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Bruno Cheviron, Roger Moussa

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

B. Cheviron[1] **and R. Moussa**[2]

[1]IRSTEA, UMR G-EAU Gestion de l'Eau, Acteurs et Usages, 361 rue Jean-François Breton, BP 5095, 34196 Montpellier CEDEX 5, France
[2]INRA, UMR LISAH, Laboratoire d'étude des Interactions entre Sol – Agrosystème – Hydrosystème, 2 Place Pierre Viala, 34060 Montpellier CEDEX 1, France

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Correspondence to: B. Cheviron (bruno.cheviron@irstea.fr)

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Abstract

This review paper investigates the determinants of modelling choices, for numerous applications of 1-D free-surface flow and erosion equations, across multiple spatiotemporal scales. We aim to characterize each case study by its signature composed of model refinement (Navier-Stokes: NS, Reynolds-Averaged Navier-Stokes: RANS, Saint-Venant: SV or Approximations of Saint-Venant: ASV), spatiotemporal scales (domain length: L from 1 cm to 1000 km; temporal scale: T from 1 second to 1 year; flow depth: H from 1 mm to 10 m), flow typology (Overland: O, High gradient: Hg, Bedforms: B, Fluvial: F) and dimensionless numbers (Dimensionless time period T^*, Reynolds number Re, Froude number Fr, Slope S, Inundation ratio Λ_z, Shields number θ). The determinants of modelling choices are therefore sought in the interplay between flow characteristics, cross-scale and scale-independent views. The influence of spatiotemporal scales on modelling choices is first quantified through the expected correlation between increasing scales and decreasing model refinements, identifying then flow typology a secondary but mattering determinant in the choice of model refinement. This finding is confirmed by the discriminating values of several dimensionless numbers, that prove preferential associations between model refinements and flow typologies. This review is intended to help each modeller positioning his (her) 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, through successive flow aggregations over various bed topographies: these govern both the qualitative (flow typology) and quantitative (dimensionless numbers) flow characteristics. Each case study may thus

HESSD
12, 9091–9155, 2015

be positioned along "streamwise scenarios" (from runoff initiation to the main rivers) from unequivocal indications of the spatiotemporal scales, flow typology and associated dimensionless numbers. This literature review investigates the determinants of choices made for 1-D free-surface flow and erosion modelling, seeking links between contextual information (spatiotemporal scales, flow typologies, dimensionless numbers) and conceptual descriptions (refinement of the flow equations or, equivalently, richness of the physical basis). The entire set of descriptors, i.e. model refinement, spatiotemporal scales, flow typology and dimensionless numbers, constitutes the signature of a study, which is the open normative procedure designed to allow comparisons between studies and to be fed by the community.

For the sake of genericity, this review addresses a wide range of spatiotemporal scales, starting at the smallest plot scales (spatial scale: domain length $L < 10$ m; time scale: duration of the process $T < 10$ s; flow depth: $H < 1$ cm, Fig. 1), those of runoff genesis, overland flow hydraulics and detailed particle-scale physics (Horton, 1945; Emmett, 1970; Feng and Michaelides, 2002; Schmeeckle and Nelson, 2003). The intermediate scales of catchment and hillslope processes are these expected to exhibit the widest variety of flow typologies thus modelling strategies (Croke and Mockler, 2001; Parsons et al., 2003; Aksoy and Kavvas, 2005). The larger river basin scales ($L > 100$ km; $T > 10$ days; $H > 1$ m) are also handled here, relevant for river flow modelling, flood prediction and water resources management (Nash 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).

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 hy-

HESSD
12, 9091–9155, 2015

B. Cheviron and R. Moussa

drograph concepts (Kirkby, 1976; Robinson et al., 1995; Agnese et al., 1998), under the angle of connecting-scale hydrological and sedimentological pathways (see the review by Bracken et al., 2013) or by debating the merits of similitude laws versus upscaling issues in the description of hydrological processes (Strahler, 1956; Blöschl and Sivapalan, 1995; Slaymaker, 2006). An alternative consists in examining the scale matching between available data and modelling aims (Lilburne, 2002). This raises technical (contextual) as well as strategic (conceptual) issues, handled here from an overview on the most popular modelling practices, confronting the theoretical refinement of flow models to the specific, nominal scales of the processes at play.

Many papers or handbooks have summarised 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) for various contexts, purposes and flow typologies. Less 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 govern flow typologies then, possibly, modelling choices. Often outside any focus on friction, numerous works have provided wide overviews on erosion modelling (Ritchie and McHenry, 1990; Laflen et al., 1991; Merritt et al., 2003; Aksoy and Kavvas, 2005; Boardman, 2006). Erosion models that lean on the most sophisticated flow models calculate explicit particle detachment, transport and deposition from velocity fields or flow energetics (Vanoni, 1946; Hino, 1963; Lyn et al., 1992; Mendoza and Zhou, 1997) while reduced complexity models 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 erosion science) searches for the determinants of modelling choices. The methodology consists in defining the "signature" of each case study as the chosen model refinement and the

HESSD
12, 9091–9155, 2015

B. Cheviron and R. Moussa

given flow typology, spatiotemporal scales and dimensionless numbers, hypothesizing the conceptual element (model refinement) is the consequence of the contextual elements. The paper is organized as follows: Sect. 2 sorts the flow equations into four levels of refinement, Sect. 3 plots these refinements versus the spatiotemporal scales of the studies, also depicting the influence of flow typologies and dimensionless numbers. Section 4 discusses the results and future research leads. Some of the best documented references among the cited literature have been gathered in Appendix A: most figures in this manuscript were plotted from this database.

