Determinants of modelling choices for 1-D free-surface flow and morphodynamics in hydrology and hydraulics: a review

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Abstract

This review paper investigates the determinants of modelling choices, for numerous applications of 1-D free-surface flow and morphodynamic equations in hydrology and hydraulics, across multiple spatiotemporal scales. We aim to characterize each case study by its signature composed of model refinement (Navier-Stokes: NS, Reynolds-Averaged Navier-Stokes: RANS, Saint-Venant: SV or Approximations of Saint-Venant: ASV), spatiotemporal scales and subscales (domain length: L from 1 cm to 1000 km; temporal scale: T from 1 second to 1 year; Flow depth: H from 1 mm to 10 m, spatial step for modelling: δL, temporal step: δT), flow typology (Overland: O, High gradient: Hg, Bedforms: B, Fluvial: F) and dimensionless numbers (Dimensionless time period T*, Reynolds number Re, Froude number Fr, Slope S, Inundation ratio Λ_z, Shields number θ). The determinants of modelling choices are therefore sought in the interplay between flow characteristics, cross-scale and scale-independent views. The influence of spatiotemporal scales on modelling choices is first quantified through the expected correlation between increasing scales and decreasing model refinements (though modelling objectives also show through the chosen spatial and temporal subscales). Then flow typology appears a secondary but mattering determinant in the choice of model refinement. This finding is confirmed by the discriminating values of several dimensionless numbers, which prove preferential associations between model refinements and flow typologies. This review is intended to help modellers in positioning their choices with respect to the most frequent practices, within a generic, normative procedure possibly enriched by the community for a larger, comprehensive and updated image of modelling strategies.

Keywords

Free-surface flow, modelling strategy, cross-scale analysis, flow typology, dimensionless numbers.

Summary

1 Introduction

Free-surface flow models cover a wide range of environmental and engineering applications, across multiple spatiotemporal scales, involving several levels of flow aggregation in the streamwise direction, over various bed topographies: these govern both the qualitative (flow typology) and quantitative (dimensionless numbers) flow characteristics. Each case study may thus be positioned along "streamwise scenarios" (from runoff initiation to the main rivers) from unequivocal indications of the spatiotemporal scales and subscales, flow typology and associated dimensionless numbers. This literature review investigates the determinants of choices made for 1-D free-surface flow and morphodynamic modelling in hydrology and hydraulics, seeking links between contextual information (spatiotemporal scales, flow typologies, dimensionless numbers) and conceptual descriptions (data collection and/or calculation subscales, refinement of the flow equations or, equivalently, richness of the physical basis). The entire set of descriptors, *i.e.* model refinement, spatiotemporal scales and subscales, flow typology and dimensionless numbers, constitutes the signature of a study. This signature is thought normative enough to facilitate comparisons between studies, encompassing both the hydrological (i.e. more "natural") and hydraulic (i.e. more "controlled") contexts.

For the sake of generality, this review addresses a wide range of spatiotemporal scales, starting at the smallest plot scales (spatial scale: domain length L<10 m; time scale: duration of the process T<10 s; flow depth: H<1 cm, Fig.1), those of runoff genesis, overland flow hydraulics and detailed particle-scale physics (Horton 1945, Emmett 1970, Feng & Michaelides 2002, Schmeeckle & Nelson 2003). The intermediate scales of catchment and hillslope processes are these expected to exhibit the widest variety of flow typologies thus modelling strategies (Croke & Mockler 2001, Parsons et al. 2003, Aksoy & Kavvas 2005, Mosselman 2012). The larger river basin scales (L>100 km; T>10 days; H>1 m) are also handled here, relevant for river flow modelling, flood prediction and water resources management (Nash & Sutcliffe 1970, Rosgen 1994, Loucks & van Beek 2005) with regional surface-subsurface interactions (De Marsily 1986), non-point pollution, fluvial sediment budgets and global biogeochemical cycles (Walling 1983, Milliman & Syvitski 1992, Syvitski & Milliman 2007).

On the earth surface, flow aggregation in the streamwise direction occurs across several geomorphic thresholds (Kirkby 1980, Milliman & Sivitsky 1992, Church 2002, Paola et al. 2009), through a succession of flow typologies (Emmett 1970, Grant et al. 1990, Rosgen 1994, Montgomery & Buffington 1997). Flow aggregation in space and time is described, through the width function and geomorphological unit hydrograph concepts (Kirkby 1976, Robinson et al. 1995, Agnese et al. 1998), under the angle of hydrological and sedimentological pathways (see the review by Bracken et al. 2013) or questioning the merits of similitude laws and these of upscaling methods in the description of hydrological processes (Strahler 1956, Blöschl and Sivapalan 1995, Slaymaker 2006). Alternatives consist in examining the "scale matching" between available data and modelling aims (Lilburne 2002, Kim & Ivanov 2015) and the possibility to use a more complicated model not only because it replicates what a simpler model would do, plus additional information, but also because it offers different, specific outcomes (e.g. Sloff & Mosselman 2012). With similar goals but a different framework, this study proposes an overview on the most popular modelling practices, confronting the theoretical refinement of flow models to the spatiotemporal scales and characteristics of the free-surface flows described.

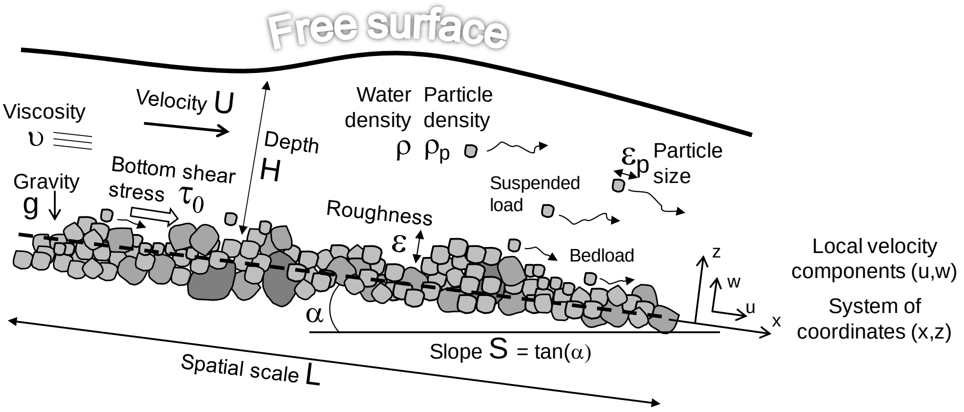


Figure 1 - Quantities most often used in the literature of free-surface flow and morphodynamic modelling, with explicit reference to the (L, T, H) spatiotemporal scales of interest. This review is limited to 1D (x) spatial representations for simplicity, focusing on the streamwise (x) component of the mass and momentum conservation equations. The streamwise length (L) and velocity (U) suggest a natural time

scale T_0=L/U for the propagation of information, waves or perturbations, to be compared with the time scales (T) opted for in the literature.

Many papers or handbooks have summarised free-surface flow modelling and numerical techniques in hydraulics (King & Brater 1963, Abbott 1979, Cunge et al. 1980, Carlier 1980, French 1985) or hydrology (Chow 1959, Kirkby 1978, Beven 2000, Elga et al. 2015, Paniconi & Putti 2015) for various contexts, purposes and flow typologies. Less works have discussed the concern of *ad hoc* friction laws (Leopold et al. 1960, Gerbeau & Perthame 2001, Nikora et al. 2001, Roche 2006, Burguete et al. 2008), at the microscopic or macroscopic scales (Richardson 1973, Jansons 1988, Priezjev & Troian 2006, Smith et al. 2007, Powell 2014) although friction, flow retardation and energy dissipation processes are closely related to bedforms, thus plausibly govern flow typologies then, possibly, modelling choices. Often outside any focus on friction, numerous works have provided wide overviews on erosion modelling (Ritchie & McHenry 1990, Laflen et al. 1991, Merritt et al. 2003, Aksoy and Kavvas 2005, Boardman 2006). Morphodynamic models that lean on the most sophisticated flow models calculate explicit particle detachment, transport and deposition from velocity fields or flow energetics (Vanoni 1946, Hino 1963, Lyn et al. 1992, Mendoza & Zhou 1997) while most 1D or 2D physics-based models (*e.g.* Sloff et al. 2001, Vetsch et al. 2014) either assume the "transport capacity" (Foster & Meyer 1972, Bennett 1974) or "transport distance" schools of thoughts (see details in Wainwright et al. 2008).

This multidisciplinary review (hydrology, hydraulics, fluid mechanics and morphodynamics) searches for the determinants of modelling choices. It focuses on hydrology but borrows from hydraulics and fluid mechanics, also when addressing morphodynamic issues (erosion, transport and deposition of bed particles). The methodology consists in defining the “signature” of each case study as the chosen model refinement and modelling subscales vs. the given spatiotemporal scales, flow typology, and dimensionless numbers, hypothesizing the conceptual element (model refinement and spatiotemporal subscales) is the consequence of the contextual elements (flow scales, typology and dimensionless numbers). The paper is organized as follows: section 2 sorts the flow equations into four levels of refinement, section 3 plots these refinements versus the spatiotemporal scales of the studies, also depicting the influence of flow typologies and dimensionless numbers. Section 4 discusses the results and future research leads. Some of the best documented references among the cited literature have been gathered in Appendix A: most figures in this manuscript were plotted from this database.

2 Flow models

2.1 List of flow models

Free-surface flow equations in the literature may roughly be sorted into four levels of decreasing refinement, i.e. depending on the number and nature of the indications included in their physical description. The choice made here (among many other possibilities) includes the Navier-Stokes equations (noted NS: Navier 1822, Stokes 1845), their average in time termed Reynolds-Averaged Navier-Stokes equations (RANS: Reynolds 1895, for turbulent flows), the depth-averaged Saint-Venant equations (SV: Saint-Venant 1871) and further approximations (referred to as ASV for Approximations to Saint-Venant), among which the Diffusive Wave Equation (DWE: Hayami 1951) and Kinematic Wave Equation (KWE: Iwagaki 1955, Lighthill & Whitham 1955).

In association with the flow equations, the equations describing morphodynamic processes (particle erosion, transport and deposition) either issue from environmental fluid mechanics (e.g. Lyn 1987, Ribberink 1987, Elghobashi 1994) or from the representation of detachment and transport more focused on hillslope processes (Bennett 1974, Van Rijn 1984a, b, Wainwright et al. 2008), arising from previous works on streams (Einstein 1950) and channel networks (Du Boys 1879, Exner 1925, Hjulström 1935, Shields 1936, Bagnold 1956). Depending on the refinement of the coupled flow and morphodynamics models as well as on flow typology, a clear trend is that some elements are explicitly addressed whenever possible, e.g. particle advection and diffusion, while others are most often parameterised, e.g. particle detachment from excess bed shear stress and friction laws in general.

Friction is the link between water flow and erosion issues in terms of physical processes at play at the particle scale, or at the scale of the erodible bed asperities. On the one hand, this advocates the examination of erosion issues from the angle of decreasing refinements of the "flow and morphodynamics" models seen as a whole (*e.g.* expecting the most complicated erosion processes to be out of reach of the simplest combined models). On the other hand, there might be a certain inconsistency between the refinement of the flow model and that of the chosen friction and erosion models, so the determinants of modelling choices should also be sought elsewhere: in flow typologies dictated by friction and flow retardation processes but also in "erosion characteristics", seen through a dimensionless descriptor (Section 3).

2.2 Navier-Stokes

2.2.1 Water flow

The Navier-Stokes (NS) equations have suitable simplifications for the shallow water cases (L>>H) commonly used to describe free-surface flows. The three-dimensional fluid motion problem is reduced here to a two-dimensional description, whose projection along the streamwise axis writes:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}\right)+\frac{\partial p}{\partial x}= \rho g_x+\frac{\partial N}{\partial x}+\frac{\partial \tau}{\partial z} \tag{1}$$

where ρ is water density [ML^{-3}] assumed constant for incompressible flows, u is the local water velocity in x [LT^{-1}], t is time [T], x is the longitudinal distance [L], w is the local water velocity in z, z is the vertical coordinate [L],, p is the local pressure [ML^{-1}T^{-2}], g_x is the projection of gravity g on x [LT^{-2}], N [ML^{-1}T^{-2}] is the normal stress in x (accounting for example for non-hydrostatic pressure effects) and τ [ML^{-1}T^{-2}] is the tangential stress in x, which is noted τ_0 on the bed in Fig.1. The normal and tangential stresses also write $N=\mu\partial u/\partial x$ and $\tau=\mu\partial u/\partial z$, respectively, where μ [$ML^{-1}T^{-1}$] is the dynamic viscosity.

The Navier-Stokes equations stay valid throughout the full range of flow regimes, scales and contexts. They are preferentially used where much complexity is needed, often when relevant simplified flow descriptions could not be derived, for example for particle-scale applications (Chen & Wu 2000, Wu & Lee 2001, Feng & Michaelides 2002), overland flow (Dunkerley 2003, 2004) or flows over pronounced bedforms (Booker et al. 2001, Schmeeckle & Nelson 2003). A very wide review of numerical methods and applications for the NS equations is provided by Gresho & Sani (1998) and a benchmark of numerous solvers by Turek (1999). The general trend is that improvements in efficiency of the algorithms have approximately kept pace with exponential improvements in computer power over the past 50 years (Moore 1965, Mavriplis 1998, Koomey et al. 2010, Mosselman & Le 2016) which tends to push the limitations of numerical methods further away.

2.2.2 Morphodynamics

One of the earliest modern contributions on the rheology of two-phase flows is due to Einstein (1906) with the recognition that the viscosity of a mixture increases with the volumetric concentration of solid particles, at least for "slow flows". Brinkman (1947), Happel & Brenner (1965) then Leal (1980) studied the shearing strength of multiphase viscous flows while Batchelor (1974) and Russell (1981) addressed turbulent flows. Drew (1983) provided a general framework for the "*mathematical modelling of multiphase flow*", cited as a predecessor by Elghobashi (1994) who described particle-laden turbulent flows, discarding several assumptions (e.g. compressibility, phase change and thermodynamic effects) to yield a momentum conservation equation suitable for most natural flows and purposes:

$$\rho_k\left(\frac{\partial c_k u_k}{\partial t}+\frac{\partial c_k u_k^2}{\partial x}+\frac{\partial c_k u_k w_k}{\partial z}\right)+c_k\frac{\partial p_k}{\partial x}=\rho_k g_x+\frac{\partial c_k N_k}{\partial x}+\frac{\partial c_k \tau_k}{\partial z}+M_k \tag{2}$$

where the subscript k is an index for the phase (carrier: k=c, dispersed phase: k=d), c_k (-) is the local volumetric fraction ($c_c+c_d=1$), u_k [LT^{-1}] and w_k [LT^{-1}] are the local velocities in x and z, respectively, ρ_k [ML^{-3}] is density, p_k [$ML^{-1}T^{-2}$] is pressure, N_k [$ML^{-1}T^{-2}$] and τ_k [$ML^{-1}T^{-2}$] account for local non-hydrostatic pressure and shear stress effects, respectively, and M_k [$ML^{-2}T^{-2}$] is the momentum exchange term between phases. The exchange term vanishes for "one-way" couplings in which particles move in response to water motion (dispersed flows or dilute suspensions with $c_2<10^{-6}$) but should be kept for "two-way" couplings (dispersed flows with $10^{-6}<c_2<10^{-3}$ with non-negligible solid-fluid interactions, at the necessity of iterative resolution procedures) and also for "four-way" couplings (dense suspensions or collision-dominated flows with $c_2>10^{-3}$). In the latter case, additional models are needed to simulate particle-particle or particle-scale interactions (Nabi et al. 2012, 2013a,b) in the form of collisions, buoyancy and local pressure, drag or viscosity effects to be included in the above N_k and/or τ_k stresses (Drew 1983, Elghobashi 1994, Fernando 2012).

