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Inherent Autogenic Avulsion of Aggradational Submarine Channels*

R. M. Dorrell[1], A. D. Burns[1], and William D. McCaffrey[1]

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[1]University of Leeds, Leeds, UK (r.m.dorrell@leeds.ac.uk)

Abstract

Both internal and external forcing may influence the development of aggradational submarine channels, and in particular, their likelihood of avulsion. Simple geometric modelling is used here to show that the channel-levee form is inherently unstable. Thus, given steady input conditions, submarine channel levee systems cannot grow with a fixed geometry, necessitating changes in one or more of: 1) the relative amounts of sediment depositing on the levee vs. in the channel; 2) the outer-levee slope and 3) the channel cross-sectional area. It can be shown that any of these changes will ultimately increase the likelihood of system re-organisation via avulsion. Allogenic forcing, expressed by temporal variations in the type of flow entering a channel-levee system, likely modulates the development of the disequilibrium conditions that lead to avulsion. Thus, inspection of the downstream changes in channel-levee geometry, and of patterns of avulsion, may permit inferences regarding changes in input conditions, and may ultimately allow better a priori estimates of the patterns of grain-size distribution within channel-levee system sedimentary bodies.

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Inherent autogenic avulsion of aggradational submarine channels

Dr. R. M. Dorrell

Dr. A. D. Burns

Prof. W. D. McCaffrey

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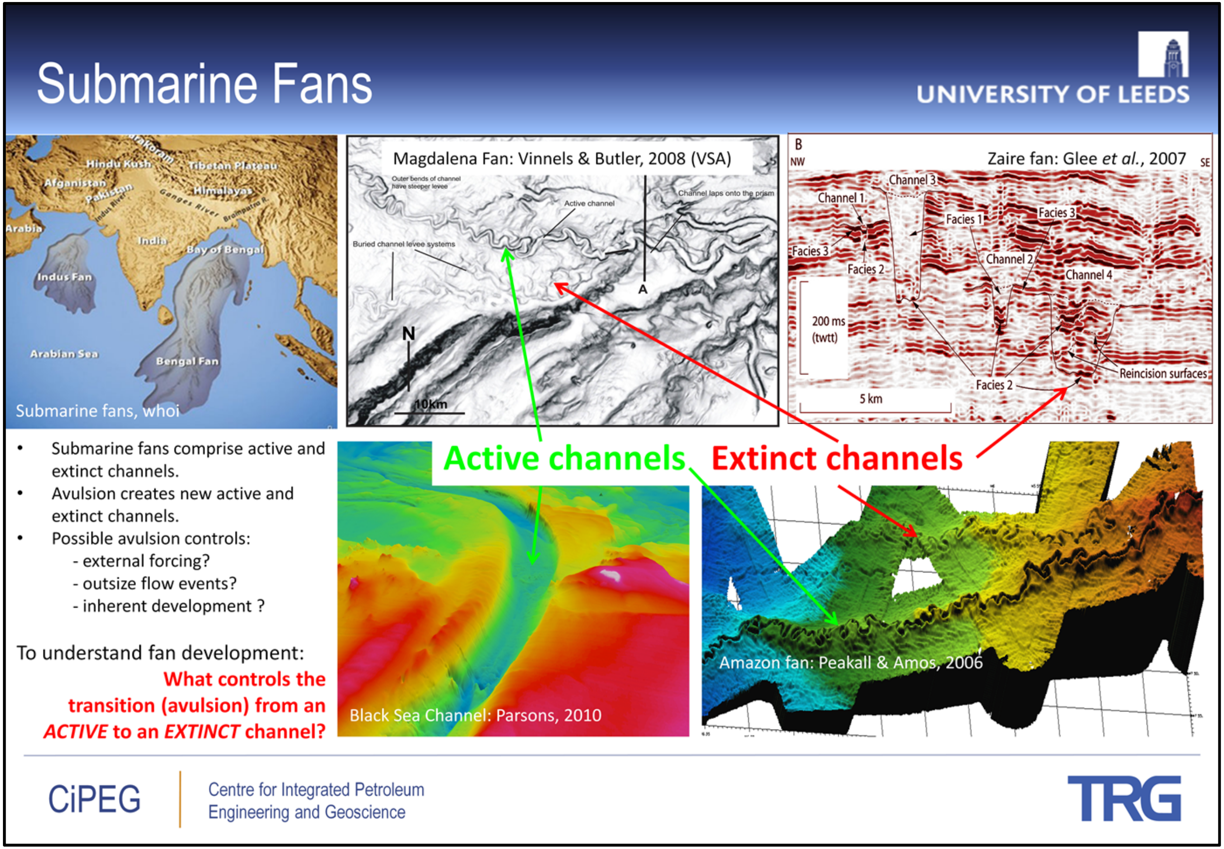

Presenter's notes: Submarine fans form some of the largest sedimentary deposits in the world. Fans are formed from networks of active and extinct channels. Extinct channels are formed when a channel avulses and takes a new path. To understand how submarine fans are constructed it is therefore crucial to understand how channels avulse.

