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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 to Saint-Venant: ASV), spatiotemporal scales and subscales (domain length: L from 1 cm to 1000 km; temporal scale: T from 1 s 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 and 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 important 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.

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 $L < 10\,\mathrm{m}$; timescale: duration of the process $T < 10\,\mathrm{s}$; flow depth: $H < 1\,\mathrm{cm}$, Fig. 1), those of runoff genesis, overland flow hydraulics, and detailed particle-scale physics (Horton, 1945; Emmett, 1970; Feng and Michaelides, 2002; Schmeeckle and Nelson, 2003). The intermediate scales of catchment and hillslope processes are those expected to exhibit the widest variety of flow typologies, i.e. modelling strategies (Croke and Mockler, 2001; Parsons et al., 2003; Aksoy and Kavvas, 2005; Mosselman, 2012). The larger river basin scales ($L > 100\,\mathrm{km}$; $T > 10$ days; $H > 1\,\mathrm{m}$) are also handled here, relevant for river flow modelling, flood prediction, and water resources management (Nash and Sutcliffe, 1970; Rosgen, 1994; Loucks and van Beek, 2005) with regional surface–subsurface interactions (De Marsily, 1986), non-point pollution, fluvial sediment budgets, and global biogeochemical cycles (Walling, 1983; Milliman and Syvitski, 1992; Syvitski and Milliman, 2007).

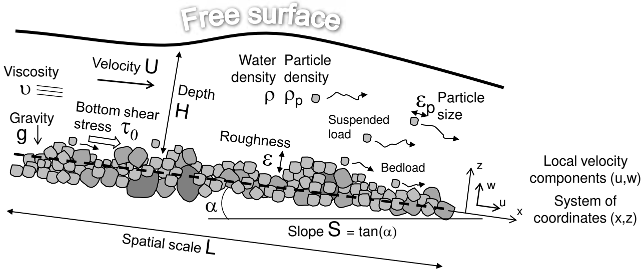

Figure 1. Quantities most often used in the literature of free-surface flow and morphodynamic modelling, with explicit reference to the $(L,\ T,\ H)$ spatiotemporal scales of interest. This review is limited to 1-D (x) spatial representations for simplicity, focusing on the streamwise (x) component of the mass and momentum conservation equations. The streamwise length (L) and velocity (U) suggest a natural timescale $T_0 = L/U$ for the propagation of information, waves, or perturbations, to be compared with the timescales (T) opted for in the literature.

On the Earth's surface, flow aggregation in the streamwise direction occurs across several geomorphic thresholds (Kirkby, 1980; Milliman and Sivitsky, 1992; Church, 2002; Paola et al., 2009) through a succession of flow typologies (Emmett, 1970; Grant et al., 1990; Rosgen, 1994; Montgomery and 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 by 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 and Ivanov, 2015) and the possibility of using 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 and Mosselman, 2012). With similar goals but a different framework, this study proposes an overview of the most popular modelling practices, confronting the theoretical refinement of flow models to the spatiotemporal scales and characteristics of the free-surface flows described.

Many papers or handbooks have summarized free-surface flow modelling and numerical techniques in hydraulics (King and 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 and Putti, 2015) for various contexts, purposes, and flow typologies. Fewer works have discussed the concern of ad hoc friction laws (Leopold et al., 1960; Gerbeau and Perthame, 2001; Nikora et al., 2001; Roche, 2006; Burguete et al., 2008) at the microscopic or macroscopic scales (Richardson, 1973; Jansons, 1988; Priezjev and Troian, 2006; Smith et al., 2007; Powell, 2014), although friction, flow retardation, and energy dissipation processes are closely related to bedforms, thus plausibly governing flow typologies and, possibly, modelling choices. Often outside any focus on friction, numerous works have provided wide overviews of erosion modelling (Ritchie and 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, 1992; Mendoza and Zhou, 1997), while most 1-D or 2-D physics-based models (e.g. Sloff et al., 2001; Vetsch et al., 2014) either assume the "transport capacity" (Foster and 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: Sect. 2 sorts the flow equations into four levels of refinement, and Sect. 3 plots these refinements vs. 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 paper 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 (denoted 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: de Saint-Venant, 1871), and further approximations (referred to as ASV for approximations to Saint-Venant), among them the diffusive wave equation (DWE: Hayami, 1951) and the kinematic wave equation (KWE: Iwagaki, 1955; Lighthill and 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 parameterized, 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 (Sect. 3).

2.2 Navier–Stokes

2.2.1 Water flow

The Navier–Stokes (NS) equations have suitable simplifications for the shallow water cases ($L \gg H$) commonly used to describe free-surface flows. The 3-D fluid motion problem is reduced here to a 2-D description, whose projection along the streamwise axis is written as

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

where ρ is water density ($\mathrm{M\,L^{-3}}$) assumed constant for incompressible flows, u is the local water velocity in x ($\mathrm{L\,T^{-1}}$), 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 ($\mathrm{M\,L^{-1}\,T^{-2}}$), g_x is the projection of gravity g onto x ($\mathrm{L\,T^{-2}}$), N ($\mathrm{M\,L^{-1}\,T^{-2}}$) is the normal stress in x (accounting for example for non-hydrostatic pressure effects), and τ ($\mathrm{M\,L^{-1}\,T^{-2}}$) is the tangential stress in x, which is denoted τ_0 on the bed in Fig. 1. The normal and tangential stresses are also written as $N=\mu\partial u/\partial x$ and $\tau=\mu\partial u/\partial z$, respectively, where μ ($\mathrm{M\,L^{-1}\,T^{-1}}$) is the dynamic viscosity.

