What controls the transition from fluvial regime to a debris-flow regime?

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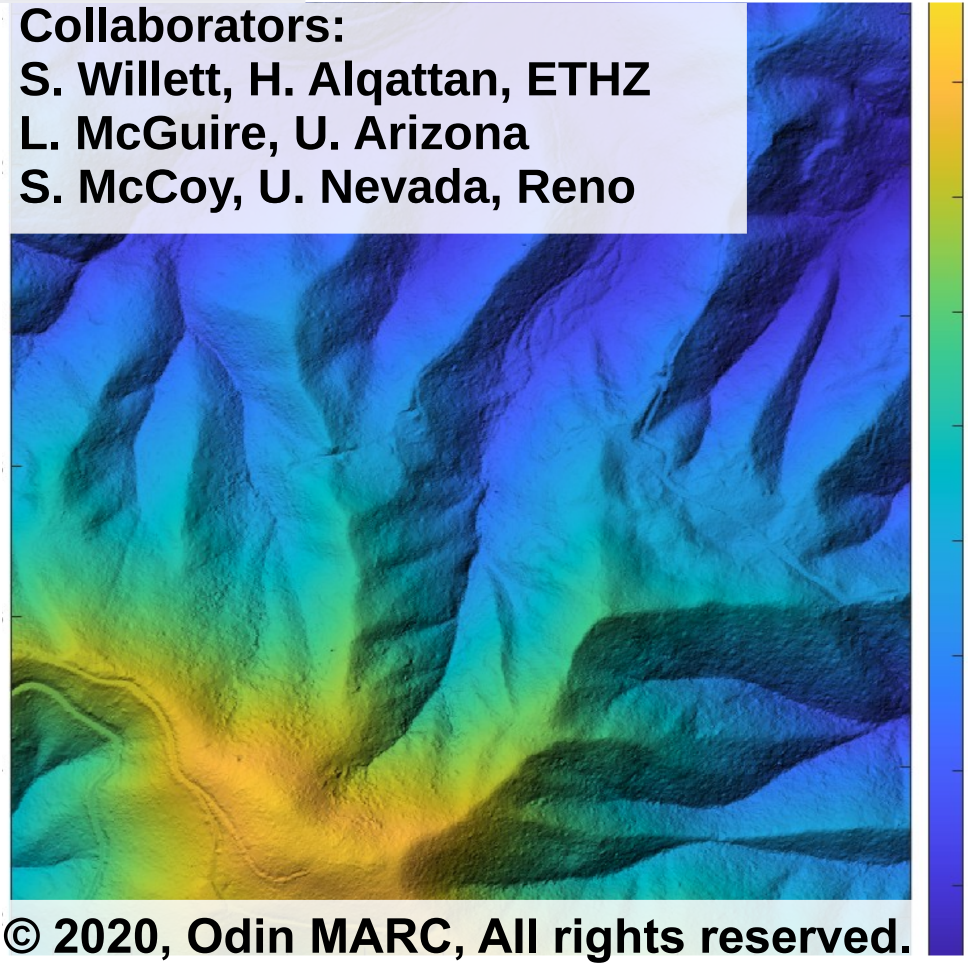
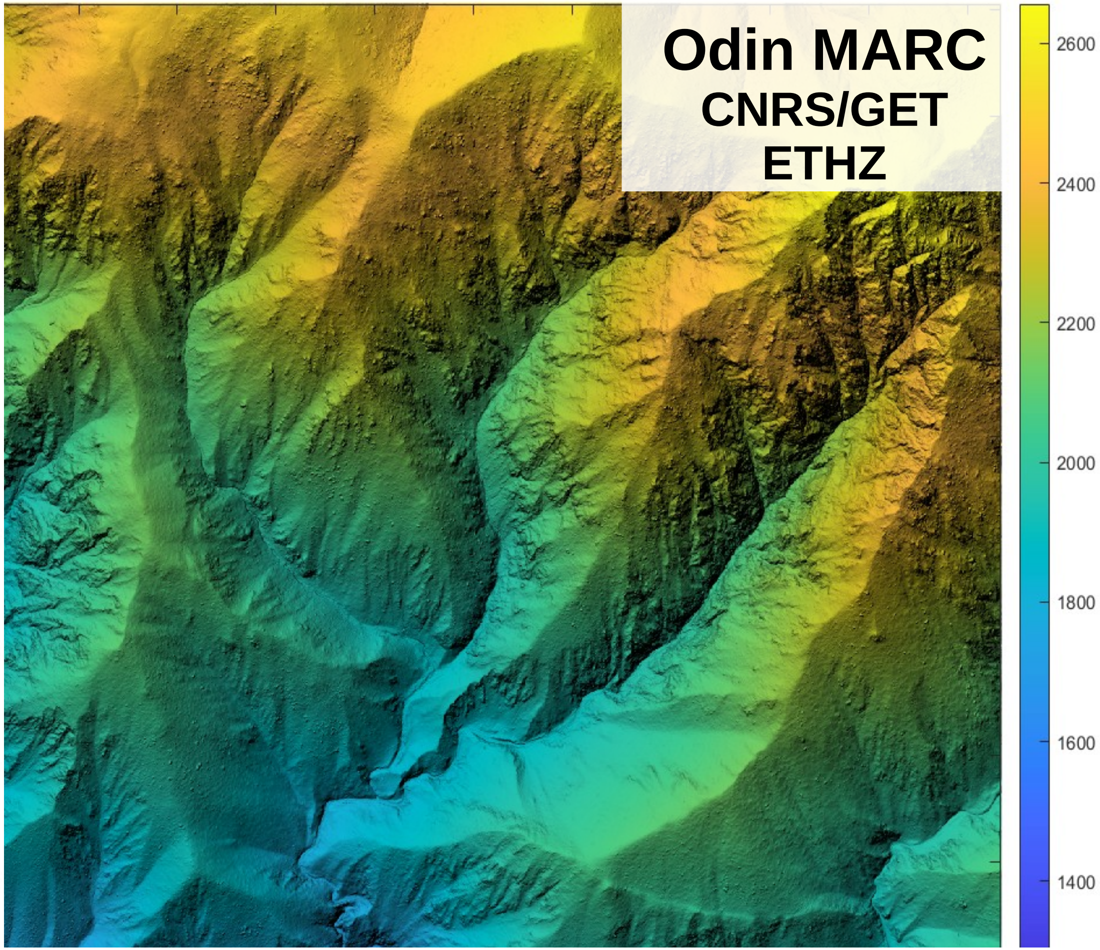


Odin MARC
CNRS/GET
ETHZ



Fluvial scaling seems limited upstream

With,
A=Drainage area
K=Fluvial Erodibility
U=Uplift rate
θ=m/n=concavity

The widely used stream-power incision model state : $E=K\,A^m\,(dz/dx)^n$

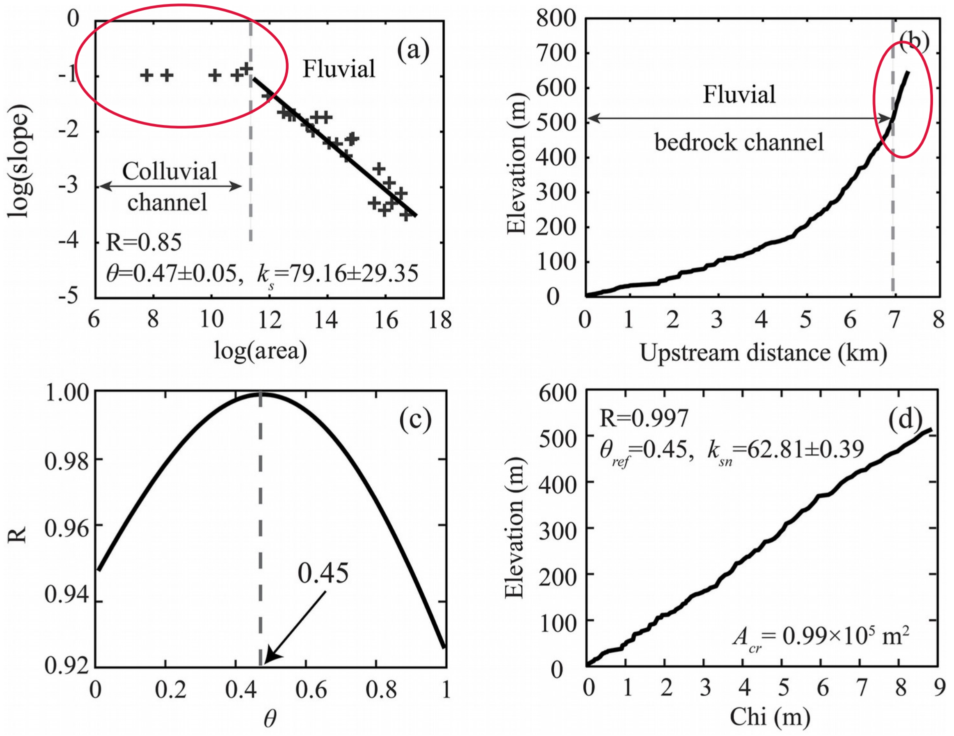
Leading at steady-state to a slope area scaling:

$$dz/dx = (U/K)^{1/n}\,A^{-\theta}$$

Or, in its integral form a proportionality between z and χ

$$z - z_0 = (U/K)^{1/n}\,\chi \text{ with } \chi = \int_0^x \left(\frac{A_o}{A(x')}\right)^{\theta} dx'$$

