OPTIMAL CHOICE OF FLOOD, INUNDATION AND EROSION MODELS

PhD director and co-director: Roger MOUSSA (UMR LISAH, Montpellier; roger.moussa@inrae.fr) et Bruno CHEVIRON (UMR GEau, Montpellier ; bruno.cheviron@inrae.fr)

Labs: LISAH and G-Eau Montpellier, France

Doctoral School: University of Montpellier, “Ecole Doctorale GAÏA”, Montpellier, France (https://gaia.umontpellier.fr/)

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Context and objectives

Inundations, floods and soil erosion cover most part of the damages caused by natural disasters in the World and in France. The quest for a better understanding and forecast of free-surface flow and erosion processes in space and time necessary involves coupling hydrological, hydraulic and erosion models with the ability to target the crucial scales and processes in a contextual analysis. Recent advances in modelling fluxes owe much to new concepts in modelling, to theoretical developments in solving equations, to the increase of calculation facilities, to a larger access to high-resolution topographic data (LiDAR) and generally to the contribution of remote sensing tools in identifying the first-order topographic elements in any landscape, to the use of crowdsourced data, and even to the re-examination of historical data to guide modelling choices through comparisons with choices previously made by other authors.

In the literature, numerous free-surface flow and erosion models have been developed [see the reviews of Bates and de Roo, 2000; Cheviron and Moussa, 2016]. However, the choice of the model stays often uncommented and not justified (except through partial *a posteriori* indications) whereas it is almost always possible to compare this choice to choices previously made by other modellers in similar contexts. Typically, one should start by questioning the adequacy of the chosen model structure (whether the model exists or is to be derived) and equations (classical or new formulation) to the objectives of the study and to the required data (either existing or to be collected). The generic question in the background is "***what are the optimality conditions for the modelling choice?***"

Hydrological, hydraulic and erosion models, used separately or through couplings, may be classified from the spatial discretization they resort to (by increasing complexity [Moussa and Cheviron, 2015]: no discretization, lumped, semi-distributed or distributed model), from the number of dimensions used to represent the processes (0-D for an empirical local description, 1-D, 2-D or 3-D for a spatial representation), from the choice of free-surface flow equations (conceptual models, Saint-Venant or approximations, fluid mechanics approaches), from the choice of the erosion model (coupled or not with flow model, strong or weak coupling) and also from the choice of the space and time steps (i.e., discretization).

Hydrological models often rely on the coupling between a production function and a transfer function. The production function aims to quantify the several vertical fluxes, separating rain into surface runoff and infiltration, evaporation, baseflow, exchanges with soil water tables and networks. The transfer function aims to route surface, subsurface and groundwater flows across hillslopes and catchments, to the hydrographic network and to its outlet. Several main types of hydrological models may be listed according to their structure: lumped models use a single spatial unit to represent the whole basin (e.g. the family of GR models [Perrin et al., 2000]), models that account for the spatial variability of topography (e.g. TOPMODEL [Beven and Kirkby, 1979]), spatially-distributed models based on a spatial segmentation of the studied domain, in a square grid as in SHE [Abbott et al., 1986], in sub-basins as in MARINE [2011], in homogeneous hydrological units as in HYDROTEL [Fortin et al., 1995], in hillslope elements as in KINEROS [Smith et al., 1995] or in plots as in MHYDAS [Moussa et al., 2002].

Hydraulic models may be sorted by increasing refinement, as the description of processes, scales and geometries becomes more and more explicit: conceptual models, Manning equation, approximations of the Saint-Venant equations (Kinematic and Diffusive Wave), full Saint-Venant equations, fluid mechanics equations based on the Navier-Stokes formalism or its simplifications. The most popular approaches to model fluvial hydraulics, thus also overflow and inundation issues, have been to provide solutions to the 1-D Saint-Venant equations [Moussa and Bocquillon, 1996; Bates and de Roo, 2000]. In the literature, numerous flood routing and inundation models have also been developed to address 2-D and 3-D cases, as for example TELEMAC-2D and 3D [Galland et al., 1991], LISFLOOD [Bates and De Roo, 2000], HEC RAS [2002], MIKE11 [2003] or MASCARET [2012].