2 Flow models

2.1 List of flow models

2.1.1 Water flow

Free-surface flow equations in the literature may roughly be sorted into four levels of decreasing refinement, from the richness of their physical basis. The choice made here includes the Navier-Stokes equations (noted NS: Navier, 1822; Stokes, 1845), their average in time termed Reynolds-Averaged Navier-Stokes equations (RANS: Reynolds, 1895), the depth-averaged Saint-Venant equations (SV: Saint-Venant, 1871) and further approximations (referred to as ASV), among which the Diffusive Wave (DW: Hayami, 1951) and Kinematic Wave equations (KW: Iwagaki, 1955; Lighthill and Whitham, 1955).

2.1.2 Erosion

The associated erosion equations (not shown) are based on a representation of detachment and transport on hillslopes (Bennett, 1974; Van Rijn, 1984a, b; Wainwright et al., 2008), in streams (Einstein, 1950) or through the channel network (Du Boys, 1879; Exner, 1925; Hjulström, 1935; Shields, 1936; Bagnold, 1956). Friction is the link

HESSD
12, 9091–9155, 2015

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. However, the scope here is not to review the choices made for friction modelling; friction phenomena, with the associated flow retardation and energy dissipation processes, are rather considered for their influence on flow typologies, as discussed later in the manuscript.

2.2 Navier-Stokes

2.2.1 Water flow

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

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} + \frac{1}{\rho}\frac{\partial p}{\partial x} = g_x + \frac{1}{\rho}\frac{\partial \tau}{\partial x} \tag{1}$$

where x is the longitudinal distance [L], z the vertical coordinate [L], t is time [T], u is the local water velocity in x [LT^{-1}], ρ is water density [ML^{-3}], g_x is the projection of gravity g on x [LT^{-2}] and τ is the tangential stress due to water [$ML^{-1}T^{-2}$] noted τ_0 on the bed in Fig. 1.

The Navier-Stokes equations stay valid throughout the full range of flow regimes 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).

HESSD
12, 9091–9155, 2015

2.2.2 Erosion

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, 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 also needed to describe strong water-sediment 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; Parker and Coleman, 1986; Parker et al., 1986; Davies et al., 1997; Mulder and Alexander, 2001). Moreover, the NS formalism offers the possibility to work on the energy equations: the erosive power and transport capacity of sediment-laden flows may be estimated from the energy of the flow, debating the case of turbulence damping (or not) with increasing sediment loads (Vanoni, 1946; Hino, 1963; Lyn et al., 1992; Mendoza and Zhou, 1997). The matter is not free from doubt today (Kneller and Buckee, 2001) and frictional drag, abrasion due to impacts of the travelling particles and increased flow viscosity have been described prone to enhance the detachment capacities of loaded flows (Alavian et al., 1992; Garcia and Parker, 1993).

2.3 Reynolds-Averaged Navier-Stokes

2.3.1 Water flow

The Reynolds-Averaged Navier–Stokes (RANS) equations are a turbulence model, using time-averaged equations of fluid motion, less generic than the NS formalism. The hypothesis behind these equations is that instantaneous pressure and velocities may be decomposed into time-averaged and randomly fluctuating turbulent parts, which finally yields:

$$\frac{\partial \overline{u}}{\partial t} + \overline{u}\frac{\partial \overline{u}}{\partial x} + \overline{w}\frac{\partial \overline{u}}{\partial z} + g\frac{\partial H}{\partial x} = gS + \frac{1}{\rho}\frac{\partial \tau}{\partial z} \tag{2}$$

where $\overline{u}$ [LT^{-1}] and $\overline{w}$ [LT^{-1}] are the time-averaged local water velocities in x and z, H is the flow depth [L] and S is the bed slope [–].

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 ($\tau = -\rho\, \overline{u'w'}$) and second because the Reynolds stresses have been closely related, in magnitude and direction, to the size and arrangement of bed asperities. The combined analysis of the relative magnitude of the u' and w' terms has become the purpose of "quadrant analysis" (Kline et al., 1967; Raupach, 1981; Kim et al., 1987) that identifies the four cases of outward interactions (quadrant I: $u' > 0$, $w' > 0$), ejections (quadrant II: $u' < 0$, $w' > 0$), inward interactions (quadrant III: $u' < 0$, $w' < 0$) and sweeps (quadrant IV: $u' > 0$, $w' < 0$). Depending on the submergence and geometry of bed asperities, the maximal Reynolds stresses, those with significant effects on flow structure, have most often been reported to occur near or just above the roughness crests (see Nikora et al., 2001; Pokrajac et al., 2007 and the review by Lamb et al., 2008a).

2.3.2 Erosion

In their paper on movable river beds, Engelund and Fredsoe (1976) judiciously 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

HESSD
12, 9091–9155, 2015

become private hunting grounds 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 then 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 integration process (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:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + g\frac{\partial H}{\partial x} = gS + \frac{\tau_0}{\rho H} \quad (3)$$

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

12, 9091–9155, 2015

1-D free-surface flow and erosion issues in hydrology

B. Cheviron and R. Moussa

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 hydraulics and hydrology is rather to approximate steady-state equilibrium between bottom friction τ_0 and the streamwise stress exerted at the bottom of a water column ($\tau_0 = \rho g H S_f$) to reach the popular formulation:

$$\underset{\text{(i)}}{\frac{\partial U}{\partial t}} + \underset{\text{(ii)}}{U\frac{\partial U}{\partial x}} + \underset{\text{(iii)}}{g\frac{\partial H}{\partial x}} = \underset{\text{(iv)}}{g\,(S} \underset{\text{(v)}}{- S_f)} \tag{4}$$

