Similitude

in Sediment Transport Processes

Oscar Link

Department of Civil Engineering

Faculty of Engineering

Universidad de Concepción

www.udec.cl/~olink

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Outline

1.- Relevance / Motivation / Background

2.- Modelling the sediment transport

3.- Modelling the bridge pier scour

Relevance / Motivation / Background

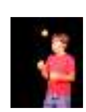
To build physical scale models of complex situations without known solution

To develop formulas from laboratory experiments for estimation of key parameters, such as the scour depth around piles

Relevance / Motivation / Background

Identic

Similar



Distorted

Heller, V. (2011). Scale Effects in Physical Hydraulic Engineering Models. Journal of Hydraulic Research, 49(3), 293-306.

Heller, V. (2017). Self-similarity and Reynolds number invariance in Froude modelling. Journal of Hydraulic Research, 55(3), 293-309.

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Relevance / Motivation / Background

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Dimensional analysis and similitude theory

Fluid: density, viscosity

Flow: gravitational acc., velocity, depth

Sediment: size, density

Obstacle: Length scale

Time

A variable of interest: i.e. scour depth

$$f(\rho, \mu, g, u_{ef}, h, d_s, \rho_s, D, t, z) = 0$$

$$f\left(\mathrm{Re}', Fr', \rho', \frac{h}{d_s}, \frac{D}{d_s}, \frac{u_{ef}t}{d_s}, \frac{z}{d_s}\right) = 0$$

➔It is impossible to have identic *Re* and *Fr* in prototype and scale model

$$\lambda_{\mathrm{Re}} \neq \lambda_{Fr} = 1$$

➔Scale effects arise

Buckingham, E. (1914). On physically similar systems; illustrations of the use of dimensional equations. Physical review, 4(4), 345.

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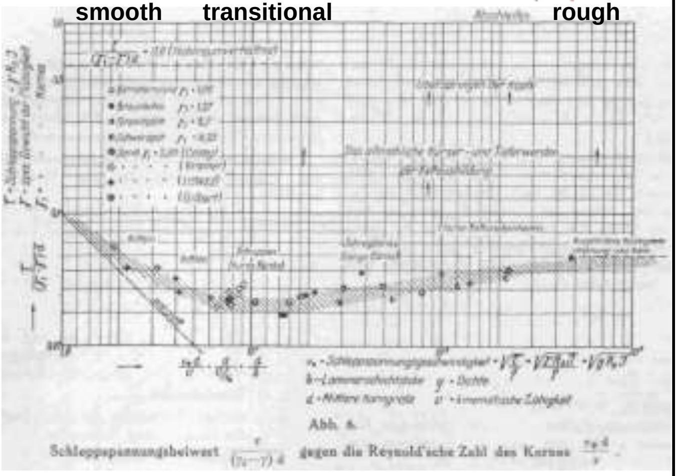
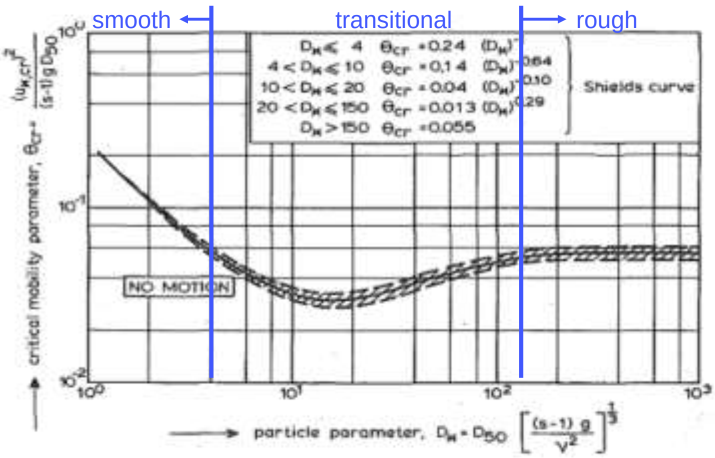
$$\theta_{cr} = \frac{u_*^2}{\rho' g d} = f(\mathrm{Re}_*)$$



Shields A (1936) Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung. PhD Thesis. TU Berlin.
Mantz PA (1977) Incipient transport of fine grains and flakes by fluids-extended shield diagram. Journal of the ASCE Hydraulics Division, 103(12992).
Yalin MS & Karahan E (1979) Inception of sediment transport. Journal of the ASCE Hydraulics Division, 105(11): 1433-1443.