However, many upstream segments have constant slope. They are considered colluvial channel (DiBiase et al.,2012, Wang et al., 2017) or debris-flow channels (Stock and Dietrich 2003, Penserini et al., 2017)

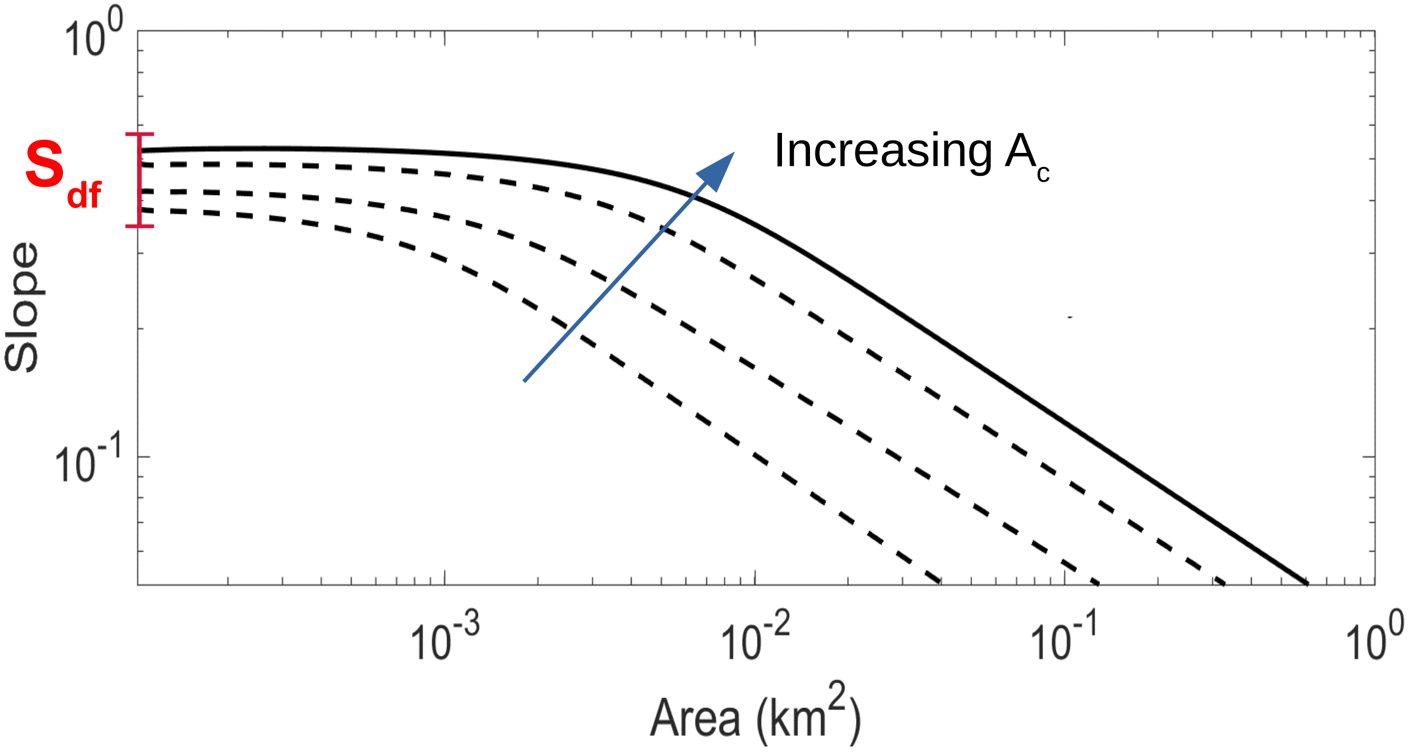


Wang et al., Esurf, 2017

An empirical hybrid model for channel erosion

To describe the slope-area data going to a constant slope upstream, Stock and Dietrich, 2003 prposed a simple mathematical model, that can be rewritten as:

$$\frac{dz}{dx} = \frac{S_{df}}{1+\left(A/A_c\right)^{\theta}}$$



What are typical values of S_{df} and A_c ?

How do they depend on erosion rates and hillslope processes ?

Penserini et al., 2017 suggested that A_c increase with erosion rates but not S_{df}...

We analyzed the morphometry of >60 catchments with LIDAR DEM and average denudation constrained by ^{10}Be.

Consistency of the hybrid model and SPIM: implications

$$\frac{dz}{dx}=\left(\frac{U}{K}\right)^{1/n}\frac{1}{A^{\theta}}$$ Classic SPIM

$$\frac{dz}{dx}=\frac{S_{df}}{1+\left(A/A_c\right)^{\theta}}=\frac{S_{df}\,A_c^{\theta}}{A_c^{\theta}+A^{\theta}}$$ Hybrid model

For consistency the model should match for $A>A_c$. For a small catchment, where the maximum value is A_t (with $A_t>\sim A_c$) we get:

$$\left(\frac{U}{K}\right)^{1/n}=S_{df}\,A_c^{\theta}\left(\frac{A_t^{\theta}}{A_t^{\theta}+A_c^{\theta}}\right)$$

And where A>>Ac (i.e., $A^{\theta}+A_c^{\theta}\sim A^{\theta}$) , we obtain:

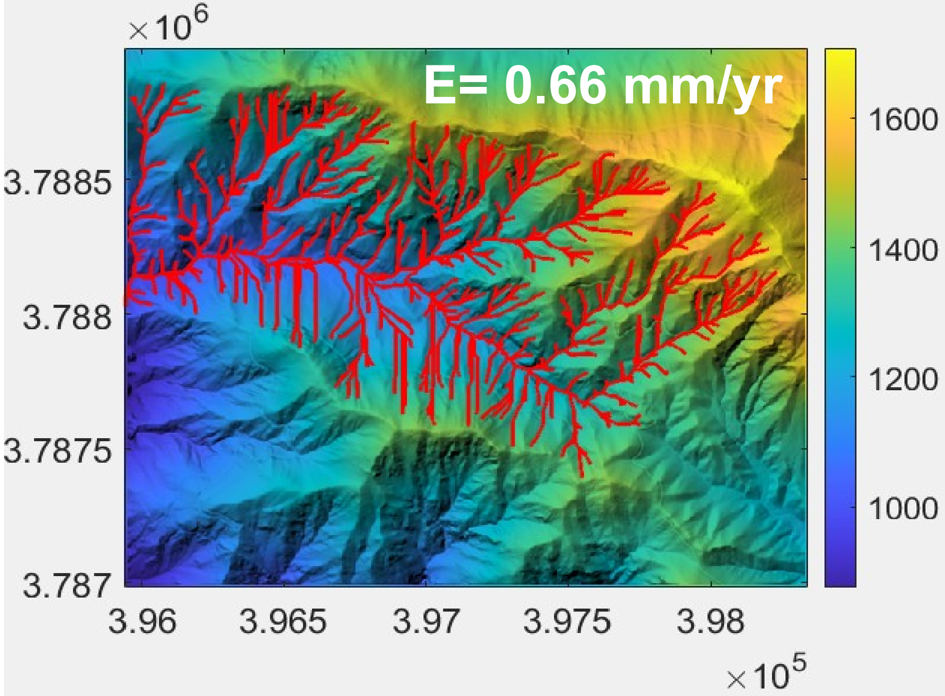
$$\left(\frac{U}{K}\right)^{1/n}\approx S_{df}\,A_c^{\theta}$$