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

In the above, S_f (–) is the "friction slope" whose expression depends on flow velocity and on the chosen friction law, often one of the Chézy, Darcy-Weisbach or Manning formulations (e.g. $S_f = nU^2/8\,gH$ 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 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), with overpressure in drainage systems (Henine et al., 2014), in man-made channels (Zhou, 1995; Sen and Garg, 2002; Sau et al., 2010), for vegetation flushing (Fovet et al., 2013), in channel networks (Choi and Molinas, 1993; Camacho and Lees, 1999) 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

HESSD
12, 9091–9155, 2015

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 now write (Sivapalan et al., 1997):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_a \quad (5)$$

$$\frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{1}{gA}\frac{\partial}{\partial x}\left(\beta\frac{Q^2}{A}\right) + \frac{\partial H}{\partial x} + S_\mathrm{f} - S = 0 \quad (6)$$

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

2.4.2 Erosion

In the hydrology-erosion community, the SV level is that of the *Concepts of mathematical modelling of sediment yield* by Bennett (1974). This landmark paper extended Exner's (1925) conservation of sediment mass, adding the possibility to handle different fluid and particle velocities, also accounting for particle dispersion via a diffusion term. Unfortunately, most citing papers discard this term, taking particle velocity equal to water velocity. The assumption seems false if transport occurs as bedload or saltation load, questionable for suspended load trapped into turbulent motions, exact only for very small particles borne by laminar flows. Although warning against the capability of first-order laws to "*represent the response of sediment load to changes in transport and detachment capacity*" (Bennett, 1974; p. 491), the author recommended the use of such a model (Foster and Meyer, 1972). The proposed simplification writes $e/D_\mathrm{c} = 1 - c/T_\mathrm{c}$, where the net erosion rate (e) is normalised by the maximal detachment capacity (D_c) while sediment load (c) is normalised by the maximal transport capacity of the flow (T_c). An additional (uncertain) hypothesis was that of maximal detachment capacity for

HESSD
12, 9091–9155, 2015

B. Cheviron and R. Moussa

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 describe 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, 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) and bedload transport (Van Rijn, 1984b; Julien and Simmons, 1985; Hairsine and Rose, 1992b; Wainwright et al., 2008) have received much attention within the SV or ASV 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) 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), 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

HESSD
12, 9091–9155, 2015

B. Cheviron and R. Moussa

more specific applications. Cited limitations of the SV approaches are their inability to explicitly describe the near-bed velocity fluctuations, especially the local accelerations responsible for particle entrainment but also the vertical gradients of the streamwise velocity, for bedload transport in the laminar layer. This lack of accuracy in the description of flow characteristics also endangers the possibility to predict the formation, transformation and migration of geometrical bed patterns, which in turn requires the full set of 3-D (x, y, z) NS equations in several cases (Lagrée, 2003; Charru, 2006; Devauchelle et al., 2010).

There seems to exist a dedicated "NS-SV Morphodynamics" research lead that uses rather simple bedload transport formulae (Du Boys, 1890; Meyer-Peter 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 neglecting the unsteadiness term in the momentum equation but on no account in the continuity equation (Exner law) that describes bed modifications (Parker, 1976). Moreover, shear stresses are generally calculated from near-bed laminar or near-laminar velocity profiles, sometimes with the regularising hypothesis that detachment and transport occur just above the criterion for incipient motion (see the review by Lajeunesse et al., 2010). Various applications address rivers with mobile bed and banks (Parker, 1978a, b), focus on self-channelling (Métivier 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 a lack of data, 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; Moussa and Bocquillon, 2000). 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):

$$\frac{\partial Q}{\partial t} + C\left(\frac{\partial Q}{\partial x} - q\right) - D\left(\frac{\partial^2 Q}{\partial x^2} - \frac{\partial q}{\partial x}\right) = 0 \quad (7)$$

where $C\,[\mathrm{LT}^{-1}]$ and $D\,[\mathrm{L}^2\mathrm{T}^{-1}]$ 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). The Diffusive Wave (Cunge, 1969; Akan and Yen, 1981; Rutschmann and Hager, 1996, Wang et al., 2006; Wang et al., 2014) 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 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 small catchments (Moussa et al., 2002; Chahinian et al., 2005; Charlier et al. 2007), for mountainous catchments (Moussa et al., 2007) 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 (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

HESSD
12, 9091–9155, 2015

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 Erosion

Whereas common practices in fluid mechanics and hydraulics are rather to seek context-specific strategies in erosion 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). Many catchment-scale hydrology-erosion models (e.g. ANSWERS: Beasley et al., 1980; CREAMS: Knisel 1980; KINEROS: Smith et al., 1995; LISEM: De Roo et al., 1996; WEPP: Ascough et al., 1997; EUROSEM: Morgan et al., 1998; MAHLERAN: Wainwright et al., 2008; MHYDAS-Erosion: Gumiere et al., 2011) 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 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 agronomical, 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 fitting bedload transport formulae against mean discharge values as a surrogate to the overcomplicated explicit descriptions of erosion figures in high-gradient streams with macro-roughness elements (Smart, 1984; Aziz 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 158 studies listed in Appendix A.

3.1 Spatiotemporal scales

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

A cross-disciplinary analysis of the cited literature indicates a clear correlation between the (L,T) scales and the chosen model refinement (NS, RANS, SV or ASV). In this (L,T) plane, Fig. 2 quantifies the expected trend that sophisticated (NS,

HESSD
12, 9091–9155, 2015

RANSS) 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). Typical scales of application may be identified for each model refinement: NS (10 cm < L < 100 m, 10 s < T < 1 h), RANS (1 m < L < 100 m, 10 s < T < 1 h), SV (10 m < L < 20 km, 1 min < T < 5 days) and ASV (10 m < L < 1000 km, 30 min < T < 1 year). However, some studies consider larger spatial or temporal scales, for example Charru et al. (2004) for overland granular flows (RANS, $L \sim 20$ cm, $T \sim 2$ days) or Rathburn and Wohl (2003) for pool-riffle sequences (SV, $L \sim 70$ 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 details but could the modelling choices also be dictated by the scientific background of the modeller? A striking example is that of the SV models, responsible for the largest overlaps in Fig. 2. They may for example be used by physicists, as an upgraded alternative to the NS equations, in the field of environmental fluid mechanics (for limited scales). They may as well be convenient for soil scientists interested in high-resolution hydrology or for civil engineers who may need to cope with flow unsteadiness to handle erosion issues or to allow correct sizing of the man-made structures (for rather large scales).