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 and Wu, 2000; Wu and Lee, 2001; Feng and Michaelides, 2002), overland flow (Dunkerley, 2003, 2004), or flows over pronounced bedforms (Booker et al., 2001; Schmeeckle and Nelson, 2003). A very wide review of numerical methods and applications for the NS equations is provided by Gresho and Sani (1998) and a benchmark of numerous solvers by Turek (1999). The general trend is that improvements in the 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 and 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 and Brenner (1965), and Leal (1980) studied the shearing strength of multiphase viscous flows, while Batchelor (1974) and Russel (1981) addressed turbulent flows. Drew (1983) provided a general framework for the *mathematical modelling of multi-phase 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:

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

where the subscript k is an index for the phase (carrier: $k=c$; dispersed phase: $k=d$), c_k (–) is the local volumetric fraction ($c_\mathrm{c}+c_\mathrm{d}=1$), u_k ($\mathrm{LT^{-1}}$) and w_k ($\mathrm{LT^{-1}}$) are the local velocities in x and z, respectively, ρ_k ($\mathrm{ML^{-3}}$) is density, p_k ($\mathrm{ML^{-1}T^{-2}}$) is pressure, N_k ($\mathrm{ML^{-1}T^{-2}}$) and τ_k ($\mathrm{ML^{-1}T^{-2}}$) account for local non-hydrostatic pressure and shear stress effects, respectively, and M_k ($\mathrm{ML^{-2}T^{-2}}$) 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 and 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 and Paquier, 2001), or incipient motion conditions, calculated from grain size, shape, and weight (Stevenson et al., 2002). The NS formalism is especially appropriate for describing 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 and Coleman, 1986; Davies et al., 1997) to density currents (Parker et al., 1986), hyperconcentrated flows (Mulder and Alexander, 2001), and up to debris flows (Bouchut et al., 2003; Bouchut and Westdickenberg, 2004), the latter derived as mathematical generalizations of the well-known Savage and Hütter (1989, 1991) avalanche models over explicit, pronounced topographies. Moreover, the NS formalism offers the possibility of working 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, 1992; Mendoza and Zhou, 1997). The matter is not completely free from doubt today (Kneller and Buckee, 2001), though the diagram proposed by Elghobashi (1991, 1994, p. 310) to describe the regimes of interactions between particles and turbulence seems rather widely accepted. For the most dilute suspensions ($c_\mathrm{d}<10^{-6}$) the sediment load is not supposed to have any influence on turbulence characteristics. For the intermediate case ($10^{-6}<c_\mathrm{d}<10^{-3}$) the sediment load is supposed to enhance turbulence only if the particle response time is at least 2 orders of magnitude greater than the Kolmogorov timescale, 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 ($c_\mathrm{d}>10^{-3}$) frictional drag, abrasion due to impacts of the travelling particles, and increased flow viscosity have been described as prone to enhancing the detachment capacities of loaded flows (e.g. Alavian et al., 1992; Garcia and 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 and 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 and 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. $u=\overline{u}+u'$) assuming the temporal average of any turbulent fluctuation is zero. The RANS formulation usually arising from the NS equations is

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

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; Nakagawa and Nezu, 1977; 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 as occurring 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 and Jha (2009) and Jha and 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) vs. "Reynolds stress models" (expressing closure terms as a function of the turbulent kinetic energy). The momentum balance in x for 1-D approaches is the same for the dispersed phase in the complete and partial two-fluid models (Bombardelli and Jha, 2009):

$$\rho_{\mathrm{d}}\left(\frac{\partial c_{\mathrm{d}}\overline{u_{\mathrm{d}}}}{\partial t}+\frac{\partial c_{\mathrm{d}}\overline{u_{\mathrm{d}}w_{\mathrm{d}}}}{\partial z}\right)=\rho_{\mathrm{d}}c_{\mathrm{d}}gS-\frac{\partial \rho_{\mathrm{d}}c_{\mathrm{d}}\overline{u'_{\mathrm{d}}w'_{\mathrm{d}}}}{\partial z}+F_{\mathrm{D}}, \quad (4)$$

where F_{D} ($\mathrm{ML^{-2}T^{-2}}$) is the drag force term that allows two-way couplings, most often written as $F_{\mathrm{D}} = 0.5\rho_{\mathrm{m}}C_{\mathrm{D}}A(\overline{u_{\mathrm{c}}}-\overline{u_{\mathrm{d}}})^2$, where ρ_{m} ($\mathrm{ML^{-3}}$) is the density of the two-phase mixture, C_{D} (–) is the drag coefficient, and A ($\mathrm{L^2}$) is the cross-sectional area of the particles.

In their paper on movable river beds, Engelund and Fredsoe (1976) reformulated and exploited the existing hypotheses (Einstein and Banks, 1950; Bagnold, 1954; Fernandez-Luque and 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 and 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 and 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 and 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, 1957; Johnson, 1998; Whitham, 1999). The SV equations, also termed "shallow water equations", assume the $H \ll L$ 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:

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+g\frac{\partial H}{\partial x}=gS+\frac{\tau_0}{\rho H}. \quad (5)$$

Recent attempts have been made in the field of fluid mechanics to derive specific expressions for τ_0 (laminar flows: Gerbeau and 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 ($\tau_0 = \rho g H S_{\mathrm{f}}$) to reach the popular formulation:

$$\underset{\text{(i)}}{\frac{\partial U}{\partial t}} + \underset{\text{(ii)}}{U\frac{\partial U}{\partial x}} + \underset{\text{(iii)}}{g\frac{\partial H}{\partial x}} = \underset{\text{(iv)(v)}}{g\left(S - S_{\mathrm{f}}\right)}, \tag{6}$$

where (i) is the unsteadiness term, (ii) the convective acceleration term, and (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 de Chézy, Darcy–Weisbach, or Manning formulations (e.g. $S_{\mathrm{f}} = nU^2/8gH$ 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 and Brater, 1963; Chen, 1992) to account for stratification effects in the vertical distribution of velocities, especially plausible in sediment-laden flows or in the presence of density currents.