Several types of practical applications dictate the use of high-level formalisms in the description of particle detachment and transport, typically to handle explicit bed geometries and alterations (Colombini 2014, Kidanemariam & Uhlmann 2014), for example jet scours and regressive erosion (Stein et al. 1993, Bennett et al. 2000, Alonso et al. 2002), diverging sediment fluxes in canals (Belaud & Paquier 2001) or incipient motion conditions, calculated from grain size, shape and weight (Stevenson et al. 2002). The NS formalism is especially appropriate to describe strong water-sediment couplings, *i.e.* couplings in which the solid phase exerts an influence on the liquid phase, acting upon velocity fields, flow rheology and erosive properties (Sundaresan et al. 2003). Such couplings may be sorted by increasing sediment loads, from dispersed multiphase flows (Parker & Coleman 1986, Davies et al. 1997) to density currents (Parker et al. 1986), hyperconcentrated flows (Mulder & Alexander 2001) and up to debris flows (Bouchut et al. 2003, Bouchut & Westdickenberg 2004), the latter derived as mathematical generalisations of the well-known Savage & Hütter (1989, 1991) avalanche models over explicit, pronounced topographies. Moreover, the NS formalism offers the possibility to work on the energy equations: the erosive power and transport capacity of sediment-laden flows may be estimated from the energy of the flow, examining turbulence damping (or not) with increasing sediment loads (Vanoni 1946, Hino 1963, Lyn et al. 1992, Mendoza & Zhou 1997). The matter is not completely free from doubt today (Kneller & Buckee 2001) though the diagram proposed by Elghobashi (1991, 1994, p310) to describe the regimes of interactions between particles and turbulence seems rather widely accepted. For the most dilute suspensions ($c_d<10^{-6}$) the sediment load is not supposed to have any influence on turbulence characteristics. For the intermediate case ($10^{-6}<c_d<10^{-3}$) the sediment load is supposed to enhance turbulence only if the particle response time is at least two orders of magnitude greater than the Kolmogorov time scale, i.e. the characteristic time for the turbulent eddies to vanish: for the same sediment load and water viscosity, larger particles tend to enhance turbulence while smaller particles tend to damp it. For dense suspensions ($c_d>10^{-3}$)frictional drag, abrasion due to impacts of the travelling particles and increased flow viscosity have been described prone to enhance the detachment capacities of loaded flows (e.g. Alavian et al. 1992, Garcia & Parker 1993).

2.3 Reynolds-Averaged Navier-Stokes

2.3.1 Water flow

There are many turbulence models (*e.g.* DNS-Direct Numerical Simulations, LES-Large Eddy Simulations and RANS-Reynolds-Averaged Navier-Stokes) suitable for free-surface flow modelling (Katopodes & Bradford 1999). Direct Numerical Simulations explicitly resolve all turbulence scales at the cost of more than Re^3 calculations (Härtel 1996) while Large Eddy Simulations (Smagorinsky 1963, Leonard 1974) filter out the smallest scales and resolve only the larger ones. The RANS equations (Smith & McLean 1977, Rödi 1988) do not resolve any scale but the stress terms used for their closure have proven useful for the modelling of near-bed turbulent patterns. The RANS equations are time-averaged equations of fluid motion, less generic than the NS formalism. The hypothesis behind these equations is that instantaneous pressure (p), stresses (N, τ) and velocities (u, w) may be decomposed into time-averaged and randomly fluctuating turbulent parts (e.g. $u=\bar{u}+u'$) assuming the temporal average of any turbulent fluctuations is zero. The RANS formulation usually arising from the NS equations is:

$$\rho\left(\frac{\partial \overline{u}^2}{\partial x}+\frac{\partial \overline{u}\,\overline{w}}{\partial z}\right)+\rho g\frac{\partial H}{\partial x}= \rho g S+\frac{\partial \overline{N}}{\partial x}-\frac{\partial \rho\overline{u'^2}}{\partial x}+\frac{\partial \overline{\tau}}{\partial z}-\frac{\partial \rho\overline{u'w'}}{\partial z} \tag{3}$$

where the hydrostatic approximation has been used for the pressure term together with the hypothesis of small bed slopes. In the above, $\overline{N}$ accounts for the viscous (laminar) pressure stresses, $\rho\overline{u'^2}$ is the normal stress due to turbulence, $\overline{\tau}$ becomes the viscous shear stress and $\rho\,\overline{u'w'}$ is the (turbulent) Reynolds stress.

In this formulation, the "Reynolds stress" term τ is of crucial importance for free-surface flow, friction and erosion modelling, especially for shallow flows, first because it is the closure term and second because the Reynolds stresses have been closely related, in magnitude and direction, to the size and arrangement of bed asperities. The combined analysis of the relative magnitude of the u' and w' terms has become the purpose of "quadrant analysis" (Kline et al. 1967, Raupach 1981, Kim et al. 1987) that identifies the four cases of outward interactions (quadrant I: u'>0, w'>0), ejections (quadrant II: u'<0, w'>0), inward interactions (quadrant III: u'<0, w'<0) and sweeps (quadrant IV: u'>0, w'<0). Depending on the submergence and geometry of bed asperities, the maximal Reynolds stresses, those with significant effects on flow structure, have most often been reported to occur near or just above the roughness crests (see Nikora et al. 2001, Pokrajac et al. 2007 and the review by Lamb et al. 2008a).

2.3.2 Morphodynamics

Comparative reviews of RANS-level approaches to modelling sediment-laden two-phase flows within various two-way couplings have been performed by Bombardelli & Jha (2008) then Jha & Bombardelli (2009), assessing the performances of "standard sediment transport models" (an advection-turbulent diffusion equation for the liquid-solid mixture), "partial two-fluid models" (distinct momentum conservation equations for the dispersed phase and the carrier phase, the latter seen as a liquid-solid mixture) and "complete two-fluid models" (general balance equations for both phases, inherited from the previous NS formulations) versus "Reynolds stress models" (expressing closure terms in function of the turbulent kinetic energy). The momentum balance in x for 1D approaches is the same for the dispersed phase in the complete and partial two-fluid models (Bombardelli & Jha 2008):

$$\rho_d\left(\frac{\partial c_d\overline{u_d}}{\partial t}+\frac{\partial c_d\overline{u_d}\,\overline{w_d}}{\partial z}\right)=\rho_d c_d gS-\frac{\partial\rho_d c_d\overline{u'_d\,w'_d}}{\partial z}+F_D \tag{4}$$

where F_D $[ML^{-2}T^{-2}]$ is the drag force term that allows two-way couplings, most often written as $F_D = 0.5\rho_m C_D A\left(\overline{u_c}-\overline{u_d}\right)^2$ where ρ_m $[ML^{-3}]$ is the density of the two-phase mixture, C_D (-) is the drag coefficient and A $[L^2]$ is the cross-sectional area of the particles.

In their paper on movable river beds, Engelund & Fredsoe (1976) reformulated and exploited the existing hypotheses (Einstein & Banks 1950, Bagnold 1954, Fernandez Luque & van Beek 1976) of a partition between “tractive” destabilizing shear stresses and “dispersive” equalizing drags. The vertical concentration profiles of bedload and suspended load were calculated from incipient sediment motion conditions, relating stresses on the particles to the values and variations of near-bed velocities. One step further, the physical explanation, mathematical definition, point of application, main direction and erosive efficiency of the turbulent near-bed stresses have become an interesting feature of the RANS models throughout the years (Nikora et al. 2001, Nino et al. 2003).

The maximal Reynolds stresses are located near the crests of the submerged bed asperities, where turbulent velocity fluctuations reach several times the average near-bed velocity values, which greatly enhances particle detachment (Raupach et al. 1991, Nikora & Goring 2000, Lamb et al. 2008a). Very few studies deal with the magnitude and point of application of the Reynolds stresses for partial inundation cases (Bayazit 1976, Dittrich & Koll 1997, Carollo et al. 2005) although turbulent flows between emergent obstacles often occur in natural settings. Particle detachment is generally attributed to “sweeps” (quadrant IV: u’>0, w’<0) (Sutherland 1967, Drake et al. 1988, Best 1992) or “outward interactions" (u'>0, w'>0) (Nelson et al. 1995, Papanicolaou et al. 2001) but depends on bed geometries and bed packing conditions. Finally, the RANS equations allow explicit calculations of shear stresses and particle-scale pick-up forces, thus incipient motion conditions (Nino et al. 2003, Afzalimehr et al. 2007). They may handle the movements of detached particles in weak transportation stages (Bounvilay 2003, Julien & Bounvilay 2013) down to near-laminar regimes (Charru et al. 2004).

2.4 Saint-Venant

2.4.1 Water flow

The Saint-Venant (SV) equations are obtained by depth-integrating the Navier–Stokes equations, neglecting thus the vertical velocities as well as vertical stratifications in the streamwise velocity (Stoker 1958, Johnson 1998, Whitham 1999). The SV equations also termed "shallow water equations" assume the H<<L hypothesis of shallow water which limits the admissible free-surface slope and implies a quasi-hydrostatic pressure distribution over the vertical. The integration process from NS to SV (Chow 1959, Abbott 1979) incorporates an explicit bottom friction term τ_0 that previously appeared only as a boundary condition in the NS and RANS equation:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + g\frac{\partial H}{\partial x} = gS + \frac{\tau_0}{\rho H} \tag{5}$$

Recent attempts have been made in the field of fluid mechanics to derive specific expressions for τ_0 (laminar flows: Gerbeau & Perthame 2001, macro-roughness: Roche 2006, thin flows: Devauchelle et al. 2007, turbulent flows: Marche 2007, multi-layer SV model: Audusse et al. 2008). However, the common practice in hydrology and hydraulics is rather to approximate steady-state equilibrium between bottom friction τ_0 and the streamwise stress exerted at the bottom of a water column ($\tau_0=\rho gHS_f$) to reach the popular formulation:

$$\underset{\text{(i)}}{\frac{\partial U}{\partial t}} + \underset{\text{(ii)}}{U\frac{\partial U}{\partial x}} + \underset{\text{(iii)}}{g\frac{\partial H}{\partial x}} = g\big(\underset{\text{(iv)}}{S} - \underset{\text{(v)}}{S_f}\big) \tag{6}$$

where (i) is the unsteadiness term, (ii) the convective acceleration term, (iii) the pressure gradient term, while (iii), (iv) and (v) form the diffusive wave approximation (later discussed).

In the above, S_f (-) is the “friction slope” whose expression depends on flow velocity and on the chosen friction law, often one of the Chézy, Darcy-Weisbach or Manning formulations (*e.g.* S_f=nU^2/8gH with Manning’s n friction coefficient). The derivation of the SV equations by Boussinesq (1877) involved a momentum correction coefficient β [-] in the advection term (King & Brater 1963, Chen 1992) to account for stratification effects in the vertical distribution of velocities, especially plausible in sediment-laden flows or in presence of density currents.

The SV equations may account for flows of variable widths and depths, for example in floodplains (Bates & De Roo 2000, Beltaos et al. 2012), rivers (Guinot & Cappelaere 2009), overland flow (Berger & Stockstill 1995, Ghavasieh et al. 2006, Kirstetter et al. 2016), overpressure in drainage systems (Henine et al. 2014), man-made channels (Zhou 1995, Sen & Garg 2002, Sau et al. 2010), vegetation flushing (Fovet et al. 2013), channel networks (Choi & Molinas 1993, Camacho & Lees 1999, Saleh et al. 2013), on benchmarks (Dimitriadis et al. 2016), interaction with subsurface (Pan et al., 2015), or natural settings (Moussa & Bocquillon 1996a, Wang & Chen 2003, Roux & Dartus 2006, Burguete et al. 2008, Bates et al. 2010), including these with curved boundaries (Sivakumaran & Yevjevich 1987). Discharge and cross-sectional area may conveniently be used instead of velocity and water depth, and the two equations describing mass and momentum in the Saint-Venant system now write (Sivapalan et al. 1997):

$$\frac{\partial \mathrm{A}}{\partial \mathrm{t}}+\frac{\partial \mathrm{Q}}{\partial \mathrm{x}}=\mathrm{q}_{\mathrm{a}} \tag{7}$$

$$\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{1}{gA}\frac{\partial}{\partial x}\left(\beta\frac{Q^2}{A}\right)+\frac{\partial H}{\partial x}+S_f-S=0 \tag{8}$$

where A is the cross-sectional area [L^2], Q is the discharge [L^{3}T^{-1}], q_a is the lateral flow per unit channel length [L^{2}T^{-1}]. The magnitudes of the various terms in equations (5) and (6) are given in the literature (*e.g.* Henderson 1966, Kuchment 1972).

2.4.2 Morphodynamics

In the hydro-morphodynamics community, the SV level is that of the *Concepts of mathematical modelling of sediment yield* by Bennett (1974). This landmark paper extended Exner's (1925) conservation of sediment mass, adding the possibility to handle different fluid and particle velocities, also accounting for particle dispersion *via* a diffusion term:

$$\frac{\partial H c_d}{\partial t} + \left(1-\phi_0\right)\frac{\partial z_0}{\partial t} + \frac{\partial H c_d U_d}{\partial x} = \frac{\partial}{\partial x}\left(H \eta_d \frac{\partial c_d}{\partial x}\right) \tag{9}$$

where ϕ_0 (-) is bed porosity, z_0 (-) is the bed level, U_d [L T^{-1}] is the spatial average of particle velocity over the cross section of the flow and η_d [L^2 T^{-1}] is a diffusivity coefficient. See for example Ancey & Heyman (2010) and Ballio et al. (2014) for the various possible formulations of the sediment continuity equation and associated numerical aspects, depending on the strength of the intended coupling with the carrier phase. The authors rather belong to the fluid mechanics-type of use of the SV equations, for hydro-environmental applications that necessitate taking maximum advantage of the level of details offered by (9), often by using SV-level formulations of the Exner equation in combination with RANS or NS-level flow models (e.g. Riberink 1987, Blom 2008, Sloff & Mosselman 2012).