Figure 2 bears another type of information than the trend to decreasing model refinement with increasing spatiotemporal scales. As the x ordinate indicates the spatial scale L and the y ordinate the time scale T, then the L/T ratio has dimensions of a velocity. However, this quantity should not be interpreted as a flow velocity. It rather indicates which of the temporal (long-term, low L/T ratio) or spatial (short-term, high L/T ratio) aspects are predominant in the study. Hence, the five dotted diagonals ($L/T = 10^{-4}$, 10^{-3}, 10^{-2}, 0.1 and 1 m s^{-1}) establish the numerical link between the spatial and temporal scales of the cited experiments. They also show the dispersion with respect to the expected (say "natural") correlation between increasing L and T values. This dispersion contains a lot of information. Judging from the plotted literature, the lowest L/T ratios (e.g. 10^{-4} m s^{-1}) tend to indicate systems with low "evolution velocities", possibly associated with long-term changes or effects (high T values, low L values) obtained from repeated phenomena, multiple cycles and slow 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.

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

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.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
HESSD
12, 9091–9155, 2015
1-D free-surface flow and erosion issues in hydrology
B. Cheviron and R. Moussa

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, $L \sim 3\,\text{km}$, $\text{H} \sim 10\,\text{m}$) or Cassan et al. (2012) for flows in lined channels (RANS, $L \sim 50\,\text{cm}$, $\text{H} \sim 75\,\text{cm}$). In an overview, wider overlaps and more dispersion occur in the (L,H) than in the (L,T) plane, especially for low to medium scales: flow depth (H) seems less discriminating than the time scale (T) in the choice of a flow model.

The transverse analysis of H/L "fineness ratios" (dotted diagonals $H/L = 10^{-1}$, 10^{-2}, 10^{-3}, 10^{-4} and 10^{-5}) provides additional information, or rather a complementary reading grid on the information already plotted. First, only the NS and RANS models allow 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 $H << L$ 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), time scale (T) and flow depth (H)

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

HESSD
12, 9091–9155, 2015

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

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

3.2 Flow typology

3.2.1 From friction laws and bed topography to flow characteristics

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

Several studies at the NS level of refinement advocate the use of the "partial slip" (Navier, 1827) condition or parented formulations in which the near-bed slip velocity is either proportional to the shear stress (Jäger 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 and Diaz, 2003; Myers, 2003; Bucur et al., 2008, 2010) or suggest the separation of flow domains within or outside bed asperities, with a complete slip condition (non-zero tangential velocity) at the interface (Gerard-Varet 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, deriving 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). The latter 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, 2002) and a recent mathematical study of the Diffusive Wave equation (Alonso et al., 2008) introduces generalized friction laws for

HESSD
12, 9091–9155, 2015

flows over non-negligible topographic obstacles. The event-based variability of the friction coefficient in ASV models has been investigated by Gaur and Mathur (2002).

If not decided from the level of refinement of the flow model, the friction coefficient (f) is chosen in accordance with flow typology and bed topography, the former often described by the Reynolds number (*Re*), the latter by the inundation ratio (Λ_z =H/ε where ε is the size of bed asperities, to which flow depth H is compared). Such arguments were already present in the works of Keulegan (1938) and Moody (1944) on flow retardation in open-channel and pipe flows, relating values of the friction coefficient to the relative roughness (ε/H =1/Λ_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 lead to the identification of key dimensionless groups, to be included in any comprehensive analysis, formed from the “obvious”, available elements of bed geometry previously mentioned (Julien 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 becomes then to include as many geometrical effects as possible in the chosen friction laws, for example these obtained from composite roughness experiments (Schlichting, 1936; Colebrook 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 retardation may exist across scales, from similar geometries and flow characteristics. This makes the description somewhat generic, possibly used to constitute a set of flow typologies.

In Fig. 4a, the isolated roughness flow is laminar or weakly turbulent and the shade (streamline diversion) of an obstacle does not reach the next. This setting ensures maximum energy dissipation, which also holds for stepped cascades of natural or man-made nature in Fig. 4b: "nappe flows" loose strength through energy-consuming fully-developed hydraulic jumps, isolated behind the major obstacles (Peyras et al., 1992; Chanson, 1994b; Wu 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 that 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).

At this point, our set of flow typologies should be obtained from the geometrical arguments available in Fig. 4 (bed slope S, water depth H, inundation ratio $\Lambda_z = H/\varepsilon$). The simplest way to proceed is to work in the (S,H) plane, then to add a criterion on Λ_z if the values of S and H are not discriminating enough. The first two flow typologies (Overland flow, noted O, and High-gradient flow, noted Hg) may be identified by a single criterion on H only ($H < H_{\mathrm{LIM}}$; 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. 4e 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.

HESSD
12, 9091–9155, 2015

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. 6 seems more discriminating than the (L,T) plot of Fig. 7 though identical 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 multipurpose 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 refinements. 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 and weak friction, often resulting in very turbulent, high-velocity flow. Moreover, studies handling erosion issues within the ASV formalism often hypothesize particle transport to occur as suspended load only, equating particle and flow velocities, thus typically not extending the time scale of the study to address the long-term, low velocity bedload transport involved in morphodynamics, for example.