The SV equations may account for flows of variable widths and depths, for example, in floodplains (Bates and De Roo, 2000; Beltaos et al., 2012), rivers (Guinot and Cappelaere, 2009), overland flow (Berger and Stockstill, 1995; Ghavasieh et al., 2006; Kirstetter et al., 2016), overpressure in drainage systems (Henine et al., 2014), man-made channels (Zhou, 1995; Sen and Garg, 2002; Sau et al., 2010), vegetation flushing (Fovet et al., 2013), channel networks (Choi and Molinas, 1993; Camacho and Lees, 1999; Saleh et al., 2013), on benchmarks (Dimitriadis et al., 2016), interaction with subsurfaces (Pan et al., 2015), or natural settings (Moussa and Bocquillon, 1996a; Wang and Chen, 2003; Roux and Dartus, 2006; Burguete et al., 2008; Bates et al., 2010), including these with curved boundaries (Sivakumaran and 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 are now written as (Sivapalan et al., 1997)

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_a, \tag{7}$$

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

where A is the cross-sectional area (L^2), Q is the discharge (L^3 T^{-1}), and q_a is the lateral flow per unit channel length (L^2 T^{-1}). The magnitudes of the various terms in Eqs. (7) and (8) 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 of handling different fluid and particle velocities, also accounting for particle dispersion via a diffusion term:

$$\frac{\partial Hc_{\mathrm{d}}}{\partial t} + (1-\varphi_0)\frac{\partial z_0}{\partial t} + \frac{\partial Hc_{\mathrm{d}}U_{\mathrm{d}}}{\partial x} = \frac{\partial}{\partial x}\left(H\eta_{\mathrm{d}}\frac{\partial c_{\mathrm{d}}}{\partial x}\right), \tag{9}$$

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 and Heyman (2014) 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 prefer 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 Eq. (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 and 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 to be 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 is written as $e/D_{\mathrm{c}} = 1 - c/T_{\mathrm{c}}$, where the net erosion rate (e) is normalized by the maximal detachment capacity (D_{c}), while sediment load (c) is normalized 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 and Papanicolaou, 2008), especially in shallow laminar flows (Charpin and 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 and Ivanov, 2014), slope effects (Polyakov and Nearing, 2003), particle-size effects (Van Rijn, 1984a; Hairsine and 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 and Simmons, 1985; Hairsine and 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 and Castelltort, 2006; Nord and Esteves, 2010; Stecca et al., 2016) 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 and Parker, 1995) or the impact of travelling particles (Sklar and Dietrich, 2004; Lamb et al., 2008b). Sediment detachment and transport over plane beds (Williams, 1970), rough beds (Afzalimehr and Anctil, 1999, 2000; Gao and Abrahams, 2004), channels (Villaret et al., 2013, 2016), step pools (Lamarre and Roy, 2008), or pool-riffle sequences (Sear, 1996; Rathburn and 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 of predicting the formation, transformation, and migration of geometrical bed patterns, which in turn requires the full set of 3-D (x, y, z) NS equations in several cases (Lagrée, 2003; Charru, 2006; Devauchelle et al., 2010).

There seems to exists a dedicated "NS–SV morphodynamics" research lead that uses rather simple bedload transport formulae (Du Boys, 1879; Meyer-Peter and Müller, 1948; Einstein and 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 one to neglect 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 regularizing 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 and 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 and Bocquillon, 1996a, 2000; Rousseau et al., 2015). In most practical applications for flood routing, the unsteadiness (i) and convective acceleration (ii) terms in Eq. (4) may be neglected, suppressing the first two terms from Eq. (6). Combining the remaining terms in Eqs. (5) and (6), we obtain the diffusive wave equation (Moussa, 1996):

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

where C ($\mathrm{L\,T^{-1}}$) and D ($\mathrm{L^2T^{-1}}$) 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 Eq. (4) can also be neglected, the third term of Eq. (6) also vanishes and the diffusive wave becomes the kinematic wave equation, with $D = 0$ in Eq. (7) (Singh, 2001, 2002). The diffusive wave in the historic formulations (Cunge, 1969; Akan and Yen, 1981) or in more recent works (Rutschmann and Hager, 1996; Wang et al., 2006, 2014; Cimorelli et al., 2015; Swain and Sahoo, 2015) can thus be considered a higher-order approximation than the kinematic wave approximation (Katopodes, 1982; Zoppou and O'Neill, 1982; Daluz Vieira, 1983; Ferrick, 1985; Ponce, 1990). Both have been largely studied (since Wooding, 1965a, b; Singh, 1975; Lane and Woolhiser, 1977; Ponce, 1991) until more recently (Szymkiewicz and Gasiorowski, 2012; Yu and Duan, 2014) and have proven very useful for canal control algorithms (Rodellar et al., 1993) or flood routing procedures, with lateral inflow (Fan and Li, 2006), in rectangular channels (Keskin and Agiralioglu, 1997), for real-time forecast (Todini and Bossi, 1986), in lowland catchments (Tiemeyer et al., 2007), for overland flows (Pearson, 1989; Chua et al., 2008; Chua and Wong, 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, 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 and Moussa, 2013), to address backwater effects (Munier et al., 2008), stormwater runoff on impervious surfaces (Singh, 1975; Pearson, 1989; Blandford and Meadows, 1990; Parsons et al., 1997), stream–aquifer interactions (Perkins and Koussis, 1996), or volume and mass conservation issues (Perumal and Price, 2013). Given their "nominal" scales of application, the ASV models are sometimes fed by airborne (remote sensing) data acquisition (Jain and 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 and Woolhiser, 1967; Ponce and Simons, 1977; Ponce et al., 1978; Moussa and Bocquillon, 1996b; Bajracharya and Barry, 1997); the evaluation of modelling strategies is that of Horritt and 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 and 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 and 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, 1965; 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:

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

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

$$\frac{\partial A c_{\mathrm{d}}}{\partial t} + \frac{\partial Q c_{\mathrm{d}}}{\partial x} - E = 0, \tag{12}$$

where E ($\mathrm{L}^2\,\mathrm{T}^{-1}$) 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 II et al. (1997); EUROSEM: Morgan et al. (1998); MAHLERAN: Wainwright et al. (2008); and MHYDAS-Erosion: Gumiere et al. (2011b), Gregoretti et al. (2016), Hould-Gosselin et al., 2016) adopt the 1-D 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 and 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 and Rustomji, 2000; Croke and Mockler, 2001; Pickup and 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 and Abrahams (1992) have established how the agronomic, engineering, and fluvial families of approaches have converged into similar modelling techniques, especially on the subject of erosion in overland flows (Prosser and Rustomji, 2000). The ASV formalism also allows for fitting of bedload transport formulae against mean discharge values as a surrogate for the overcomplicated explicit descriptions of erosion figures in high-gradient streams with macro-roughness elements (Smart, 1984; Aziz and 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 and 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 (Sect. 3.1), spatiotemporal scales and flow typologies (Sect. 3.2), spatiotemporal scales, flow typologies, and dimensionless numbers (Sect. 3.3). Figures 2, 3, 5, 6, and 7 in this section were drawn from the 179 studies listed in Appendix A.