Submarine Channels

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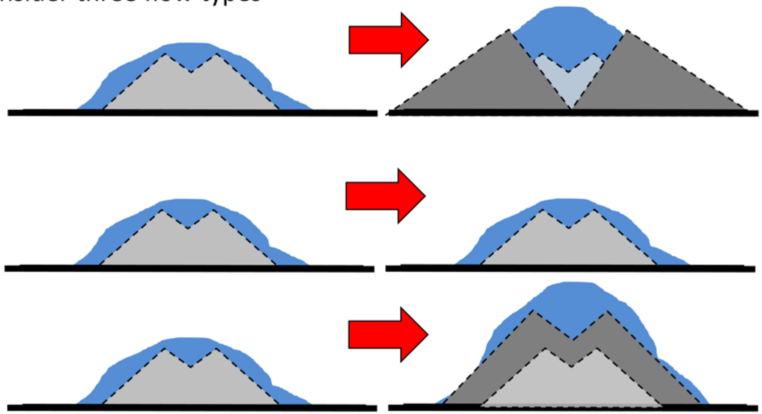
Given a submarine channel we may consider three flow types

Erosional flows
- Flow cuts into local topography.
- Channel increases in size.
- Avulsion unlikely.

Bypassing flows
- Zero net erosion / deposition.
- System remains constant.
- Avulsion unlikely.

Aggradational flows
- Channel grows with net deposition.
- Unapparent if channel remains stable.
- Channel may avulse.



To understand inherent avulsion:

what constrains the evolution of aggradational flows?

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Presenter's notes: Assumption is that flows are of constant magnitude. Different types of flows effect channel growth in different ways. Erosional flows incising into bedrock will increase area of channel and the degree by which a flow of given magnitude is constrained by topography. As flows are better constrained they are less likely to avulse. In bypassing flows, there is negligible change in bounding topography. However, in aggradtional flows, it is not apparent if the channel remains stable with progressive deposition. This is where avulsion may be driven by infilling of the channel.

Aggradational channels

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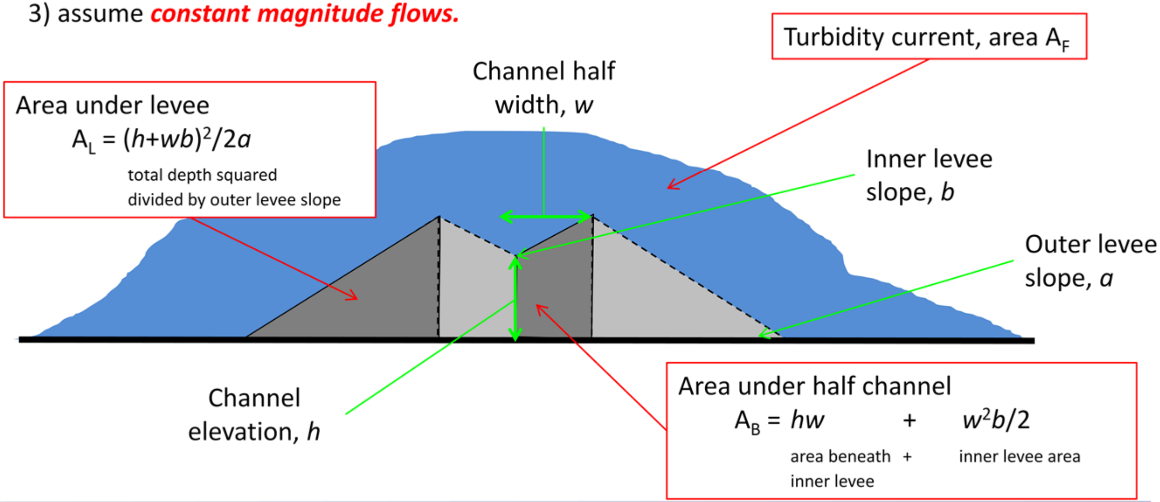
To ***model the inherent evolution*** of a submarine channel and its bounding levees:

1) use simplified ***cross-sectional transect*** to describe channel and levee.
2) neglect time periods between flows.
3) assume ***constant magnitude flows.***



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Presenter's notes: To study evolution of an aggradational channel system, we consider an idealized channel levee system.