Conversely, in the field of hydrology, numerous citing papers discard one or several terms from the Bennett (1974) equations, typically taking particle velocity equal to water velocity. The assumption seems false if transport occurs as bedload or saltation load, questionable for suspended load trapped into turbulent motions, exact only for very small particles borne by laminar flows. Although warning against the capability of first-order laws to "*represent the response of sediment load to changes in* *transport and detachment capacity*" (Bennett 1974, p.491), the author recommended the use of such a model (Foster and Meyer 1972). The proposed simplification writes e/D_c=1-c/T_c, where the net erosion rate (*e*) is normalised by the maximal detachment capacity (D_c) while sediment load (*c*) is normalised by the maximal transport capacity of the flow (T_c). An additional (uncertain) hypothesis was that of maximal detachment capacity for minimal sediment load, *i.e.*, clear water. See the controversial comments around the Wainwright et al. (2008) paper: the areas of disagreement revolve around the ability of models to handle unsteady flow conditions, to deal with suspended and/or bedload transport, to consider particles of different sizes and to stay valid over realistic ranges of sediment concentration.

Those questions directly address the possibilities of SV-level approaches. Higher-level models (NS, RANS) better address the dynamics of incipient motion (Dey & Papanicolaou 2008), especially in shallow laminar flows (Charpin & Myers 2005) or focusing on granular flows (Parker 1978a, b, Charru et al. 2004, Charru 2006). Refined models are also needed to explicitly handle specific particle velocities (Bounvilay 2003), to describe particle diffusion in secondary currents (Sharifi et al. 2009), to account for the spatial heterogeneity of "neither laminar nor turbulent" overland flows (Lajeunesse et al. 2010) or to introduce modifications in flow rheology (Sundaresan et al. 2003). On the other hand, many erosion controls have received attention within the SV or ASV formalisms, i.e. without explicit descriptions of particle-scale flow features: micro-scale variability (Risse et al. 1993, Kinnell et al. 2005), local sheltering effects (Nearing et al. 2007, Kim & Ivanov 2014), slope effects (Polyakov & Nearing 2003), particle-size effects (Van Rijn 1984a, Hairsine & Rose 1992a, Sander et al. 2007, Wainwright et al. 2008), flow stratification effects (van Maren 2007), the effects of hyperconcentrated flows (Hessel 2006). Bedload transport (e.g. Van Rijn 1984b, Julien & Simmons 1985, Hairsine & Rose 1992b, Wainwright et al. 2008) has also motivated the search for dedicated formalisms.

Whatever the liquid-solid coupling opted for, the SV level covers the widest variety of contexts, from overland erosion models (Simpson & Castelltort 2006, Nord & Esteves 2010, Stecca et al. 2015) to dam-break hydraulics over erodible beds (Cao et al. 2004) and the analysis of channel inception driven by the variations of the Froude number (Izumi & Parker 1995) or the impact of travelling particles (Sklar & Dietrich 2004, Lamb et al. 2008b). Sediment detachment and transport over plane beds (Williams 1970), rough beds (Afzalimehr & Anctil 1999, 2000, Gao & Abrahams 2004), channels (Villaret et al. 2013, 2016), step-pools (Lamarre & Roy 2008) or pool-riffle sequences (Sear 1996, Rathburn & Wohl 2003) have yielded often-cited studies, while sediment flushing in reservoirs (Campisano et al. 2004) and vegetation flushing in canals (Fovet et al. 2013) constitute more specific applications. Cited limitations of the SV approaches are their inability to explicitly describe the near-bed velocity fluctuations, especially the local accelerations responsible for particle entrainment but also the vertical gradients of the streamwise velocity, for bedload transport in the laminar layer. This lack of accuracy in the description of flow characteristics also endangers the possibility to predict the formation, transformation and migration of geometrical bed patterns, which in turn requires the full set of 3D (x, y, z) NS equations in several cases (Lagrée 2003, Charru 2006, Devauchelle et al. 2010).

There seems to exist a dedicated "NS-SV Morphodynamics" research lead that uses rather simple bedload transport formulae (Du Boys 1890, Meyer-Peter & Müller 1948, Einstein & Banks 1950, Bagnold 1966, Yalin 1977) to calculate sediment fluxes from excess bed shear stresses, in studies of long-term system evolutions. These low "system evolution velocities" appear under the "quasi-static" flow hypothesis: particle velocity may be neglected before water velocity, which allows neglecting the unsteadiness term in the momentum equation but on no account in the continuity equation (Exner law) that describes bed modifications (Parker 1976). Although derived for turbulent natural flows, shear stresses may also be calculated from near-bed laminar or near-laminar velocity profiles, sometimes with the regularising hypothesis that detachment and transport occur just above the criterion for incipient motion (see the review by Lajeunesse et al 2010). Various applications address rivers with mobile bed and banks (Parker 1978a, b), focus on self-channelling (Métivier & Meunier 2003, Mangeney et al. 2007) and often resort to formulations at complexity levels between these of the NS and the SV approaches (Devauchelle et al. 2007, Lobkovsky et al. 2008).

2.5 Approximations to Saint-Venant

2.5.1 Water flow

When the full Saint-Venant equations are not needed or impossible to apply due to calculation time, an option is to neglect one or several terms of the momentum equation (Ponce and Simons 1977, Romanowicz et al. 1988, Moussa & Bocquillon 1996a, Moussa & Bocquillon 2000, Rousseau et al. 2015). In most practical applications for flood routing, the unsteadiness (i) and convective acceleration (ii) terms in (4) may be neglected, suppressing the first two terms from (6). Combining the remaining terms in (5) and (6), we obtain the Diffusive Wave equation (Moussa, 1996):

$$\frac{\partial Q}{\partial t} + C\left(\frac{\partial Q}{\partial x} - q_a\right) - D\left(\frac{\partial^2 Q}{\partial x^2} - \frac{\partial q_a}{\partial x}\right) = 0 \qquad (10)$$

where *C* [LT^{-1}] and *D* [L^2T^{-1}] are non-linear functions of the discharge *Q* (and consequently the flow depth *H)* known as the celerity and diffusivity, respectively.

In cases where the pressure-gradient term (iii) in (4) can also be neglected, the third term of (6) also vanishes and the Diffusive Wave becomes the Kinematic Wave equation, with *D*=0 in (7). The Diffusive Wave in the historic formulations (Cunge 1969, Akan & Yen 1981) or in more recent works (Rutschmann & Hager 1996, Wang et al. 2006, Wang et al. 2014, Cimorelli et al. 2015, Swain & Sahoo 2015) can thus be considered a higher order approximation than the Kinematic Wave approximation (Katopodes 1982, Zoppou & O'Neill 1982, Daluz Vieira 1983, Ferrick 1985, Ponce 1990). Both have been largely studied (since Wooding 1965a,b, Singh 1975, Lane & Woolhiser 1977, Ponce 1991) until more recently (Szymkiewicz & Gasiorowski 2012, Yu & Duan 2014) and have proven very useful for canal control algorithms (Rodellar et al. 1993) or flood routing procedures, with lateral inflow (Fan & Li 2006), in rectangular channels (Keskin & Agiralioglu 1997), for real time forecast (Todini & Bossi 1986), in lowland catchments (Tiemeyer et al. 2007), for overland flows (Pearson 1989, Chua et al. 2008, 2010, 2011), on urban catchments (Gironás et al. 2009, Elga et al. 2015), for small catchments (Moussa et al. 2002, Chahinian et al. 2005, Charlier et al. 2007), for mountainous catchments (Moussa et al. 2007), for medium size catchments (Emmanuel et al. 2015) or tropical catchments (Charlier et al. 2009), at the largest scale of the Amazon basin (Trigg et al. 2009, Paiva et al. 2013), for anthropogenic hillslopes (Hallema & Moussa 2013), to address backwater effects (Munier et al. 2008), stormwater runoff on impervious surfaces (Singh 1975, Pearson 1989, Blandford & Meadows 1990, Parsons et al. 1997), stream-aquifer interactions (Perkins & Koussis 1996) or volume and mass conservation issues (Perumal & Price 2013). Given their "nominal" scales of application, the ASV models are sometimes fed by airborne (remote sensing) data acquisition (Jain & Singh 2005, Reddy et al. 2007). In addition, predictive uncertainties (Elhanafy et al. 2008) or the applicability of the kinematic and diffusive wave equations are the main scope of several studies (Liggett & Woolhiser 1967, Ponce & Simons 1977, Ponce et al. 1978, Moussa & Bocquillon 1996b, Bajracharya & Barry 1997), the evaluation of modelling strategies is that of Horritt & Bates (2002), while parameter estimation is addressed, among others, by Koussis et al. (1978).

2.5.2 Morphodynamics

Whereas common practices in fluid mechanics and hydraulics are rather to seek context-specific strategies in morphodynamic modelling, two simplifying and unifying trends, if not paradigms, have developed in the field of hydrology. The first one is the transport capacity concept (Foster & Meyer 1972) in which the erosive strength of the flow decreases with increasing suspended sediment load, until a switch occurs from detachment- to transport-limited flows. The second one is the stream power concept (Bagnold 1956) that *slope times discharge* is the explicative quantity for erosion, with adaptations that mentioned unit stream power (*slope times velocity*, Yang 1974, Govers 1992) or fitted exponents to the slope and discharge terms (Julien & Simmons 1985).

However, in all cases where the volumetric concentration of the dispersed phase is difficult to know, a possible surrogate is the division of the sediment mixture into size fractions with specific erosion and transport properties (Einstein 1950, Egiazaroff 1957, Hirano 1970, Day 1980, Ribberink

1987) possibly expressed as specific travel distances (Kirkby 1991, 1992, Parsons et al. 2004, Wainwright et al. 2008). The latter presents the following formulation of sediment continuity:

$$\frac{\partial h_{s,\varphi}}{\partial t} + \frac{\partial q_{s,\varphi}}{\partial x} - \varepsilon_{\varphi} + d_{\varphi} = 0 \tag{11}$$

where the subscript φ represents "size-φ" sediments, $h_{s,\varphi}$ [L] is the equivalent depth of sediment transport per unit width of the flow, $q_{s,\varphi}$ [L^2 T^{-1}] is the unit discharge of sediment, ε_{φ} [L T^{-1}] is the rate of erosion of the surface and d_{φ} [L T^{-1}] is the rate of deposition. This equation is more general than the sediment continuity equation most often used in combination with ASV flow models,

$$\frac{\partial A c_d}{\partial t} + \frac{\partial Q c_d}{\partial x} - E = 0 \tag{12}$$

where E [L^2 T^{-1}] is the areal erosion rate.

Many catchment-scale hydrology-erosion models (*e.g.* ANSWERS: Beasley et al. 1980, CREAMS: Knisel 1980, KINEROS: Smith et al. 1995, LISEM: De Roo et al. 1996, WEPP: Ascough et al. 1997, EUROSEM: Morgan et al. 1998, MAHLERAN: Wainwright et al. 2008, MHYDAS-Erosion: Gumiere et al. 2011b, Gregoretti et al. 2016, Hould-Gosselin et al. 2016) adopt the 1D Diffusive or Kinematic Wave Equations to route water fluxes, possibly through vegetated strips (Muñoz-Carpena et al. 1999), together with the simplest possible couplings between water and sediment fluxes (Aksoy & Kavvas 2005). A known difficulty when embracing larger scales with simplified models is to describe the spatially-distributed sources and sinks of sediments (Jetten et al. 1999, 2003) with or without explicit descriptions of the permanent or temporary connectivity lines, for water and sediment movements (Prosser & Rustomji 2000, Croke & Mockler 2001, Pickup & Marks 2001, Bracken et al. 2013). What tends to force reduced complexity approaches in most catchment-scale erosion models is the necessity to handle distinct detachment, transport and deposition processes (from the very shallow diffuse flows formed during runoff initiation to the regional-scale basin outlets) with only sparse data on flow structure and soil characteristics (cohesion, distribution of particle sizes, bed packing). Parsons & Abrahams (1992) have established how the agronomical, engineering and fluvial families of approaches have converged into similar modelling techniques, especially on the subject of erosion in overland flows (Prosser & Rustomji 2000). The ASV formalism also allows fitting bedload transport formulae against mean discharge values as a surrogate to the overcomplicated explicit descriptions of erosion figures in high-gradient streams with macro-roughness elements (Smart 1984, Aziz & Scott 1989, Weichert 2006, Chiari 2008). ASV-level couplings have also been applied to study the slope independence of stream velocity in eroding rills (Gimenez & Govers 2001) and the appearance of bed patterns in silt-laden rivers (van Maren 2007).

3 Determinants of modelling choices

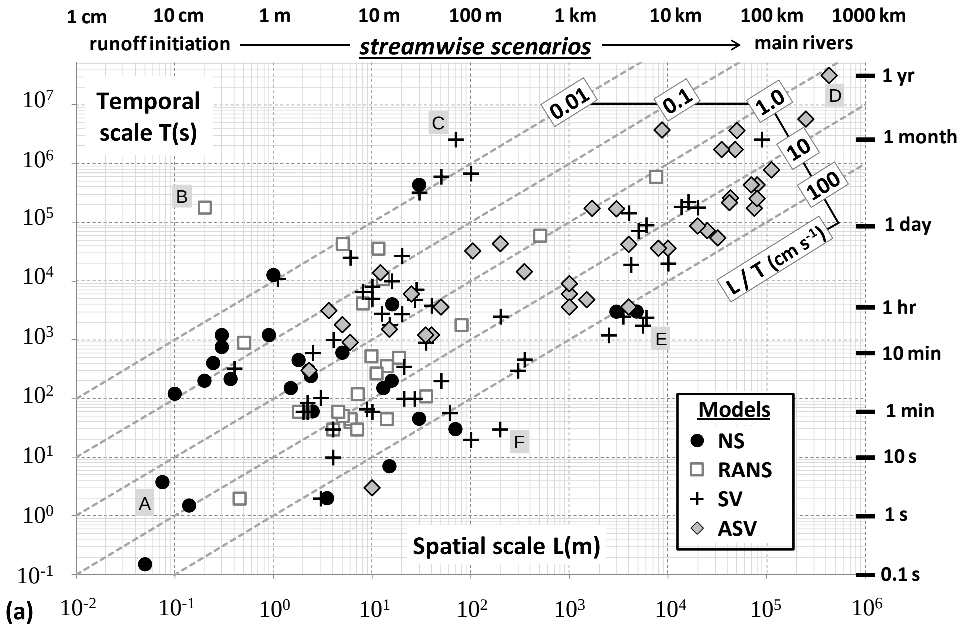
This section aims at the construction of a signature for each case study, relating the "conceptual" choice of a model refinement (Navier-Stokes: NS, Reynolds-Averaged Navier-Stokes: RANS, Saint-Venant: SV or Approximations to Saint-Venant ASV) to the "contextual" descriptors, *i.e.* the spatiotemporal scales (section 3.1), spatiotemporal scales and flow typologies (section 3.2), spatiotemporal scales, flow typologies and dimensionless numbers (section 3.3). Figures 2, 3, 5, 6 and 7 in this section were drawn from the179 studies listed in Appendix A.