Modelling the sediment transport

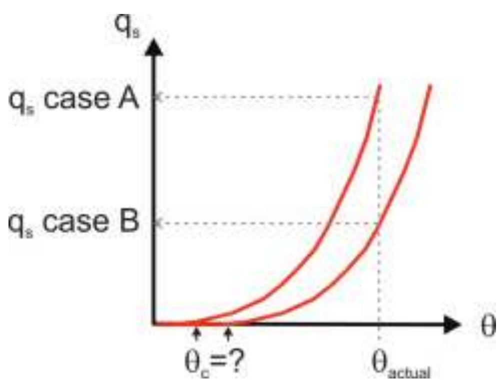
$$D^* = \left(\mathrm{Re}_*^2/\theta\right)^{1/3} = \left(\left(\rho' g\right)/\nu^2\right)^{1/3} d_s$$



van Rijn LC (1984) Sediment transport: Part I: Bed load transport. Journal of Hydraulic Engineering 110(10): 1431–1456.

Modelling the sediment transport

$$q_s = f\left(\theta_{actual} - \theta_c\right)^{\alpha}$$

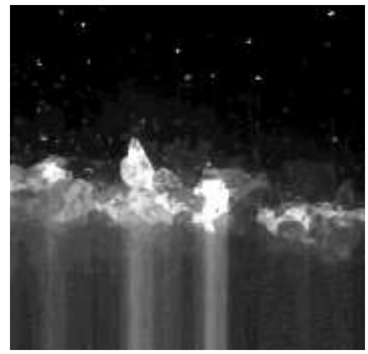


Modelling the sediment transport

A flow producing the same sediment behavior is needed, but taking Fr similarity...

$$\lambda_{Fr} = 1 \qquad \lambda_g = 1:100$$

$$\frac{u_m}{\sqrt{gh_m}} = \frac{u_p}{\sqrt{gh_p}}$$



Video: Prof. M.Schmeeckle, http://www.public.asu.edu/~mschmeec/

$$\rightarrow u_m = u_p \sqrt{\lambda_g} \approx 0.1 u_p$$

We can‘t use the same sediment in model and prototype

Modelling the sediment transport

Lightweight material	d_s (mm)	Specific gravity (-)	D* (-)	Equivalent sand (mm)
Acrylonitrile butadiene styrene (ABS)	2.3-3.0	1.22	30-39	1.18-1.53
Bakelite	0.35-4.0	1.30-1.45	5-66	0.2-2.59
Coal	0.1-40.0	1.37-1.61	1.5-726	0.06-28.70
Lightweight Aggregate	1.0-3.0	1.70	19-57	0.75-2.25
Perspex	0.3-1.0	1.18-1.19	3.6-12.3	0.14-0.49
Polyamidic Resins (Nylon)	0.1-5.0	1.16	1.2-58.1	0.05-2.30
Polystyrene	0.5-3.2	1.035-1.05	3.5-25.2	0.14-1.00
PVC	1.5-4.0	16.70	16.7-53.9	0.66-2.13
Sawdust treated with Asphalt	0.6-1.0	1.05	4.7-7.9	0.19-0.31
Sand of Loire	0.63-2.25	1.50	10.7-38.2	0.42-1.51
Walnut Shells, Ground	0.15-0.41	1.33	2.2-6.1	0.09-0.24
Granulated Obeche wood	0.8	1.10	7.9	0.31

Bettess, R. (1990). Survey of lightweight sediments for use in mobile-bed physical models. in Movable Bed Physical Models (pp. 115-123). Springer, Netherlands.