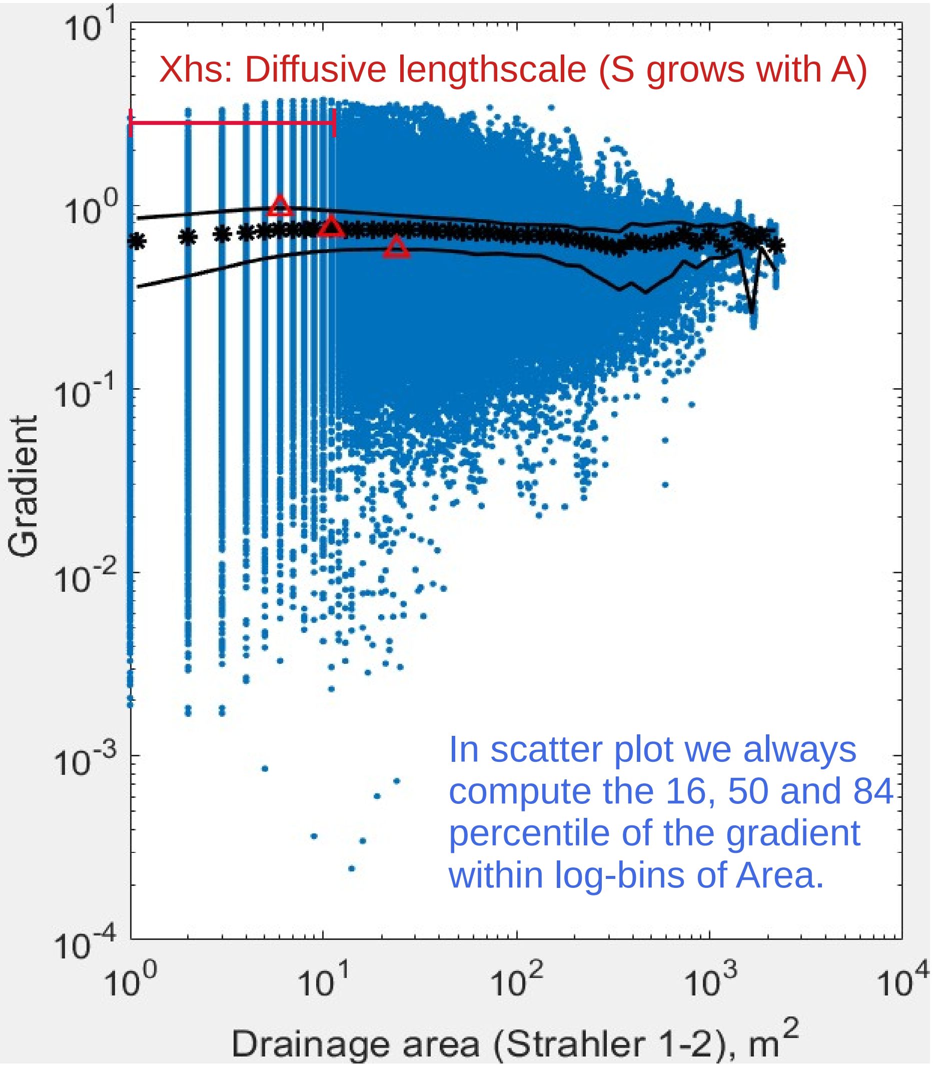
Then note that the integral of the hybrid model yields a modified Chi definition (**Equivalent to Eq. 15 of Hergarten et al., 2016**):

$$z-z_0=S_{df}\frac{A_c^{\theta}}{A_0^{\theta}}\chi_{df}\approx\left(\frac{U}{KA_0^{m}}\right)^{1/n}\chi_{df}$$ With: $$\chi_{df}=\int_0^{x}\left(\frac{A_o^{\theta}}{A(x')^{\theta}+A_c^{\theta}}\right)dx'$$

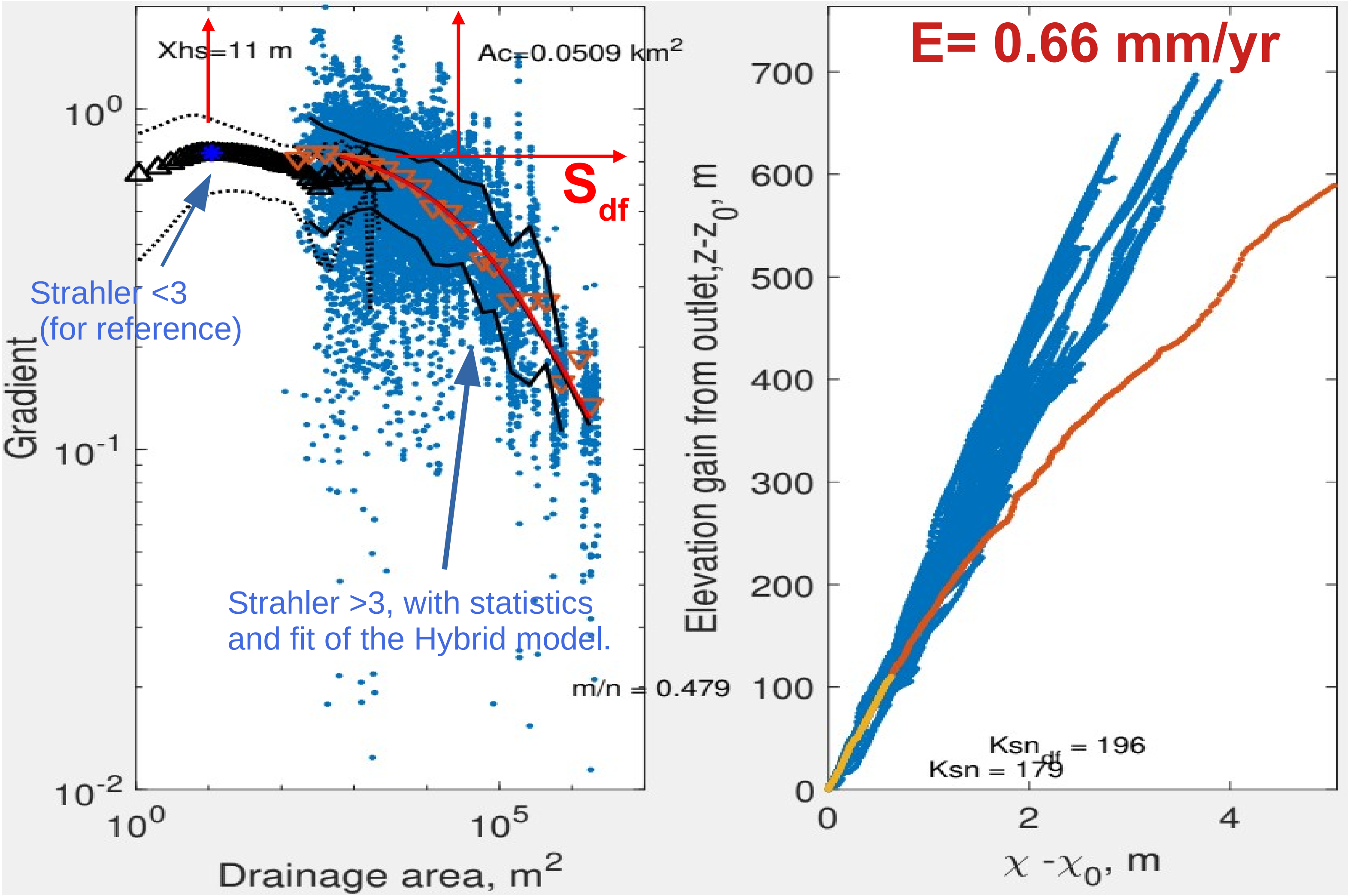
Extracting morphometry from LIDAR DEM: Ex 1

We use a D8 flow routing from the first pixel. Pixels with Strahler order <3 are considered preliminary "hilllsopes", and the others "channels" (below in red).





Extracting morphometry from LIDAR DEM: Ex 1



We fit the slope-area median with the hybrid model and obtain A_c, S_{df} and θ.

We compute the fluvial steepness k_s as the slope of a Chi-Z plot.