3.1 Spatiotemporal scales

3.1.1 Influence of domain length (L) and timescale (T)

A cross-disciplinary analysis of the cited literature indicates a clear correlation between the (L, T) spatiotemporal scales on the one hand 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 hand. 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 ($10\,\mathrm{cm} < L < 100\,\mathrm{m}$, $10\,\mathrm{s} < T < 1\,\mathrm{h}$), RANS ($1\,\mathrm{m} < L < 100\,\mathrm{m}$, $10\,\mathrm{s} < T < 1\,\mathrm{h}$), SV ($10\,\mathrm{m} < L < 20\,\mathrm{km}$, $1\,\mathrm{min} < T < 5$ days), and ASV ($10\,\mathrm{m} < L < 1000\,\mathrm{km}$, $30\,\mathrm{min} < T < 1$ year). However, some studies consider larger spatial or temporal scales, for example, Charru et al. (2004) for overland granular flows (RANS, $L \sim 20\,\mathrm{cm}$, $T \sim 2$ days) or Rathburn and Wohl (2003) for pool-riffle sequences (SV, $L \sim 70\,\mathrm{m}$, $T \sim 30$ 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 detail, 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 also 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 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 timescale T, the L/T ratio has the 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 $1\,\mathrm{m\,s^{-1}}$) 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. $10^{-4}\,\mathrm{m\,s^{-1}}$) 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. $1\,\mathrm{m\,s^{-1}}$) rather refer to single-event situations, more associated with quick modifications of flow patterns or bed morphologies. Most applications find themselves in the $10^{-2} < L/T < 10^{2}\,\mathrm{cm\,s^{-1}}$ range, exhibiting no clear difference between the NS, RANS, SV, or ASV refinements. Conversely, this indicates that each level of refine-

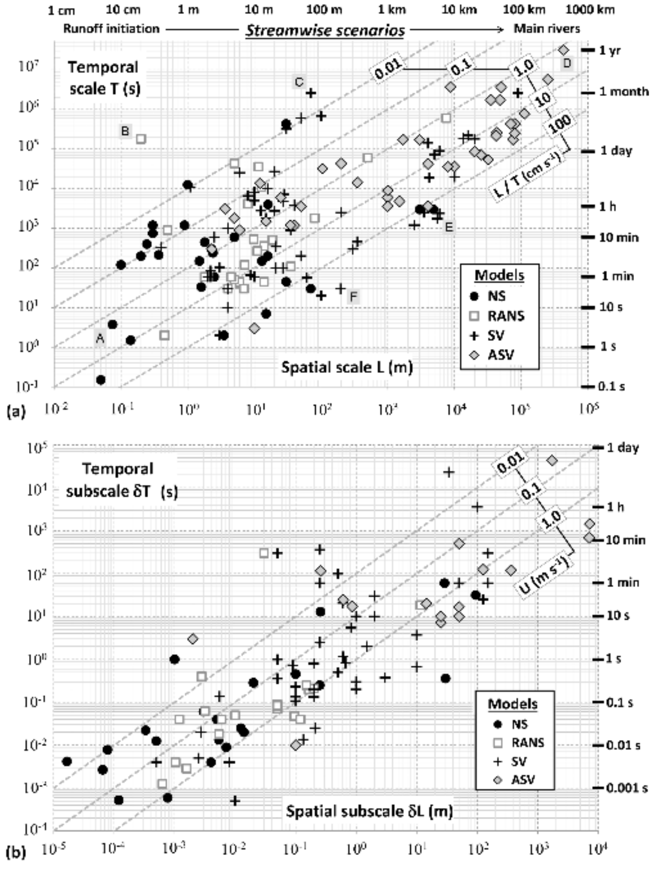

Figure 2. How increasing (L, T) spatiotemporal scales **(a)** and (δL, δT) subscales **(b)** of the flow domain tend to be associated with decreasing complexity in the choice of flow models, sorted here into four levels of refinement: Navier–Stokes (NS), Reynolds-averaged Navier–Stokes (RANS), Saint-Venant (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 ($Cr = U\delta T/\delta L$) have been used to trace characteristic flow velocities of $U = 0.01$, 0.1, and $1\,\mathrm{m\,s^{-1}}$, and the indicative numerical stability criterion is $Cr \leq 1$: 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)**.

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 Sect. 3.1. The additional influences of flow typology and dimensionless numbers are discussed in Sects. 3.2 and 3.3.

Case	Context	Authors	Model refinement	Spatiotemporal scales					Flow typology[b]	Dimensionless numbers[c]					
				L (m)	T (s)	H (m)	L/T ($\mathrm{m\,s^{-1}}$)	H/L[a] (–)		T^*	Re	Fr	S (%)	Λ_z	θ
A	Film flow	Charpin and 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 and 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	–

[a] See Sect. 3.1.2 – H/L is the fineness ratio of the flow comparing flow depth (H) to the length of the flow domain (L).
[b] See Sect. 3.2 – O: Overland; Hg: High-gradient; B: Bedforms; F: Fluvial.
[c] See Sect. 3.3 – T^*: dimensionless period; Re: Reynolds number; Fr: Froude number; S: slope; Λ_z: inundation ratio; θ: Shields number.

ment has been used to model high or low system evolution velocities, sometimes by relying on specific (adapted or upgraded) formulations of the systems of equations (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) would probably require stretching up the temporal scale so that low "system evolution velocities" would fall beneath $L/T = 10^{-2}\,\mathrm{m\,s^{-1}}$, while event-based modelling (dam breaks, formative discharges, flash floods) should be able to handle high "system evolution velocities" near or beyond $L/T = 1\,\mathrm{m\,s^{-1}}$. This "fixed-$L$, chosen-$T$" description of system evolution and characteristic timescales also refers to Figs. 1 and 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 into the field of morphodynamics (Paola et al., 1992, 2009; Howard, 1994; Van Heijst et al., 2001; Allen, 2008). 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 timescale (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 words, 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 envelope of cases in the L–T plane of Fig. 2a) followed in the forthcoming stages of the analysis and associated figures in Sect. 3.1.2 (determinants of modelling choices in the L–H plane, Fig. 3), Sect. 3.2 (determinants sought in flow typology, Figs. 6a and 7a), and Sect. 3.3 (determinants sought in the values of dimensionless numbers attached to the flow).