3.1 Spatiotemporal scales

3.1.1 Influence of domain length (L) and time scale (T)

A cross-disciplinary analysis of the cited literature indicates a clear correlation between the (L, T) spatiotemporal scales on one side and the chosen model refinement (NS, RANS, SV or ASV) with the (δL, δT) spatiotemporal subscales (data collection and/or numerical schemes) on the other side. In the (L, T) plane, Fig.2a quantifies the expected trend that sophisticated (NS, RANS) models are required to represent rapidly-varying small-scale phenomena (lower left) while simplified approaches (ASV) pertain to increased durations and spatial extensions (upper right). The same pattern is visible in Fig.2b for the (δL, δT) subscales, reporting a strong correlation between the choice of a model and the size of the modelling subscales, for given (L, T) values. Typical scales of application may be identified for each model refinement: NS (10 cm<L<100 m, 10 s<T<1 hr), RANS (1 m<L<100 m, 10 s<T<1 hr), SV (10 m<L<20 km, 1 min<T<5 days) and ASV (10 m<L<1000 km, 30 min<T<1 yr). However, some studies consider larger spatial or temporal scales, for example Charru et al. (2004) for overland granular flows (RANS, L~20 cm, T~2 days) or Rathburn & Wohl (2003) for pool-riffle sequences (SV, L~70 m, T~30 days). Nevertheless, the existence of overlap regions suggests that the (L, T) spatiotemporal scales are not the only factor governing the choice of flow models.

The influence of flow typologies is discussed later in details but could the modelling choices be dictated by the scientific background of the modeller? A striking example is that of the SV models, responsible for the largest overlaps in Fig.2. They may for example be used by physicists, as an upgraded alternative to the NS equations, in the field of environmental fluid mechanics (for limited scales). They may as well be convenient for soil scientists interested in high-resolution hydrology or for civil engineers who may need to cope with flow unsteadiness to handle morphodynamic issues or to allow correct sizing of the man-made structures (for somewhat wider scales).



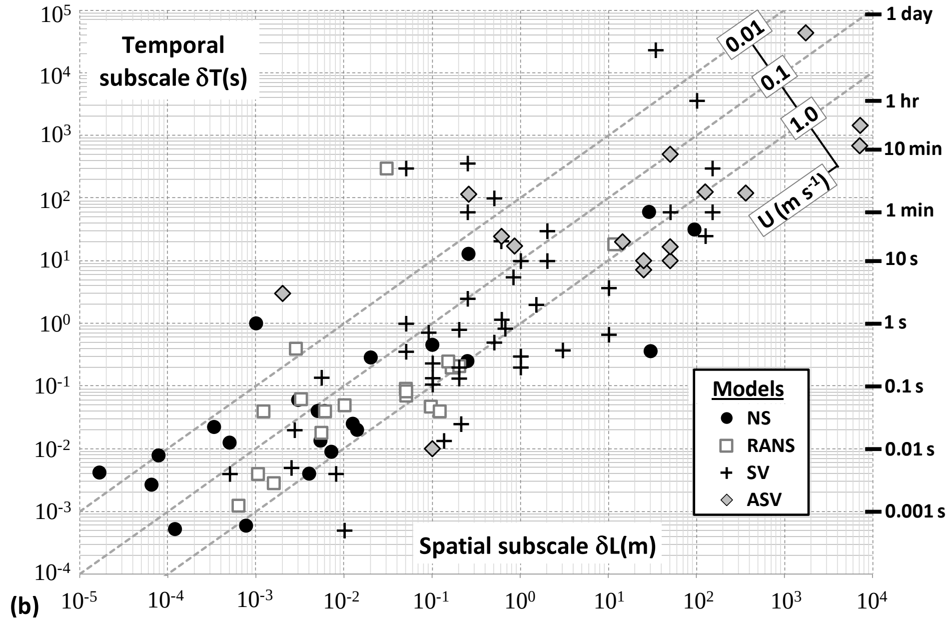


Figure 2 – How increasing (L, T) spatiotemporal scales (a) and (δL, δT) subscales (b) of the flow domain tend to be associated with decreasing complexity in the choice of flow models, sorted here into four levels of refinement: Navier-Stokes (NS), Reynolds-Averaged Navier-Stokes (RANS), Saint-Venant (SV) or Approximations to Saint-Venant (ASV). A transverse analysis involves forming L/T ratios, searching for clues to model selection according to these "system evolution velocities" or governed by flow typologies that would exhibit specific L/T ratios (a). Unit values of the Courant number (Cr=UδT/δL) have been used to trace characteristic flow velocities of U=0.01, 0.1 and 1 m s^{-1} and the indicative numerical stability criterion is Cr≤1: for given δL and U values, δT should lie behind the dotted line (b). Both plots were assembled from information available in the studies cited in Appendix A, selecting six textbook cases (sketches A to F, Table 1) for illustration (a).

Figure 2a bears another type of information than the trend to decreasing model refinement with increasing spatiotemporal scales. As the x-ordinate indicates the spatial scale L and the y-ordinate the time scale T, then the L/T ratio has dimensions of a velocity. However, this quantity should not be interpreted as a flow velocity. It rather indicates which of the temporal (long-term, low L/T ratio) or spatial (short-term, high L/T ratio) aspects are predominant in the study. Hence, the five dotted diagonals (L/T=10^{-4}, 10^{-3}, 10^{-2}, 0.1 and 1 m s^{-1}) establish the numerical link between the spatial and temporal scales of the cited experiments. They also show the dispersion with respect to the expected (say "natural") correlation between increasing L and T values. Judging from the plotted literature, the lowest L/T ratios (e. g. 10^{-4} m s^{-1}) tend to indicate systems with low "evolution velocities", possibly associated with long-term changes or effects (high T values, low L values) obtained from repeated phenomena, multiple cycles and progressive modifications. By contrast, high L/T ratios (*e.g.* 1 m s^{-1}) rather refer to single-event situations, more associated with quick modifications of flow patterns or bed morphologies. Most applications find themselves in the $10^{-2}<L/T<10^{2}$ cm s^{-1} range, exhibiting no clear difference between the NS, RANS, SV or ASV refinements. Conversely, this indicates that each level of refinement has been used to model high or low system evolution velocities, sometimes by relying on specific (adapted or upgraded) formulations of the systems of equation (see for example the hybrid NS-SV level of refinement needed for detailed morphodynamics, especially to reproduce the long-term evolution of bed topography).

If rules of thumb in problem dimensioning were to be drawn from Fig.2a, geomorphological concerns (dune migration, basin sedimentation, long-term bed modifications) probably require stretching up the temporal scale so that low "system evolution velocities" would fall beneath $L/T=10^{-2}$ m s^{-1} while event-based modelling (dam breaks, formative discharges, flash floods) should be able to handle high "system evolution velocities" near or beyond L/T=1 m s^{-1}. This "fixed-L, chosen-T" description of system evolution and characteristic time scales also refers to Fig.1 and Fig.2b in which the choice of T and that of δT are somehow left at the modeller’s discretion, as degrees of freedom: how different from T_0 should T be to allow long-enough observation and/or simulation periods? These points are the subject of detailed investigations in the field of morphodynamics (Paola et al. 1992, Howard 1994, Van Heijst et al. 2001, Allen 2008, Paola et al. 2009). Indicators of "system evolution velocities" with units of a velocity but different definitions may for example be found in Sheets et al. (2002), who took the channel depth (H) divided by the average deposition rate to obtain a relevant, characteristic time scale (T). For the same purpose, Wang et al. (2011) took the characteristic bed roughness (ε) instead of channel depth. The objective is often to discriminate what Allen (2008) called the "reactive" (high L/T) and "buffer" (low L/T) systems. With or without morphodynamic issues, a reasonable hypothesis here seems that the dispersion in L/T ratios arises from the variety of flow contexts, which may necessitate different modelling strategies. In other terms, it is deemed in this study that this secondary trend, associated with flow typologies, is also a determinant in the choice of the flow model.

To take a few examples and guide the reader through the arguments and the figures of this paper, Table 1 gathers the information available for the six textbook cases outlined by sketches A to F in Fig.2a. The selected studies represent a wide variety of cases (drawing an approximate envelop of cases in the L-T plane of Fig.2a) followed in the forthcoming stages of the analysis and associated figures in Section 3.1.2 (determinants of modelling choices in the L-H plane, Fig.3), Section 3.2 (determinants sought in flow typology, Fig.6a and 7a) and Section 3.3 (determinants sought in the values of dimensionless numbers attached to the flow).

Case	Context	Authors	Model refinement	Spatiotemporal scales					Flow typology‡	Dimensionless numbers§					
				L (m)	T (s)	H (m)	L/T (m s^{-1})	H/L† (-)		T*	Re	Fr	S (%)	Λ_z	θ
A	Film flow	Charpin & Myers (2005)	NS	0.075	3.75	0.003	0.02	0.04	O	5	300	0.11	10	8.0	-
B	Laminar dynamics	Charru et al. (2004)	RANS	0.2	1.8 10^5	0.007	1.1 10^{-6}	0.035	O	6428	50	0.02	<0.01	12.1	0.14
C	Pool-riffles	Rathburn & Wohl (2003)	SV	70	2.6 10^6	0.47	3.5 10^{-5}	6.7 10^{-3}	B	7.8 10^4	7.1 10^5	0.69	1.1	5108	34.1
D	Amazon River	Trigg et al. (2009)	ASV	4.3 10^5	3.15 10^8	10	1.4 10^{-3}	2.3 10^{-5}	F	58.5	8 10^5	0.05	<0.01	6600	-
E	Step-pools	Grant et al. (1990)	SV	5530	1755	0.87	3.15	1.5 10^{-4}	Hg	1.0	2.7 10^6	1.03	4.5	1.25	-
F	Step-pools	Chin (1999)	SV	197.25	30	0.50	6.58	0.025	Hg	1.21	4.0 10^6	3.58	6.25	1.22	-

† See section 3.1.2 - H/L is the fineness ratio of the flow comparing flow depth (H) to the length of the flow domain (L)
‡ See Section 3.2 - O: Overland, Hg: High-gradient, B: Bedforms, F: Fluvial
§ See Section 3.3 - T*: dimensionless period, Re: Reynolds number, Fr: Froude number, S: slope, Λ_z inundation ratio, θ Shields number

Table 1 - Six textbook cases representing an approximate envelope of all the tested cases in the L-T plane of Fig.2a, where L is the spatial scale (length of the flow domain) and T the temporal scale (duration of the process studied). Spatiotemporal scales are the determinants of modelling choices discussed in Section 3.1. The additional influence of flow typology and dimensionless numbers are discussed in Sections 3.2 and 3.3.

3.1.2 Influence of domain length (L) and flow depth (H)

The NS, RANS, SV and ASV equations are now positioned with respect to the spatial scale (L) and flow depth (H) of the reported experiments (Fig.3), showing patterns and trends very similar to those of the (L, T) plane, though less pronounced . The global trend stays a decrease in refinement of the flow models from the smallest to the largest (L, H) values and typical scales of application may again be identified for each model refinement, NS (10 cm<L<100 m, 1 mm<H<30 cm), RANS (1 m<L<100 m, 5 cm<H<50 cm), SV (10 m<L<20 km, 1 cm<H<2 m) and ASV (10 m<L<1000 km, 10 cm<H<10 m). Some studies provide outliers for example Gejadze & Copeland (2006) for canal control purposes (NS, L~3 km, H~10 m) or Cassan et al. (2012) for flows in lined channels (RANS, L~50 cm, H~75 cm). In an overview, wider overlaps and more dispersion occur in the (L, H) than in the (L, T) plane, especially for low to medium scales: flow depth (H) seems less discriminating than the time scale (T) in the choice of a flow model.

The transverse analysis of H/L "fineness ratios" (dotted diagonals H/L=10^{-1}, 10^{-2}, 10^{-3}, 10^{-4} and 10^{-5}) provides additional information, or rather a complementary reading grid on the information already plotted. First, only the NS and RANS models allow 2D (x, z) flow descriptions, which explains why these models have many of the largest H/L ratios (which, in most cases, stay within the H<<L shallow water hypothesis). Second, low H/L ratios provide justifications to discard 2D (x, z) descriptions at the benefit of 1D (x) descriptions within but also without the NS and RANS formalisms, so that the second diagonal of Fig.3 (roughly from the upper right to the lower left) also shows a decrease in model refinement, towards SV and ASV points.

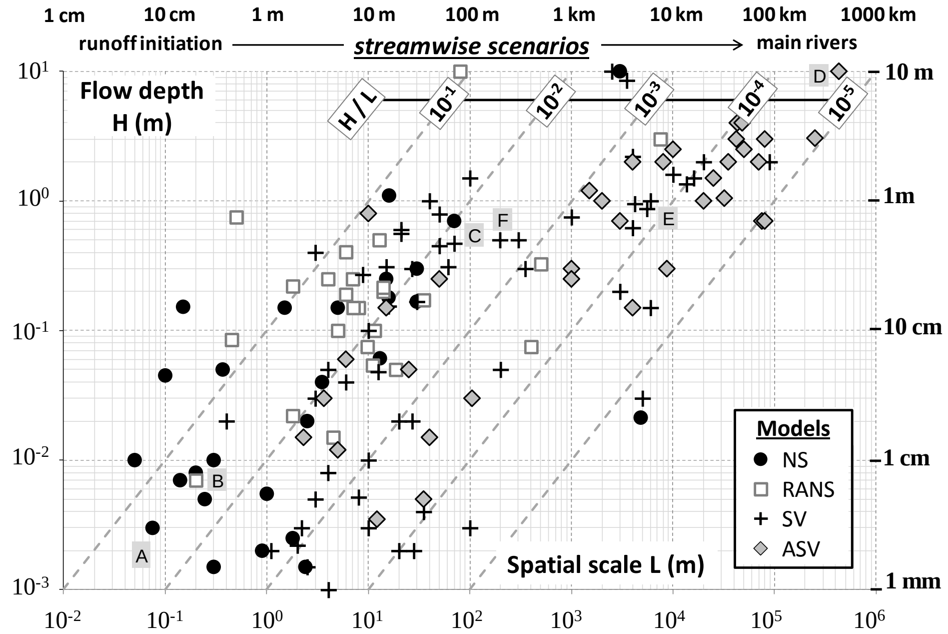


Figure 3 – How increasing (L, H) spatiotemporal scales of the flow domain tend to be associated with decreasing complexity in the choice of flow models, sorted here into four levels of refinement: Navier-Stokes (NS), Reynolds-Averaged Navier-Stokes (RANS), Saint-Venant (SV) and Approximations to Saint-Venant (ASV). A transverse analysis involves forming H/L ratios, searching for clues to model selection according to the "fineness" of the flow or governed by flow typologies that would exhibit specific H/L ratios. This figure was assembled from information available in the studies cited in Appendix A, selecting six textbook cases (sketches A to F, Table 1) for illustration.