Red: Chi for trunk channel

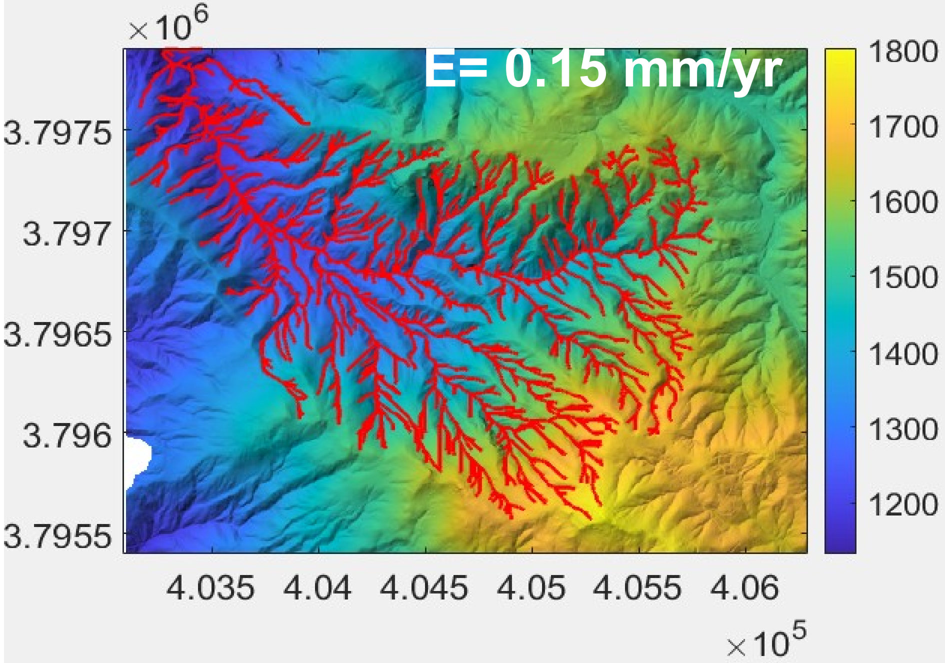
Yellow: idem but where $A>0.66A_t$, A_t the max of A.

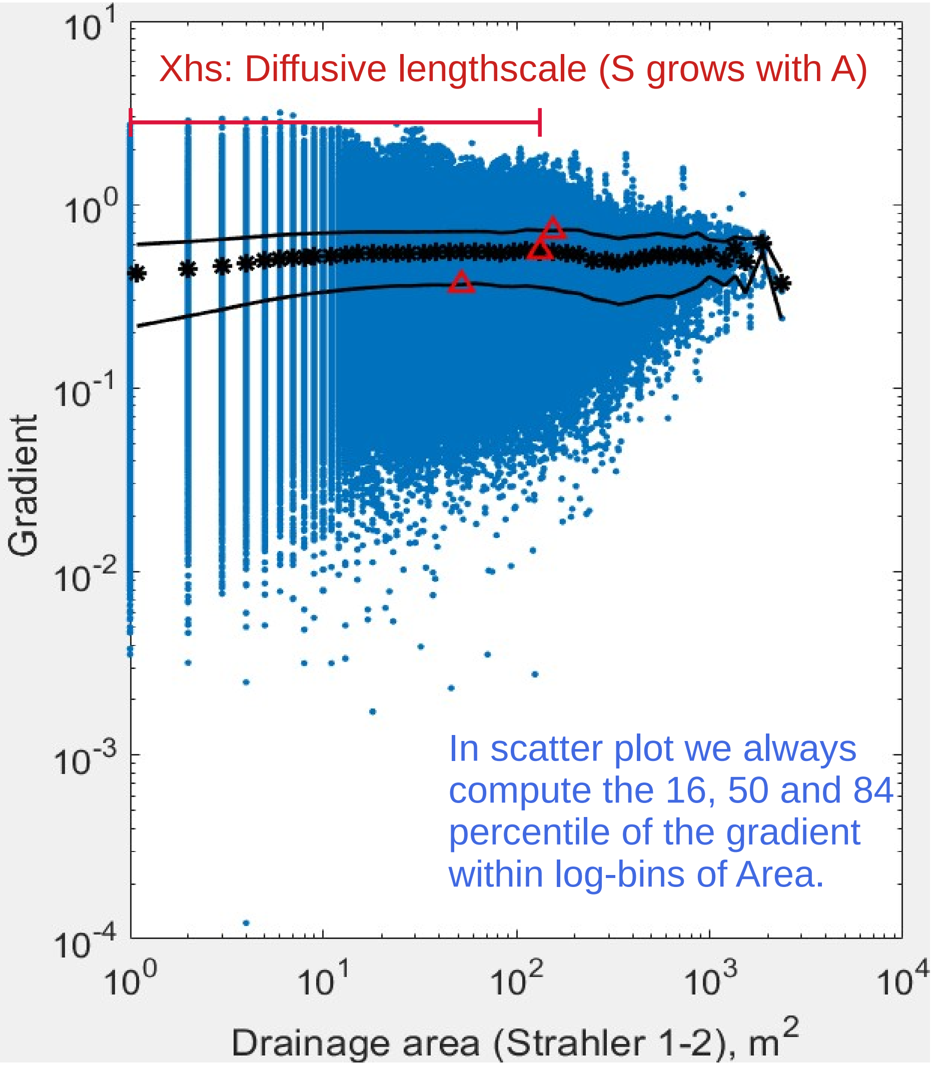
Blue: Chi_df (slide 4) for trunk and tributaries.

k_s and k_{sdf} is extracted from yellow and blue curves, respectively. Note their similar values.

Extracting morphometry from LIDAR DEM: Ex 2

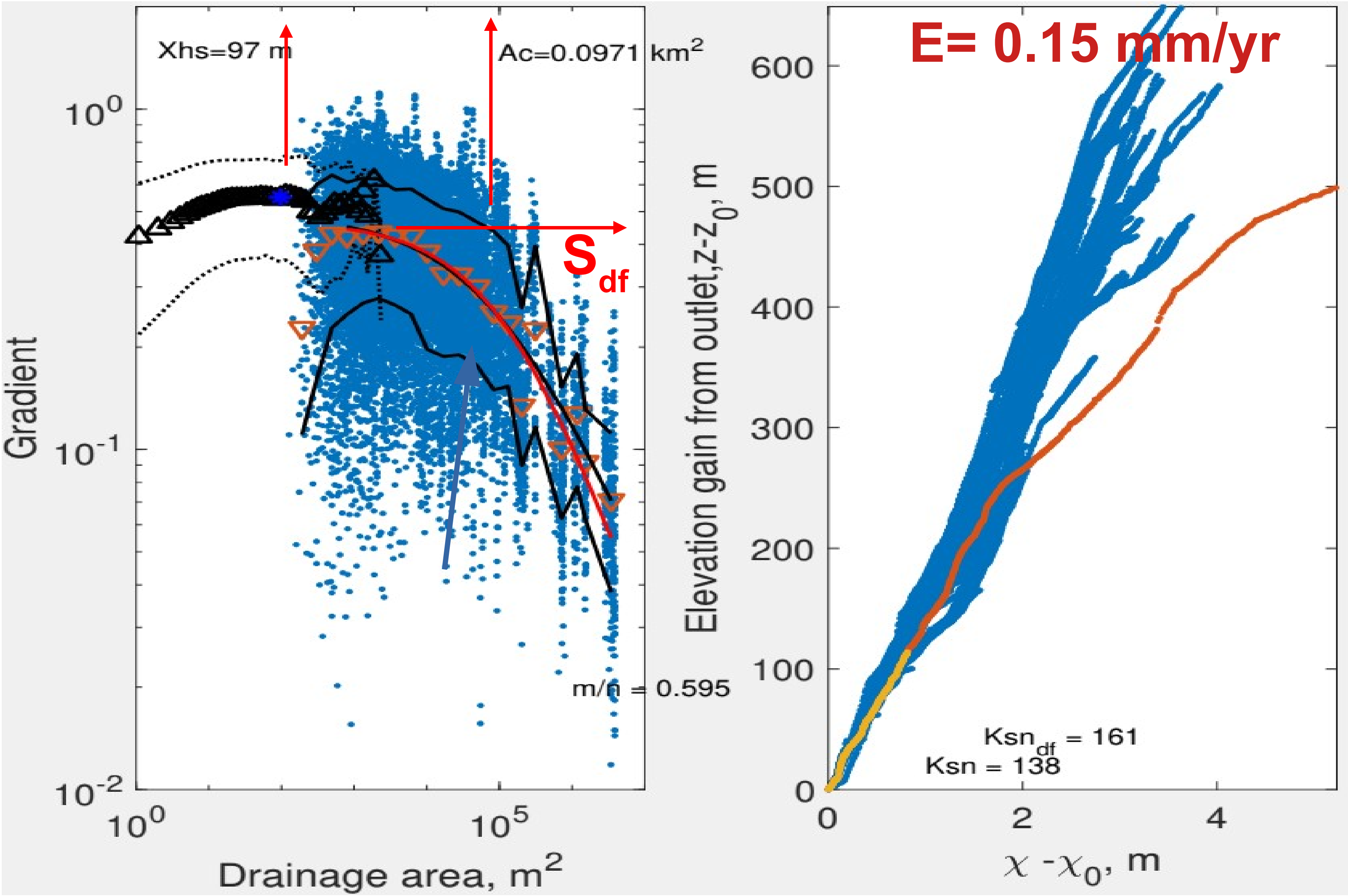
We use a D8 flow routing from the first pixel. Pixels with Strahler order <3 are considered preliminary “hilllslopes”, and the others “channels” (below in red).