Modelling aggradational channels

(width averaged Exner equation)

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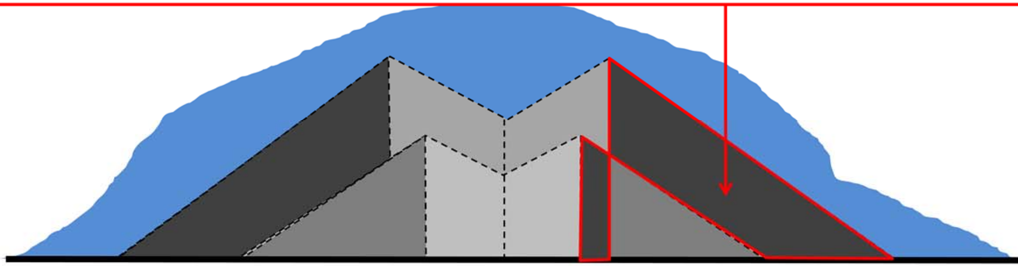
$$\frac{\mathrm{d}}{\mathrm{d}t}A_L = \frac{\mathrm{d}}{\mathrm{d}t}\frac{(h+wb)^2}{2a} = EN - (h+wb)\frac{\mathrm{d}}{\mathrm{d}t}w$$

Change in area under an outer levee

sedimentation on an outer levee

change in the area under the outer levee with migrating levee crests



N **is the net sedimentation rate**

E **is the *fraction* of material deposited on the outer levee ($0 \le E \le 1$)**

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Presenter's notes: Channel evolution is modelled by a width-averaged Exner equation, describing the change in bed depth with time. Neglecting time periods between individual flow events, with progressive deposition (flow events), the net area of the channel bed and levees will increase. Change in area of a single outer levee equals the net deposition on the levee minus the volume of material lost to the bed with levee crest migration.

Modelling aggradational channels
(width averaged Exner equation)

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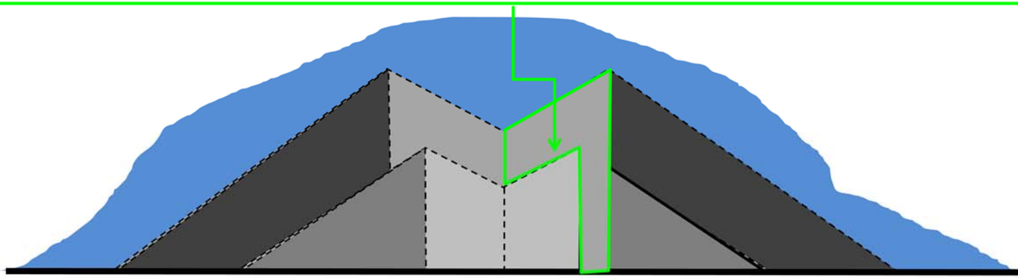
$$\frac{\mathrm{d}}{\mathrm{d}t}A_B = \frac{\mathrm{d}}{\mathrm{d}t}hw + \frac{w^2 b}{2} \quad = \quad (1-E)N + \quad (h+wb)\frac{\mathrm{d}}{\mathrm{d}t}w$$

Change in area under half of the channel

sedimentation in half of channel

change in half area under channel with migrating levee crests



1-E **is the *fraction* of material deposited over half of the channel (0 ≤ 1-*E* ≤ 1)**

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Presenter's notes: Similarly, change in the half area of the bed equals the net deposition in channel plus the volume of material gained from the adjacent levee with levee crest migration.

Modelling assumptions

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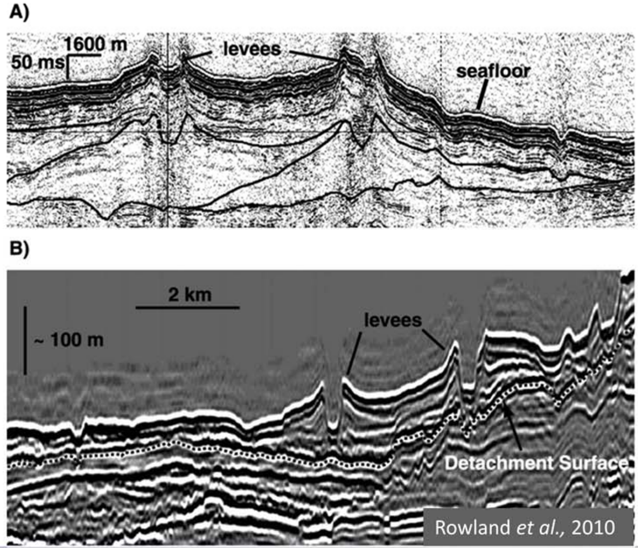
Problem: Two governing equations (channel and levee evolution)
Four unknowns (elevation, h, width, w, and outer, a, and inner, b, levee slope)

Assume after initial growth, levees tend to an ***equilibrium slope…***

as driven by:

1) slope failure (critical angle of repose)
2) down slope erosional processes (outer levee)
3) secondary flow effects (inner levee)



Assume a and b constant

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Presenter's notes: While channel bed and levee growth equations describe channel evolution, there is a problem. We have four unknowns but only two equations. Therefore to proceed, we must close the problem by making assumptions about these variables. Here it is assumed that after the initial period of growth-levee slopes tend to some constant value, as driven by slope failure or erosional flow process acting at much shorter timescales than the long timescales of levee growth.