3.1.3 Influence of domain length (L), time scale (T) and flow depth (H)

The links between model refinements (NS, RANS, SV or ASV) and spatiotemporal scales (L, T, H) were shown in the (L, T) and (L, H) planes (Fig.2a and 3). There was first the expected correlation between increasing scales and decreasing model refinements. Then the transverse analyses involved re-examining the same dataset from the values of the L/T and H/L ratios, also seeking the determinants of modelling choices in the "system evolution velocity" (L/T) and "fineness" of the flow (H/L).

- The values of the L/T ratios indicate that modelling choices owe much to the long-term (low L/T) or short-term (high L/T) objectives associated with the target variables (velocity, discharge, particle transport, bed modifications) thus influencing the choice of T values. However, this choice is not totally free: it is likely constrained by flow characteristics and typologies.

- The values of the H/L ratios also indicate that flow typology (here, only its "fineness" is explicit) may be a mattering determinant for the choice of a modelling strategy. This idea is explored in far more details hereafter. The next section outlines the influence of friction, flow retardation and energy dissipation processes on flow typology. It advocates thus the definition of flow typologies from quantities related to the different types and/or magnitudes of flow retardation processes, provided these quantities are easily accessible (*e.g.* bed geometry, water depth, bed slope, size of the roughness elements).

3.2 Flow typology

3.2.1 From friction laws and bed topography to flow characteristics

Early insights on fluid friction and the definition of shear stress proportional to local velocity gradients came together with the action-reaction law (Newton 1687): friction exerted on the flow was of equal magnitude as the erosive drag, originally termed "critical tractive force" (Du Buat 1779) and held responsible for particle detachment. The friction laws mostly resorted to in present-day modelling do not often involve adaptations or generalisations of their famous empirical predecessors in civil engineering (Chézy 1775, Weisbach 1845, Darcy 1857, Manning 1871) even if practitioners and modellers are now confronted to far less controlled bed topographies and flow conditions, thus to a wider variety of flow typologies. The theoretical derivation (or justification) of contextually relevant friction laws seems therefore crucial, for water flow modelling at the microscopic (Richardson 1973, Jansons 1988, Priezjev & Troian 2006) or macroscopic scales (Smith et al. 2007, Powell 2014), and even more for morphodynamic issues. In the literature, the modelling choices to account for friction phenomena are most often correlated with the refinement of the flow models used (NS, RANS, SV, ASV) but also constrained by bed topographies and flow typologies in numerous cases.

Several studies at the NS level of refinement advocate the use of the "partial slip" (Navier 1827) condition or parented formulations in which the near-bed slip velocity is either proportional to the shear stress (Jäger & Mikelic 2001, Basson & Gerard-Varet 2008) or depends on it in a non-linear way (Achdou et al. 1998, Jäger & Mikelic 2003). Other works plead for "no-slip" conditions (Panton 1984, Casado & Diaz 2003, Myers 2003, Bucur et al. 2008, 2010) or suggest the separation of flow domains within or outside bed asperities, with a complete slip condition (non-zero tangential velocity) at the interface (Gerard-Varet & Masmoudi 2010). A wider consensus exists at the RANS level, calculating bottom friction as the local grain-scale values of the "Reynolds stresses" (Kline et al. 1967, Nezu & Nekagawa 1993, Keshavarzy & Ball 1997), which has proven especially relevant for flows in small streams over large asperities (Lawless & Robert 2001, Nikora et al. 2001, Pokrajac et al. 2007, Schmeeckle et al. 2007). However, he who can do more, can do less, and it is still possible to use the simplest empirical friction coefficients (Chézy, Manning) within sophisticated flow descriptions (NS: Lane et al. 1994, RANS: Métivier & Meunier 2003). In the literature, the SV level of refinement is a tilting point in complexity, that allows fundamental research, deriving *ad hoc* shear stress formulae from the local fluid-solid interactions (Gerbeau & Perthame 2001, Roche 2006, Devauchelle et al. 2007, Marche 2007) or applied research, adjusting parameter values in existing expressions, for specific contexts (*e.g.* boulder streams: Bathurst 1985, 2006, step-pool sequences: Zimmermann & Church 2001, irrigation channels: Hauke 2002, gravel-bed channels: Ferro 2003). This trend holds for most studies at the ASV level of refinement, though theoretical justifications of Manning's empirical formula were recently derived (Gioia & Bombardelli 2002) and a recent mathematical study of the diffusive wave equation (Alonso et al. 2008) introduces generalized friction laws for flows over non-negligible topographic obstacles. The event-based variability of the friction coefficient in ASV models has been investigated by Gaur & Mathur (2002).

If not decided from the level of refinement of the flow model, the friction coefficient (*f*) is chosen in accordance with flow typology and bed topography, the former often described by the Reynolds number (*Re*), the latter by the inundation ratio (Λ_z=H/ε where ε is the size of bed asperities, to which flow depth H is compared). Such arguments were already present in the works of Keulegan (1938) and Moody (1944) on flow retardation in open-channel and pipe flows, relating values of the friction coefficient to the relative roughness ($\varepsilon/H=1/\Lambda_z$) of the flow, across several flow regimes (laminar, transitional, turbulent) but only for small relative roughness (high inundation ratios). The existence of implicit relations between f, Re and Λ_z has somehow triggered the search for contextual alternatives to the sole f-Re relation for turbulent flows. Progressively lower inundation ratios were investigated (Smith et al. 2007) until the real cases of emergent obstacles received attention (Bayazit 1976, Abrahams & Parsons 1994, Bathurst 2006, Meile 2007, Mügler et al. 2010) including for non-submerged vegetation (Prosser et al. 1995, Nepf 1999, Järvelä 2005, Nikora et al. 2008). For site-specific friction laws, the default f-Re relation is sometimes complemented by f-Fr trends (Grant 1997, Gimenez et al. 2004, Tatard et al. 2008) or f-Λ_z relations (Peyras et al. 1992, Chin 1999, Chartrand & Whiting 2000, Church & Zimmermann 2007) in steep bed morphologies, where Fr is the Froude number (Froude 1868).

Knowledge gained on flow retardation processes lead to the identification of key dimensionless groups, to be included in any comprehensive analysis, formed from the "obvious", available elements of bed geometry previously mentioned (Julien & Simons 1985, Lawrence 2000, Ferro 2003, Yager et al. 2007). In numerous practical cases though, explicit bed geometries cannot be handled by the flow models. A crucial surrogate becomes then to include as many geometrical effects as possible in the chosen friction laws, for example these obtained from composite roughness experiments (Schlichting 1936, Colebrook & White 1937, Einstein & Banks 1950). A crucial advance was due to Smith & McLean (1977) who attributed distinct retardation effects to bed particles, particle aggregates and bedforms, corresponding to “grain spill”, “obstructions” and “long-wave form resistance” in the subsequent literature. From then on, friction forces exerted by multiple roughness elements or scales have often been described as additive-by-default, in shallow overland flows (Rauws 1980, Abrahams et al. 1986), gravel-bed streams (Bathurst 1985, Lawless & Robert 2001, Ferro 2003), natural step-pool formations (Chin & Wohl 2005, Canovaro & Solari 2007, Church & Zimmermann 2007) and man-made spillways or weirs (Peyras et al. 1992, Chinnarasri & Wongwise 2006).

3.2.2 From flow characteristics to flow typologies

Several authors have put forward the existence of a scale-independent link between bed geometry, flow retardation and flow structure, through the existence of three distinct flow regimes, from geometrical arguments: "isolated roughness", "wake interference" and "skimming" flow (Morris 1955, 1959, Leopold et al. 1960, Fig.4a, c and e). These flow descriptions were later applied in very different contexts (Abrahams & Parsons 1994, Chanson 1994a, Papanicolaou et al. 2001, Zimmermann & Church 2001), which suggests that analogies in energy dissipation and flow retardation may exist across scales, from similar geometries and flow characteristics. This makes the description somewhat generic, possibly used to constitute a set of flow typologies.

In Fig.4a, the isolated roughness flow is laminar or weakly turbulent and the shade (streamline diversion) of an obstacle does not reach the next. This setting ensures maximum energy dissipation, which also holds for stepped cascades of natural or man-made nature in Fig.4b: "nappe flows" loose strength through energy-consuming fully-developed hydraulic jumps, isolated behind the major obstacles (Peyras et al. 1992, Chanson 1994b, Wu & Rajaratnam 1996, 1998). In Fig.4c the wake-interference flow is transitional or turbulent. The drag reduction and partial sheltering between obstacles depend on their spatial distribution and arrangements, as in Fig.4d that shows "partial nappe flow" in relatively flat step-pool formations, with incomplete hydraulic jumps between obstacles of irregular sizes and spacing (Wu & Rajaratnam 1996, 1998, Chanson 2001). In Fig.4e, the turbulent skimming flow exhibits a coherent stream cushioned by the recirculating fluid trapped between obstacles and responsible for friction losses. Similar characteristics appear in Fig.4f, for submerged cascades or large discharges on stepped spillways. Air entrapment begins where the boundary layer reaches the free surface and flow aeration triggers subscale energy dissipation (Rajaratnam 1990, Chanson 1994b).

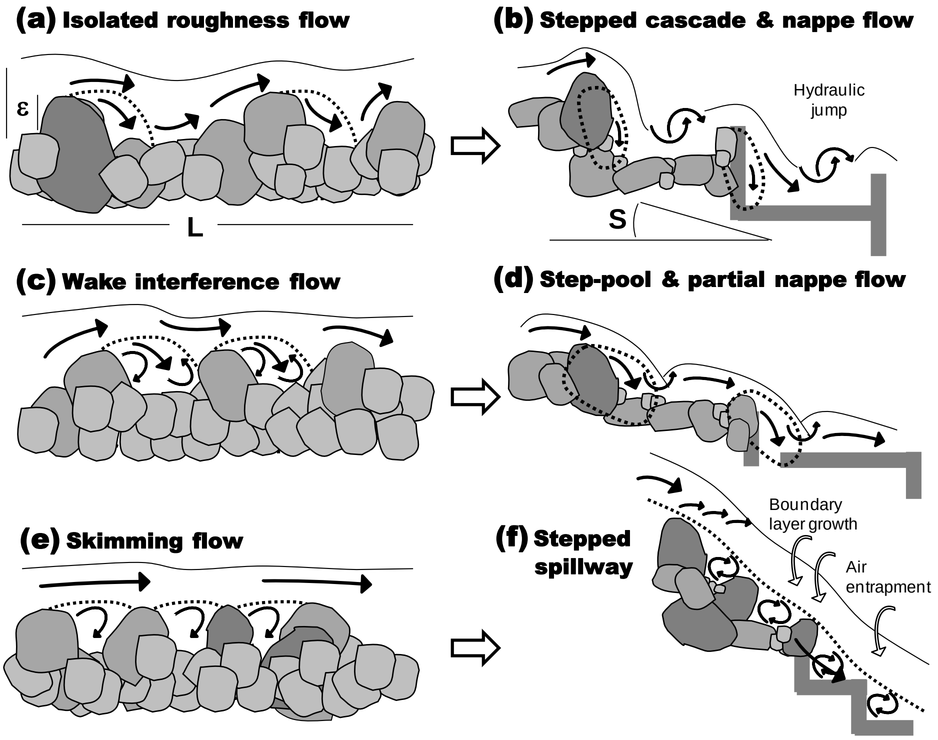


Figure 4 – Analogies in flow characteristics, retardation processes and energy dissipation structures for very different flow typologies: streams (a, c, e) and high-gradient natural or man-made stepped flows (b, d, f). The combined values of flow depth (H), slope (S) and inundation ratio (Λ_z=H/ε, where ε is the roughness size) appear as strong geometrical controls over flow characteristics and typologies. The very small inundation ratios (Λ_z<1) typical of overland flows in hydrology (flows through emergent obstacles, including vegetation) correspond to ε values larger than H values (tortuous flows are best seen in the top views of Fig.8).

At this point, our set of flow typologies should be obtained from the geometrical arguments available in Fig.4 (water depth H, bed slope S, inundation ratio Λ_z=H/ε). The simplest way to proceed is to work in the (S, H) plane, then to indicate the values of Λ_z for each pair of (S, H) values. The first two flow typologies (Overland flow, noted O, and High-gradient flow, noted Hg) may be identified by a single criterion on H only ($H<H_{LIM}$, Emmett 1970, Wainwright et al. 2008) or on S only ($S>S_{LIM}$, Grant et al. 1990, Rosgen 1994, Montgomery & Buffington 1997). At least two flow typologies remained to be distinguished, Fluvial flows (F) and flows over significant bedforms (*e.g.* rough plane bed, dune-ripples or pool riffles, as suggested by Montgomery & Buffington 1997), referred to as Bedforms (B) in the following. Though Fluvial flows are expected to have the highest flow depths, an additional criterion on Λ_z may be used to make the difference between these last two typologies. Figure 5 positions the selected (O, Hg, B, F) flow typologies in the (S, H) plane.

