambank Erosion

- Erosion rate is given by an excess shear stress relation

$$E = K\left(\tau - \tau_c\right)$$

- Osman & Thorne (1988)

$$K = \frac{0.037}{\rho_s}\exp(-1.3\tau_c)$$

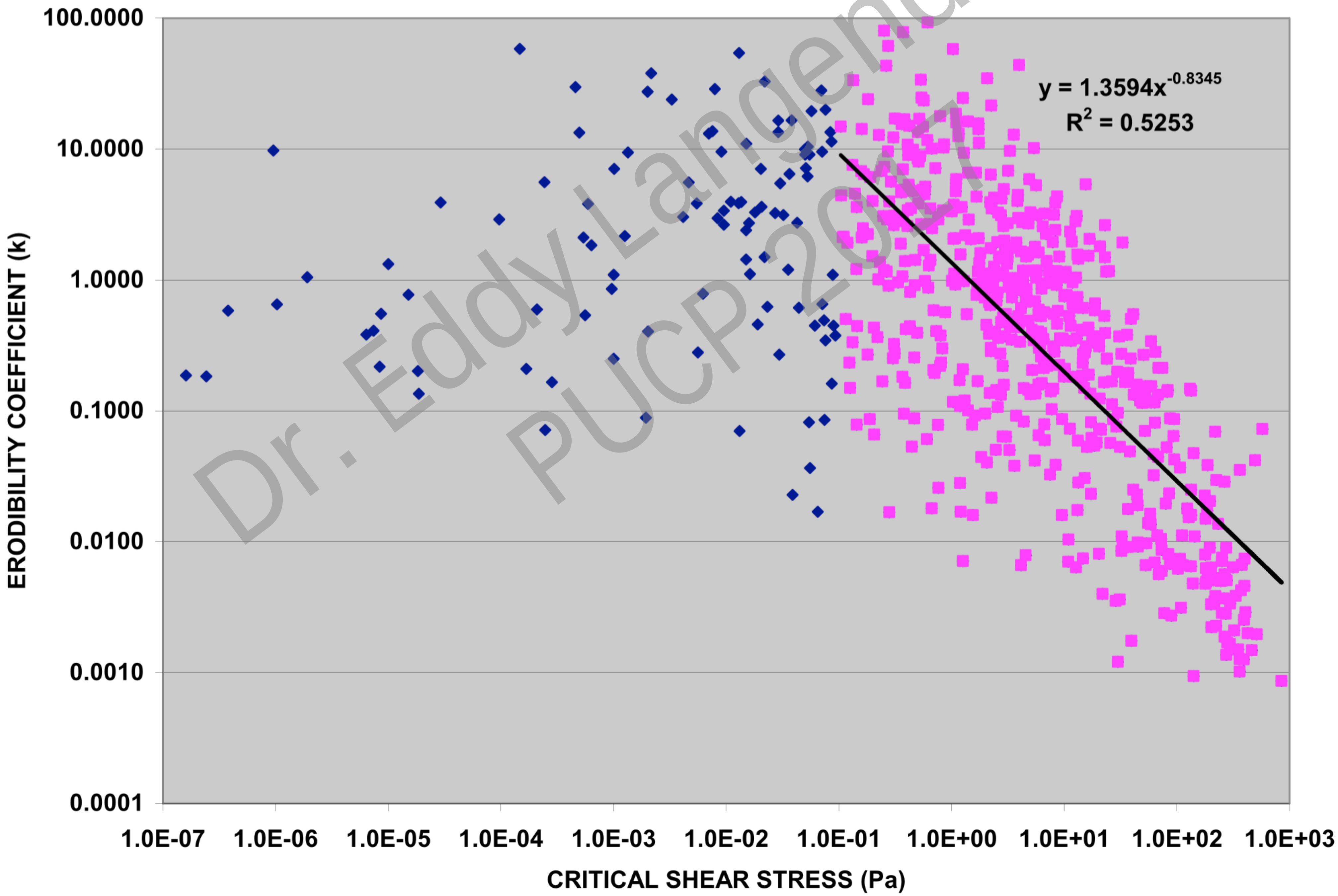
- Hanson & Simon (2001)

$$K = 0.1 \times 10^{-6}\tau_c^{-0.5}$$

- Lateral erosion distance

$$\Delta W = E\Delta t$$

Revised Erodibility Relation – Thomas and Simon (2010)



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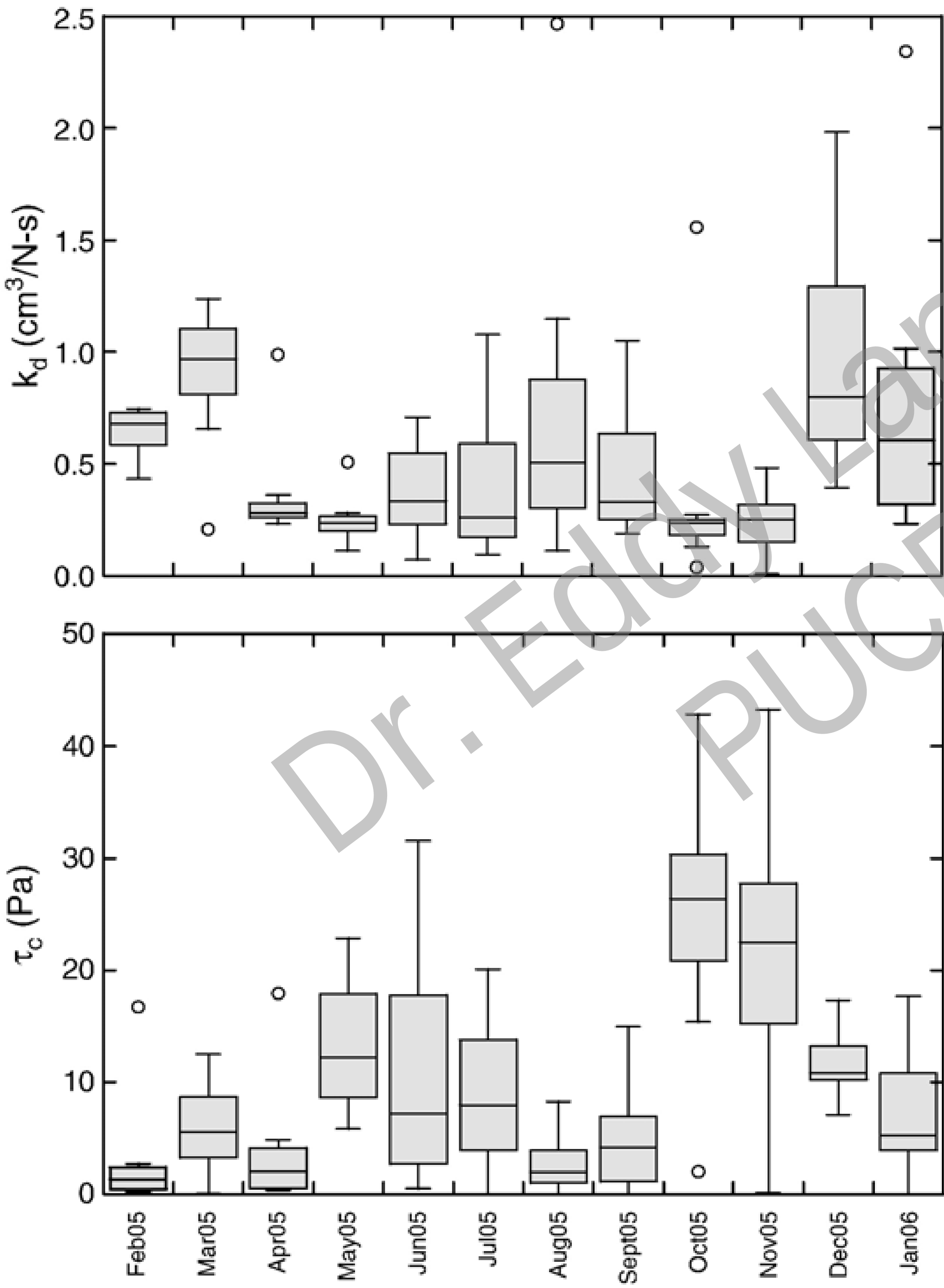
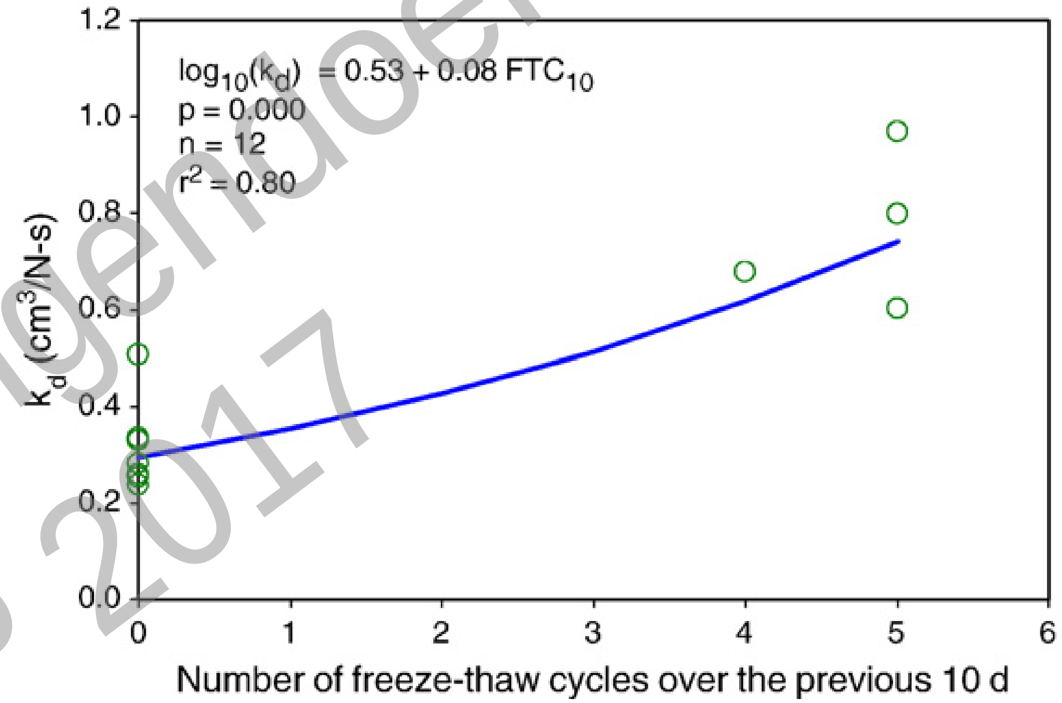
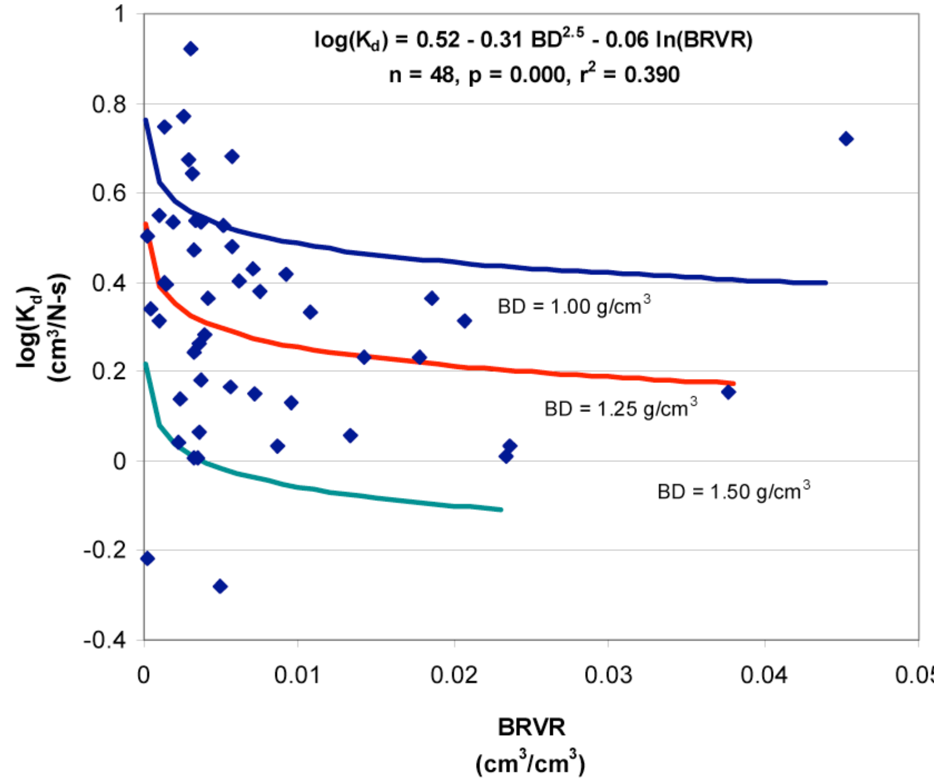
Variability in τ_c and K