System evolution

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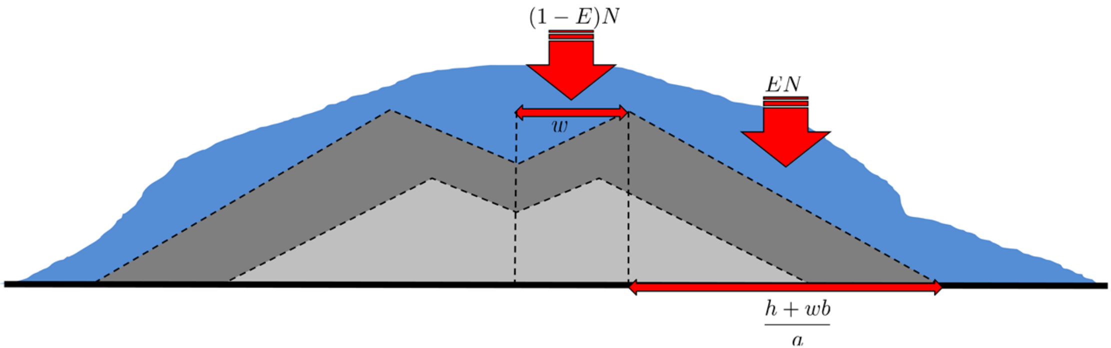
subtract channel evolution from levee evolution equation

$$\frac{EN}{\frac{h+wb}{a}} - \frac{(1-E)N}{w} = (a+b)\frac{\mathrm{d}}{\mathrm{d}t}w$$

deposition on levee per unit width

deposition in channel per unit width

levee crest migration rate



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Presenter’s notes: Subtracting the channel evolution equation from the levee evolution equation it is apparent that deposition on levee (per unit width) minus deposition (per unit width) in channel is equal to the levee crest migration rate.

Channel widening

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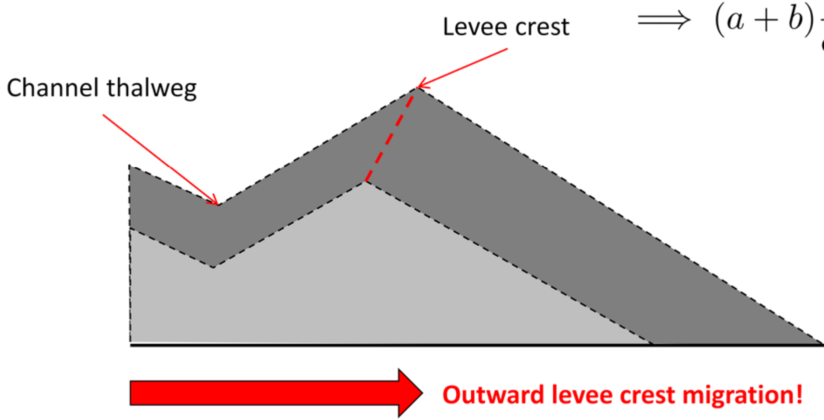
Deposition per unit width greatest on levee
$$\frac{EN}{\frac{h+wb}{a}} > \frac{(1-E)N}{w}$$
$$\implies (a+b)\frac{\mathrm{d}}{\mathrm{d}t}w > 0$$



Inference: widening channels indicative of (fine-grained??) flows primarily depositing on levee…