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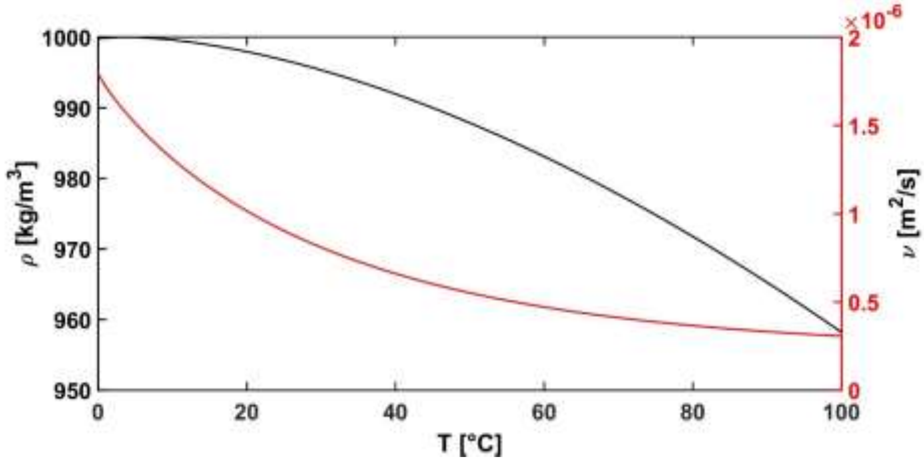

Heggen RJ (1983) Thermal dependent physical properties of water. Journal of Hydraulic Engineering 109(2):298-302

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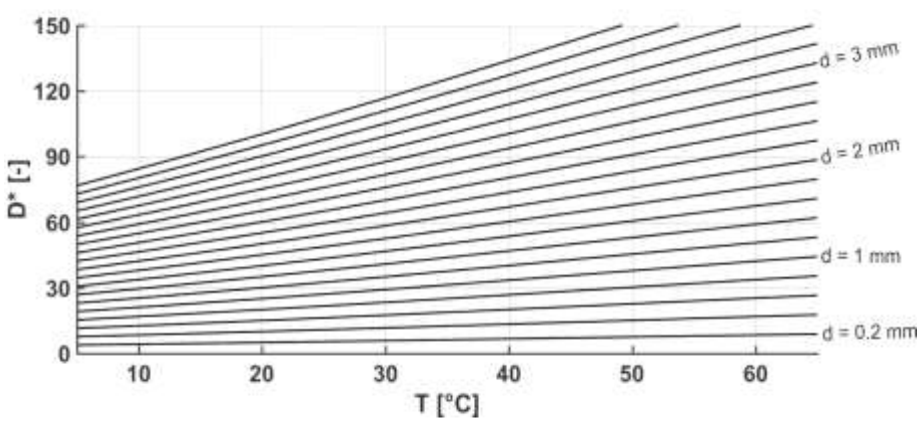

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Is it incipient motion or not?

Classic criteria:

Kramer (1932, 1935)
US WES (1935)
Shields (1936)

Keshavarzy & Bell (1999): ~10%

Keshavarzy A & Ball JE (1999) An application of image processing in the study of sediment motion. Journal of hydraulic research, 37(4): 559-576.

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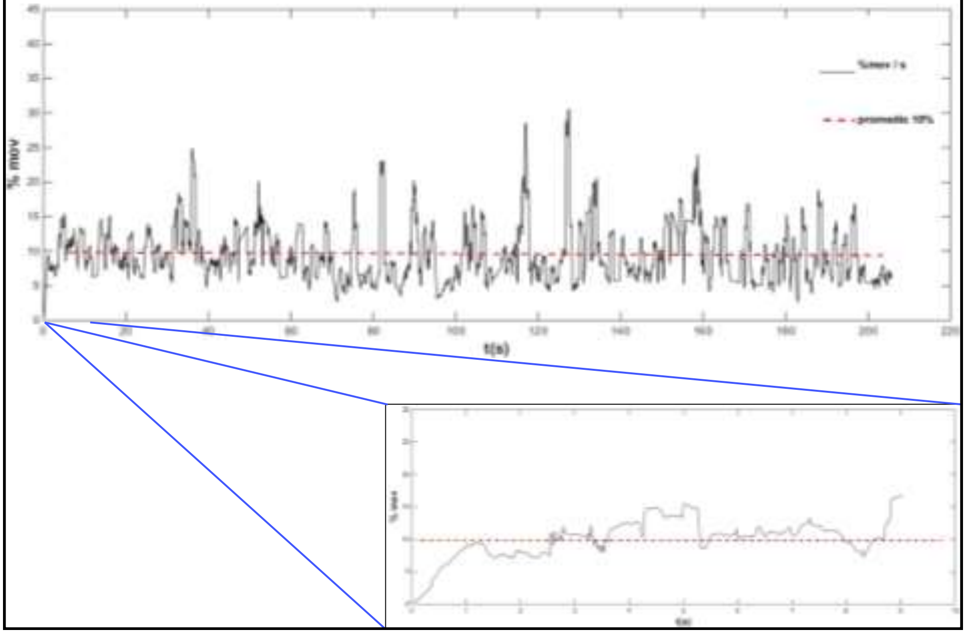