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 ($10\,\text{cm} < L < 100\,\text{m}$, $1\,\text{mm} < H < 30\,\text{cm}$), RANS ($1\,\text{m} < L < 100\,\text{m}$, $5\,\text{cm} < H < 50\,\text{cm}$), SV ($10\,\text{m} < L < 20\,\text{km}$, $1\,\text{cm} < H < 2\,\text{m}$), and ASV ($10\,\text{m} < L < 1000\,\text{km}$, $10\,\text{cm} < H < 10\,\text{m}$). Some studies provide outliers, for example, Gejadze and Copeland (2006) for canal control purposes (NS, $L \sim 3\,\text{km}$, $H \sim 10\,\text{m}$) or Cassan et al. (2012) for flows in lined channels (RANS, $L \sim 50\,\text{cm}$, $H \sim 75\,\text{cm}$). In an overview, wider overlaps and more dispersion occur in the (L, H) than in the (L, T) planes, especially for low to medium scales: flow depth (H) seems less discriminating than the timescale (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 2-D (x, z) flow descriptions, which explains why these models have many of the largest H/L ratios (which, in most cases, stay within the $H \ll L$ shallow water hypothesis). Second, low H/L ratios provide justifications to discard 2-D (x, z) descriptions at the benefit of 1-D (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.

3.1.3 Influence of domain length (L), timescale (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 (Figs. 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 data set 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).

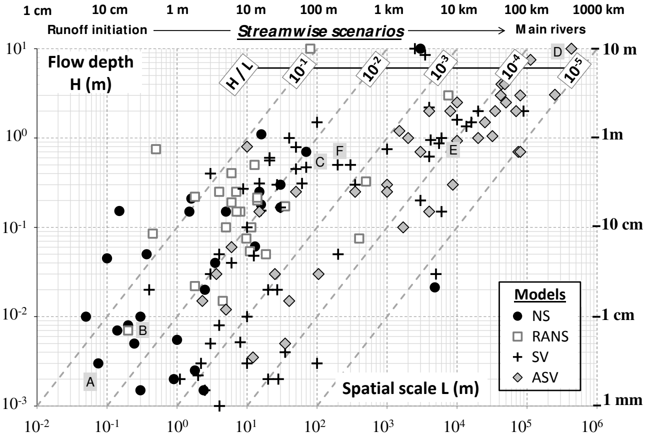

Figure 3. How increasing (L, H) spatiotemporal scales of the flow domain tend to be associated with decreasing complexity in the choice of flow models, sorted here into four levels of refinement: Navier–Stokes (NS), Reynolds-averaged Navier–Stokes (RANS), Saint-Venant (SV), and approximations to Saint-Venant (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.

3.2 Flow typology

3.2.1 From friction laws and bed topography to flow characteristics

Early insights into 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 generalizations of their famous empirical predecessors in civil engineering (Chézy, 1775; Weisbach, 1845; Darcy, 1857; Manning, 1871) even if practitioners and modellers are now confronted with far less controlled bed topographies and flow conditions, and thus with 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 and

Troian, 2006) or macroscopic scales (Smith et al., 2007; Powell, 2014), and even more so 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 are 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 related formulations in which the near-bed slip velocity is either proportional to the shear stress (Jäger and Mikelic, 2001; Basson and Gerard-Varet, 2008) or depends on it in a non-linear way (Achdou et al., 1998; Jäger and Mikelic, 2003). Other works plead for "no-slip" conditions (Panton, 1984; Casado-Diaz et al., 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 and 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 and Nekagawa, 1993; Keshavarzy and Ball, 1997), which has proven especially relevant for flows in small streams over large asperities (Lawless and 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 and Meunier, 2003). In the literature, the SV level of refinement is a tilting point in complexity that allows fundamental research to derive ad hoc shear stress formulae from the local fluid–solid interactions (Gerbeau and 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 and 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 and Bombardelli, 2001) 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 and Mathur (2003).

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 ($\Lambda_z = H/\varepsilon$, 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 and 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 and Whiting, 2000; Church and Zimmermann, 2007) in steep bed morphologies, where *Fr* is the Froude number (Froude, 1868).

Knowledge gained on flow retardation processes led 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 and 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 then becomes to include as many geometrical effects as possible in the chosen friction laws, for example, those obtained from composite roughness experiments (Schlichting, 1936; Colebrook and White, 1937; Einstein and Banks, 1950). A crucial advance was due to Smith and 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 and Robert, 2001; Ferro, 2003), natural step-pool formations (Chin and Wohl, 2005; Canovaro and Solari, 2007; Church and Zimmermann, 2007), and man-made spillways or weirs (Peyras et al., 1992; Chinnarasri and 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 and Parsons, 1994; Chanson, 1994a; Papanicolaou et al., 2001; Zimmermann and Church, 2001), which suggests that analogies in energy dissipation and flow retar-

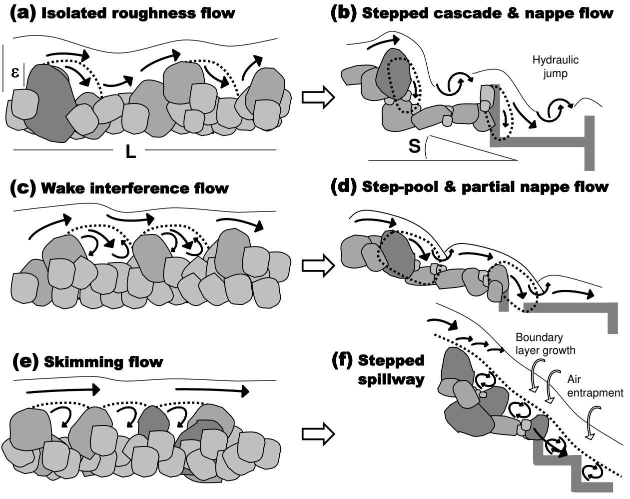

Figure 4. Analogies in flow characteristics, retardation processes, and energy dissipation structures for very different flow typologies: streams **(a, c, e)** and high-gradient natural or man-made stepped flows **(b, d, f)**. The combined values of flow depth (H), slope (S), and inundation ratio ($\Lambda_z = H/\varepsilon$, where ε is the roughness size) appear as strong geometrical controls over flow characteristics and typologies. The very small inundation ratios ($\Lambda_z < 1$) 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 views from above of Fig. 8).

dation 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 a natural or man-made nature in Fig. 4b: "nappe flows" lose strength through energy-consuming fully developed hydraulic jumps, isolated behind the major obstacles (Peyras et al., 1992; Chanson, 1994b; Wu and 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, which shows "partial nappe flow" in relatively flat step-pool formations, with incomplete hydraulic jumps between obstacles of irregular sizes and spacing (Wu and 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).