Erosion models may also be sorted by increasing complexity, starting for example with the SDR (Sediment Delivery Ratio) concept which uses empirical equations to predict erosion rates, then the family of rating curves approaches that relates the concentration of suspended sediments to flow discharge [Delmas et al., 2009], then the very popular USLE (Universal Soil Loss Equation) that includes climatic and physiographic factors as well as soil erodibility, then physics-based models [Wainwright et al., 2008] compatible with the approximations of the Saint-Venant equation. Finally, more complex models in the field of fluid mechanics rely on the interactions between the solid and fluid phases of the flow to predict flow characteristics, among which its erosive power [Garcia and Parker, 1993]. In the literature, most models calculate erosion rates as a consequence of water flow features, as for example at the catchment or basin scales: SHESED [1996], ANSWERS [Beasley et al., 1980], CREAMS [Knisel, 1980], KINEROS [Smith et al., 1995], LISEM [De Roo et al., 1996], WEPP [Ascough II et al., 1997], EUROSEM [Morgan et al., 1998], MAHLERAN [Wainwright et al., 2008] or MHYDAS-Erosion [Gumiere et al., 2011].

For **practical applications**, these models should be able to generate the required variables, as flow stage, discharge and velocity, or particle mass flow with indications of erosion and deposition sites, in the hydrographic network and the inundation plain, also evaluating and announcing the associated uncertainties [Pappenberger et al., 2005]. Hence, the choice of the model may be decided from the identification of the terms possibly neglected in the theoretical equations, as an outcome of the analysis of flow phenomenology and/or of the relevant dimensionless formulation of the equations [Moussa et Bocquillon, 1996]. The choice of the model will also be constrained, if not dictated, by the availability and accuracy of input data (uncertainty and sampling steps in space and time: topography, hydraulic properties of the main channel and of the inundation plain, spatial extension of the inundation plain, flood hydrograph).

If various models of different structures prove capable of meeting the objectives of the study (variables, criteria, sites) with the same "performance" then the objective becomes to choose the simplest model, thus the lesser "cost", to satisfy the principle of parsimony. This necessitates defining the "**cost-performance**" relation for the candidate models. Here, "cost" refers to the various expenses for model development and transfer: cost of the tool itself and the required data, cost of model development or learning, cost of results analysis. Model "performance" would be estimated through calculated vs. measured variables (e.g. water depth and discharge) and classical criteria (e.g. NSE, RMSE) possibly on multiple sites, but also by evaluating the adequacy between the model features and its planned future usages.

It is a challenge for future research on flood and inundation modelling to associate hydrological, hydraulic or erosion models (used separately or coupled) and scenarios of climate change or land management. Testing models to evaluate their performances and their costs necessitates "benchmarking" them on several sites and in different hydro-climatic contexts, with different land uses and operational stakes. Recently, Cheviron and Moussa [2016] discussed the determinants of modelling choices for 1-D free surface flows, on the basis of a wide review of international literature.

Moussa and Cheviron [2018] then extended the approach for 0-D, 1-D, 2-D and 3-D models in the fields of hydrology, hydraulics and erosion. Hdeib et al. [2021] followed the same lead to establish a new cost-performance grid, to compare different 1-D coupled hydrological and hydraulic models for 18 applications. These first results are encouraging and need to be presented in a wider and more formal way, involving a wider data set of cases. However, to our knowledge **there is no framework or common database in the literature that would allow comparing different case studies and modelling choices from the cost-performance point of view**.

In this context, this PhD thesis proposal aims at establishing a methodology for the optimal choice of the hydrological-hydraulic-erosion model and operational purposes, simulating the impact of land management and climate change on floods and inundations. The application of the principle of parsimony will guide the modeller to choose the model with the lesser cost for acceptable performances. Applications will be conducted across multiple domain scales (100 m^2 to 1000 km^2) and for different climatic contexts (Mediterranean, Tropical, Humid) and land uses (agricultural, urban), leaning on hydro-meteorological databases of LISAH, G-EAU and partners (or found in the literature).

Methodology

Three successive steps will guide the modeller to the choice of the most adequate model for a given objective and context. The first step is to position the problem with respect to the international literature, to characterize the context and the determinants of the choice. The second step is to evaluate the cost-performance relation by benchmarking the candidate models on different sites and for close objectives. The third step is to propose a methodology to identify the optimal choice, relying on the previous two steps.