In scatter plot we always compute the 16, 50 and 84 percentile of the gradient within log-bins of Area.

Extracting morphometry from LIDAR DEM: Ex 2



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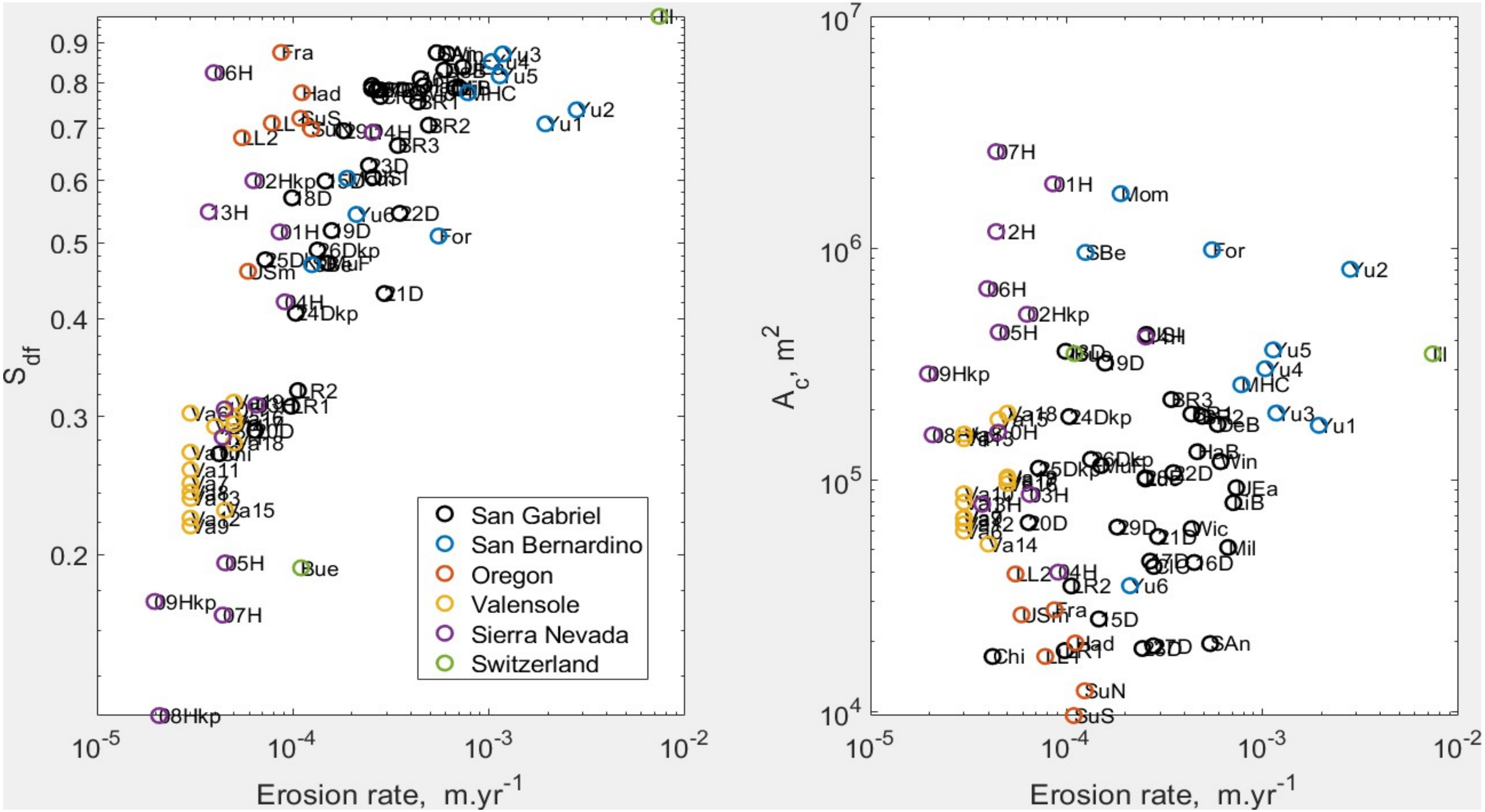
Summary of debris-flows (DF) parameters vs erosion:

1) S_{df} seems to increase with E with saturation near 0.8-1...

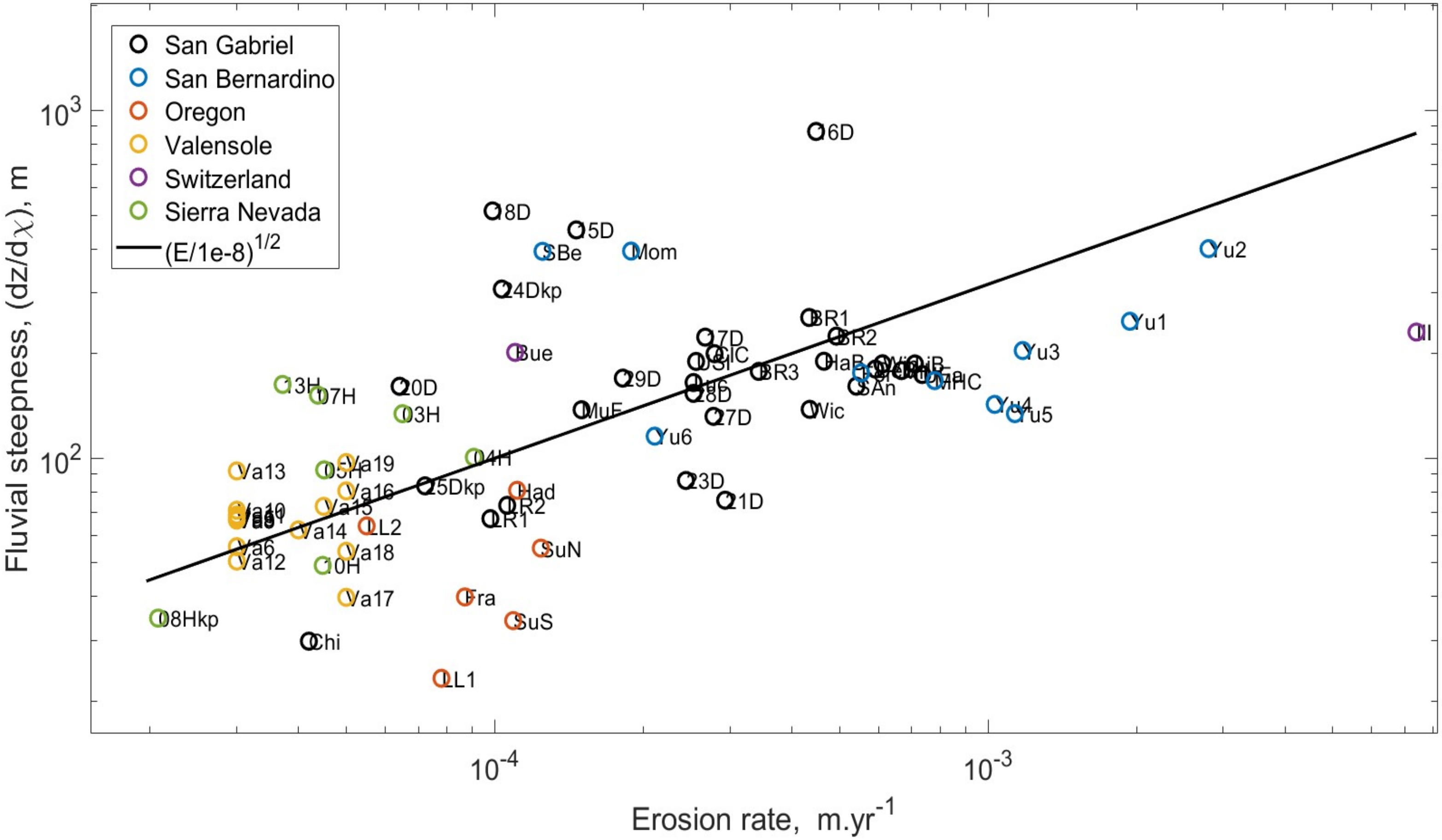


2) Sdf can be pretty low ~0.2 (10°)
But not inconsistent with DF angle of arrest.