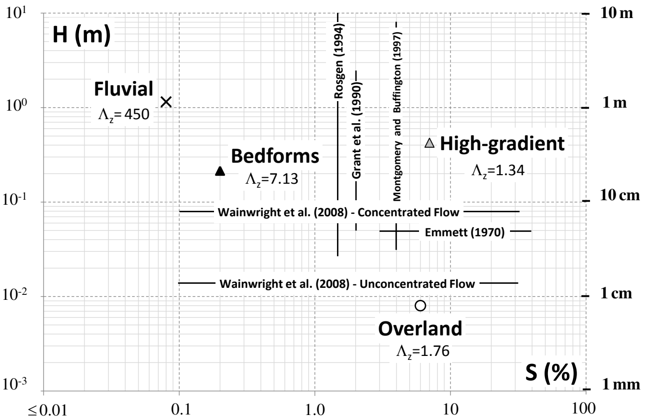

Figure 5. Median position of the studies belonging to the "Overland", "High-gradient", "Bedforms", and "Fluvial" flow typologies, plotted on the (S: slope, H: water depth) plane, with indication of the associated inundation ratio ($\Lambda_z = H/\varepsilon$, and ε is the roughness size). This figure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

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 $\Lambda_z = H/\varepsilon$). The simplest way to proceed is to work in the (S, H) plane, and then to indicate the values of Λ_z for each pair of (S, H) values. The first two flow typologies (Overland flow, denoted O, and High-gradient flow, denoted Hg) may be identified by a single criterion on H only ($H < H_{\mathrm{LIM}}$, Emmett, 1970; Wainwright et al., 2008) or on S only ($S > S_{\mathrm{LIM}}$, Grant et al., 1990; Rosgen, 1994; Montgomery and 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 and 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.

Moreover, there is a strong link between Figs. 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.

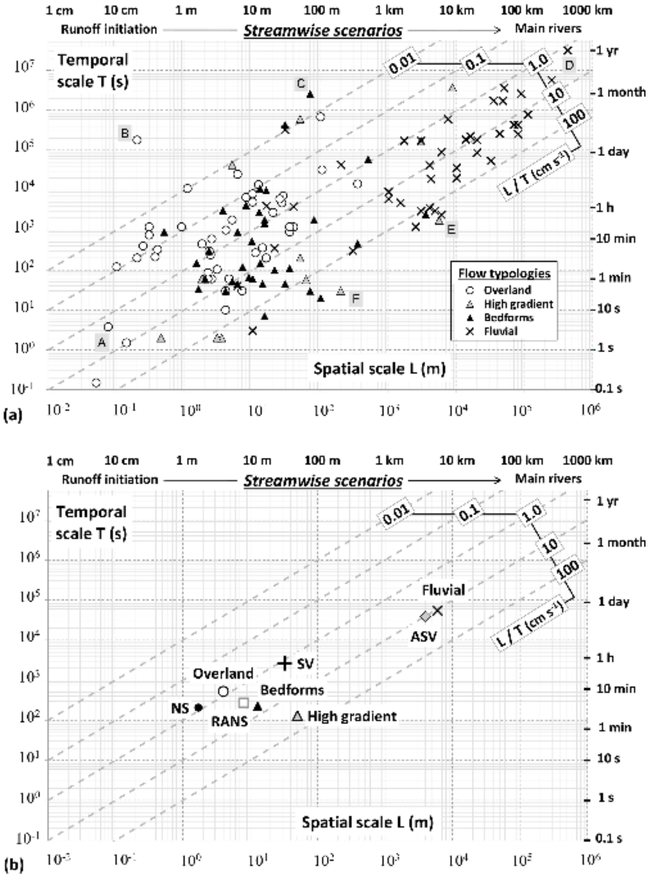

Figure 6. Position of the flow typologies in the (L, T) plane for the studies listed in Appendix A, selecting six textbook cases (sketches A to F, Table 1) for illustration **(a)**. Median positions for the choice of free-surface flow models (Navier–Stokes: NS; Reynolds-averaged Navier–Stokes: RANS; 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.

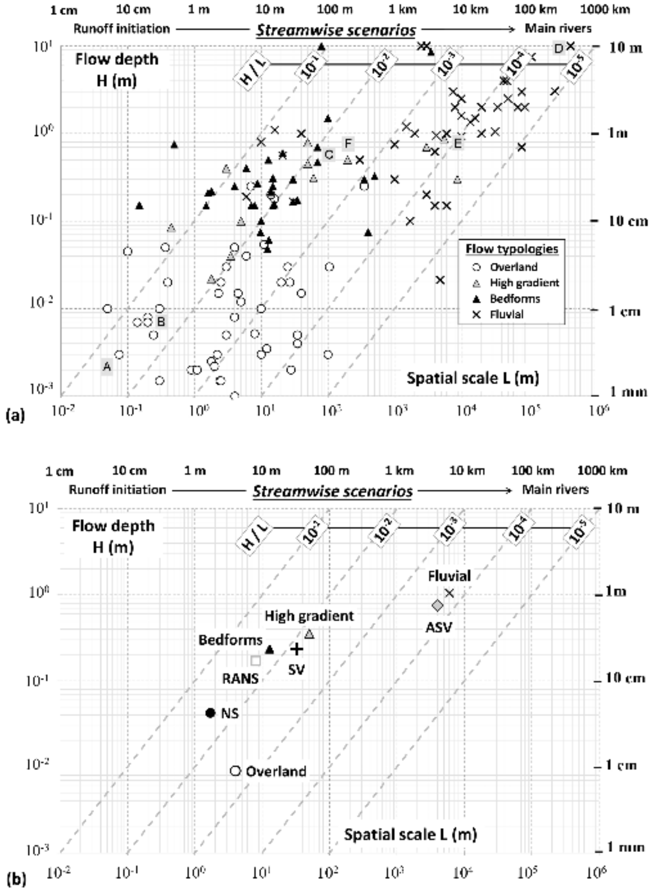

Figure 7. Position of the flow typologies in the (L, H) plane for the studies listed in Appendix A, selecting six textbook cases (sketches A to F, Table 1) for illustration **(a)**. Median positions for the choice of free-surface flow models (Navier–Stokes: NS; Reynolds-averaged Navier–Stokes: RANS; 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.