Wynn et al. (2007)

Mass wasting

Mass Failure

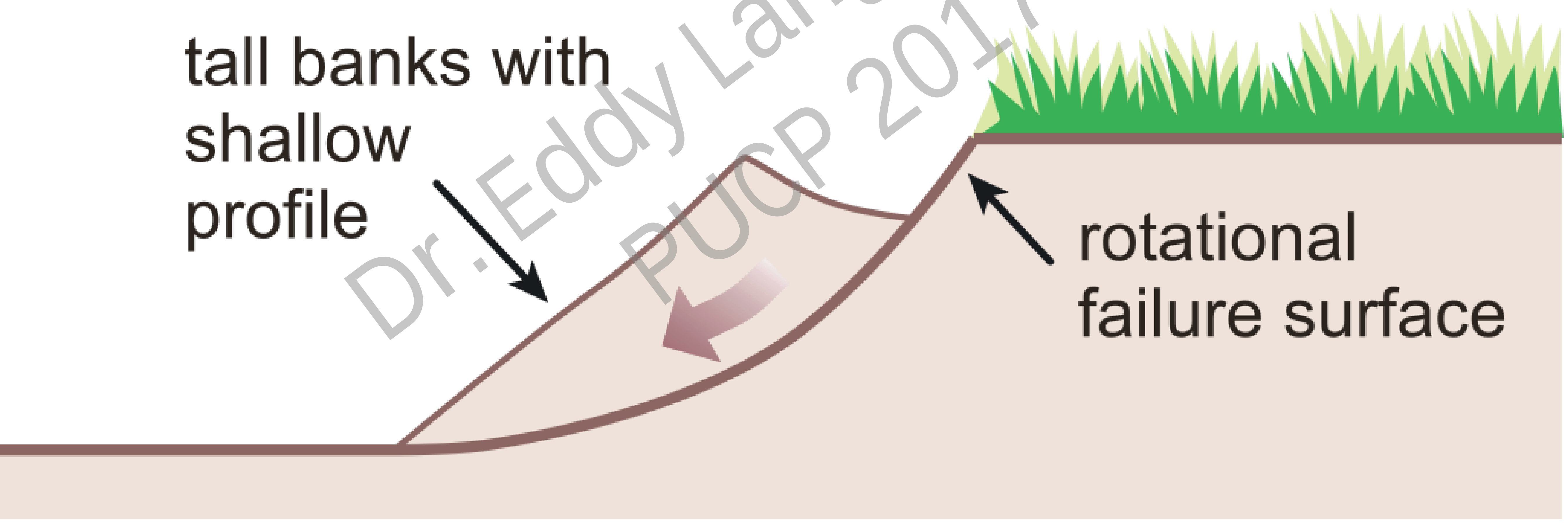
- Weight of the bank material exceeds the shear strength of the soil
- Often results of heightening and steepening of the bank
  - Channel incision
  - Toe erosion
- Depends on bank geometry and stratigraphy, soil water distribution, and riparian vegetation

Cohesionless vs Cohesive Mass Failures

- Cohesionless
  - Dislodgement and avalanching of individual particles
  - Shear failure along shallow slip surfaces
- Cohesive
  - Deep-seated failures
  - Block of disturbed soil sliding or toppling along a slip surface