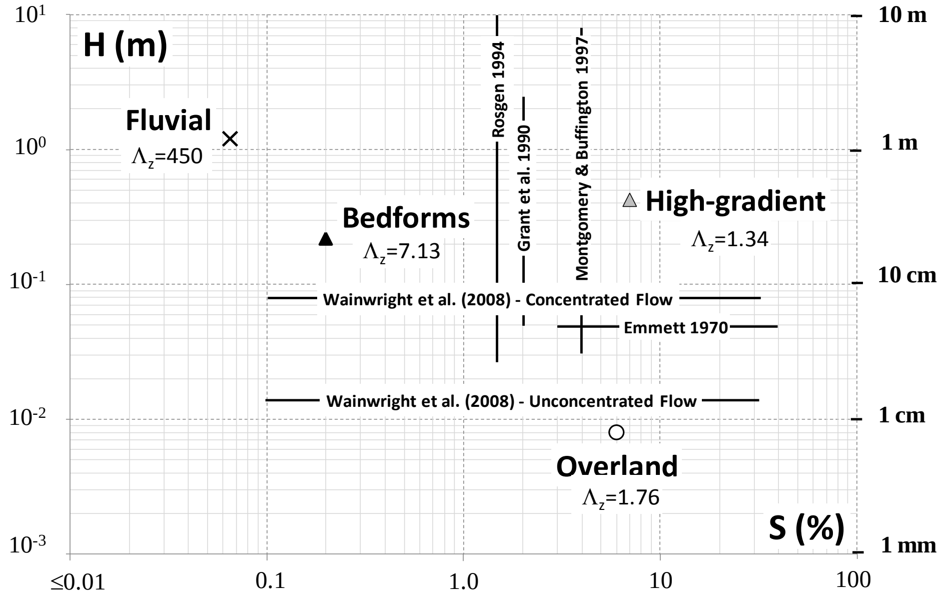


Figure 5 – Median position of the studies belonging to the "Overland", "High-gradient", "Bedforms" and "Fluvial" flow typologies, plotted on the (S: slope, H: water depth) plane, with indication of the associated inundation ratio (Λ_z=H/ε) This figure was assembled from information available in the studies cited in Appendix A.

Moreover, there is a strong link between Fig.4 and 5, which tends to ensure the genericity (if not uniqueness) of the selected set of typologies. The Overland typology corresponds to Fig.4a or c, the Bedforms typology likely appears in Fig.4c, the Fluvial typology in Fig.4 and the High-gradient typology in Fig.4b, d or f. In coherence with Fig.5, an increase in bed slope changes the Bedforms and Fluvial typologies into the High-gradient typology, while an increase in both water depth and bed slope is needed to do the same from the Overland typology.

3.2.3 Influence of flow typologies on modelling choices

Figures 6 and 7 provide a comprehensive picture of the most used associations between models (NS, RANS, SV or ASV), scales (L, T, H) and flow typologies (O, Hg, B or F) just added to the analysis. These figures seem to indicate preferential [NS, O], [RANS, B] and [SV, Hg] associations, in addition to the obvious [ASV, F] pair. The (L, H) plot of Fig.7b seems more discriminating than the (L, T) plot of Fig.6b though similar trends appear.

The [NS, O] association arises from the fact that several Overland studies involve very shallow laminar flows and low sediment transport rates, best handled by adapted formulations of the NS equations (nearly at the SV level), made suitable for low "system evolution velocities" ($L/T \approx 0.01$ m s^{-1}, Fig.6). At somewhat larger spatial scales, the widely-used and multipurpose SV model has rather low median $L/T \approx 0.02$ m s^{-1} values, mainly because many of its applications concern laminar flow modelling and granular transport, as an alternative to the NS system or in formulations at complexity levels intermediate between the NS and SV descriptions. These are clues that the [SV, O] association may also be of special interest, despite the closest median positions of the NS and O points in the (L, T) and (L, H) plots.

The RANS model (median $L/T \approx 0.07$ m s^{-1}) and the ASV models (median $L/T \approx 0.1$ m s^{-1}) tend to involve higher "system evolution velocities". The former typically targets the description of numerous short-term, high-frequency events (quadrant analysis for fluctuations in near-bed velocity, particle pick-up by turbulent bursts). The latter is often associated with Fluvial flows: low H/L ratios with high enough H and Λ_z values with weak friction, often resulting in very turbulent, high-velocity flow. Moreover, studies handling morphodynamic issues within the ASV formalism often hypothesize particle transport to occur as suspended load only, equating particle and flow velocities, thus typically not extending the time scale of the study to address the long-term, low velocity bedload transport involved in morphodynamics, for example.

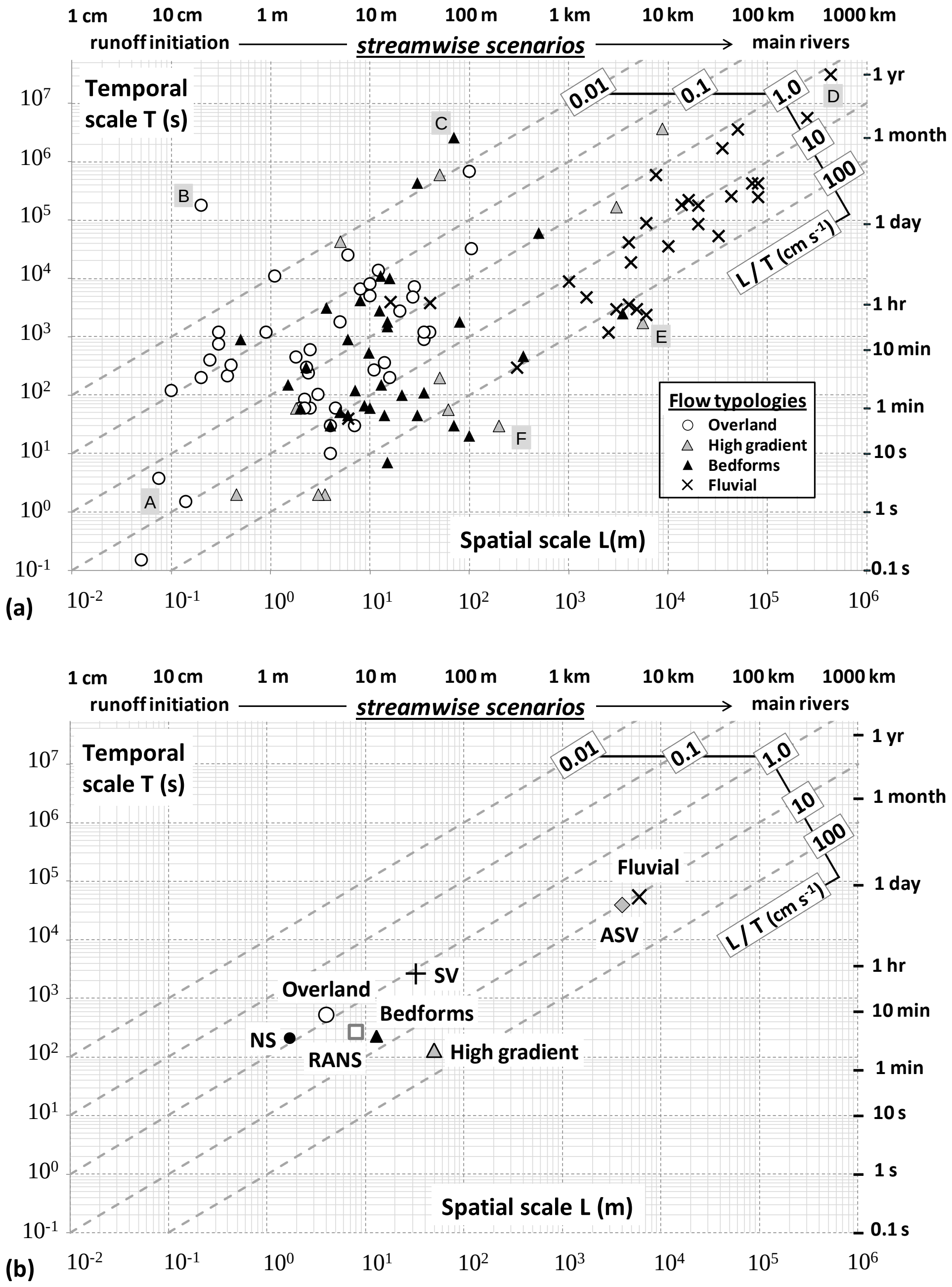


Figure 6 – Position of the flow typologies in the (L, T) plane for the studies listed in Appendix A, selecting six textbook cases (sketches A to F, Table 1) for illustration (a). Median positions for the choice of free-surface flow models (Navier-Stokes: NS, Reynolds-Averaged Navier-Stokes: RANS, Saint-Venant: SV or Approximations to Saint-Venant: ASV) and the study of flow typologies (Overland, High-gradient, Bedforms or Fluvial) across scales in the (L, T) plane (b). A transverse analysis involves forming L/T

ratios, searching for clues to model selection according to these "system evolution velocities" or governed by flow typologies that would exhibit specific L/T ratios.

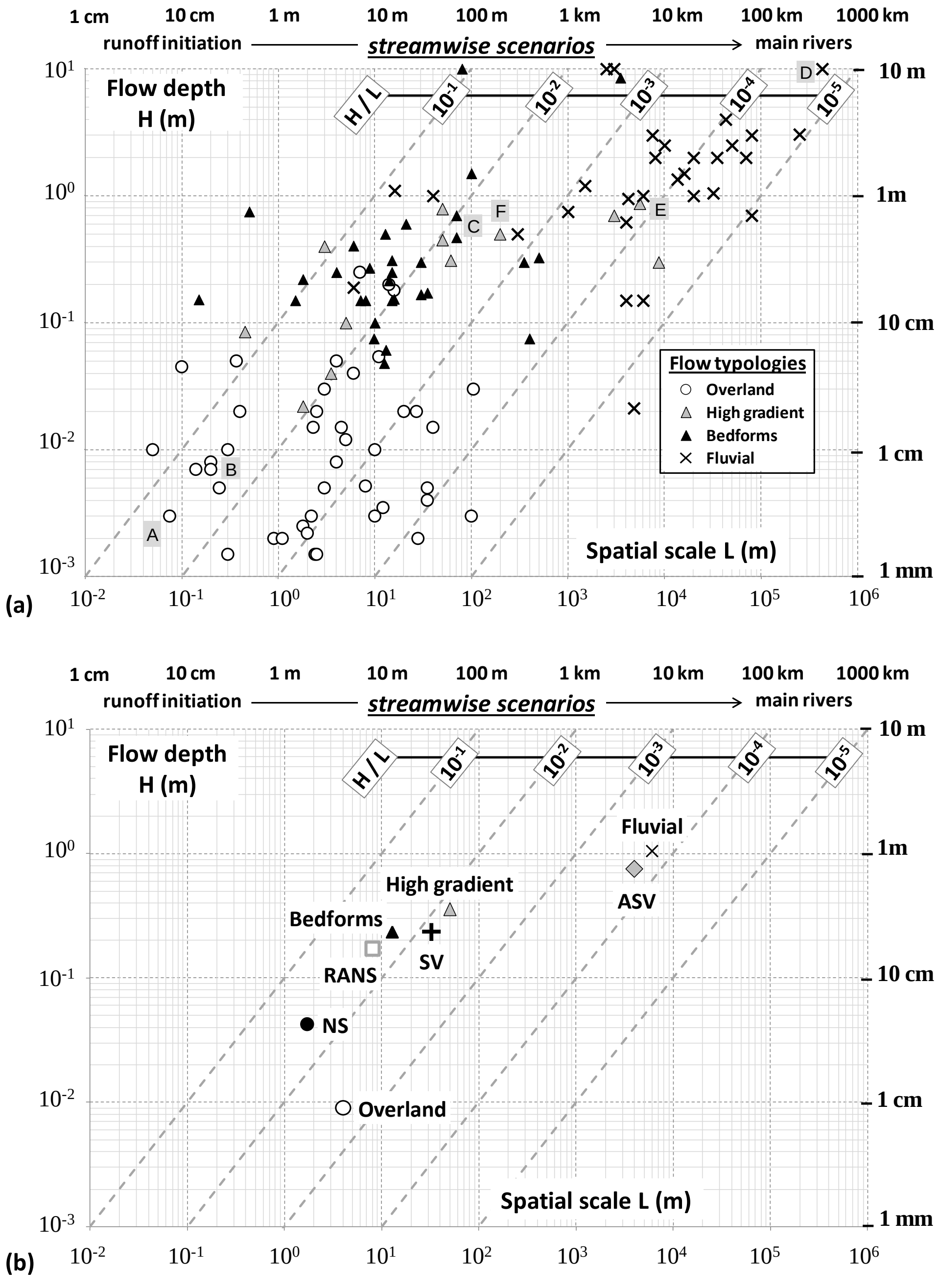


Figure 7 – Position of the flow typologies in the (L, H) plane for the studies listed in Appendix A, selecting six textbook cases (sketches A to F, Table 1) for illustration (a). Median positions for the choice of free-surface flow models (Navier-Stokes: NS, Reynolds-Averaged Navier-Stokes: RANS, Saint-Venant: SV or Approximations to Saint-Venant: ASV) and the study of flow typologies (Overland, High-gradient,

Bedforms or Fluvial) across scales in the (L, H) plane (b). A transverse analysis involves forming H/L ratios, searching for clues to model selection according to these "finenesses" of the flow domain or governed by flow typologies that would exhibit specific H/L ratios.

Several principles of organization between flow typologies may be inferred from reference studies (Grant et al. 1990, Montgomery & Buffington 1997, Church 2002) that discuss their succession in space (along longitudinal profiles) but also in time (which flow typologies are "experienced" by the flowing water during its course and which are the associated time scales). Plausible "streamwise scenarios" may therefore be assembled (Fig.8), routing flow aggregations across increasing spatiotemporal scales and through several flow typologies, from the narrow-scale upland flows (runoff initiation) to the regional scales of the main rivers.

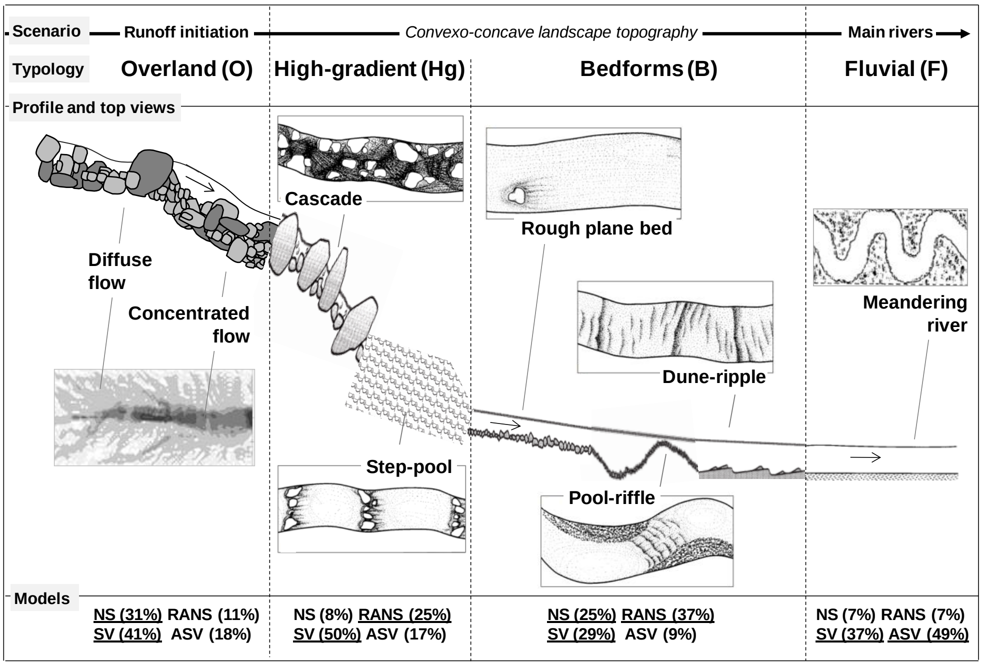


Figure 8 – Streamwise scenario for a convexo-concave landscape topography, from runoff initiation to the main rivers, across flow typologies (Overland O, High-gradient Hg, Bedforms B or Fluvial F) and spatiotemporal scales (L, T, H). All sketches and drawings for the High-gradient and Bedforms typologies were taken from Montgomery & Buffington (1997). The top view for Overland flow is from Tatard et al. (2008) and that of a meandering river from Rosgen (1994). The "Models" panel indicates the model refinements most used (Navier-Stokes NS, Reynolds-Averaged Navier-Stokes RANS, Saint-Venant SV or

Approximations to Saint-Venant ASV) to describe a given flow typology in the literature cited in Appendix A.