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" ($L/T \approx 0.01\,\mathrm{m\,s^{-1}}$, Fig. 6). At somewhat larger spatial scales, the widely used and multi-purpose SV model has rather low median $L/T \approx 0.02\,\mathrm{m\,s^{-1}}$ 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 $L/T \approx 0.07\,\mathrm{m\,s^{-1}}$) and the ASV models (median $L/T \approx 0.1\,\mathrm{m\,s^{-1}}$) 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 as occurring as suspended load only, equating particle and flow velocities, thus typically not extending the timescale of the study to address the long-term, low-velocity bedload transport involved in morphodynamics, for example.

Several principles of organization between flow typologies may be inferred from reference studies (Grant et al., 1990; Montgomery and 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 timescales). 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.

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, 1963; Langhaar, 1951; 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-dimensionalization 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 and thus correlated (or not) with the use of one or another 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 timescale (T) to the natural timescale (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 and Simons, 1977; Moussa and Bocquillon, 1996a; Julien, 2010) or to quantify the long characteristic times ($T^* \gg 1$) of basin-scale sedimentation. In the latter, particle transport (and significant bed modifications) typically involve lower velocities (and larger timescales) than these of water flow (Lyn, 1987; Paola et al., 1992; Howard, 1994; Van Heijst et al., 2001), and the chosen T value shows this discrepancy.

- The Reynolds number $Re = UH/\upsilon$ compares flow inertia (velocity U times depth H) with the adverse action of (kinematic) viscosity (υ (LT^{-2})). In natural settings, over very rough boundaries, fully turbulent flows are often reported for $Re > 2000$, while the onset of turbulence within transitional regimes occurs at $Re \sim 500$. 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 localized 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 sub- and super-critical regimes less obvious, as additional phenomena come into play (Lyn, 1987; Lyn and Altinakar, 2002).

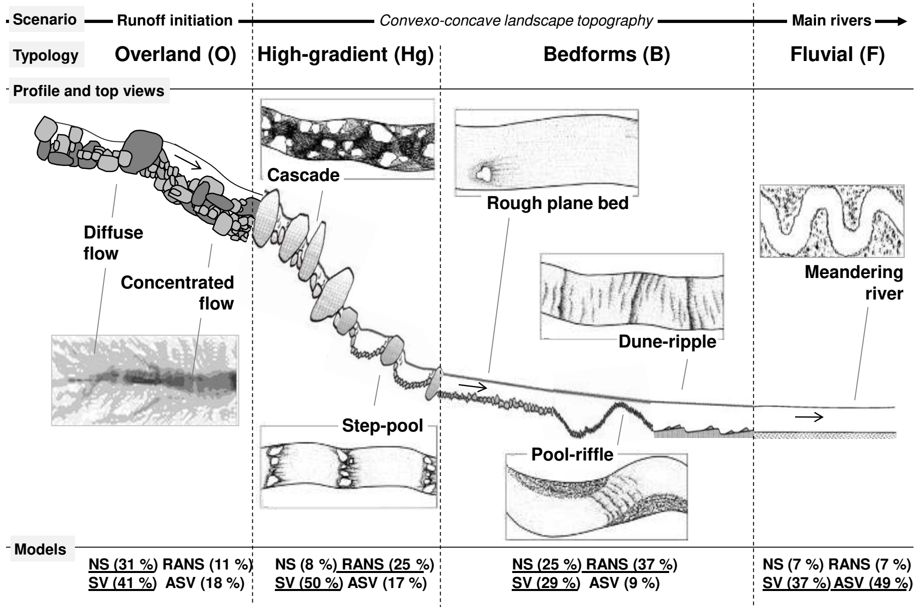

Figure 8. Streamwise scenario for a convexo-concave landscape topography, from runoff initiation to the main rivers, across flow typologies (Overland: O; High-gradient: Hg; Bedforms: B; or Fluvial: F) and spatiotemporal scales (L, T, H). All sketches and drawings for the High-gradient and Bedforms typologies were taken from Montgomery and 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.

- 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 and Papanicolaou, 2005; Manes et al., 2008; 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 and Solari, 2007; Ferguson, 2007; Lamb et al., 2008a), 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 critical θ_c values indicates local flow conditions of deposition ($\theta < \theta_c$), incipient motion ($\theta \approx \theta_c$), and transportation as bedload ($\theta > \theta_c$) or into suspension ($\theta \gg \theta_c$) (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 and Smith, 1987; Zanke, 2003; Lamb et al., 2008a) 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 of the use of the Shields number to determine incipient motion conditions, over 8 decades of experimental studies, may be found in Buffington and 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 and 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, to identify the hydrological and hydraulic contexts.

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 num-

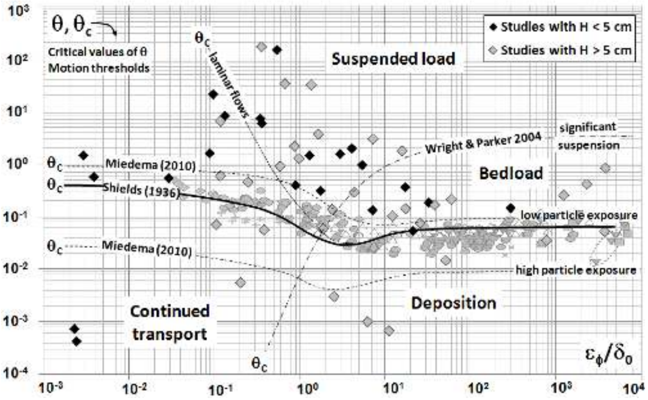

Figure 9. Generalized dimensionless Shields diagram that summarizes the conditions and regimes of sediment transport or deposition, from the relative values of the Shields parameter (θ) and incipient motion criterion (θ_c). The x axis bears the values of the ratio of particle size (ε_φ) on the depth 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 and Montgomery (1997) review of incipient motion conditions for varied flow regimes, particle forms and exposures.

bers, 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.