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 time scales). Plausible "streamwise scenarios" may therefore be assembled (Fig. 8), routing flow aggregations across increasing spatiotemporal scales and through several flow typologies, from the narrow-scale upland flows (runoff initiation) to the regional scales of the main rivers.

3.3 Dimensionless numbers

3.3.1 Contextual dimensionless numbers

An angle of attack for the establishment of modelling strategies is provided by dimensional analysis, to delineate the domains of validity of the selected flow models (NS, RANS, SV or ASV), across their multiple spatiotemporal scales of application but in a powerful scale-independent analysis. Justifications for the use of dimensionless numbers may be sought in the developments of similitude laws (Fourier, 1822; Rayleigh, 1877; Bertrand, 1878; Vaschy, 1892; Riabouchinsky, 1911), later extended to dimensional analysis, providing guidance for the sizing of experimental facilities used in reduced-scale modelling as well as more general arguments for the choice of adequate sets of dimensionless quantities (Buckingham's, 1914 π-theorem; Bridgman, 1922; Langhaar, 1951; Bridgman, 1963; Barenblatt, 1987). Throughout history, the establishment of dimensionless numbers has led to the recognition of contextually dominant terms in the flow equations, rendering them prone to dedicated simplifications, provided these would not be used outside their conditions of validity, following successive hypotheses made during their derivation.

From a wide overview of free-surface flow and erosion 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

HESSD
12, 9091–9155, 2015

B. Cheviron and R. Moussa

others have even been used to define flow typologies (bed slope S, inundation ratio Λ_z). As all dimensionless numbers aim to describe flow typology, the introduction of two more dimensionless numbers may be seen as an attempt to re-examine the influence of flow typologies on modelling choices, from a different, more complete perspective (especially if the dimensionless numbers not used in the definition of flow typologies prove discriminating for the modelling choices).

- The dimensionless period $T^* = T/T_0$ handles temporal aspects by comparing the chosen time scale (T) to the natural time scale (T_0) of the system, the latter obtained from the spatial scale of the system and the depth-averaged 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 ($T^* >> 1$) of basin-scale sedimentation. In the latter, particle transport and significant bed modifications typically involve lower velocities (and larger time scales) than these of water flow (Paola et al., 1992; Howard, 1994; Van Heijst et al., 2001) and the chosen T value witnesses this discrepancy.

- The Reynolds number $Re = UH/\upsilon$ compares flow inertia (velocity U times depth H) with the adverse action of (kinematic) viscosity (υ [$L\ T^{-2}$]). In natural 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 $Fr = U/(\mathrm{gH})^{0.5}$ denotes the influence of gravity (g) on fluid motion. Supercritical $Fr > 1$ values indicate torrential flows, accelerated by pressure effects, in which waves propagate only downstream, also compatible with the appearance of localised energy dissipation patterns (white waters, hydraulic jumps). Subcritical $Fr < 1$ values indicate tranquil flows with downstream controls.

HESSD
12, 9091–9155, 2015

- 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., 2007; Cooper et al., 2013). The encountered values of Λ_z are very high for rivers flowing on smooth, cohesive, fine-grained beds ($\Lambda_z > 100$) and very low for all types of flows between emergent obstacles ($\Lambda_z < 1$).
- The dimensionless Shields number $\theta = \tau_0/\mathrm{g}\varepsilon_p(\rho_p - \rho)$ compares the drag force exerted on bed particles to their immersed weight, where ε_p [L] and ρ_p [M L^{-3}] account for the size and density of erodible particles. The ratio between the current θ and the critical θ_c values indicates local flow conditions of deposition ($\theta<\theta_\mathrm{c}$), incipient motion ($\theta \approx \theta_\mathrm{c}$), transportation as bedload ($\theta>\theta_\mathrm{c}$) or into suspension ($\theta>>\theta_\mathrm{c}$) (Shields, 1936). This number seems appropriate for most erosion 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., 2008) and also because of its numerous possible adaptations (Neill, 1968; Parker et al., 2003; Ouriémi et al., 2007; Miedema, 2010) to various flow typologies. An impressive review on the use of the Shields number to determine incipient motion conditions, over eight decades of experimental studies, may be found in Buffington and Montgomery (1997).

3.3.2 Influence of the dimensionless numbers

As the purpose here is to re-examine the influence of flow typologies from the angle of the dimensionless numbers, the chosen representation (Fig. 9) discards the (L,T,H)

spatiotemporal scales. It first recalls the preferential associations between models and flow typologies (see the "model use" 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. 9. 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, P_4 for Λ_z) signals something new: an influence not yet accounted for.

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 indicate the break of the [NS-O] and [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. The P_4 point indicates the break of the [NS-O] association when considering the values of the inundation ratio, with the same conclusion as above.

4 Conclusions

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 ($1\,\text{cm} < L < 1000\,\text{km}$), the time duration ($1\,\text{s} < T < 1$ year) and flow depth ($1\,\text{mm} < H < 10\,\text{m}$).
- 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), the given spatiotemporal scales (L, T, H), flow typology (O, H, B or F) and dimensionless numbers (T^*, Re, Fr, S, Λ_z, θ). Though nonunique, this signature is a generic and normative classification of studies interested in free-surface flow modelling, with or without erosion issues.

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

- A more exhaustive set of flow typologies was then derived from simple geometrical arguments, combining criteria on S, H and Λ_z, represented in the (S,H) plane. This allowed quantifying the median scales associated with studies interested in the Overland (*O*), Bedforms (*B*), High-gradient (*Hg*) and Fluvial (*F*) typologies, sorted here by increasing spatiotemporal scales. Then came the identification of preferential associations between flow models, scales and typologies: [NS, *O*] or [SV, *O*], [RANS, *B*] or [SV, *B*], [SV, *Hg*] or [ASV, *Hg*] and [ASV, *F*] for increasing spatiotemporal scales.