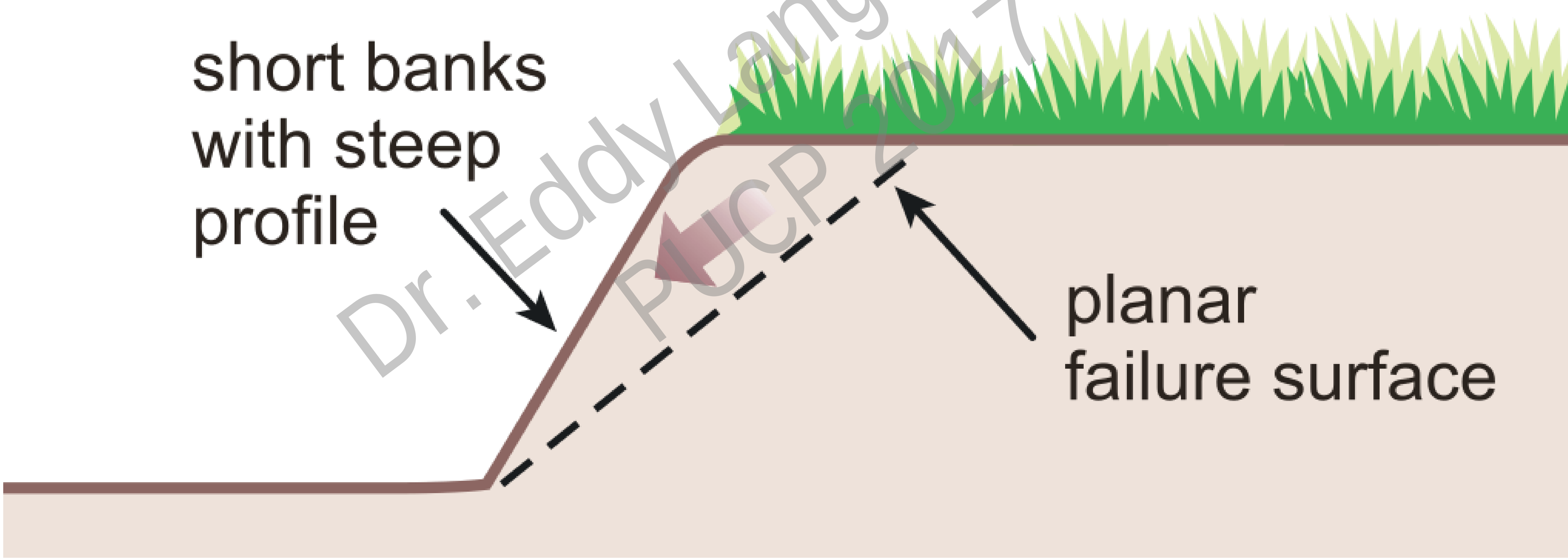
Mass Failure Mechanisms – I

- Rotational failure



Mass Failure Mechanisms – II

- Planar failure



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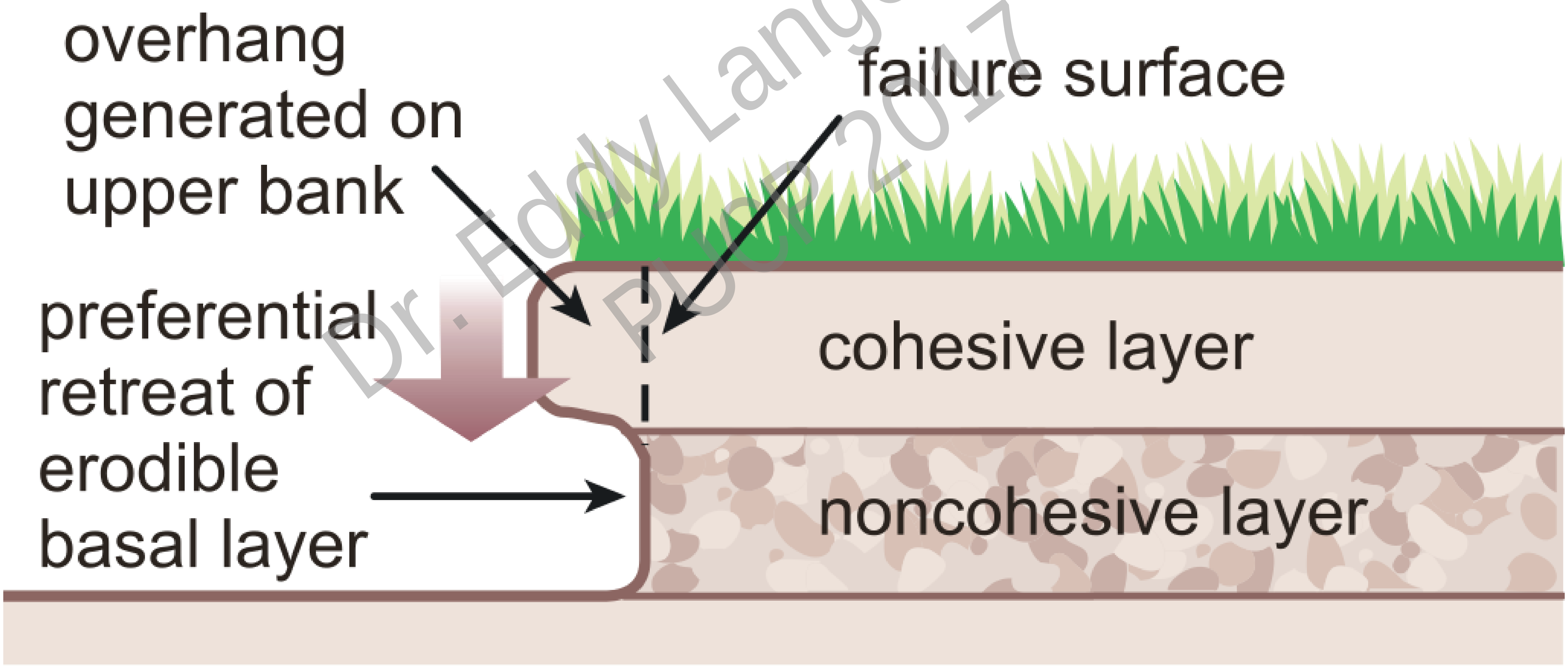
Mass Failure Mechanisms – III

- Cantilever failure



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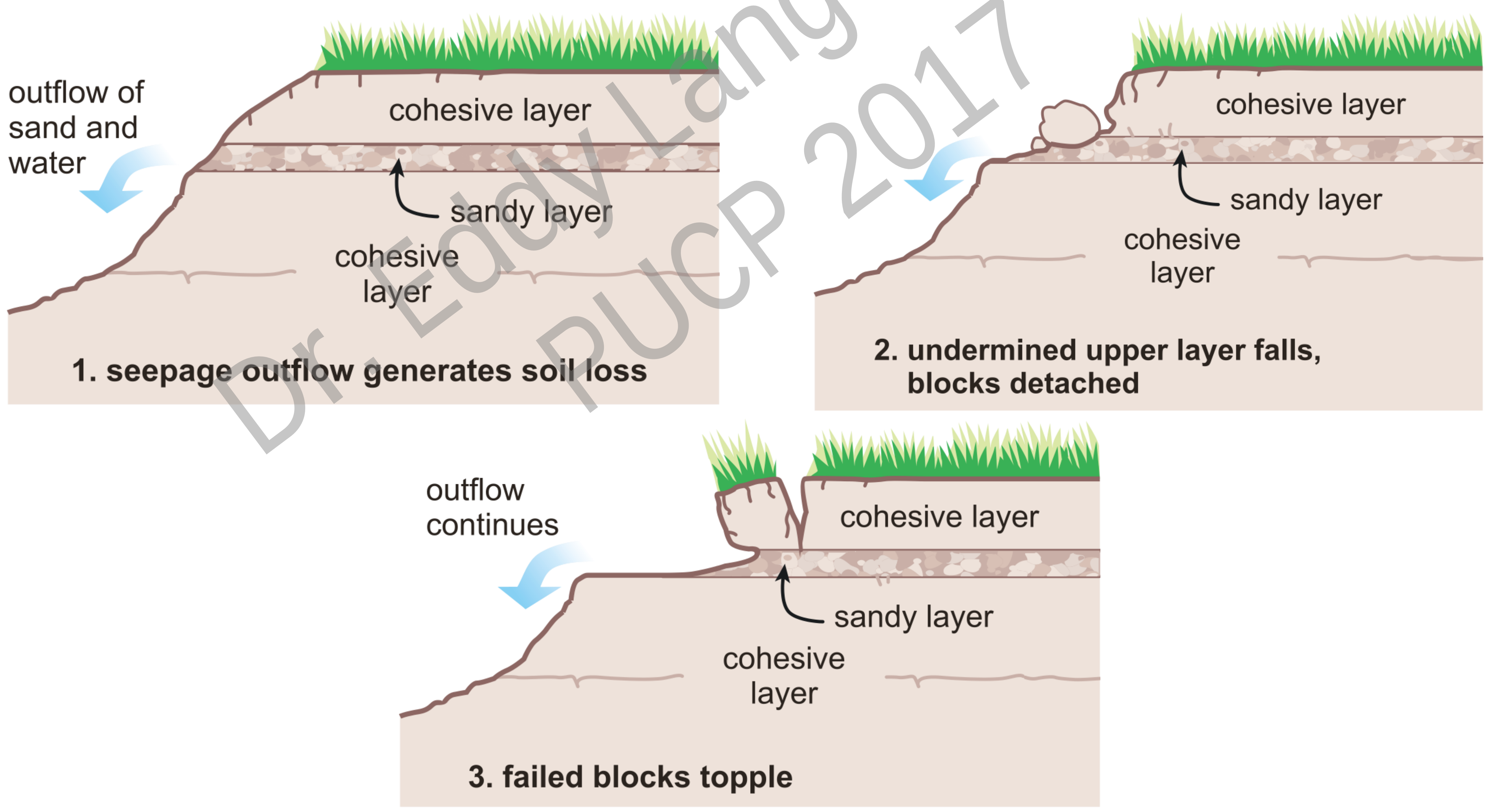
Mass Failure Mechanisms – IV