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Serie experimental_Estado mov [d_{50} = 0.36 mm]						
Serie 1(T°)	Ensayo N°	h (cm)	Q_c (l/s)	U_c (cm/s)	%mov	Cond. Incipiente
6°C	E1	12	15.5	32.05	9.0%	
	E2	12	15.8	32.67	10.4%	OK
10°C	E1	12	15.0	31.02	10.2%	OK
	E2	12	15.5	32.05	11.5%	
20°C	E1	12	15.0	31.02	10.0%	OK
	E2	12	15.5	32.05	12.0%	
40°C	E1	12	13.5	27.92	8.0%	
	E2	12	14.0	28.95	9.8%	OK
53°C	E1	12	13.8	28.54	10.2%	OK
	E2	12	13.5	27.92	8.0%	

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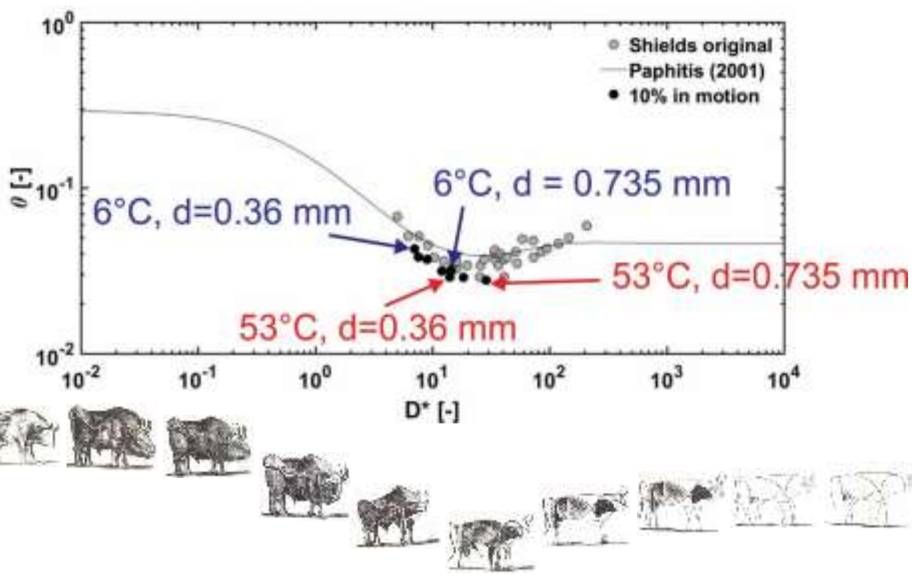

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Modelling the bridge pier scour

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$\overset{?}{\approx}$

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$$f(\mu, \rho, u_{ef}, h, g, d_s, \rho_s, D, t, z) = 0$$

$$f\left(\mathrm{Re}', Fr', \rho', \frac{h}{d_s}, \frac{D}{d_s}, \frac{u_{ef}t}{d_s}, \frac{z}{d_s}\right) = 0$$

"*The use of laboratory flumes in developing accurate predictors of scour depth at full-scale piers is limited due to scale effects that may produce greater scour depths at the laboratory than at actual piers in rivers*" (Ettema et al. 1998)

Ettema et al.(1998) Scale Effect in Pier Scour Experiment. J. of Hydraulic Engrg. 124(6):639-642.
Ettema et al. (2006) Similitude of Large-Scale Turbulence in Experiments on Local Scour at Cylinders. J. of Hydraulic Engrg. 132(1):33-40.
Cheng et al. (2016) Scaling Analysis of Pier-Scouring Processes. J. of Engrg Mechanics. DOI: 10.1061/(ASCE) EM.1943-7889.0001107

