Response to Reviewer #2

by Bruno Cheviron and Roger Moussa

N.B. The line numbers noted LXXX-YYY refer to the revised word document

The paper presents an interesting attempt to draw links between different modelling approaches and to find appropriate time and length scales for different types of models. The approach adopted in the paper intends to be a general approach considering very different types of flows, from runoff to flows in large rivers.

R: We thank Reviewer #2 for his positive comments. We totally agree with his comments, and in the revised version we will introduce responses to all points raised by Reviewer #2 as shown below.

However, it must be stressed that this generalization still remains in the field of hydrology, with a point of view that is not as general as it could be. In particular, the Navier-Stokes (NS) equations are mentioned, but without being considered in their general fluid mechanics framework. So, the NS model is presented as the most general one, which is certainly the case, but turbulence is not discussed. However, considering that the flow velocity is the sum of a mean velocity and a fluctuating component, the NS equations can be solved to resolve as many as possible of the turbulence scales in DNS type simulations, also in flows with significant water depths. These DNS simulations are not discussed here, and NS models always appear in the "runoff" range of applications, which is quite limiting. Of course, if one remembers that the general review concerns hydrological modelling, then it becomes acceptable. But if this is the intention of the authors, then it should be stated much more clearly in the objectives of the paper.

R: The paper is indeed turned towards applications in the field of hydraulics and hydrology. The word "hydrology" was mentioned in the title for disambiguation, especially for readers' specialists in fluid mechanics who would expect the usual analytical framework. This "hydrological" option will be recalled for clarity, in one word or two, at several places in the introductory parts of the manuscript (abstract L21, introduction L83 and L140-141).

However, high-precision hydraulics (for example) requires the NS models and may involve various (turbulence) scales and flow structures. We have thus followed the recommendation to mention the possible context-dependent strategies (DNS, LES, RANS) to solve these equations, which hopefully restore a bit more genericity. An additional comment will be added (L194-203).

"There are many turbulence models (e.g. DNS-Direct Numerical Simulations, LES-Large Eddy Simulations and RANS-Reynolds-Averaged Navier-Stokes) suitable for free-surface flow modelling (Katopodes & Bradford 1999). Direct Numerical Simulations explicitly resolve all turbulence scales at the cost of more than Re^3 *calculations (Härtel 1996) while Large Eddy Simulations (Smagorinsky 1963, Leonard 1974) filter out the smallest scales and resolve only the larger ones. The RANS equations (Smith & McLean 1977, Rödi 1988) do not resolve any scale but the stress terms used for their closure have proven useful for the modelling of near-bed turbulent patterns (see next subsection). The general trend is that improvements in efficiency of the algorithms have approximately kept pace with exponential improvements in computer power over the past 50 years (Moore 1965, Mavriplis 1998, Koomey et al. 2010) which tends to push the limitations of DNS and LES further away."*

In a similar way, it then appears quite strange to read the word “turbulence” only when RANS models are discussed.

R: The term will be added L157, Section 2.1.1: "*(RANS: Reynolds 1895, for turbulent flows)*"

Indeed, RANS models were developed because performing DNS simulations to resolve all turbulence scales is impossible in practice due to excessive computational cost. Current research tends to push this limitation of NS still further away because of increasing available computational power using e.g. parallel computing. This is also an issue that deserves to be discussed.

R: These points will be mentioned L194-198.

“There are many turbulence models (e.g. DNS-Direct Numerical Simulations, LES-Large Eddy Simulations and RANS-Reynolds-Averaged Navier-Stokes) suitable for free-surface flow modelling (Katopodes & Bradford 1999). Direct Numerical Simulations explicitly resolve all turbulence scales at the cost of more than Re^3 *calculations (Härtel 1996) while Large Eddy Simulations (Smagorinsky 1963, Leonard 1974) filter out the smallest scales and resolve only the larger ones."*

On the way erosion processes are handled, there can also be some debate. The references used by the authors are certainly pertinent in the field. However, the attempt of classifying the different approaches for erosion and grain movement at the same level as the NS, RANS, SV and ASV models is questionable. The distinction is not so clear, and a different classification, not directly linked to the flow models, but rather to the type of grain movement considered would maybe have been more appropriate.

R: We agree that erosion issues are not fully addressed with such a "parallel" strategy in terms of decreasing model refinements, which only provides a trend. Section 2.1.2 will be modified to clarify this point (L166-173) and to indicate that complementary indications on the determinants of modelling choices regarding erosion will be found in Section 3.

"*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 erosion" 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 disconnection 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 types", seen through a dimensionless descriptor (Section 3).*"

These new lines (L166-173) mention a dimensionless descriptor for erosion (which will be the Shields number) which refers to phenomenologies that are not directly related to the NS, RANS, SV or ASV level, but rather to friction, bedforms and flow retardation processes as "proxys" for particle pick-up. What we intend to do is to introduce a new figure that shows a generalized Shields diagram. This would first offer an alternative to the reasoning in terms of refinement levels and second explicitly refer to the different erosion-transportation-deposition modes. This new Fig.9 comes at the end of Section 3.3.1 and is introduced by modifications in the text L824-832.