- The first step is to position the problem with respect to the international literature, to characterize the context and the determinants of the choice. For this, a literature review will be made, to establish the cost-performance relation for the models cited in the references of Cheviron and Moussa [2016]. Then this review will be extended to a larger set of models, objectives and case studies in France and in the world, in different hydro-climatic contexts. The cost-performance grid proposed by Hdeib et al. [2021] will be modified and adapted. This grid could be used to classify and compare studies found in the international literature, position a problem with respect to the literature, or identify historical trends and schools of thoughts in modelling.

- The second step is to evaluate the cost-performance relation by benchmarking the candidate models on different sites and for close objectives. In this part we will focus on the hydraulic discharge-discharge models in reach segments or hydrographic networks. For this, selected case studies will rely on previous works of LISAH and G-Eau and allow comparison of the cost-performance relations of different model types (Saint-Venant and approximations, fluid mechanics approaches) for different operational purposes, data availability and performance criteria.

- The third step is to propose a methodology to identify the optimal choice, relying on the previous two steps: for a given, commanded operational purpose, which model structure (existing or to be derived) should be chosen in accordance with the required data (available or to be collected). This part deals with the transfer of methodology for practical applications, to guide the modeller to the optimal choice in function of the objective-data couple. For this, we will identify the operational objectives formulated for resource management, then (i) position the context and determinants of the study with respect to the international literature, (ii) evaluate the cost-performance relation for candidate models and (iii) choose the most appropriate (said "optimal") model. The topic is closed by comparing the performances of the selected model to those of reference models of the literature.

Collaborations: Silvio Gumiere (Université Laval Québec), Nicolas Le Moine (Université Paris Sorbonne), Charles Perrin (INRAE, Antony), Service Central d'Hydrométéorologie et d'Appui à la Prévision des Inondations (SCHAPI), Service de Prévision des Crues (SPC).

Period: 2021-2024.

Key-words: modeling, hydrology, hydraulics, erosion, floods, natural basins, agricultural basins, land use changes.

Profile: Master or Engineering in Hydrology, Hydraulic or Environmental Sciences.

To apply:

- Prepare a CV, covering letter and letters of recommendation
- Contact: Roger MOUSSA (roger.moussa@inrae.fr) and Bruno CHEVIRON (bruno.cheviron@inrae.fr)
- Submit the application online on the GAIA Doctoral School website

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References

Abbott M. B., Bathurst J. C., Cunge J. A., O'Connell P. E., Rassmussen J. (1986). - An introduction to the European Hydrologic System - Système Hydrologique Européen, SHE. J. Hydrol., 87: 45-59 et 61-77.

Ascough II J. C., Baffaut C., Nearing M. A., Liu, B.Y. (1997). - The WEPP watershed model: I. Hydrology and erosion. Transactions of the ASAE, 40(4): 921–933.

Bates P. D., De Roo A. P. J. (2000). - A simple raster-based model for flood inundation simulation. J. Hydrol., 236: 54-77.

Beasley D. B., Huggins L. F, Monke E. J. (1980). - ANSWERS: a model for watershed planning. Transactions of the ASAE, 938-944.

Beven K. J., Kirkby M. J. (1979). - A physically based, variable contributing area model of basin hydrology. Hydrol. Sci. J., 24: 43-69.

Cheviron B., Moussa R. (2016). - Determinants of modelling choices for 1-D free-surface flow and morphodynamics in hydrology and hydraulics: a review. Hydrol. Earth Syst. Sci., 20: 3799-3830.

Delmas M., Cerdan O., Mouchel J. M., Garcin M. (2009). A method for developing large-scale sediment yield index for European river basins. J. Soils Sed., 9(6): 613–626.

De Roo A. P. J., Wesseling C. G., Ritsema, C. J. (1996). - LISEM: a single event physically-based hydrologic and soil erosion model for drainage basins. I: Theory, input and output. Hydrol. Proces., 10: 1107–1117.

Dorchies, D., Baume, J.P., Malaterre, P.O. (2013). SIC², un logiciel pour la gestion des canaux, rivières et fleuves. Sciences Eaux and Territoires: la Revue d'IRSTEA, IRSTEA, 48-50.

Fortin J. P., Moussa R., Bocquillon C., Villeneuve J. P. (1995). - HYDROTEL: Un modèle hydrologique distribué pouvant bénéficier des données fournies par la télédétection et les Systèmes d'Information Géographique. Revue des Sciences de l'Eau, 8(1): 97-124.