- Seepage or sapping failure

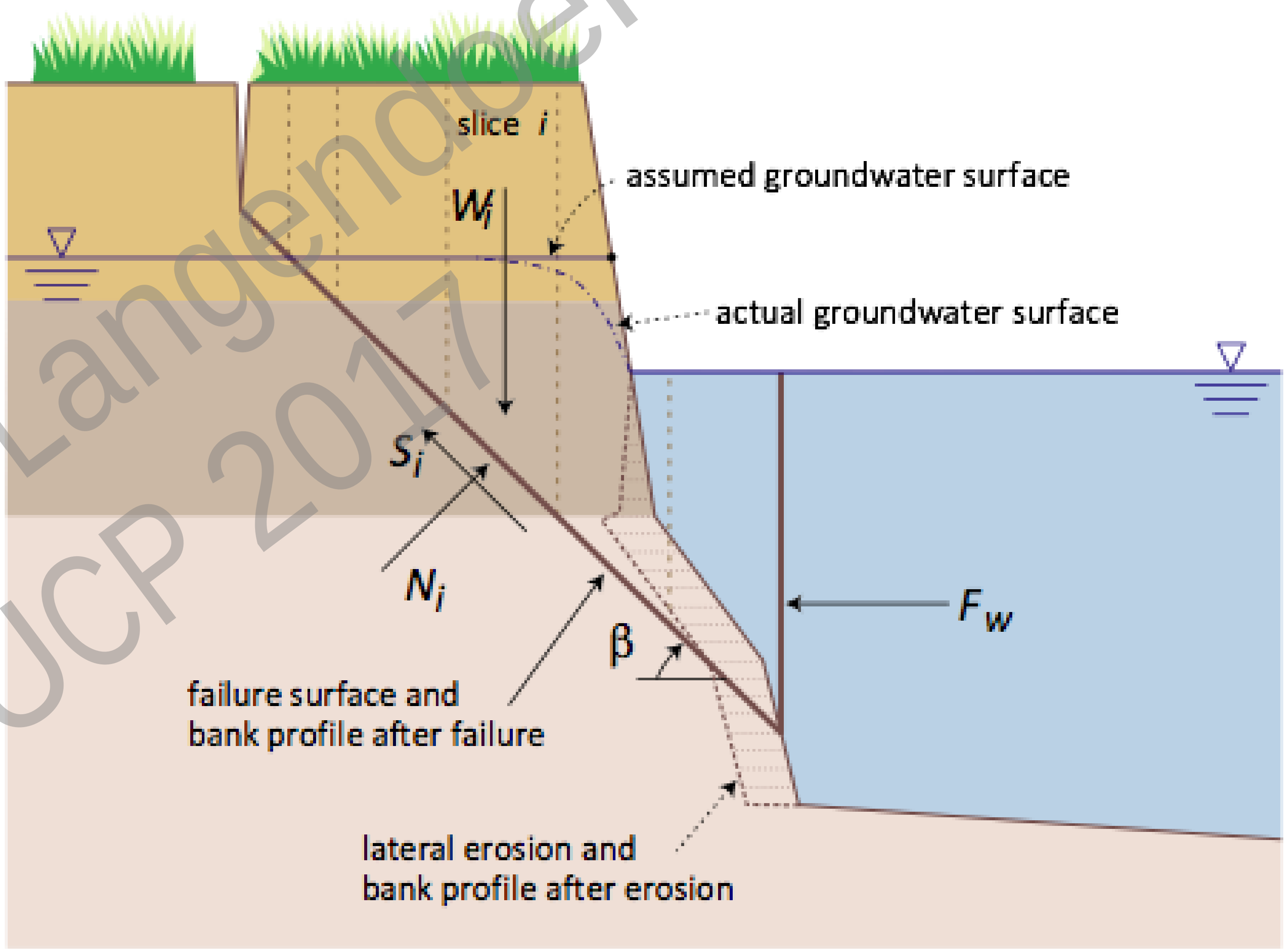


Planar Failure Analysis

- Stability charts
- Early models, such as Osman & Thorne (1988), Simon et al. (1991), Darby and Thorne (1996), had limited capabilities
  - Simplified bank profile
  - Homogeneous bank material
  - Slip surface angle prescribed
  - Evaluation of pore-water effects
- Enhancements made in late 1990s and early 2000s (e.g., Rinaldi & Casagli, 1999; Simon et al., 2000)
  - Matric suction
  - Heterogeneous bank material

Streambank Stability Analysis

- Stability is analyzed using limit equilibrium methods => FOS
  - Based upon static equilibriums of forces and/or moments
- Method of slices to account for:
  - heterogeneous bank material
  - Pore and confining pressures



F_w = confining force (N/m)
N = normal force (N/m)
S = mobilized shear force (N/m)
W = weight of composite soil (N/m)
β = angle of slip surface

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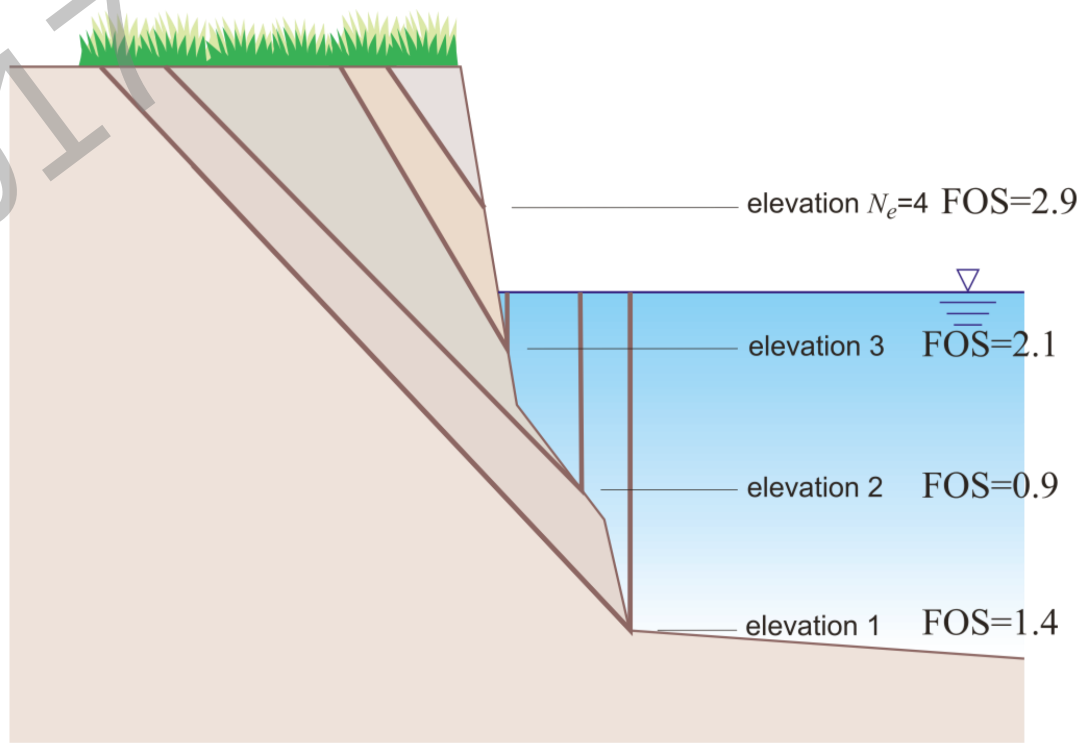
Streambank Stability Analysis – Inclination of Failure Surface

- The inclination of the failure plane is that for which the factor of safety is a minimum

$$\frac{\partial \mathrm{FOS}}{\partial \beta} = 0$$

- CONCEPTS uses a search method to find smallest FOS
- Factor of safety is evaluated at N_e number of points along the bank profile