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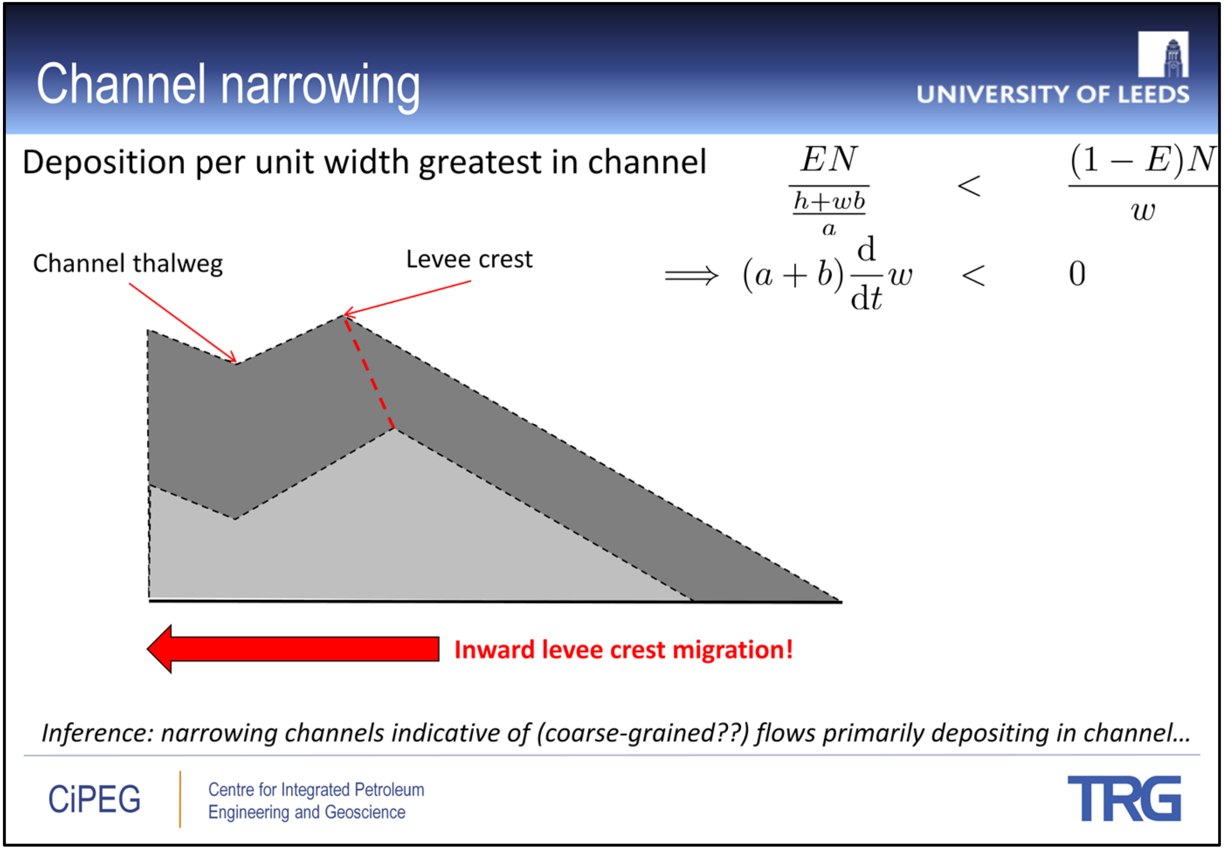
Presenter's notes: This further implies that if deposition (per unit width) is greatest on levee, there will be outward levee crest migration or widening of the channel. Interestingly, one would, therefore, expect that widening channels are indicative of unstratified fine-grained flows which lose more material overbank.



Presenter's notes: Similarily we see that if deposition (per unit width) is greatest in channel, there will be inward levee crest migration or narrowing of the channel. Interestingly, one would, therefore expect, that narrowing channels is indicative of stratified coarse-grained flows which are better constrained in channel.

System evolution

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To understand the ***inherent behavior*** of the system:

1) integrate governing channel and levee evolution equations.
2) investigate solutions at long timescales.

Integration is ***simplified*** by summing equations to yield

$$A_L + A_B = Nt + A_0$$

A_L: area under levee; A_B: area under channel; Nt: linear growth rate; A_0: initial area of levee and bed

Which, after rearranging:

$$\left(\frac{h}{\sqrt{2a(Nt+A_0)}} + (a+b)\frac{w}{\sqrt{2a(Nt+A_0)}}\right)^2 - \left(\sqrt{\frac{a+b}{2(Nt+A_0)}}w\right)^2 = 1$$

Or

$$X(t)^2 - Y(t)^2 = 1$$

X ~ (h + bw)/t½: proxy for levee crest height

Y ~ w/t½: proxy for channel width

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Presenter's notes: To understand the inherent behavior of the channel levee system we must integrate the governing equations and investigate system behavior at longtime scales. Integration is simplified by summing the equations together, yielding a parabolic equation of the form which can be used to constrain system dynamics.

System evolution

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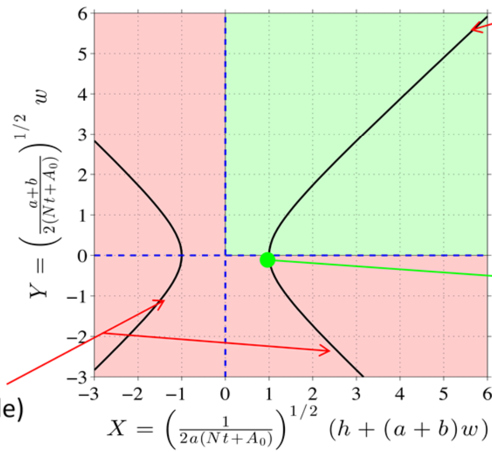
Given solutions lie on parabolic curve

$$X(t)^2 \quad - \quad Y(t)^2 = 1$$

$X(t)^2$: proxy for levee crest height

$Y(t)^2$: proxy for channel width

Positive solutions (physically feasible)



Decreasing Y, decreasing width, increasing likelihood of avulsion

$Y = 0$ Zero channel width

Channel must have avulsed by this point!

Negative solutions (physically unfeasible)

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Presenter's notes: While all solutions lie on the parabola X^2-Y^2=1, we can constrain the physically feasible phase space (shaded green) to X>0 and Y>0 such that channel width and levee crest height are strictly greater than zero. The point Y=0 X=1 describes vanishing channel width and vanishing channel area. Solutions tending to Y=0 may, therefore, be associated with channel avulsion events as the flow is poorly constrained by the channel.