3) Unclear for A_c.

→ However we saw (slide 4) that $S_{df}A_c$ scales with U/K. What about variability in K ?

Steepness against erosion: we expect $k_s=(E/K)^{1/n}$



[10]Be Erosion rates:

S. Gab: DiBiase et al., 2010, 2012

S. Ber: Binnie et al., 2007

Oregon: Penserini et al., 2017,

Valensole: Godard et al., 2020

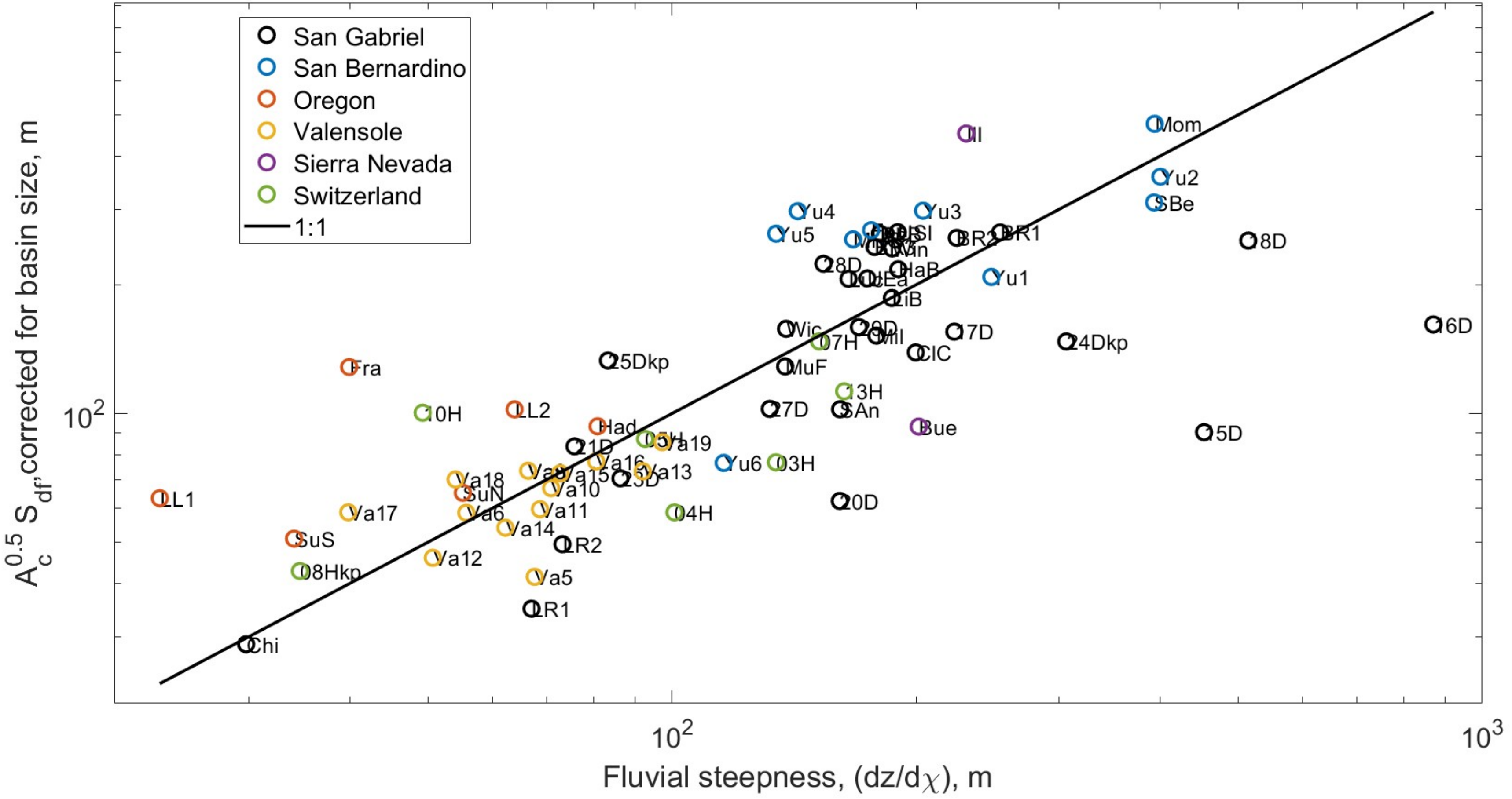
Switerzland

Sierra Nev.: Hurst et al., 2012.

→Global n rather near 2 than 1. In any case K is quite variable...
→ Let's compare A_c to steepness...

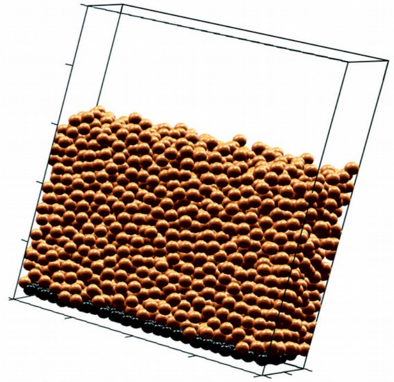
Debris-flow steepness match fluvial steepness

So knowing k_s and S_{df} we can find A_c ! But what controls S_{df} ?



Debris-flow mechanics from granular model

(courtesy S. McCoy/ L. McGuire)

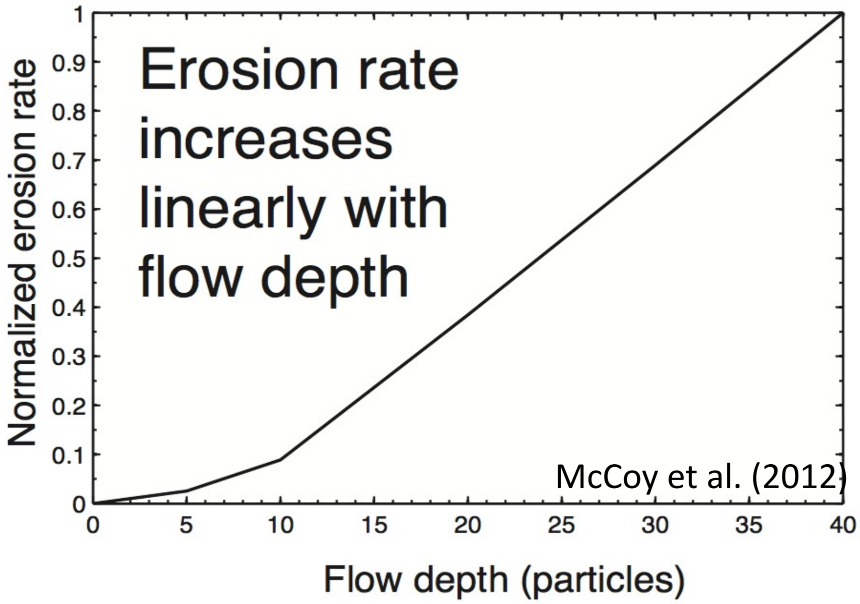


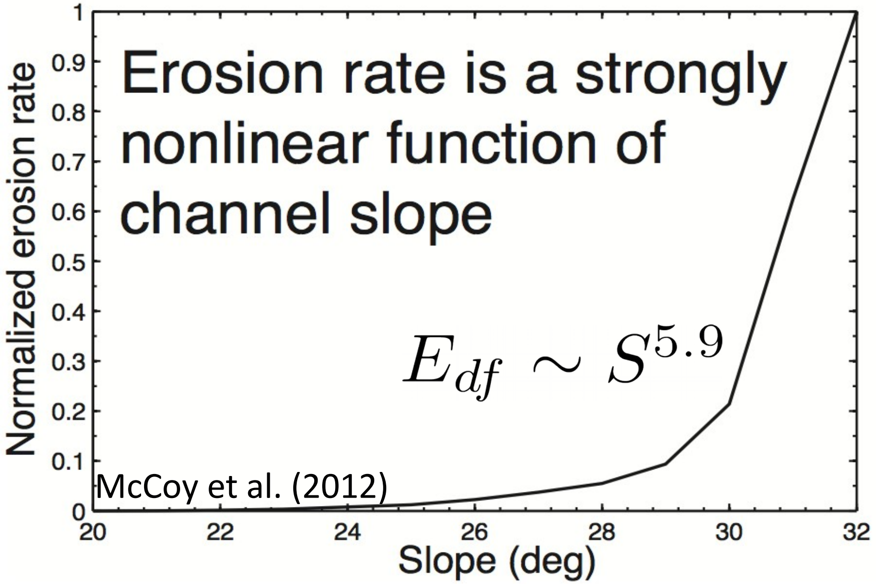
Volume eroded by impact

Impact frequency

Impact intensity

Debris flow Erosion rate $= E_{df} = V_i I_f = k_{df} I_i I_f$ (e.g. Sklar and Dietrich, 2004)





Implications of granular model scaling:

$E_{df} \propto H_{df} \left(\frac{dz}{dx} \right)^{n_{df}}$, with n_{df}~5-6, and H_{df} the DF flow height, proportional to initial volume, V_i.