Cantilever Failure Analysis

- Shear failure

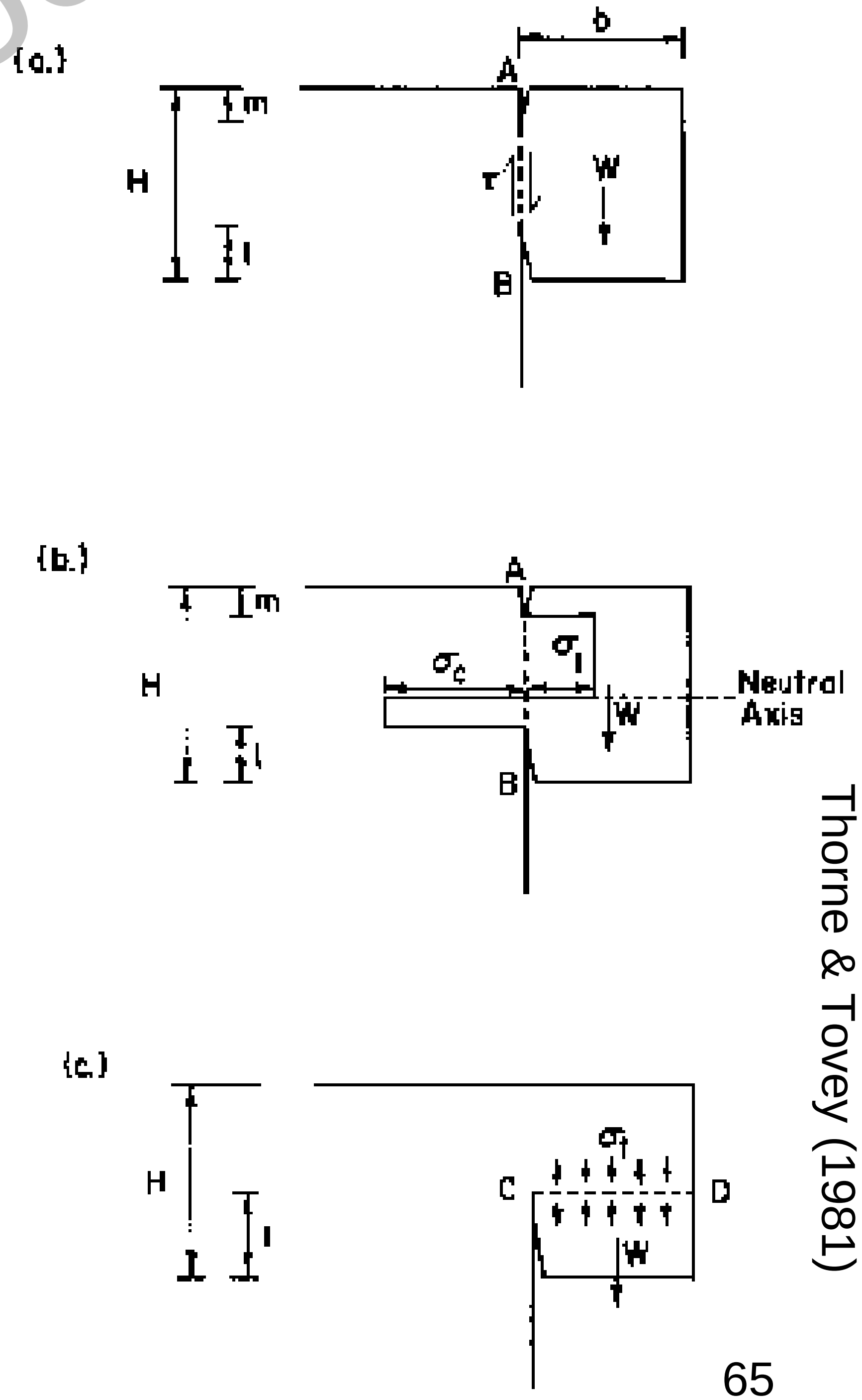
$$\mathrm{FOS}_s = \frac{(H - l - m)\,c}{\gamma H b}$$

- Beam failure

$$\mathrm{FOS}_b = \left(\frac{H - l - m}{b}\right)^2 \frac{\sigma_t \sigma_c}{\gamma H\,(\sigma_t + \sigma_c)}$$

- Tensile failure

$$\mathrm{FOS}_t = \frac{\sigma_t}{\gamma l}$$



Thorne & Tovey (1981)

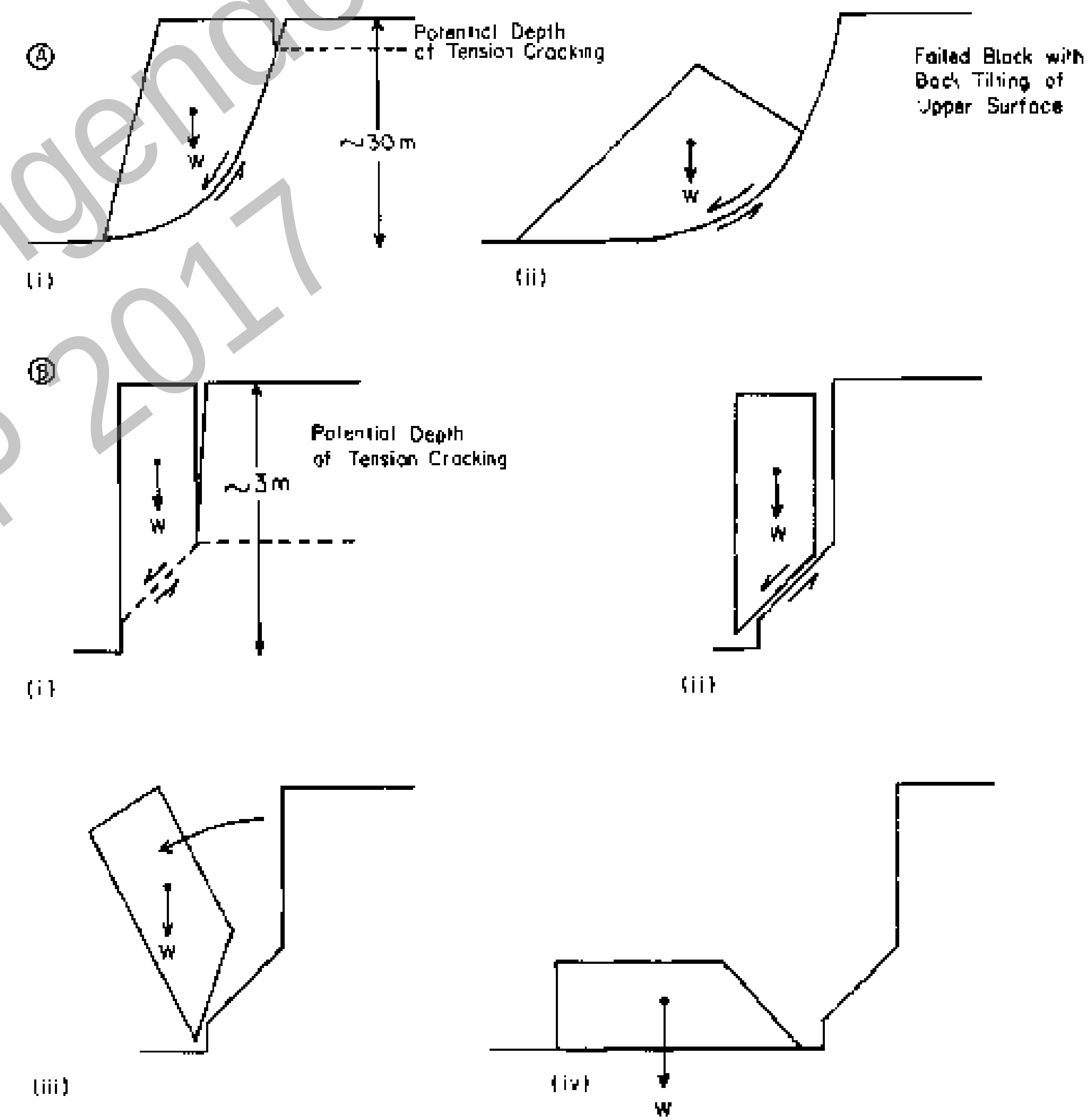
Fate of Failure Block Material

- Failed bank material may temporally protect the bank from further eroding
- Depends on:
  - Failure type
  - Soil properties
  - Vegetation presence
  - Hydraulics & hydrology

Failure Type Effects on Failure Block Fate

- Failure mode:
  - Sliding
  - Toppling
  - Falling

- Location of failed material



Vegetation Effects

Vegetation Effects on Streambank Erosion

- Reduced erosion/width:
  - Smith (1976): **20,000 times more resistance** to erosion of vegetated soils
  - Beeson and Doyle (1995): erosion **30 times more prevalent** on non-vegetated bends
  - Burckhardt and Todd (1998): unforested migration rate **3x larger**
- Increased erosion/width:
  - Davies-Colley (1997): increasing width from pasture to native to forested riparian zones.
  - Trimble (1997): grassed reaches narrower than forested reaches

Vegetation Effects on Streambank Erosion (cont.)

- Resistance to surface erosion
- Resistance to failure
- Above ground biomass (stems and leaves)
- Below ground biomass (roots)
- Vegetation affects erosion through:
  - Raindrop interception
  - Increased infiltration and infiltration capacity
  - Soil water transpiration
  - Increased surface roughness
  - Soil aggregate stability
  - Soil reinforcement

Vegetation Effects on Streambank Stability

- Shear strength equation

$$\tau = c' + \sigma_n \tan\phi' - p \tan\phi^b$$

cohesion → c'; pore-water pressure → p

- Shear strength increases with increasing cohesion and decreasing pore-water pressure
- Vegetation affects both cohesion (i.e., soil bonding) and soil water content

Vegetation Effects on Streambank Stability (cont.)