System evolution for constant *E*

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System evolution:

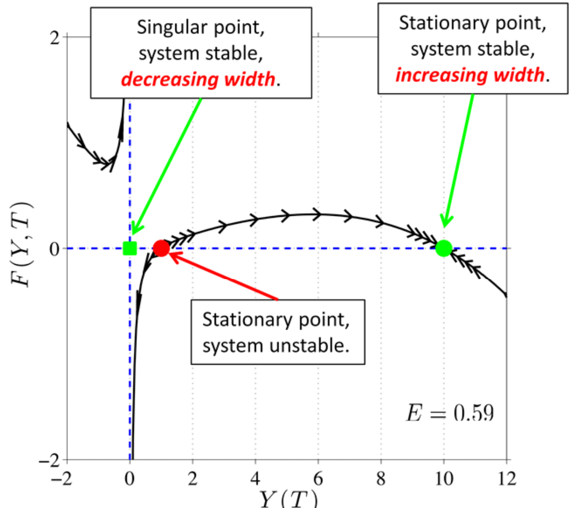
1. Constrained by $X(T)^2 - Y(T)^2 = 1$

1. Prescribed by $\dfrac{\mathrm{d}Y}{\mathrm{d}T} = F(Y,T)$

   - F=0 *Y(t)* fixed, *w(t)* increases
     [*w(t)* ~ *t*½*Y(t)*]
   - F>0 *Y(t)* increases
   - F<0 *Y(t)* decreases

$$F(Y,T) = \frac{1}{2}\,\frac{\frac{E-1}{Y} - Y + \sqrt{\frac{\gamma}{\gamma+1}}\sqrt{Y^2+1}}{\left(1 - \sqrt{\frac{\gamma}{\gamma+1}}\,\frac{Y}{\sqrt{Y^2+1}}\right)}$$

$$T = \log\left(\frac{Nt + A_0}{A_F}\right); \quad \gamma = \frac{a}{b}$$



Plotting F describes system evolution.

Location of stationary (critical) points controls system evolution

Presenter's notes: While solutions lie on the parabolic curve X^2-Y^2=1, evolution is determined by dY/dt=F(Y,t).

While F(Y,t)<0, Y(t) decreases; while F(Y,t)>0, Y(t) increases. As Y(t) goes like w(t)/t^2Y(t), channel width will increase, unless Y(t) tends to 0.

Stationary point location

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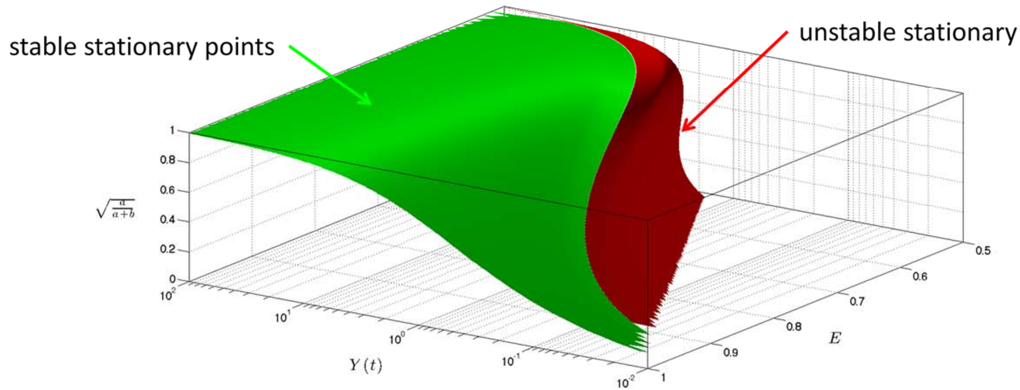
Stationary point location is dependent on input parameters

1) Sediment fraction deposited on-levee $0 \leq E \leq 1$

2) Inner and outer levee slopes (as parameterized by) $0 \leq \sqrt{\frac{a}{a+b}} \leq 1$



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Presenter's notes: Critically, solutions for the location of the critical points (and thus the stability of the system) are dependent on E and gamma.

Sediment Fractionation, *E*

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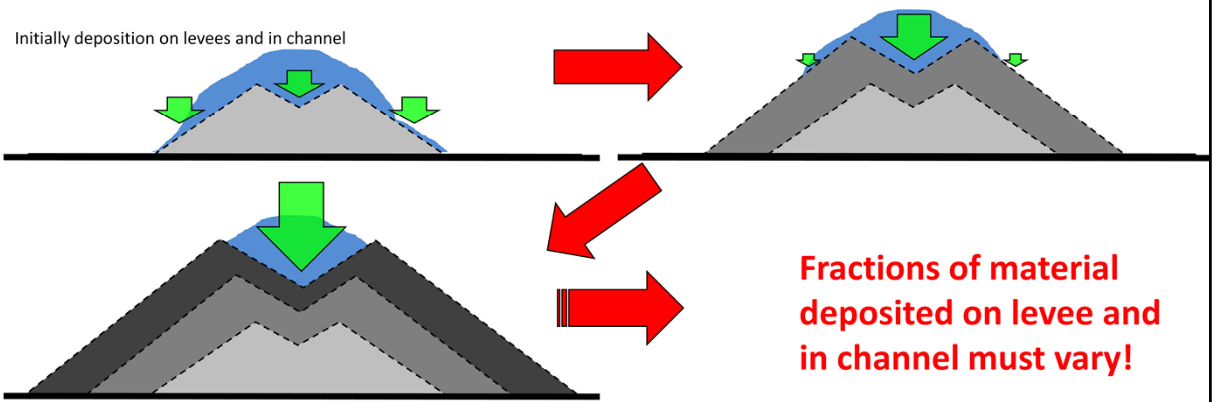
With progressive deposition:

1) sum channel bed and levee area is increased.
2) channel area varies.

Consider an end member case of a small flow (of fixed area) in a channel of growing area



Fractions of material deposited on levee and in channel must vary!

Eventually channel so large it contains all flow: no deposition on levees

Presenter's notes: However, whilet we have assumed inner and outer levee slopes to be constant it is seen that the fraction of material deposited on levee or in channel is not neccesarily fixed. For example, considering a small flow in a widening channel, it is soon seen that the channel will become large enough to constrain all the flow such that there can be no deposition on levee.

Fractionation in an evolving channel

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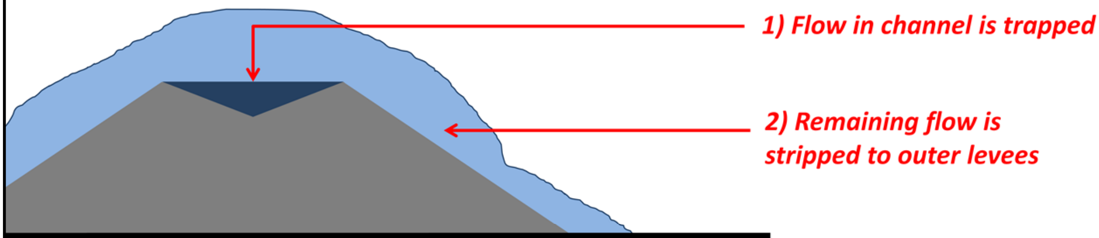
To describe fractionation in an evolving channel assume:



implying...

$$\frac{\text{material deposited in channel}}{\text{material deposited on levee}} \propto \frac{\text{channel area}}{\text{remaining flow area}}$$

$$\frac{1-E}{E} = \alpha \frac{w^2 b}{A_F - w^2 b}$$

constant of proportionality

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Presenter's notes: The fractionation ratio describes the ratio of material deposited on levee to material deposited in channel. This is proportional to the amount of material carried in the channel divided by the amount of material carried out of channel. Crudely this can be expressed by the area of the channel divided by the remaining area of the flow.

Stationary points for varying *E*

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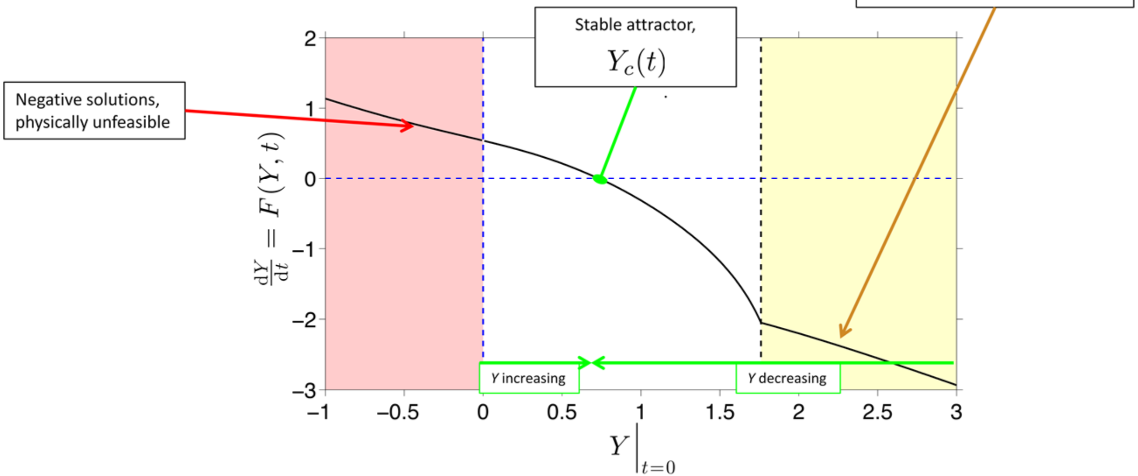
For sediment fractionation, *E*, varying with channel evolution

1) phase space describing system evolution has one attractor.