- The final step was to re-examine the previous associations from the values of the dimensionless numbers, thought here as more detailed, scale-independent descriptors of flow typologies. Several associations were confirmed by the median values of the associated dimensionless numbers but the T^* (dimensionless period), S (bed slope) and Λ_z (inundation ratio) 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 hydrology-erosion community or for other research purposes. For example, multiple flow models, scales, typologies and dimensionless numbers also intervene in the fields

HESSD
12, 9091–9155, 2015

of pesticide fate modelling and groundwater contamination issues, so the same procedure could be applied. Finally, this procedure offers the possibility to enrich the database of signatures if each modeller records his (or her) conceptual choices (flow models) in the proposed reading grid, together with the contextual elements (scales, typologies, dimensionless numbers) handled, for present and past studies. This would first help forming a comprehensive view of modelling choices, thus seeking guidance from "what has been done in similar cases", which however does not provide any critical analysis. Complementary investigations could certainly address the question of "what should be done", this time deciding the "model" part of the signatures from recommendations based on the scales, typologies and dimensionless numbers, as well as from additional elements, typically the modelling objectives.

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HESSD
12, 9091–9155, 2015

B. Cheviron and R. Moussa

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HESSD
12, 9091–9155, 2015
1-D free-surface flow and erosion issues in hydrology
B. Cheviron and R. Moussa

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HESSD

12, 9091–9155, 2015

1-D free-surface flow and erosion issues in hydrology

B. Cheviron and R. Moussa

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Devauchelle, O., Josserand, C., Lagrée, P.-Y., and Zaleski, S.: Morphodynamic modelling of erodible laminar channels, Phys. Rev. E, 76, 056318, doi:10.1103/PhysRevE.76.056318, 2007.

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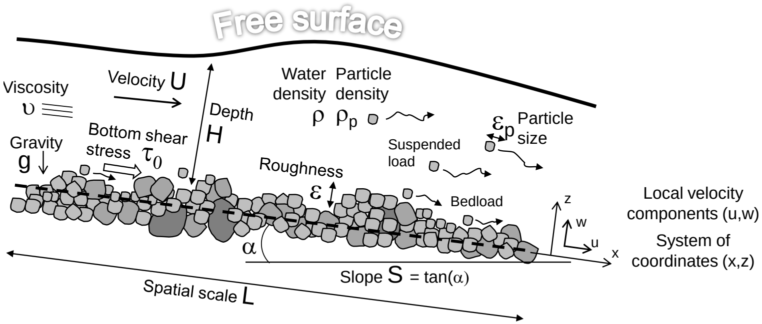

Figure 1. Quantities most often used in the literature of free-surface flow and erosion modelling, with explicit reference to the (L,T,H) spatiotemporal scales of interest. This review is limited to 1-D (x) spatial representations for simplicity, focusing on the streamwise (x) component of the mass and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

HESSD
12, 9091–9155, 2015

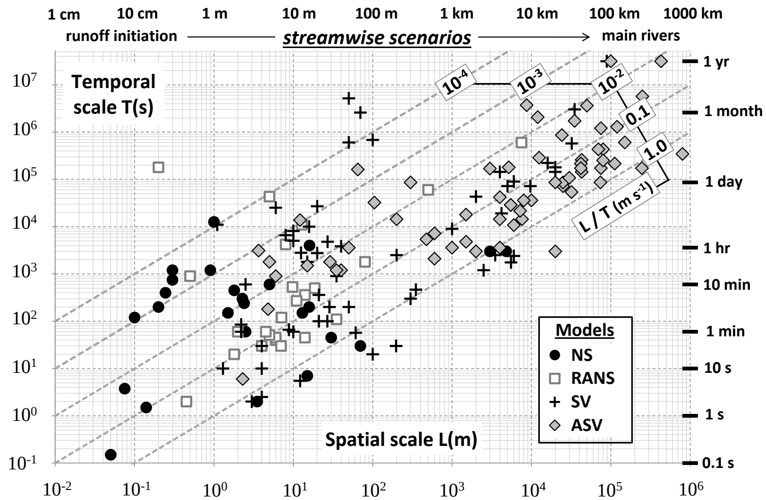

Figure 2. How increasing (L,T) spatiotemporal scales of the flow domain tend to be associated with decreasing complexity in the choice of flow models, sorted here into four levels of refinement: Navier-Stokes (NS), Reynolds-Averaged Navier-Stokes (RANS), Saint-Venant (SV) or Approximations to Saint-Venant (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. This figure was assembled from information available in the studies cited in Appendix A.

HESSD
12, 9091–9155, 2015

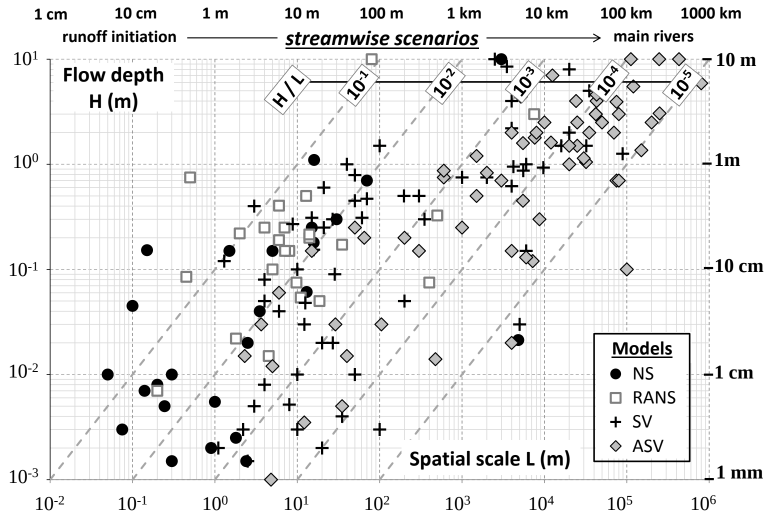

Figure 3. How increasing (L, H) spatiotemporal scales of the flow domain tend to be associated with decreasing complexity in the choice of flow models, sorted here into four levels of refinement: Navier-Stokes (NS), Reynolds-Averaged Navier-Stokes (RANS), Saint-Venant (SV) and Approximations to Saint-Venant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