	Mechanical	Hydrologic
Stabilizing	Increased strength due to roots	Transpiration and canopy interception
Destabilizing	Surcharge	Increased infiltration rate and capacity

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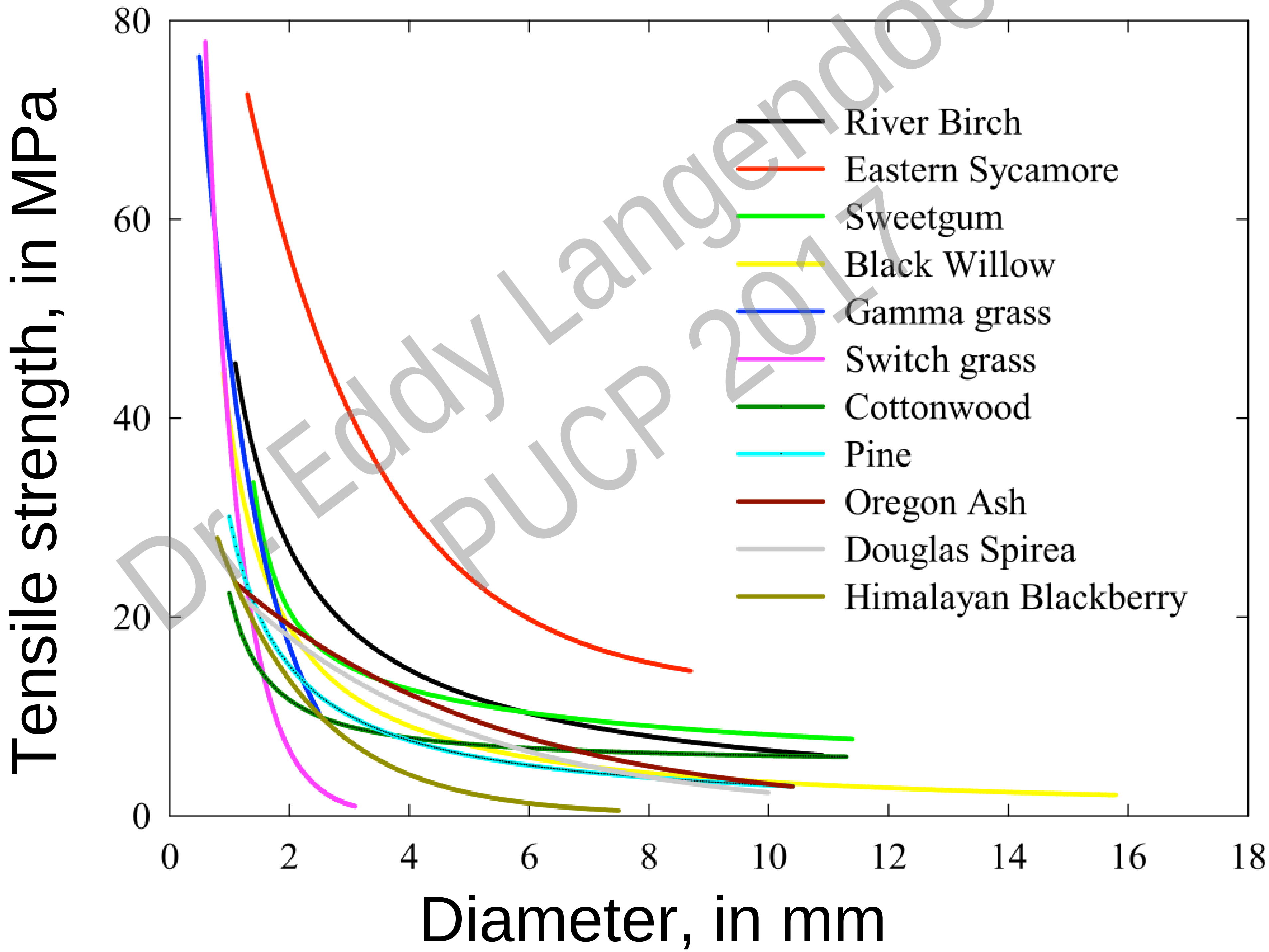
Mechanical Effects of Vegetation

- 'Root' cohesion

$$c_r = 1.2T_r\,(A_r/A)$$

- Two parameters:
  - Root tensile strength
  - Root-Area-Ratio
- Species-dependent