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$$D^* = \left(\mathrm{Re}'^2 / \left(Fr'^2/\rho'\right)\right)^{1/3} = \left(\left(\rho' g\right)/\nu^2\right)^{1/3} d_s$$

$$Fr_d = Fr'\left(\rho'\right)^{-0.5} = u_{ef} \Big/ \sqrt{\rho' g d_s}$$

$$U^* = 2\left(u_{ef} t/d_s\right)\left(D/d_s\right)^{-2} = u_{ef} t \Big/ \left(D^2/2d_s\right) = u_{ef} t / z_R$$

$$Z^* = \left(z/d_s\right)\left(D/d_s\right)^{-1} = z/D$$

$$Z^* = f\left(D^*, Fr_d, \rho', \frac{h}{d_s}, \frac{D}{d_s}, U^*\right)$$

Pizarro A, Ettmer B, Manfreda S, Rojas A & Link, O. (2017) "Dimensionless, Effective Flow Work for Estimation of Pier Scour caused by Flood Waves". Journal of Hydraulic Engineering. 143(7):1-7.
Link O, Castillo C, Pizarro A, Rojas A, Ettmer B, Escauriaza C & Manfreda S. (2017) "A model of bridge pier scour during flood waves". Journal of Hydraulic Research, 55(3):310-323.

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$$w \propto \tau_0 u \longrightarrow \tau_0 \propto \rho u^2 \longrightarrow w \propto u^3$$

$$w_{ef} \propto \int u_{ef}{}^3 \delta dt \qquad \delta = \begin{cases} 0 & u/u_{cs} < 1.0 \\ 1 & u/u_{cs} \geq 1.0 \end{cases}$$

$$u_R = \sqrt{\rho' g d_s} \qquad t_c = \frac{D^2}{2 d_s u_{ef}}$$

$$W^* \propto \int_0^{t_{end}} \frac{1}{t_c}\left(\frac{u_{ef}}{u_R}\right)^3 \delta\, dt = \int_0^{t_{end}} \frac{u_{ef}}{\left(D^2/2d_s\right)}\left(\frac{u_{ef}}{u_R}\right)^3 \delta\, dt = \int_0^{t_{end}} Fr_d{}^3 \frac{u_{ef}}{z_R} \delta\, dt$$

$$W^* \propto \int_0^{t_{end}} Fr_d{}^3 \frac{u_{ef}}{z_R} \delta\, dt$$

Bagnold (1966); Lai et al. (2009); Oliveto & Hager (2002); Guo (2014)

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Hypothesis:

$$Z^* = f\left(W^*, D^*, \frac{D}{d_s}\right)$$

Similitude:

$$\lambda_{Z^*} = \lambda_{W^*} = \lambda_{D^*} = \lambda_{D/d_s} = 1$$

Time scale:

$$\lambda_t = \left(\frac{u_{ef,p}}{u_{ef,m}}\right)^4 \left(\frac{D_m}{D_p}\right)^2 \left(\frac{\rho'_m}{\rho'_p}\right)^{3/2} \left(\frac{d_{s,m}}{d_{s,p}}\right)^{1/2} = \lambda_{u_{ef}}^{-4} \lambda_D^2 \lambda_{\rho'}^{3/2} \lambda_{d_s}^{1/2}$$

Link O, Henríquez S & Ettmer B (2018) Physical scale modelling of scour around bridge piers. Journal of Hydraulic Research, (*accepted for publication*).

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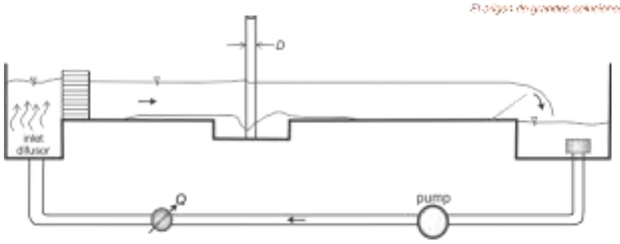
	D	B
Flume 1	0.150	1.4
Flume 2	0.046	0.4
Flume 3	0.030	0.3



	d_s (mm)	ρ (t/m³)	D*
Sand 1	0.36	2.65	9
Sand 2	0.74	2.65	18
Sand 3	0.80	2.65	21
Sand 4	1.60	2.65	40
Acetal	2.60	1.39	41
Polystyrene	2.74	1.04	20