Further the long term erosion will depend on DF frequency, yielding: $E_{df} \propto F_{df} V_i \left(\frac{dz}{dx} \right)^{n_{df}}$

At steady-state $U=E_{df}$ and the $F_{df}V_i$ should be proportional to the sediment flux equal to UA_{hs}.

Assuming $A_{hs} = w_c X_{hs}^2$ we obtain: $U = E_{df} \propto U X_{hs}^2 \left(\frac{dz}{dx} \right)^{n_{df}}$

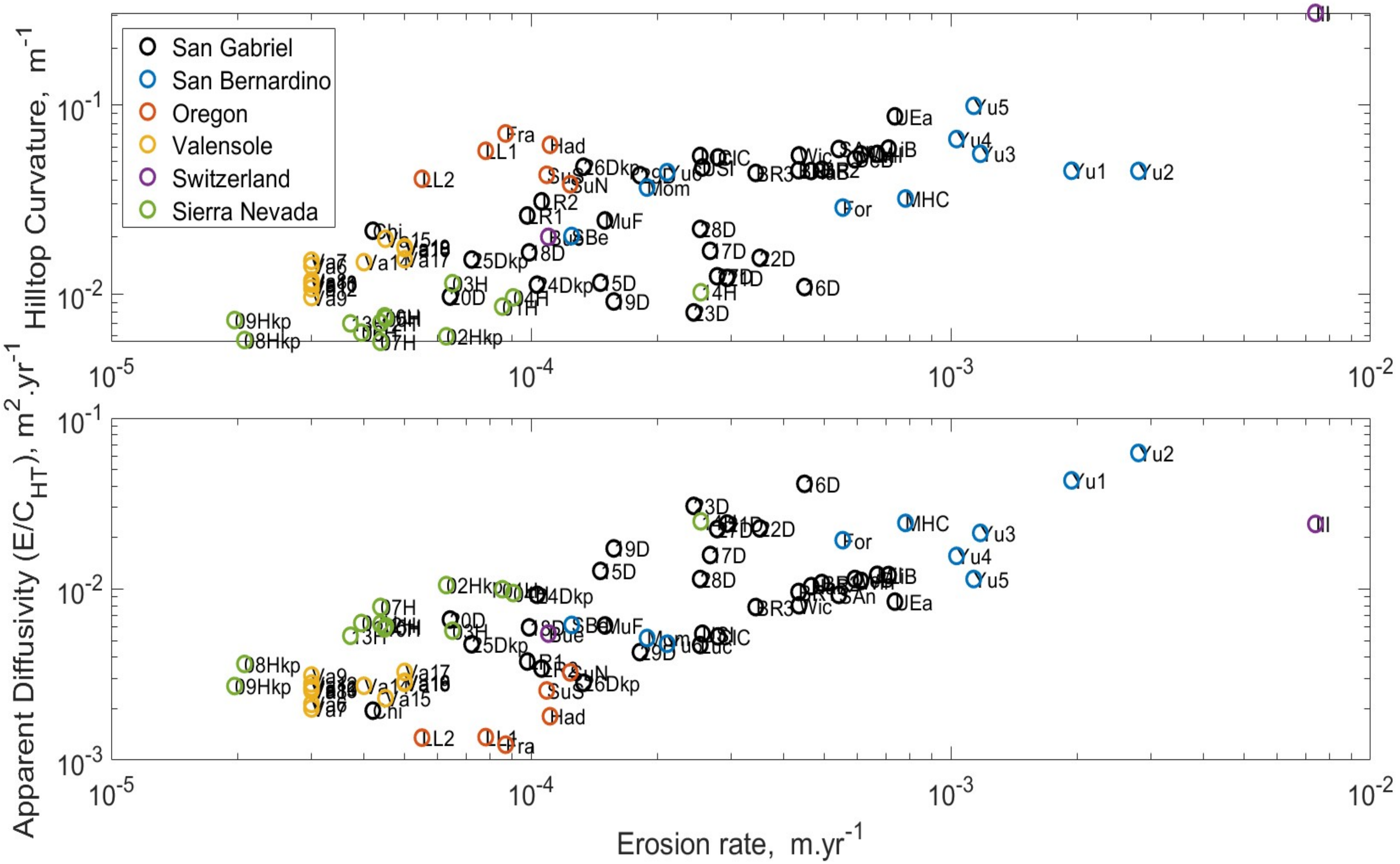
And therefore: $S_{df} \propto X_{hs}^{-2/n_{df}}$

Can we validate this scaling ? What control X_{hs} ? If we assume a simple diffusive hillslope that ends when its gradient is reaching S_{df}, (i.e., $S_{df}=UX_{hs} / D$) we obtain :

$$\boxed{S_{df} \propto \left(\frac{U}{D} \right)^{\frac{2}{(n_{df}+2)}} \qquad X_{hs} \propto \left(\frac{D}{U} \right)^{\frac{n_{df}}{(n_{df}+2)}}}$$

→ We also need to constrain D! For example by extracting hilltop curvature.

Estimation of Hilltop curvature and diffusivity



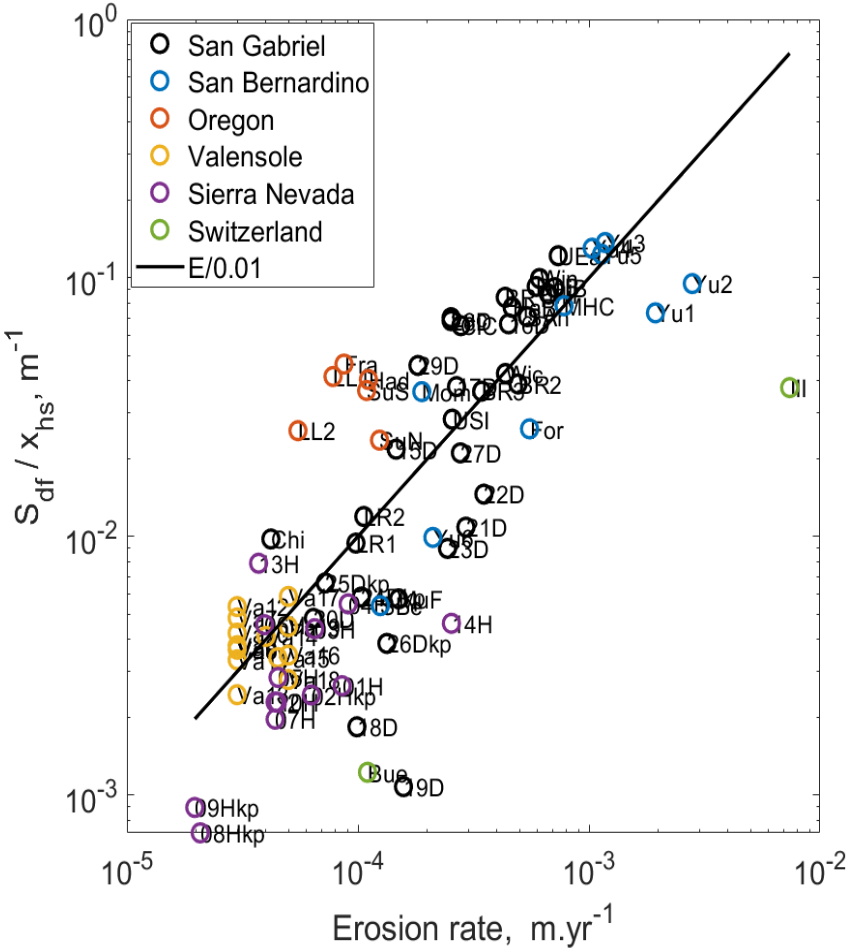
We implement a method similar to the one proposed by Hurst et al., 2012.