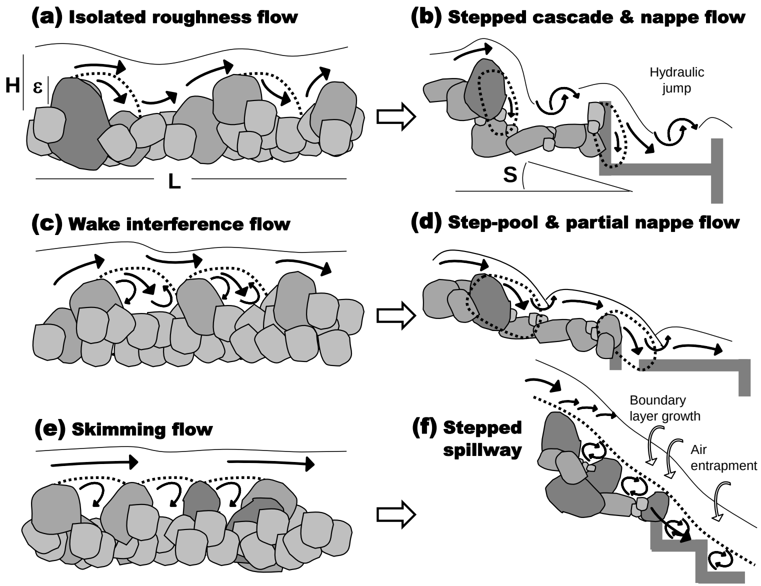

Figure 4. Analogies in flow characteristics, retardation processes and energy dissipation structures for very different flow typologies: streams **(a, c, e)** and high-gradient natural or man-made stepped flows **(b, d, f)**. The combined values of flow depth (*H*), slope (*S*) and inundation ratio (Λ_z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

HESSD
12, 9091–9155, 2015

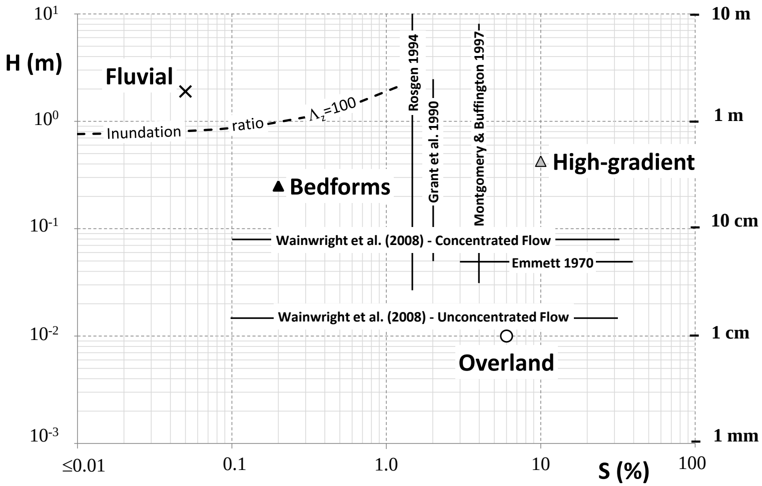

Figure 5. Median position of the studies belonging to the "Overland", "High-gradient", "Bedforms" and "Fluvial" flow typologies, plotted on the (S: slope, H: water depth) plane, also tracing an approximate additional criterion on the inundation ratio ($\Lambda_z = H/\varepsilon$, where ε is the size of the bed asperities) to separate the Fluvial and Bedforms types of flow. This figure was assembled from information available in the studies cited in Appendix A.

HESSD
12, 9091–9155, 2015

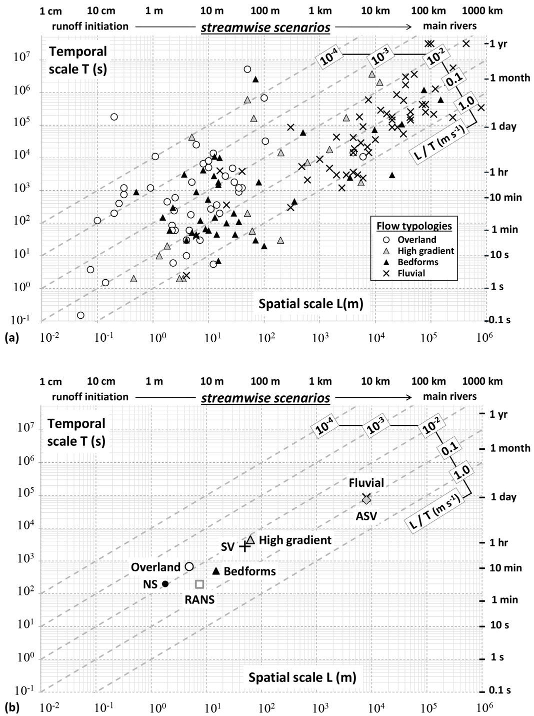

Figure 6. Position of the flow typologies in the (L,T) plane for the studies listed in Appendix A **(a)**. Median positions for the choice of free-surface flow models (Navier-Stokes: NS, Reynolds-Averaged Navier-Stokes: RANS, Saint-Venant: SV or Approximations to Saint-Venant: ASV) and the study of flow 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.