5 Series with 17 experiments:

S1: same sediment, unsteady Q

S2: sand vs polyst, clear-water and live -bed

S3: sand vs polyst, steady Q up to eq. scour

S4: different flow intensities to test time scale

S5: different D / d_s to test scale effects

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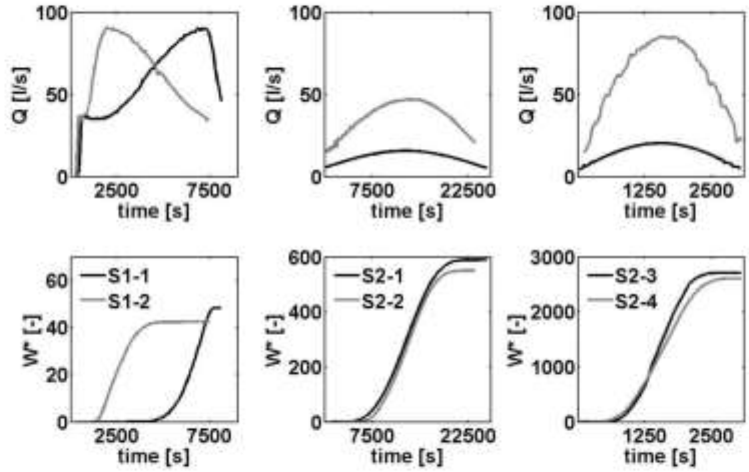
Series S1 and S2: Unsteady flow



Clear water, only sand

Clear water, sand v/s polystyrene

Live bed, sand v/s polystyrene

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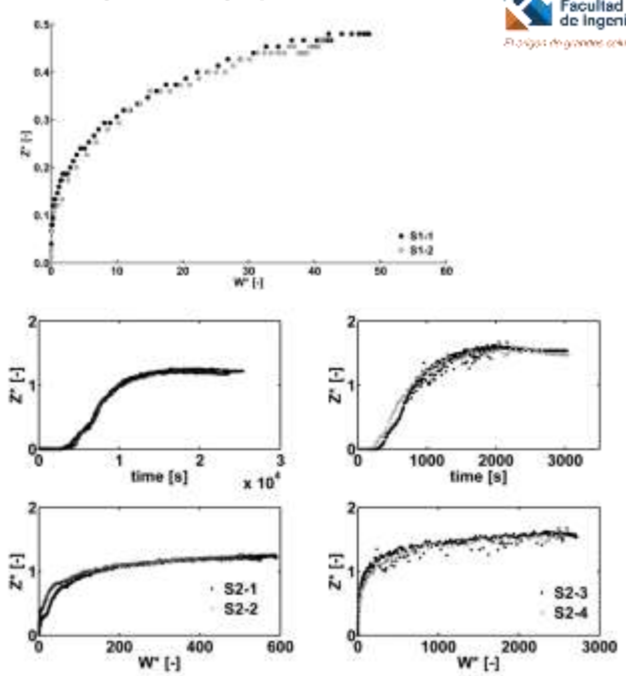
The flow parameter:



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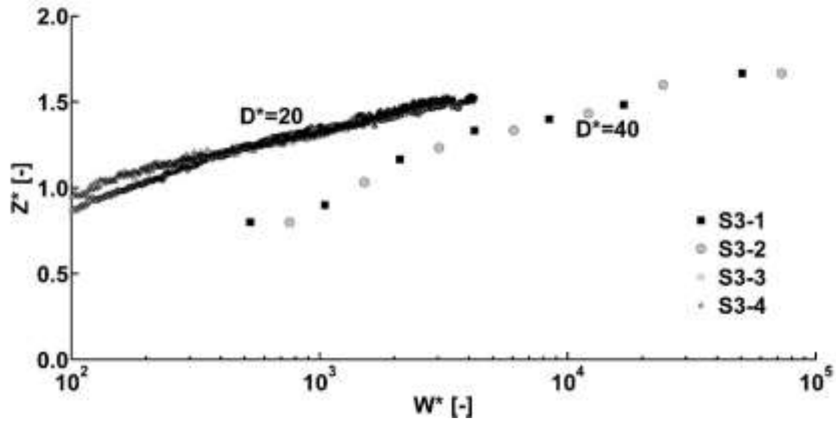
Constant discharge until advanced scour