3.3 Dimensionless numbers

3.3.1 Contextual dimensionless numbers

Complementary indications on modelling strategies are provided by dimensional analysis, to delineate the domains of validity of the selected flow models (NS, RANS, SV or ASV), across their multiple spatiotemporal scales of application but in a powerful scale-independent analysis. Justifications for the use of dimensionless numbers may be sought in the developments of similitude laws (Fourier 1822, Rayleigh 1877, Bertrand 1878, Vaschy 1892, Riabouchinsky 1911), later extended to dimensional analysis, providing guidance for the sizing of experimental facilities used in reduced-scale modelling as well as more general arguments for the choice of adequate sets of dimensionless quantities (Buckingham’s 1914 π-theorem, Bridgman 1922, Langhaar 1951, Bridgman 1963, Barenblatt 1987). Throughout history, the establishment of dimensionless numbers has led to the recognition of contextually dominant terms in the flow equations, rendering them prone to dedicated simplifications, provided these would not be used outside their conditions of validity, following successive hypotheses made during their derivation. On the one hand the dimensionless numbers arise in the non-dimensionalisation of the systems of governing equations, being an inherent feature of the model. On the other hand only the selected dimensionless numbers appear in the non-dimensional formulation of the equations, from appropriate arrangements of their terms, and this choice indicates which are the physical processes of interest for the modeller. Finally, not all dimensionless numbers can be made explicit in the simplest mathematical models (especially the ASV models) but their values can always be calculated, thus correlated (or not) with the use of one or the other of the flow models.

From a wide overview of free-surface flow and morphodynamic studies, a few dimensionless numbers stood out and will be used in the procedure presented in the following. Some have already been mentioned (Reynolds number Re, Froude number Fr) and some others have even been used to define flow typologies (bed slope S, inundation ratio Λ_z). As all dimensionless numbers aim to describe flow typology, the introduction of two more dimensionless numbers may be seen as an attempt to re-examine the influence of flow typologies on modelling choices, from a different, more complete perspective (especially if the dimensionless numbers not used in the definition of flow typologies prove discriminating for the modelling choices).

- The dimensionless period $T^*=T/T_0$ handles temporal aspects by comparing the chosen time scale (T) to the natural time scale (T_0) of the system, the latter obtained from the spatial scale of the system and the average flow velocity as $T_0=L/U$ (Fig. 1). This dimensionless group or equivalent formulations are used to model wave celerity in flood propagation issues (Ponce & Simons 1977, Moussa & Bocquillon 1996a, Julien 2010) or to quantify the long characteristic times ($T^*>>1$) of basin-scale sedimentation. In the latter, particle transport (and significant bed modifications) typically involve lower velocities (and larger time scales) than these of water flow (Lyn 1987, Paola et al. 1992, Howard 1994, Van Heijst et al. 2001) and the chosen T value witnesses this discrepancy.

- The Reynolds number $Re=UH/\upsilon$ compares flow inertia (velocity U times depth H) with the adverse action of (kinematic) viscosity (υ [L T^{-2}]). In natural setting, over very rough boundaries, fully turbulent flows are often reported for Re>2000, while the onset of turbulence within transitional regimes occurs at Re~500. Laminar overland flows, especially thin film flows, may have Re values as low as Re<100.

- The Froude number $Fr=U/(gH)^{0.5}$ denotes the influence of gravity (g) on fluid motion. Supercritical Fr>1 values indicate torrential flows, for example flows accelerated by pressure effects, in which waves propagate only downstream, also compatible with the appearance of localised energy dissipation patterns (white waters, hydraulic jumps). Subcritical Fr<1 values indicate tranquil flows with downstream controls. However, the presence of a movable bed makes the identification of suband supercritical regimes less obvious, as additional phenomena come into play (Lyn 1987, Lyn & Altinakar 2002).

- Topographical effects on flow phenomenology are almost always explicitly accounted for through the average bed slope S, typically ranging from nearly zero ($S<0.01\%$) for large rivers to extremely high values ($S \approx 100\%$) for gabion weirs, chutes or very steep cascades.

- Topography also appears through the inundation ratio $\Lambda_z=H/\varepsilon$ which allows a direct, model-independent analysis of friction phenomena (Lawrence 1997, 2000, Ferguson 2007, Smith et al. 2007) possibly dealing with large-size obstacles and form-induced stresses (Kramer & Papanicolaou 2005, Manes et al. 2007, Cooper et al. 2013). The encountered values of Λ_z are very high for rivers flowing on smooth, cohesive, fine-grained beds ($\Lambda_z>100$) and very low for all types of flows between emergent obstacles ($\Lambda_z<1$, Ferro 2003, Hogarth et al. 2005, Canovaro & Solari 2007, Ferguson 2007, Lamb et al. 2008) including flow through vegetation (see Järvelä 2004, Holden et al. 2008, Gumiere et al. 2011a, Kim et al. 2012, Nepf 2012).

- The dimensionless Shields number $\theta=\tau_0/g\varepsilon_p(\rho_p-\rho)$ compares the drag force exerted on bed particles to their immersed weight, where ε_p and ρ_p account for the size and density of erodible particles.. The ratio between the current θ and the critical θ_c values indicates local flow conditions of deposition ($\theta<\theta_c$), incipient motion ($\theta\approx\theta_c$), transportation as bedload ($\theta>\theta_c$) or into suspension ($\theta>>\theta_c$) (Shields 1936). This number seems appropriate for most morphodynamic issues because it has been widely applied and debated in the literature (Coleman 1967, Ikeda 1982, Wiberg & Smith 1987, Zanke 2003, Lamb et al. 2008) and also because of its numerous possible adaptations (Neill 1968, Ouriémi et al. 2007, Miedema 2010) to various flow typologies and non-uniform or poorly-known bed conditions. An impressive review on the use of the Shields number to determine incipient motion conditions, over eight decades of experimental studies, may be found in Buffington & Montgomery (1997). Finally, Fig.9 provides a generalized Shields diagram that includes motion threshold criteria under the effects of high or low particle exposure (Miedema 2010) or for laminar flows, also indicating the conditions of significant suspension (Wright & Parker 2004). To search for additional indications, the points in

Fig.9 have been sorted by flow depths with the arbitrary H=5 cm threshold. Other case classifications may be relevant, for example identify the hydrological and hydraulic contexts.

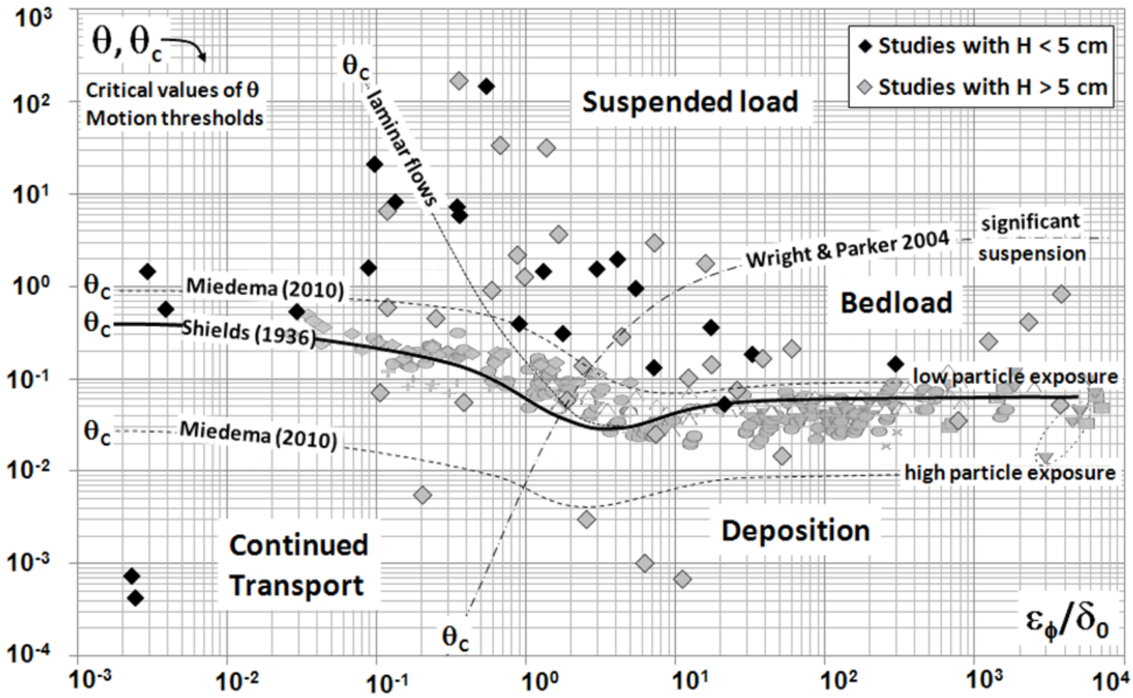


Figure 9 - Generalized dimensionless Shields diagram that summarizes the conditions and regimes of sediment transport or deposition, from the relative values of the Shields parameter (θ) and incipient motion criterion (θ_c). The X-axis bears the values of the ratio of particle size (ε_ϕ) on the depth of the laminar sublayer (δ_0). The diamonds refer to the studies cited in Appendix A that deal with morphodynamic issues: black diamonds for studies in which flow depth is H<5 cm, grey diamonds otherwise. Data in the background show the critical θ_c values reported in the wide Buffington & Montgomery (1993) review of incipient motion conditions for varied flow regimes, particle forms and exposures.

3.3.2 Influence of the dimensionless numbers

As the purpose here is to re-examine the influence of flow typologies from the point of view of the dimensionless numbers, the chosen representation (Fig.10) discards the (L, T, H) spatiotemporal scales. It first recalls the preferential associations between models and flow typologies (see the

"Models" panel of Fig.8) by tracing connecting dotted lines between flow typologies and the models most used to handle them, in the legend of Fig.10. It then examines whether these associations still hold, for each of the six dimensionless numbers, by plotting and comparing the median values of T*, Re, Fr, S, Λ_z and θ for model uses (NS, RANS, SV or ASV) and flow typologies (O, Hg, B, F). The dotted ellipses are "confirmations" (*e.g.* no additional information may likely be obtained from Re, Fr and θ). Conversely, the presence of "non-associated" points (P_1 for T*, P_2 and P_3 for S) signals cases in which the determinants of modelling strategies should be thought altogether in spatiotemporal scales, flow typologies and the values of certain dimensionless numbers.

For example, the isolated P_1 point indicates the expected [ASV, F] association does not appear on the T* values, as the ASV applications exhibit higher median T* values than the F typologies. The suggested interpretation is that large (L, T, H) scales and Fluvial flows likely trigger the use of the ASV model, though the necessity to handle large dimensionless periods makes the typological argument less conclusive. The P_2 and P_3 points also indicate the break of the [ASV, F] associations when examined from the angle of the bed slopes. This reinforces the use of bed slopes in the search for determinants of modelling choices, either in the definition of flow typologies in the (S, H) plane or as such.

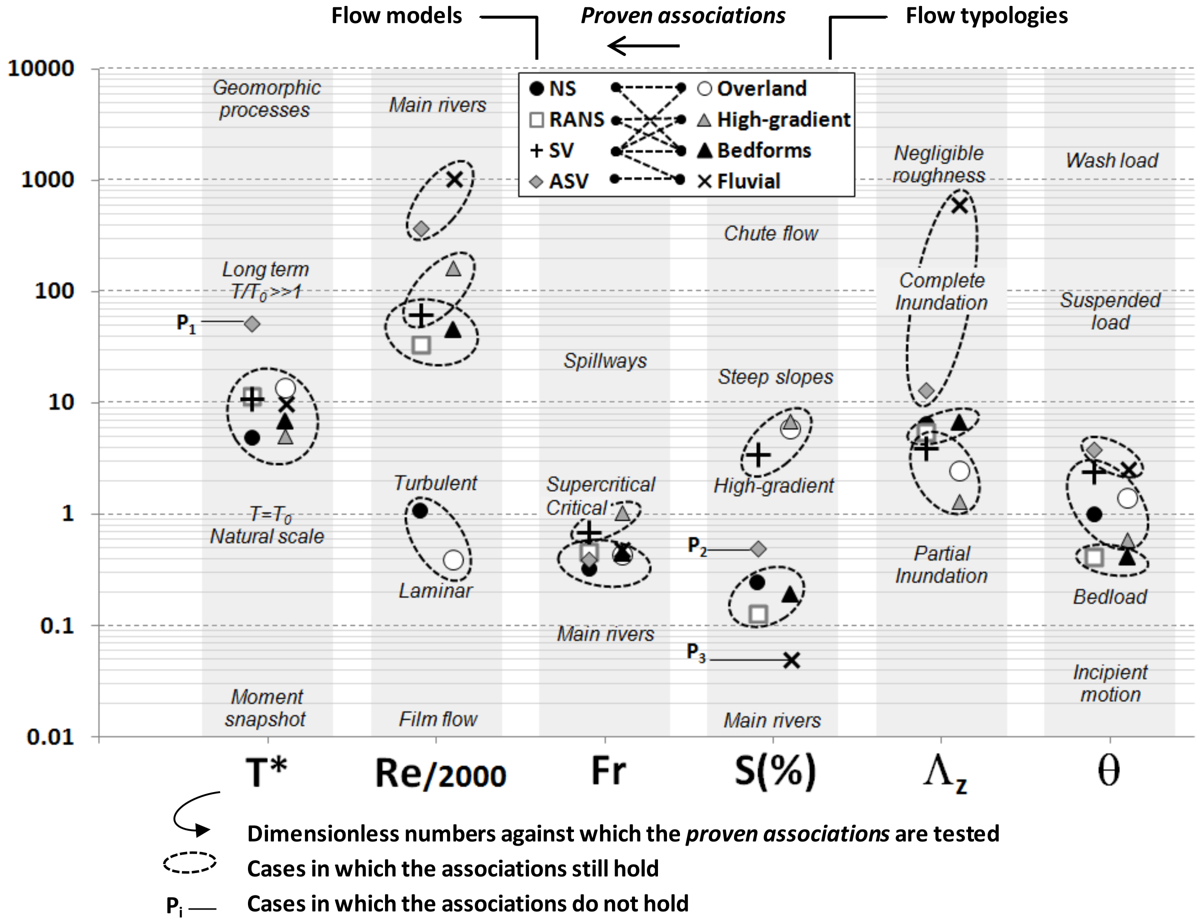


Figure 10 - Comparative overview of the median values of the six selected dimensionless numbers (dimensionless period $T^*=T/T_0$, ratio of the chosen time scale on the "natural" time scale of the flow, Reynolds number Re, Froude number Fr, slope S, inundation ratio Λ_z and Shields parameter θ) obtained for the use of systems of equations (NS, RANS, SV and ASV) and the description of flow typologies (O, Hg, B and F) in the cited literature. The expected associations are indicated by dotted connecting lines in the legend box. The confirmed associations are indicated by dotted ellipses. Broken associations (isolated points P_i) are discussed in the text. The typical and extreme ranges of the mentioned dimensionless numbers have been added for indication. This figure was assembled from information available in the studies cited in Appendix A.