HESSD
12, 9091–9155, 2015

1-D free-surface flow and erosion issues in hydrology

B. Cheviron and R. Moussa

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

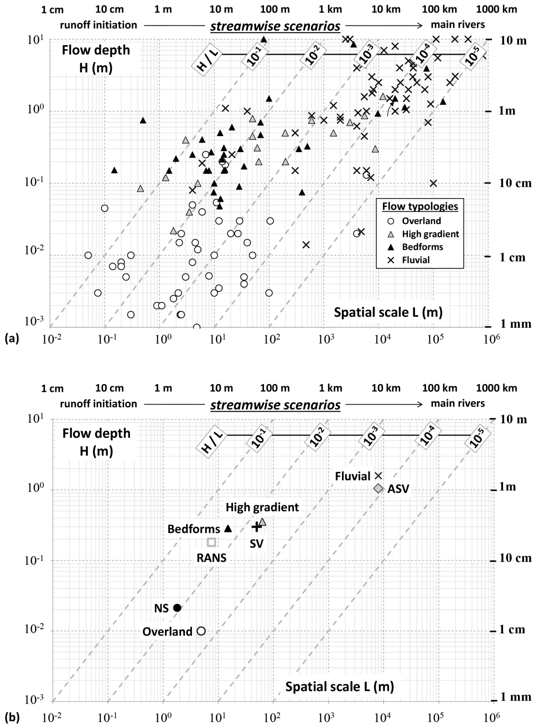

Figure 7. Position of the flow typologies in the (L,H) plane for the studies listed in Appendix A **(a)**. Median positions for the choice of free-surface flow models (Navier-Stokes: NS, Reynolds-Averaged Navier-Stokes: RANS, Saint-Venant: SV or Approximations to Saint-Venant: ASV) and the study of flow 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.

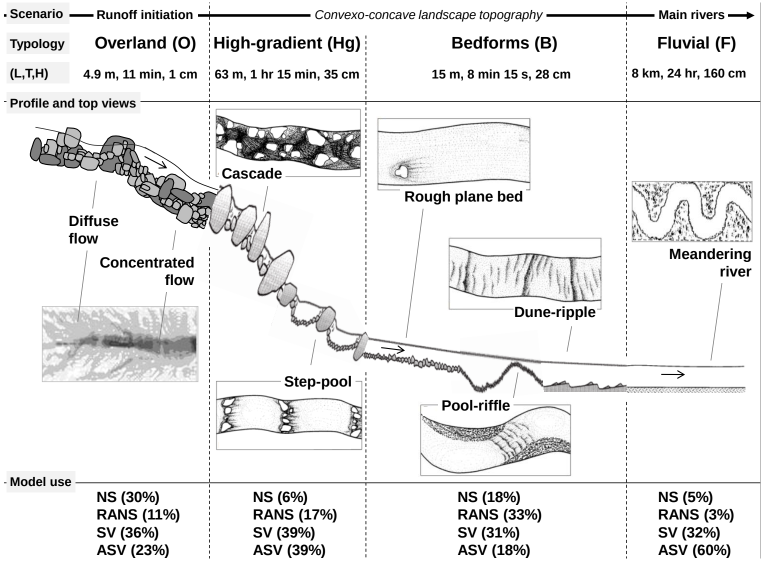

Figure 8. Streamwise scenario for a convexo-concave landscape topography, from runoff initiation to the main rivers, across flow typologies (Overland O, High-gradient Hg, Bedforms B or Fluvial F) and spatiotemporal scales (L,T,H). The indicated L, T and H values are the median values for the spatial scale, time scale and water depth, respectively, from the literature cited in Appendix A (Figs. 6 and 7). 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 "model use" panel indicates the model refinement 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 cited literature.

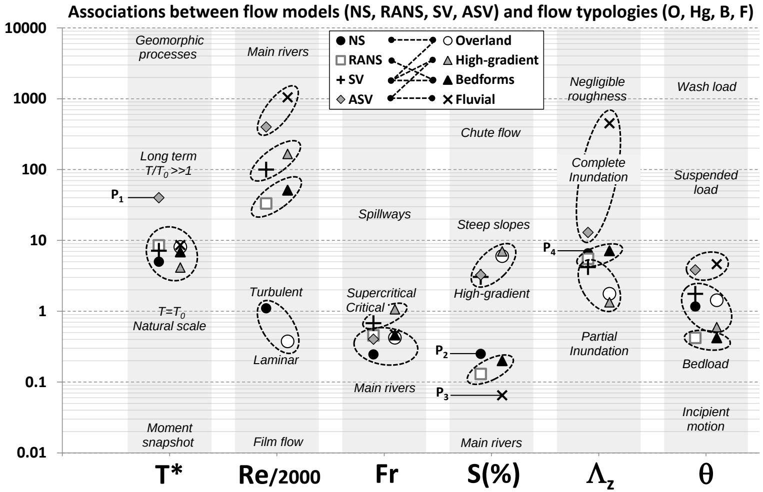

Figure 9. Comparative overview of the median values of the six selected dimensionless numbers (dimensionless period $T^* = T/T_0$, ratio of the chosen time scale on the "natural" time scale of the flow, Reynolds number Re, Froude number Fr, slope S, inundation ratio Λ_z and Shields parameter θ) obtained for the use of systems of equations (NS, RANS, SV and ASV) and the description of flow typologies (O, Hg, B and F) in the cited literature. The expected associations are indicated by dotted connecting lines in the legend box. The confirmed associations are indicated by dotted ellipses. Broken associations (isolated points P_1 to P_4) 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.

HESSD
12, 9091–9155, 2015

1-D free-surface flow and erosion issues in hydrology

B. Cheviron and R. Moussa