Galland J. C., Goutal N., Hervouet J. M. (1991). - TELEMAC: A new numerical model for solving shallow water equation. Adv. Water Res., 14(3): 143-148.

Garcia M., Parker G. (1993). - Experiments on the entrainment of sediment into suspension by a dense bottom current. J. Geophys. Res., 98: 4793-4807.

Gumiere S. J., Raclot D., Cheviron B., Davy G., Louchart X., Fabre J. C., Moussa R., Le Bissonnais Y. (2011). - MHYDAS-Erosion a distributed single-storm water erosion model for agricultural catchment. Hydrol. Proces., 25(11): 1717-1728.

Hdeib R., Moussa R., Colin F., Abdallah, C. (2021). - A new cost-performance grid to compare different flood modelling approaches, Hydrological Sciences Journal, DOI: 10.1080/02626667.2021.1873346

HEC-RAS. (2002). - HEC-RAS, River analysis system, user' manual. US Army Corps of Engineers, Hydrological Engineering Center, Davis, CA, report N° CPD-68.

Knisel W. G. (1980). - CREAMS, a field scale model for chemicals, runoff and erosion from agricultural management systems. U. C. R. Report USDA, no26.

MASCARET (2012). - MASCARET: a 1-D Open-Source Software for Flow Hydrodynamic and Water Quality, in Open Channel Networks, N. Goutal, J.-M. Lacombe, F. Zaoui and K. El-Kadi-Abderrezzak, River Flow 2012 – Murillo (Ed.), pp. 1169-1174.

MIKE 11. (2003). - A modelling system for river and channels. Short introduction tutorial, DHI Water and Environment, 88 pp.

Morgan R. P. C., Quinton J. N., Smith R. E., Govers G., Poesen J., Auerwald K., Chisci G., Torri D., Styczen M. E. (1998). - The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. Earth Surf. Proces. Land., 23: 527-544.

Moussa R., Bocquillon C. (1996). - Criteria for the choice of flood-routing methods in natural channels. Journal of Hydrology 186(1-4) : 1-30.

Moussa R., Cheviron B. (2015). - "Chapter 7: Modeling of floods - state of the art and research challenges". In "Rivers - physical, fluvial and environmental processes", Editors: Rowiński P.M. and Radecki-Pawlik A., Springer within the series: GeoPlanet: Earth and Planetary Sciences, pp 169-193.

Moussa R., Cheviron B. (2018). - Choix optimal du modèle de crue, d'inondation et d'érosion : proposition d'une grille d'analyse. Journées de la Société Hydrotechnique de France « De la prévision des crues à la gestion de crise », 14-16 Novembre 2018, Avignon, 10pp.

Moussa R., Voltz M., Andrieux P. (2002). - Effects of the spatial organization of agricultural management on the hydrological behaviour of a farmed catchment during flood events. Hydrol. Process., 16: 393-412.

Pappenberger F., Beven K. J., Horritt M. S., Blazkova S. (2005). - Uncertainty in the calibration of effective roughness parameters in HEC-RAS using inundation and downstream level observations. J. Hydrol., 302: 46-69.

Perrin C., Michel C., Andréassian V. (2001). - Does a large number of parameters enhance model performance ? Comparative assessment of common catchment model structures on 429 catchments. J. Hydrol., 242(3-4): 275-301.

Roux H., Labat D., Garambois P. A., Maubourguet M. M., Chorda J., Dartus D. (2011). - A physically-based parsimonious hydrological model for flash floods in Mediterranean catchments. Nat. Haz. Earth Syst. Sci., 11: 2567–2582.

Smith R. E., Goodrich D. C., Woolhiser D. A., Unkrich C. L. (1995). - A kinematic runoff and erosion model. In Singh V.J. (Ed), Computer Models of Watershed, Hydrology, 697-732, Water Resources Pub., Highlands, Ranch, CO.

Wainwright J., Parsons A. J., Müller E. N., Brazier R. E., Powell D. M., Fenti B. (2008). - A transport-distance approach to scaling erosion rates: I. Background and model development. Earth Surf. Proc. Land., 33: 813–826.

Wicks J. M., Bathurst J. C. (1996). - SHESED: a physically based, distributed erosion and sediment yield component for the SHE hydrological modelling system. J. Hydrol., 175: 213-238.