Root-Strength: Species Comparison

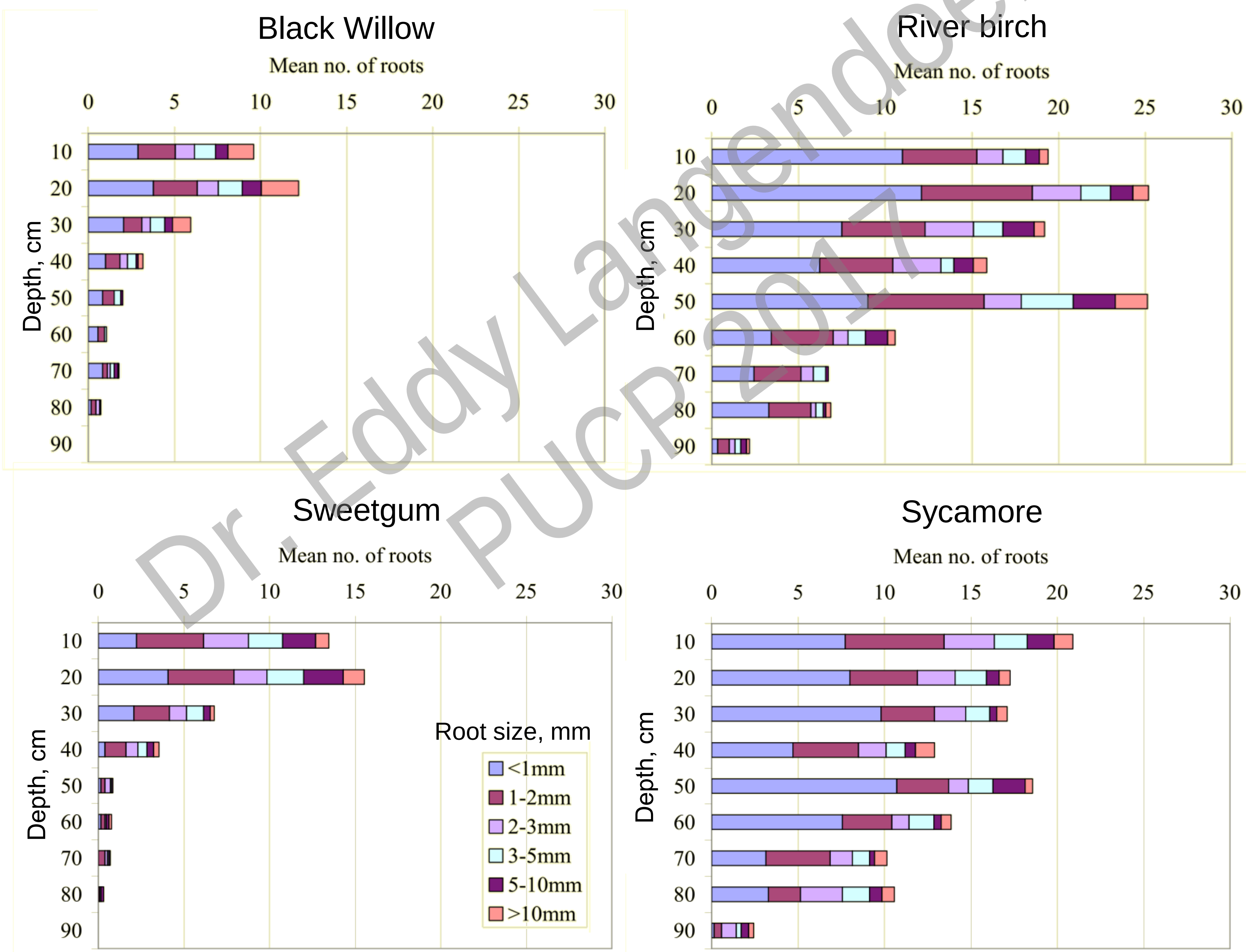


Root Distribution

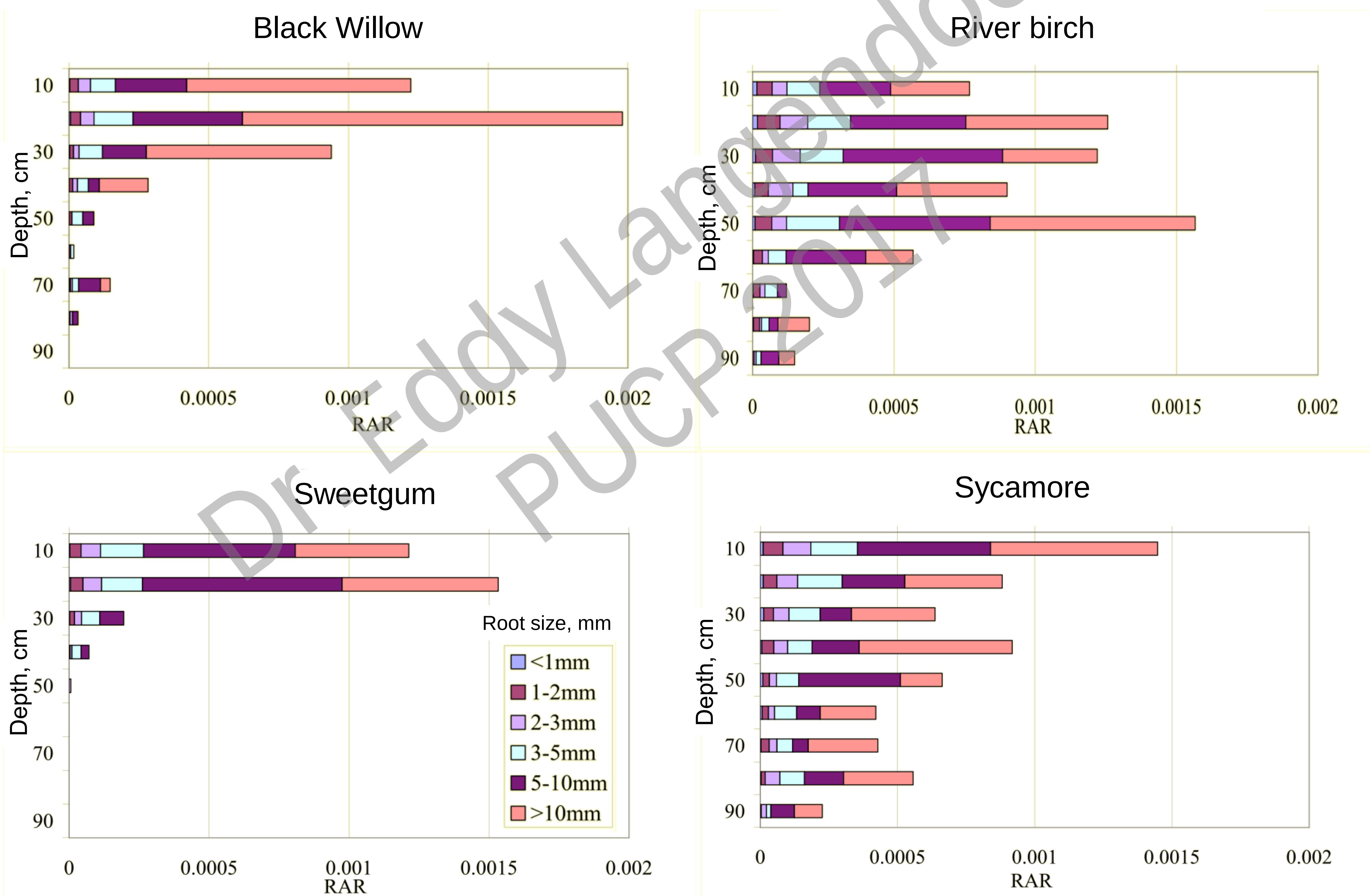
Trench around suitable riparian trees, and date tree using dendochronology

Map roots on frame and measure diameter with calipers

Number of Roots vs Depth



Root Area Ratio vs Depth



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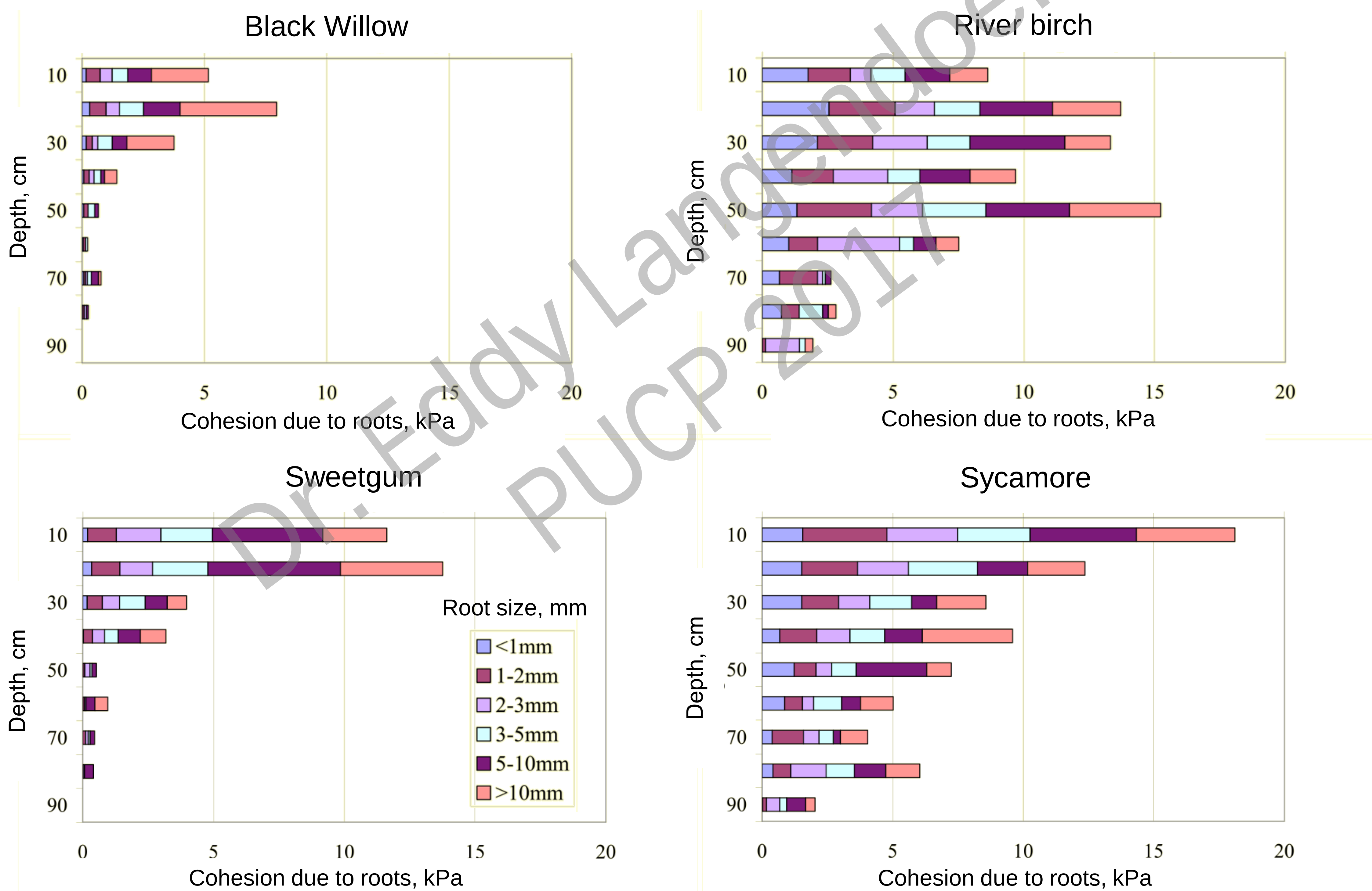
Cohesion Due to Roots vs Depth



Mechanical Findings

- Trees add 5-20 kPa cohesion to soil, over about 0-100 cm depth (black willow least effective)
- Clump grasses add 10-40 KPa cohesion
- Lots of small roots *potentially* provide greater strength than a few big roots
- However – most of the strength from trees *actually* comes from large sized roots – small roots make up too little area
- Significant strength achieved over 5-10 years growth

Quantifying the Hydrologic Effects of Vegetation

- Beneficial Effects: Increase in strength due to matric suction and reduced pore-water pressure
  - Rainfall Interception
  - Transpiration
- Detrimental Effects:
  - Enhanced infiltration
  - Enhanced permeability