4 Conclusion

4.1 Outcomes of this review

In a free opinion on the use of models in hydrology, De Marsily (1994) elegantly argued that the modelling of observable phenomena should obey "*serious working constraints, well-known from classical tragedy: unity of place, unity of time, unity of action*". This review paper investigates how known spatial scales, temporal scales and flow typologies constrain the choice of a modelling strategy. A normative procedure was built to facilitate the search for determinants of the modelling choices in the cited literature.

- Each free surface flow model was placed in one of the NS, RANS, SV or ASV categories, whose decreasing levels of refinement account for "Navier-Stokes", "Reynolds-Averaged Navier-Stokes", "Saint-Venant" or "Approximations to Saint-Venant" types of approaches.

- The explored (L, T, H) spatiotemporal scales cover multiple orders of magnitude in the streamwise direction ($5 \text{ cm} < L < 1000 \text{ km}$), the time duration ($0.1 \text{ s} < T < 1 \text{ yr}$) and flow depth ($1 \text{ mm} < H < 10 \text{ m}$) while the modelling subscales (δL, δT) used for data collection and/or the size of the calculation grid are in the $0.01 \text{ mm} < \delta L < 10 \text{ km}$ and $0.001 \text{ s} < \delta T < 1$ day intervals.

- This study also encompasses a wide variety of free-surface flows, reduced to four typologies from arguments on bed geometry, friction, flow retardation and energy dissipation processes. These typologies are Overland flow (O: diffuse or concentrated), High-gradient flow (Hg: cascades, step-pools), flows over significant Bedforms (B: rough plane beds, dune ripples, pool riffles) and Fluvial flows (F: rivers, canals). Overland flows have the shallowest depths, High-gradient flows the highest bed slopes, Fluvial flows have high flow depths and negligible bed roughness while Bedforms flows may have any flow depth, over pronounced, non-negligible bedforms.

- In addition to the spatiotemporal scales and flow typologies, the determinants of modelling choices are also sought in a series of six popular dimensionless numbers: the dimensionless period (T^*), Reynolds and Froude numbers (Re, Fr), the bed slope (S), the inundation ratio ($\Lambda_z = H/\varepsilon$ where ε is the size of bed asperities) and the Shields number (θ) that compares drag forces to particle weight.

In summary, each case-study may be defined by its signature, comprised of the *chosen* model (NS, RANS, SV or ASV) and modelling subscales (δL, δT) versus *given* spatiotemporal scales (L, T, H), flow typology (O, H, B or F) and dimensionless numbers (T*, Re, Fr, S, Λ_z, θ). Though non-unique, this signature is a generic and normative classification of studies interested in free-surface flow modelling, with or without morphodynamic issues.

- The present review first illustrated the expected dominant trend of decreasing model refinement with increasing (L, T, H) spatiotemporal scales and (δL, δT) subscales. It appeared then that model uses could also be sorted by their L/T and H/L ratios, though less clearly, which nevertheless provided indications that the spatiotemporal scales were not the only determinant of modelling choices. This result suggested that flow typologies (reduced here to the L/T "system evolution velocity" and H/L "fineness of the flow") were also influential factors.

- A more exhaustive set of flow typologies was then derived from simple geometrical arguments, combining criteria on S, H and Λ_z, represented in the (S, H) plane. This allowed quantifying the median scales associated with studies interested in the Overland (O), Bedforms (B), High-gradient (Hg) and Fluvial (F) typologies, sorted here by increasing spatiotemporal scales. Then came the identification of preferential associations between flow models, scales and typologies: [NS, O] or [SV, O], [NS, B], [RANS, B] or [SV, B], [RANS, Hg] or [SV, Hg] and [ASV, F]. - The final step was to re-examine the previous associations from the values of the dimensionless numbers, thought here as more detailed, scale-independent descriptors of flow typologies. Several associations were confirmed by the median values of the associated dimensionless numbers but T* (dimensionless period) and S (bed slope) introduced additional information., *i.e.* correcting trends.

All arguments prevailing in the identification and sorting of flow models, scales, typologies and dimensionless numbers may easily be debated and adapted, within the hydro-morphodynamics community or for other research purposes. For example, multiple flow models, scales, typologies and dimensionless numbers also intervene in the fields of pesticide fate modelling and groundwater contamination issues, so the same procedure could be applied. Finally, this procedure offers the possibility to enrich the database of signatures if modellers record their conceptual choices (flow models) in the proposed reading grid, together with the contextual elements (scales, typologies, dimensionless numbers) handled, for present and past studies. This would first help forming a comprehensive database of modelling choices, thus seeking guidance from "what has been done in similar cases", which however does not provide any critical analysis. Complementary investigations could certainly address the question of "what should be done", this time deciding the "model" part of the signatures from recommendations based on the scales, typologies and dimensionless numbers, as well as from additional elements, typically the modelling objectives (Fig.11).

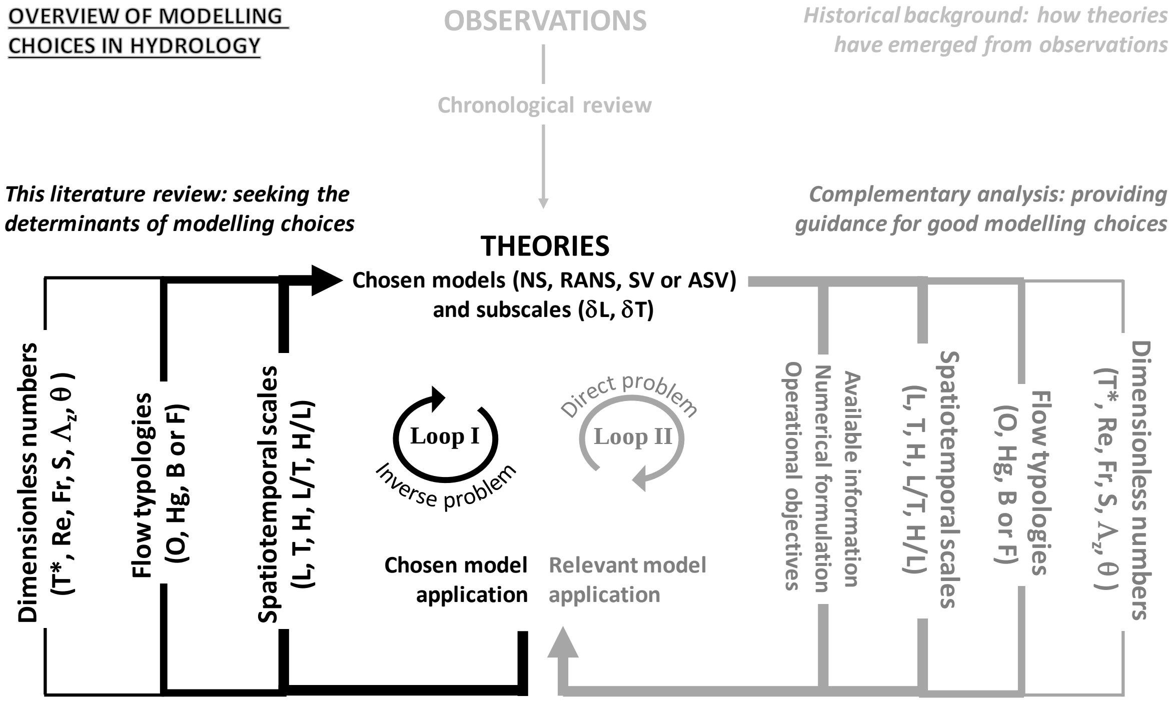


Figure 11 – This figure provides a simplified overview of the available modelling choices in hydrology, in three distinct colours associated with specific research purposes or disciplines, showing the position of the present review relative to the others. The pale grey section aims at understanding how the available flow models have emerged from observations and early formulations of the flow equations, focusing on their conditions of validity *i.e.* the successive hypotheses made during their derivation. The black section recalls the procedure followed in this review paper (Loop I, "inverse problem"). Literature sources are processed through a procedure that analyses how the spatiotemporal

scales (spatial scale L, time scale T, flow depth H, L/T and H/L ratios), then flow typology (Overland O, High-gradient Hg, Bedforms B or Fluvial F) and dimensionless numbers (dimensionless period T*, Reynolds number Re, Froude number Fr, bed slope S, inundation ratio Λ_z, Shields parameter θ) determine the choice of a flow model (Navier-Stokes NS, Reynolds-Averaged Navier-Stokes RANS, Saint-Venant SV or approximations ASV) and that of data collection and/or modelling subscales (δL, δT). Suggested in medium grey on the right are the scope and principles of future research challenges that would address the “*what should be done?”* (Loop II, "direct problem") question in echo to the current “*what has been done?*”concern (Loop I).

4.2 Research challenges and philosophy of modelling

This review has sought the determinants of modelling choices in hydrology (Fig.11, Loop I) from the basis provided by literature sources, without any intention to provide recommendations regarding appropriate (both relevant and cost-effective) modelling strategies. However, for most practical applications, the starting point is the definition of a scope and the endpoint is the evaluation of the objective function to evaluate the success or the failure of the chosen modelling strategy. A question thus arises on how to guide the modeller in the choice of an adequate model, in function of given, approximately known spatiotemporal scales, flow typology and dimensionless numbers (Fig.11, Loop II). According to the principle of parsimony, modellers should seek the simplest modelling strategy capable of (i) a realistic representation of the physical processes, (ii) matching the performances of more complex models and (iii) providing the right answers for the right reasons.

- (i) Throughout the last decades, an important change of the scope of free-surface flow modelling applications has taken place, with subsequent changes in the objective functions resorted to. The development of hydrological and hydraulic sciences has been directly linked to the progresses in understanding processes, in theoretical model development (*e.g.* computational facilities: numerical techniques, data assimilation, thorough model exploration, inverse calculus) and in data acquisition (new devices, remote sensing, LiDAR). "*It may seem strange to end a review of modelling with an* *observation that future progress is very strongly linked to the acquisition of new data and to new experimental work but that, in our opinion, is the state of the science"* (Hornberger & Boyer 1995).

- (ii) However, there remains an important need for research on classical free-surface flow (hydrological or hydraulic) modelling for engineering applications in predicting floods, designing water supply infrastructures and for water resources management, from the headwater catchment to the regional scale. More recently, free-surface flow modelling has become an indispensable tool for many interdisciplinary projects, such as predicting pollution and/or erosion incidents, the impact of anthropogenic and climate change on environmental variables such as water, soil, biology, ecology, or socio-economy and ecosystemic services. The direct consequence is a significant increase of the complexity of the objective function, from simple mono-site (*e.g.* one-point), mono-variable (*e.g.* the water depth) and mono-criterion (*e.g.* the error on peakflow) to complex multi-site (*e.g.* large number of points within a catchment), multi-variable (*e.g.* water depth, hydrograph, water table, concentrations, ecological indicators, economic impact) and multi-criteria (*e.g.* errors on peakflow, volume, RMSE) objective functions.

- (iii) There is often a mismatch between model types, site data and objective functions. First, models were developed independently from the specificities of the study site and available data, prior to the definition of any objective function. In using free-surface flow models, the context of their original purpose and development is often lost, so that they may be applied to situations beyond their validity or capabilities. Second, site data are often collected independently of the objectives of the study. Third, the objective function must be specific to the application but also meet standard practices in evaluating model performance, in order to compare modelling results between sites and to communicate the results to other scientists or stakeholders. The known danger is to use flow and morphodynamic equations outside their domains of validity (*i.e.*, breaking the assumptions made during their derivation) then to rely on the calibration of model parameters as for technical compensations of theoretical flaws, at the risk of losing the physical sense of model parameters, creating equifinality and obtaining the "*right results for the wrong reason*" (Klemeš 1986). Choosing the right model for the right reason is crucial but the identification of the optimal data-model couple to reach a predefined objective is not straightforward. We need a framework to seek the optimum balance between the model, data and the objective function as a solution for a hydrological or hydraulic problem, on the basis of the principle of parsimony. The latter follows a famous quote often attributed to Einstein, that "*everything should be made as simple as possible, but not simpler"* which somehow originates in the philosophy of William of Ockham (1317) *(Numquam ponenda est pluralitas sine necessitate [Plurality must never be posited without necessity])* or may even be traced back to Aristotle's (~350 BCE) *Analytica Posteriora* that already advocated demonstrations relying on the fewest possible number of conjectures, *i.e.* the dominant determinisms.

Finally, analytical procedures for free-surface flows and morphodynamic issues necessitates a comprehensive analysis of the interplay between models (assumptions, accuracy, validity), data requirements and all contextual information available, encompassed in the "signature" of any given application: model refinement, spatiotemporal scales, flow typology and scale-independent description by dimensionless numbers. This review helps the modeller positioning his (or her) case study with respect to the modelling practices most encountered in the literature, without providing any recommendation. A complementary step and future research challenge is to decipher relevant modelling strategies from the available theoretical and practical material, resorting to the same objects, the previously defined signatures. Its purpose clearly is to address the “*which model, for which scales and objectives?*” question. A complete analytical framework, comprised of both loops, would provide references and guidelines for modelling strategies. Its normative structure in classifying theoretical knowledge (the mathematics world, equations and models) and contextual descriptions (real-life physical processes, scales and typologies) hopefully makes it also relevant for other Earth Sciences.

Appendix A. References used in the Figures.

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