" This number seems appropriate for most erosion issues because it has been widely applied and debated in the literature (Coleman 1967, Ikeda 1982, Wiberg & Smith 1987, Zanke 2003, Lamb et al. 2008) and also because of its numerous possible adaptations (Neill 1968, Ouriémi et al. 2007, Miedema 2010) to various flow typologies and non-uniform or poorly-known bed conditions. An impressive review on the use of the Shields number to determine incipient motion conditions, over eight decades of experimental studies, may be found in Buffington & Montgomery (1997). Finally, Fig.9 provides a generalized Shields diagram that includes motion threshold criteria under the effects of high or low particle exposure (Miedema 2010) or for laminar flows, also indicating the conditions of significant suspension (Wright & Parker 2004)."

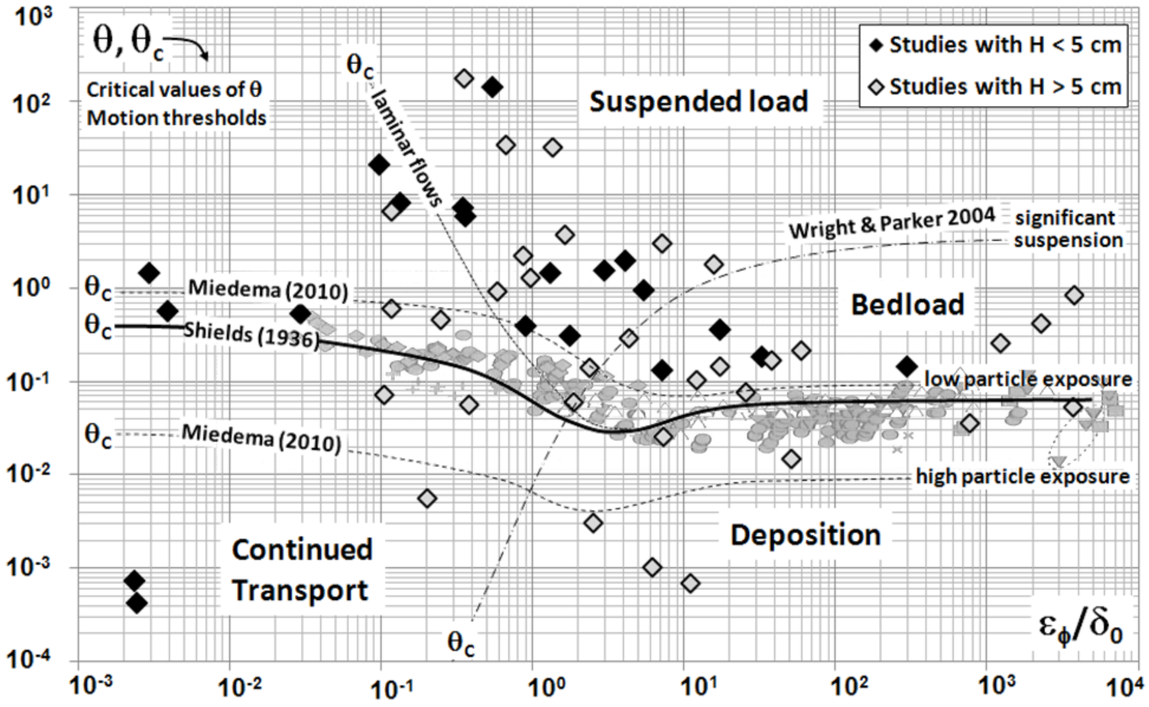

Figure 9 - Generalized dimensionless Shields diagram that summarizes the conditions and regimes of sediment transport or deposition, from the relative values of the Shields parameter (θ) and incipient motion criterion (θ_c). The X-axis bears the values of the ratio of particle size (ε_ϕ) on the depth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

In particular, the authors mention that the SV framework offers a wide field for innovative research about sediment transport, which is certainly the case. But in these recent researches, many different types of sediment transport models are considered, depending also on the necessary level of simplification of the reality that is required. Indeed, the detailed composition of the soli to be eroded is not always known, or it is not possible to include that level of detail in the representation. So it is necessary to resort to averaging concepts, such as a representative grain diameter, then some factors to account for the non-uniformity of the grain-size distribution.

R: This is now explicitly mentioned in the responses to the previous comments.

The concentration of sediment in the flow could also be discussed: debris flows or mud flows are not handled in the same way as clear-water flows with sediment transport, and this distinction does not really appear here.

R: We fully agree again and your request incites us to reintroduce several elements that we had previously discarded from our working versions (as the Shields diagram) in an attempt to make the manuscript shorter.

In the discussion paper, we only mentioned hyperconcentrated flows and stratification (i.e. density) effects for sediment laden flows, not really addressing the effect of flow density (water+sediments mixture) on modelling options.