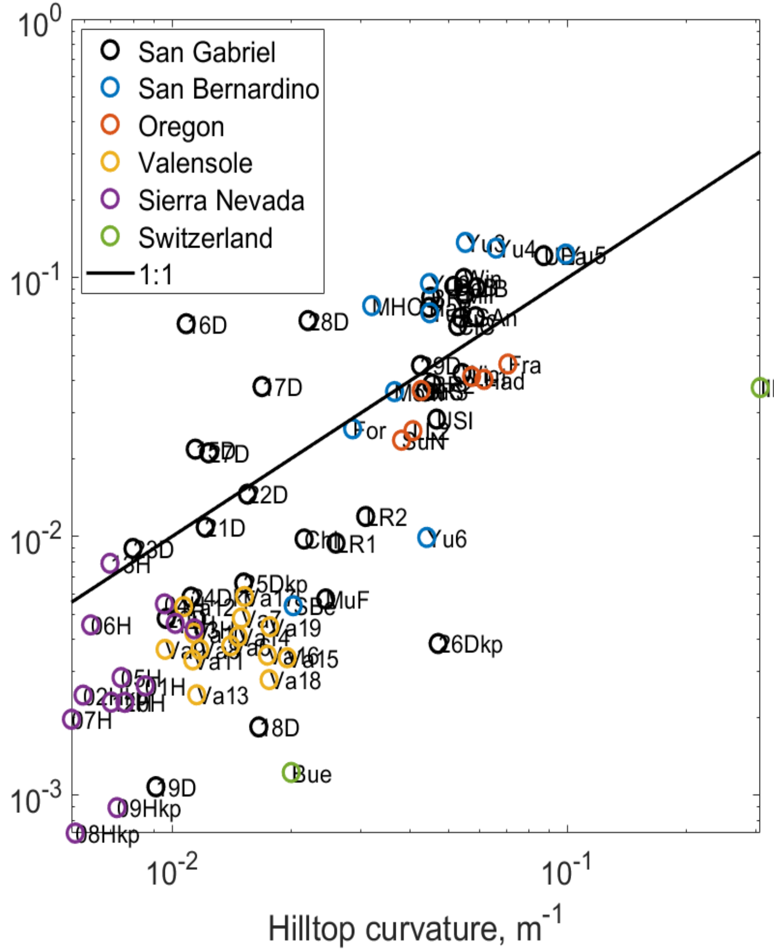
However CHT seems to increase sublinearly with E.

And thus D to increase with E.

Hillslope length and maximum slope:

Diffusion theory : S_{hs} = U/D X ; U/D = C_{HT}. Is max(S_{hs})=S_{df} ? → matches better E/0.01 than C_{ht}





Is the apparent increase in diffusion an artifact ?

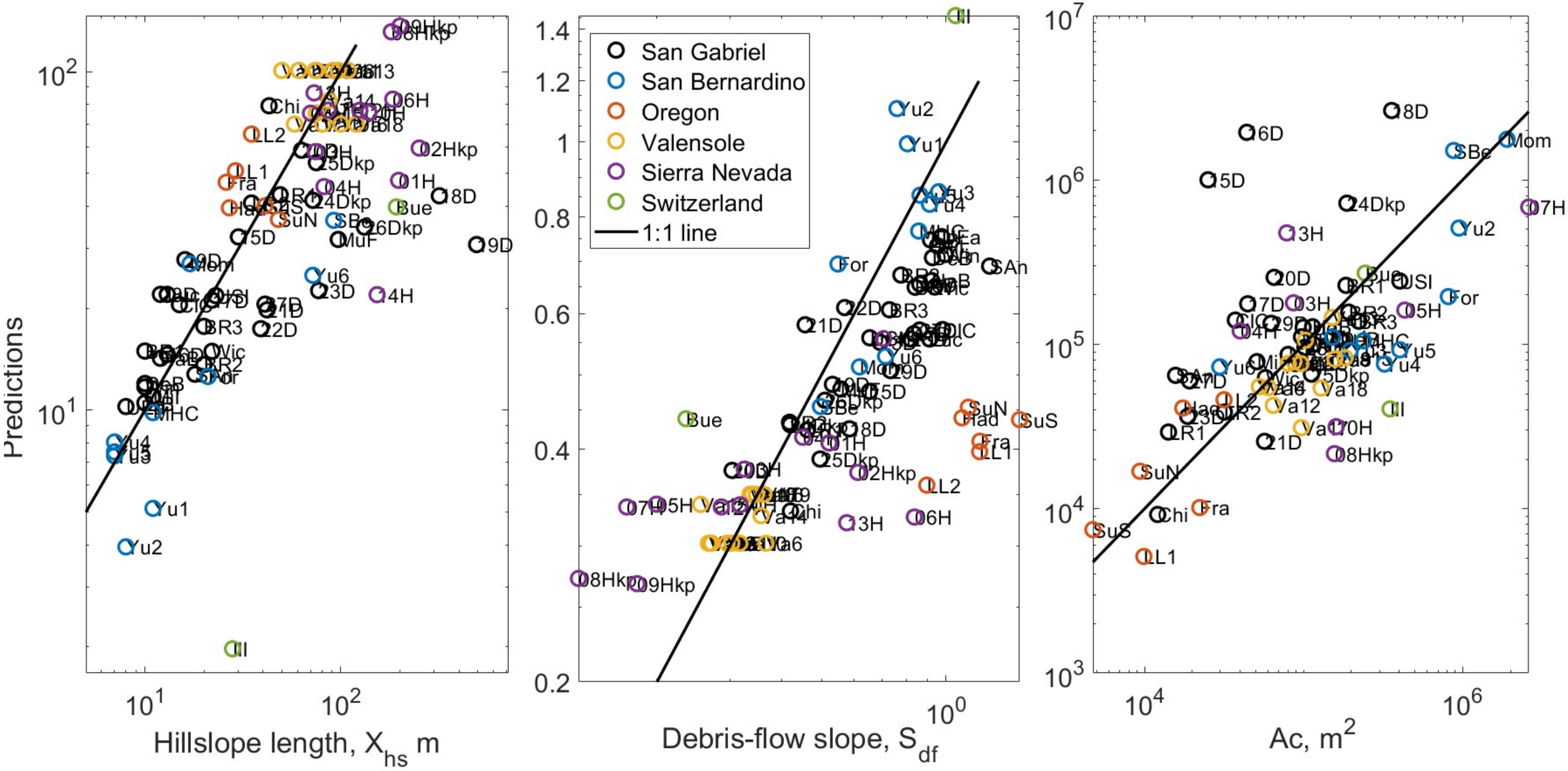
Or U/D is different of C_{HT} , ?

because of soil depth variations ?

Anyway we next assume D=0.01 to try to predict X_{hs}, S_{df} and A_c.

Predictions based on global parameters

Variable : E, K ; Fixed : D=0.01; n=2; m=1 ; n_{df}=5 ; Hacks constant. Eq. On slide 4 and 13.



Conclusions:

With LIDAR and ^{10}Be data we constrained relations between erosion rate E, fluvial erodibility K, hillslope diffusivity D and debris flow parameters A_c and S_{df}. Our major findings are:

→ Fluvial network systematically overprinted by DF upstream of 0.5-5 km^2. The upstream limit of SPIM can be found based on A_c, when knowing S_{df} and the steepness.

As a result a DF-corrected version of χ is proposed and validated (as in Hergarten et al., 2016).

→ We found S_{df} between 0.2 and 0.9, varying with E but also with the length of diffusive hillslopes, X_{hs}. Although it does not match perfectly with our estimate of D based on curvature, the assumption that hillslopes are diffusive and end where their gradient reach S_{df} is fair.

→ The (bidirectional) coupling of X_{hs} and S_{df} means that, knowing U, D and DF mechanics constant allow to predict X_{hs} and S_{df}. Then knowing fluvial steepness, A_c can be found and a profile from divide to the fluvial domain can be fully predicted.

Future work : → Include variable m/n (in this presentation we fixed m/n=0.5, often but not always matching the best-fit to the data…)

→ Better understand the relations between E, D and C_{ht} .

→ Implement the predictions into the numerical model DAC (Divide And Capture).