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 ($0.1\,\text{s} < T < 1$ year), 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) vs. *given* spatiotemporal scales (L, T, H), flow typology (O, H, B, or F) and

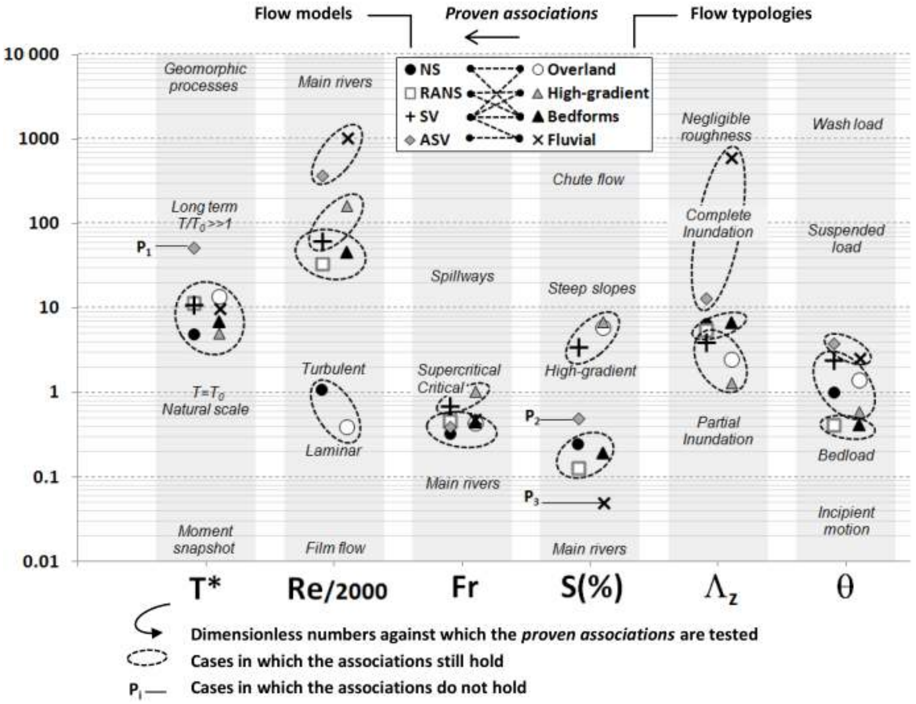

Figure 10. Comparative overview of the median values of the six selected dimensionless numbers (dimensionless period $T^* = T/T_0$, ratio of the chosen timescale to the "natural" timescale of the flow, Reynolds number *Re*, Froude number *Fr*, slope *S*, inundation ratio Λ_z, and Shields parameter θ) 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.

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 one to quantify 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 to be 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 hydromorphodynamics 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 of enriching 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 to form 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 on 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).

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, from given 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 in the scope in 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 and 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, and the impact of anthropogenic and climate change on environmental variables such as water, soil, biology, ecology, or socio-economic and ecosystemic services. The direct consequence is a significant increase in 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 in peakflow) to complex multi-site (e.g. a 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 in peakflow, volume, root mean square error – RMSE) objective functions.

iii. There is often a mismatch between model types, site data, and objective functions. First, models were developed independently of 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) and to rely on the calibration of model parameters as 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 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 ($\sim$ 350 BCE) *Analytica Posteriora* that already advocated demonstrations relying on the fewest possible number of conjectures, i.e. the dominant determinisms.

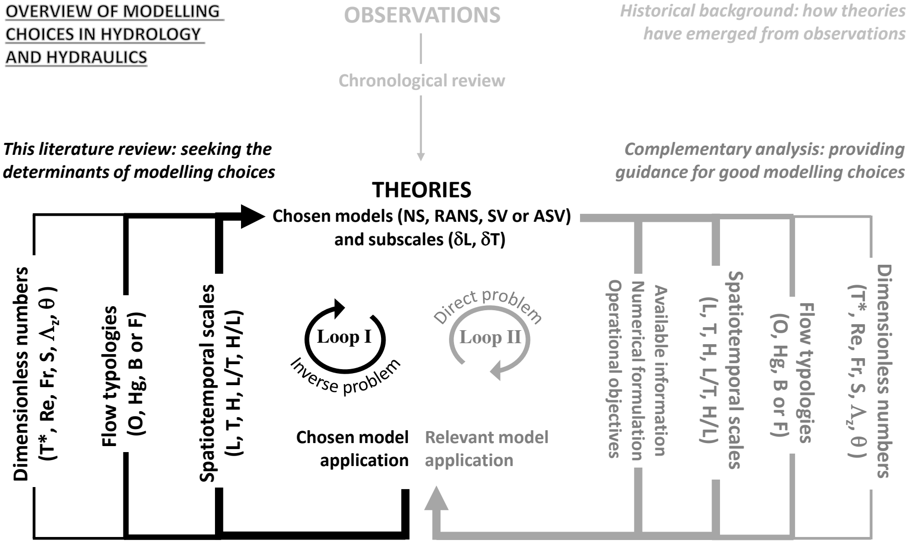

Figure 11. This figure provides a simplified overview of the available modelling choices in hydrology, in three distinct colours associated with specific research purposes or disciplines, showing the position of the present review relative to the others. The pale grey section aims at understanding how 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, timescale T, flow depth H, L/T and H/L ratios), and 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 to Saint-Venant 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 reply to the current *what has been done?* concern (Loop I). A full picture would be assembled when also reviewing the historical background, that is *how theories have emerged from observations*.

Finally, analytical procedures for free-surface flows and morphodynamic issues necessitate 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 also makes it relevant for other Earth sciences.

Appendix A: References used in the figures

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