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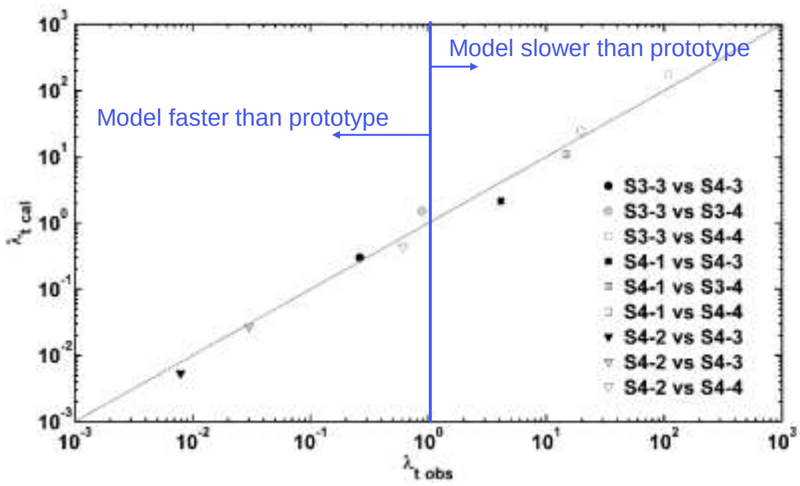
The time scale:



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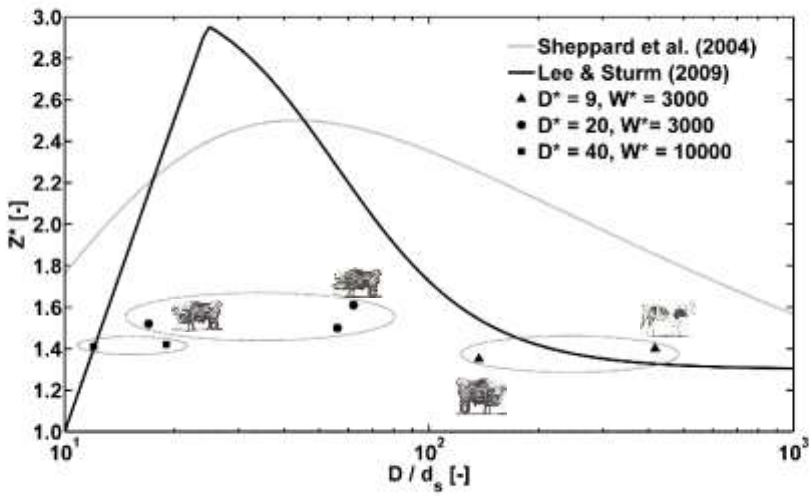
Scale effects in D / d_s distorted models:



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MERCI BEAUCOUP POUR VOTRE ATTENTION!

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Temperature effects

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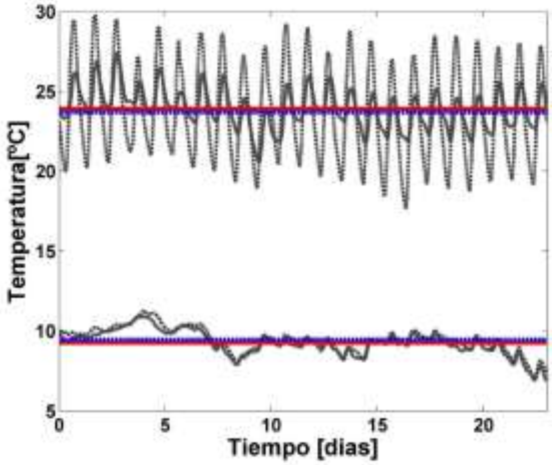

$$\frac{T_{daily\max} - T_{daily\min}}{T_{basin\ average}} = \frac{H_{SW_{in}} W}{\gamma Q}$$

Monsalve A, Link O & Stehr A (2012) The thermal regime of rivers: development, verification and application of a numerical model. Water Technology and Sciences (*in Spanish*) 3(4):41-56.

Link O, Huerta A, Stehr A, Monsalve A, Meier C & Aguayo M (2013) The Solar to Stream Power Ratio: A Dimensionless Number Explaining Diel Fluctuations of Temperature in Mesoscale Rivers. River Research & Applications 29(6): 792–803.