2) if area of flow is less than area of channel *E*=0



System evolution is limited by temporal evolution of attractor

Presenter's notes: While the sediment fraction varies with evolving channel geometry, the curve F(Y,t) has only one solution for fixed t. Solutions are further limited to the region of the phase space where the area of the flow is greater than the area of the channel. While the area of the flow is less than the area of the channel, E=0 and the curve F(y,t) is strictly negative. The single solution to the curve F describes an stable stationary point. The temporal evolution of this point, therefore, controls system evolution.

Temporal evolution of attractor

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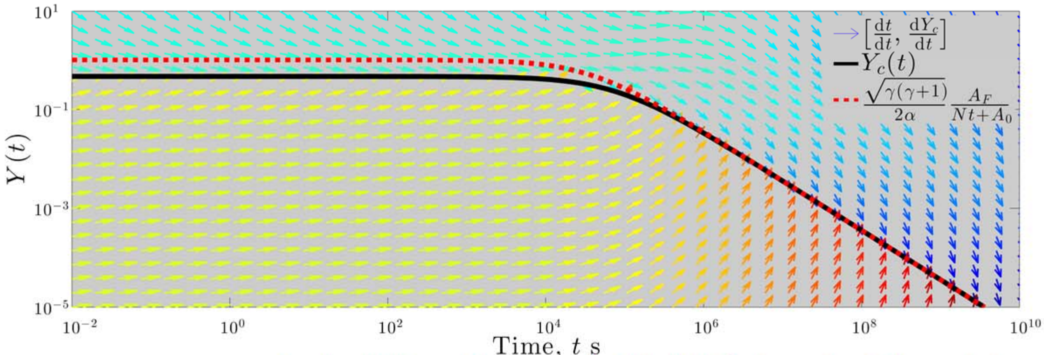
The temporal path of the attractor (stationary point in the *Y*-plane)

$$E(Y_c(t),t) - 1 - Y_c(t)^2 + \sqrt{\frac{\gamma}{\gamma+1}}\sqrt{Y_c(t)^4 + Y_c(t)^2} = 0$$

asymptotic analysis shows:

$$Y_c(t) \sim \frac{\sqrt{\gamma(\gamma+1)}}{2\alpha}\frac{A_f}{Nt + A_0} + \ldots \quad t \gg 1$$



Implies *Y(t)* tends to zero – [*w(t)* ~ $t^{1/2}$*Y(t)*] *channel width must decrease!*

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Presenter's notes: Given this fractionation law, the location of the stable critical point, which acts a the system attractor, is given by the implicit equation. Deriving the Yc, the critical point location, from this equation asymptotic and numerical analysis shows Yc ~ 1/T for T much larger than 1. As Yc decreases with increasing T, so must Y, and thus the channel width must also decrease. (Intuitively this can be seen to occur as with progressive deposition, the width of the levees become so large that deposition per unit width on them is negligible, and thus the channel becomes narrower.)

Channel evolution example

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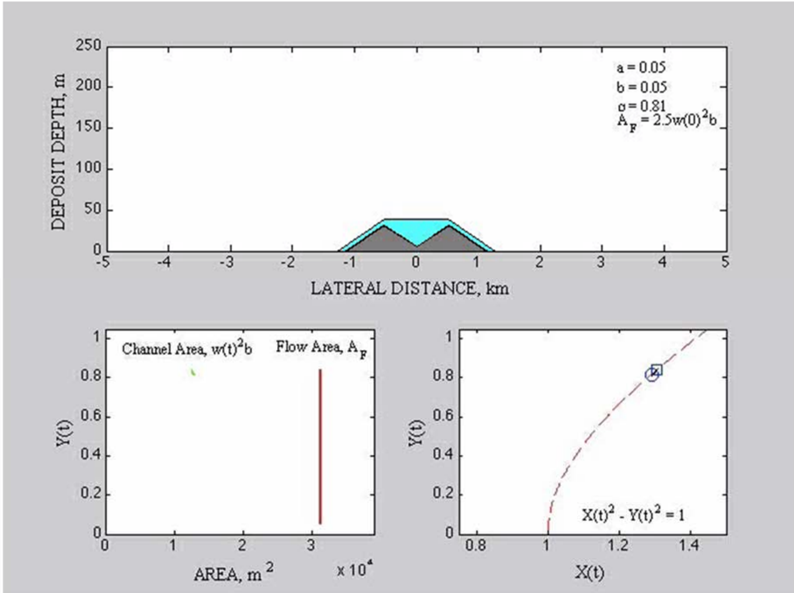

Presenter's notes: An example of this decrease in channel area is shown. Here the top figure depicts the idealized cross-sectional view of a channel-levee system (with the flow sketched in blue). The bottom left plots the variation in channel area as a function of Y(t), while the bottom right figure plots numerical solutions to the equations for the variation of X(t) and Y(t), showing they lie on the curve $X^2-Y^2=1$.

Conclusions

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1) With progressive deposition channels decrease in area over long timescales.
=> channel avulsion

2) Constrained model predicts inherent autogenic channel avulsion.

3) Channels can increase and decrease in area through purely depositional processes.

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