As far as we know, the trend is to use higher-level models when the water-sediment couplings become stronger. Again, the SV level allows many adaptations and strategies, but we feel there was a lack regarding the applications of the NS and RANS to dense, debris or avalanche flows, for example. A few lines on the subject were already present in Sections 2.2.2 and 2.4.2 but we will add some more literature elements in Section 2.2.2. (L214-218)

“Such couplings may be sorted by increasing sediment loads, from dispersed multiphase flows (Parker & Coleman 1986, Davies et al. 1997) to density currents (Parker et al. 1986), hyperconcentrated flows (Mulder & Alexander 2001) and up to debris flows (e.g. Bouchut et al. 2003, Bouchut & Westdickenberg 2004), the latter derived as mathematical generalizations of the well-known Savage & Hütter (1989, 1991) avalanche models over explicit, pronounced topographies.”

Minor comments and detailed suggestions for improvement will be submitted later as an attached file.

R: Thank you.

<u>However, it must be stressed that this generalization still remains in the field of hydrology, with a point of view that is not as general as it could be</u>.

R: Let us return to this phrase in the second comment of Reviewer#2 which pushed us to reconsider the conclusion of the paper, thus to formulate its concluding message in a quite different way. First, we split the conclusion in two and the previously existing part becomes Section 4.1 "Outcomes of this review" (L878). Second, the added part is Section 4.2 "Research challenges in hydrology and philosophy of modelling" (L955-1019) including a new Fig.11 that summarizes what has been done and what should be done in complement. Figure 11 finds itself at the tilting point between Sections 4.1 and 4.2.

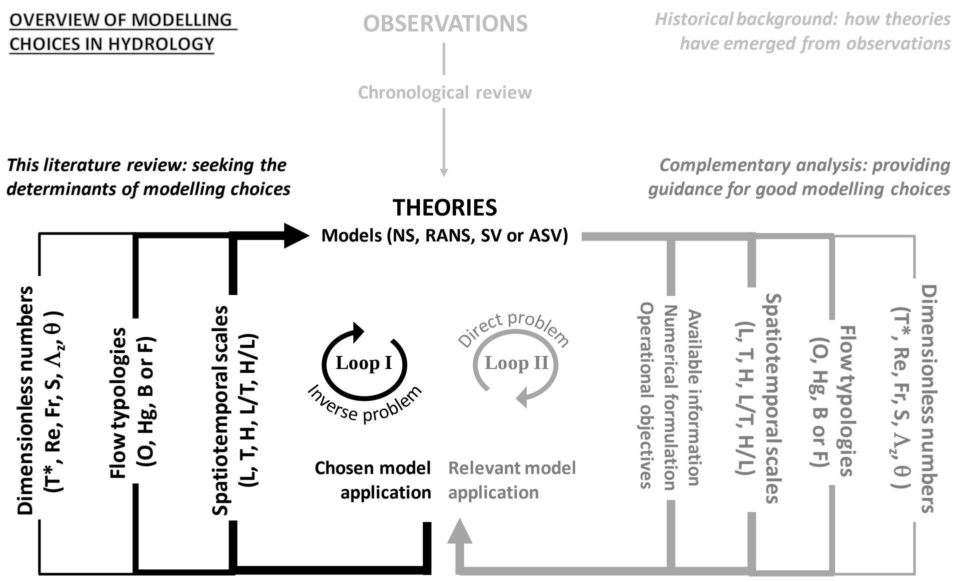

Figure 11 – This figure provides a simplified overview of the available modelling choices in hydrology, in three distinct colours associated with specific research purposes or disciplines, showing the position of the present review relative to the others. The pale grey section aims at understanding how the available flow models have emerged from observations and early formulations of the flow equations, focusing on their conditions of validity i.e. the successive hypotheses made during their derivation. The black section recalls the procedure followed in this review paper (Loop I, "inverse problem"). Literature sources are processed through a procedure that analyses how the spatiotemporal scales (spatial scale L, time scale T, flow depth H, L/T and H/L ratios), then flow typology (Overland O, High-gradient Hg, Bedforms B or Fluvial F) and dimensionless numbers (dimensionless period T*, Reynolds number Re, Froude number Fr, bed slope S, inundation ratio Λ_z, Shields parameter θ) determine the choice of a flow model (Navier-Stokes NS, Reynolds-Averaged Navier-Stokes RANS, Saint-Venant SV or approximations ASV). Suggested in medium grey on the right are the scope and principles of future research challenges that would address the "*what should be done?*" (Loop II, "direct problem") question in echo to the current "*what has been done?*"concern (Loop I).

On the one hand, the added section 4.2 discusses pending challenges and possible approaches quite specific to the fields of hydrology and hydraulics. On the other hand, it reintroduces very generic concepts and decision rules (hence the title "philosophy of modelling") in suggesting to select the approaches that respect the principle of parsimony.

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

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

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

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

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

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