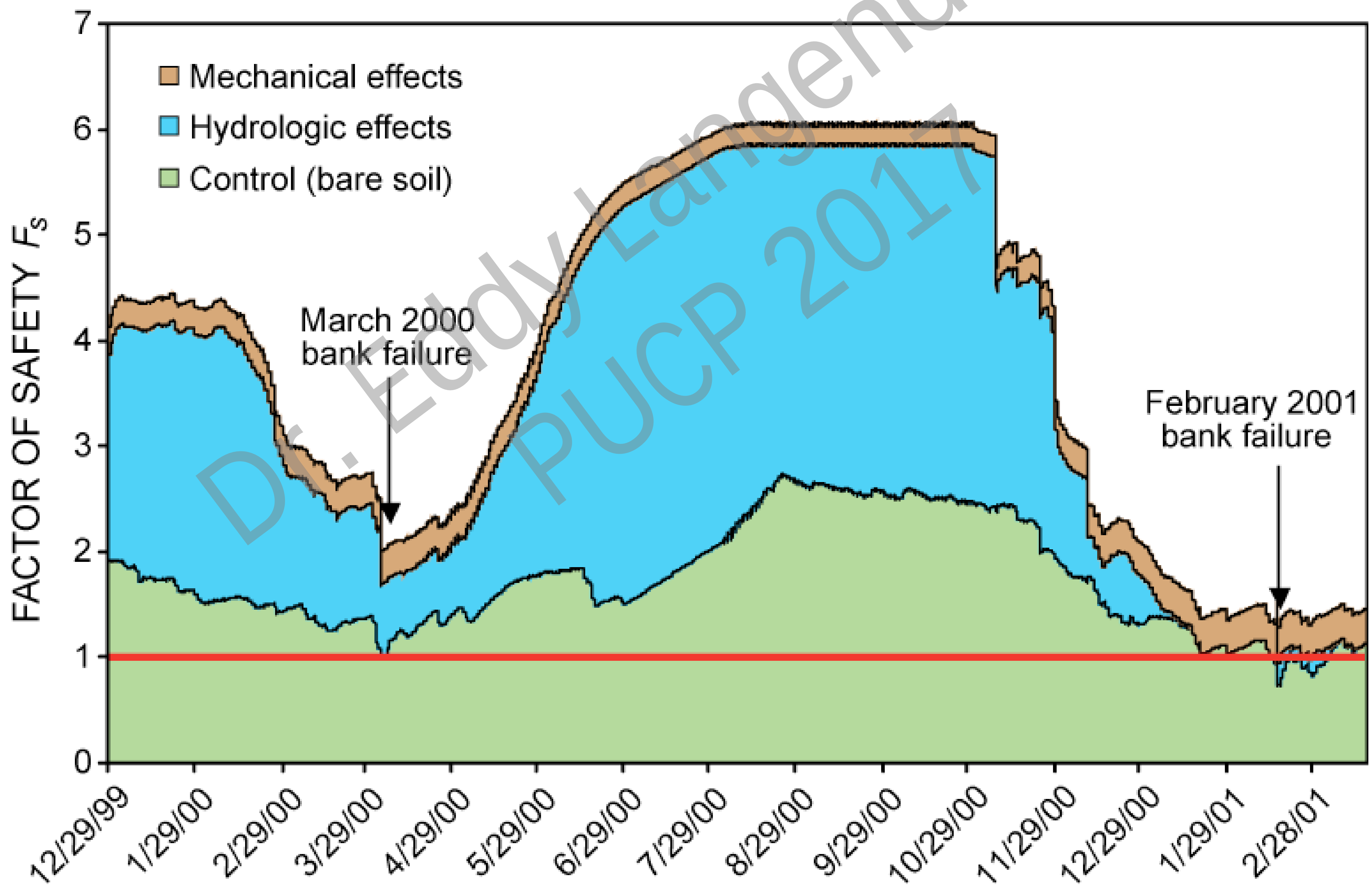
Monitoring the Hydrologic Effects of Vegetation

- Rainfall, stemflow and throughfall monitored spatially and in real-time
- Pore-water pressure below plots monitored using tensiometers

Hydrology Findings

- 2% of rain is intercepted by riparian strip canopy (high intensity events, low canopy cover during winter/spring)
- Trees increase infiltration capacity, concentrating more water in upper 30-100 cm soil than on bare or grass-covered banks
- Trees maintain suction at depth (200-300 cm) into spring
- High matric suction at depth indicates deeper roots than found in survey (?)

Vegetation Effects on Streambank Stability (cont.)



From Simon and Collison, ESPL, 2002

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Assessment Tools

- Single bank
  - BSTEM
- 1D models
  - CONCEPTS
  - HEC-RAS
- 2D models
  - SRH-2D
  - Telemac2D/Sisyphe
  - RVR-Meander

DATA NEEDS AND COLLECTION

Streambank Erosion Input Data Requirements

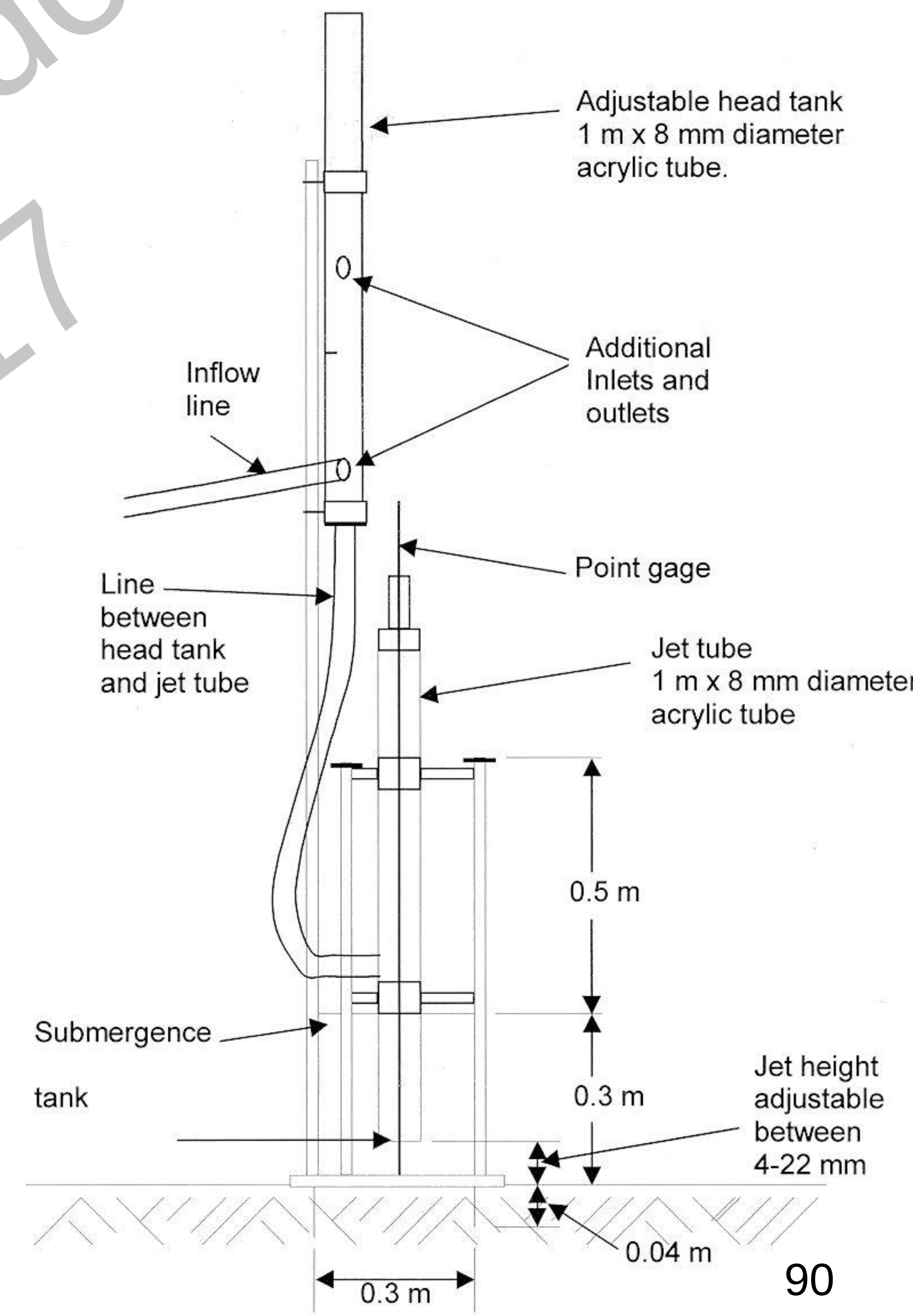
- Bank material properties
  - Composition
  - Unit weight
  - Erodibility
  - Shear strength
- Bank roughness
- Bank stability analysis options

Flume Methods to Determine Critical Shear Stress

Device	Known flow conditions	Field tests	Bedload	Depth range	Armoring	Erosion rate	Shear stress range
Annular flume	Yes	No	No	0-0.2 m	Yes	No	0-1 Pa
SEDFlume	Yes	Yes	No	0-1 m	No	Yes	0-10 Pa
SEDFlume /w trap channel	Yes	No	Yes	0-1 m	No	Yes	0-10 Pa
Oscillatory flume	Yes	Yes	No	0-1 m	Some	Yes	0-10 Pa

In-Situ Jet Test Device to Determine Critical Shear Stress

- Developed by the Agricultural Research Service (Hanson, 1990).
- Based on knowledge of hydraulic characteristics of a submerged jet and the characteristics of soil-material erodibility.
- Apparatus: pump, adjustable head tank, jet submergence tank, jet nozzle, delivery tube, and point gage.
- The stress range = 4 - 1500 Pa.
- Maximum scour measurements are taken at five to ten minute intervals over a period of 60 to 120 minutes.



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Closing remarks

- Bank erosion and channel width adjustment is common
- Channel width adjustment can be orders of magnitude greater than channel depth adjustment
- Bank erosion is controlled by fluvial and gravitational processes
- Bank erosion assessment is complex because of spatial variations in soil texture and the erosion mechanics of fine-grained soils