# Two decades of numerical modelling to understand long term fluvial archives: Advances and future perspectives

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Abstract: Fluvial archive applications of numerical models have been increasingly developed during the last decades. Based on a short questionnaire sent to researchers involved in known Quaternary numerical model applications, a perspective on current numerical modeling contributions was obtained. Current advances, limitations, surprises and future perspectives are compiled and discussed. Although fluvial system modelling is still a long way from reproducing real world fluvial landscapes, current models have proven beyond any doubt that fluvial systems display non-linear behaviour with often surprising and unforeseen dynamics causing significant external signal shredding or delayed and modified response. Many model applications demonstrate that fluvial archives are not only controlled by the interplay of (palaeo) landscape properties, climate, base level and tectonics, but also by self-organizing, intrinsic dynamics generating autogenic signals in the fluvial record. The effect of signal shredding, causing no or poor correlation between changes in system drivers and system records, is observed by most models. Despite this effect, all models can, after some calibration, produce convincing matches with real world systems suggesting that equifinality, that a given end state can be reached through many different pathways starting from different initial conditions, plays an important role in fluvial records. The overall future success of the FLuvial Archives Group (FLAG) community lies in its ability to separate intrinsic from extrinsic record signals using combined fieldwork and modelling.

UNIVERSITY OF TWENTE.

Dear Editors,

It is a pleasure to submit the paper **"Two decades of numerical modelling to understand long term fluvial archives: advances and future perspectives" by** Veldkamp, A., Baartman, J.E.M., Coulthard, T.J., Maddy, D., Schoorl, J.M., Storms J., Temme, A.J.A.M., van Balen, R., van De Wiel, M.J., van Gorp, W., Viveen, W., Whittaker, A.C. For consideration for publication in the special issue of FLAG in Quaternary Science Review.

We have made a perspective paper based on a short questionnaire all co-authors have filled in. We think that this exercise has yielded new and relevant insights for the advancement of FLAG research in the coming decade.

I hope you are willing to consider this contribution for publication in QSR.

Best regards,

Tom Veldkamp

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# Two decades of numerical modelling to understand long term fluvial archives: advances and future perspectives

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## Abstract

Fluvial archive applications of numerical models have been increasingly developed during the last decades. Based on a short questionnaire sent to researchers involved in known Quaternary numerical model applications, a perspective on current numerical modeling contributions was obtained. Current advances, limitations, surprises and future perspectives are compiled and discussed. Although fluvial system modelling is still a long way from reproducing real world fluvial landscapes, current models have proven beyond any doubt that fluvial systems display non-linear behaviour with often surprising and unforeseen dynamics causing significant external signal shredding or delayed and modified response. Many model applications demonstrate that fluvial archives are not only controlled by the interplay of (palaeo) landscape properties, climate, base level and tectonics, but also by self-organizing, intrinsic dynamics generating autogenic signals in the fluvial record. The effect of signal shredding, causing no or poor correlation between changes in system drivers and system records, is observed by most models. Despite this effect, all models can, after some calibration, produce convincing matches with real world systems suggesting that equifinality, that a given end state can be reached through many different pathways starting from different initial conditions, plays an important role in fluvial records. The overall future success of the FLuvial Archives Group (FLAG) community lies in its ability to separate intrinsic from extrinsic record signals using combined fieldwork and modelling.

*Keywords: fluvial stratigraphy, numerical model, non-linearity, equifinality, signal shredding.*

## Introduction

Numerical fluvial landscape modelling has taken off since the late nineties. Influential attempts focused on the terrestrial erosional processes of large basins aimed at understanding large-scale and long-term erosional dynamics (Howard et al., 1994; Whipple and Tucker, 1999). This led to discussions about non-linearity and steady state topography with climate and tectonic perturbations (Whipple, 2001). Attempts related to the application and scaling of stream power equations, that had their origin in empirical process geomorphology, led to the first catchment evolution models (SIBERIA, Willgoose et al., 1991; DRAINAL Beaumont et al., 2000; DELIM Howard 1994; GOLEM Tucker and Slingerland, 1997). The school of numerical modelling aimed at downstream sink areas, is illustrated by the book of Tetzlaff and Harbaugh (1989) focusing on simulating clastic sedimentation at the grain level. Their model produced relatively detailed (borehole) stratigraphy that was used to support oil exploration efforts.

Initially the gap between these modelling efforts and the fieldwork community was too large to be easily bridged. Available models were often too conceptual or abstract and could not directly be linked to the typical fluvial records studied by this community such as fluvial morphology, outcrops, boreholes and fluvial terraces. As a consequence, field studies remained focused on describing and interpreting fluvial records using their own conceptual models. Only since the late nineties has there been a surge towards the development of numerical models that produced outputs that can be more directly linked to field applications (See Table 1 for examples provided by the authors). All fluvial models use power laws derived from empirical relationships and all have unmeasurable parameters such as erodibility factors. The available numerical models have often different objects or topics of study and consequently, they have different scales of application, scale-dependent process choices and descriptions (Temme et al., 2011; 2016). It is the aim of this perspective paper from the model application community to demonstrate current progress in numerical modelling of fluvial archives during the 20 years of FLAG's existence. The paper ends with indicating future directions of numerical modelling development within FLAG.

Because the FLAG community is predominantly field record oriented we will discuss the relevant models grouped according to the specific records they simulate and/or predict. We distinguish combined Hillslope/Fluvial records, Terrace records, Delta records, Catchment records , Basin records and finally a group of coupled models. We discuss the most relevant model contributions that have been used to support fluvial archive understanding over the last 20 yrs. We will not give a complete overview of all available models nor will we go into detail about the specific model formulations as they have already been elaborately discussed in a recent overview publication by Tucker and Hancock (2010). The most recent model review by Temme et al., (2016) also discusses in detail the scale-dependent processes of the different landscape evolution models. Instead we will focus on the fluvial archive applications of the models based on a short questionnaire sent to all known researchers contributing to FLAG modelling applications. This questionnaire is available in Appendix I. A brief characterization of reported models that had more than one relevant FLAG application, including an elaborate sensitivity analysis are given in Table 1.

**Hillslope/Fluvial records**

Many headwater sediment records are often a mixture or colluvial and fluvial deposits. The LAPSUS model (Landscape Modelling at Multiple Dimensions and Scales; Schoorl et al., 2000; 2002) is one of the most commonly applied numerical models to study this type of records. The applications for KwaZulu Natal, South Africa (Temme and Veldkamp, 2009 ) and southeast Spain (Baartman et al., 2012a; 2012b) are the most elaborate examples spanning the last 50 ka. The WATEM –SEDEM models from Leuven University focus on hillslope records only and addresses mainly agriculture related case studies spanning the last millennia when tillage induced soil redistribution became an important process (Haregeweyn et al., 2013). Both models were compared for a historical case study that demonstrating similar performance in terms of generating plausible morphologies and colluvium records (Temme et al., 2011). The challenge of LAPSUS and similar models such as the model of Wainwright (2006), lies in effectively coupling hillslope-channel dynamics.

LAPSUS is effective in modelling different hillslope processes, including erosion by overland flow, tillage, biological and frost weathering, creep and solifluction (Temme and Veldkamp, 2009), landslides (Claessens et al., 2006), saturated overland flow (Buis and Veldkamp, 2008). The results yield spatially explicit erosion and deposition patterns (Schoorl et al., 2004). The weakest part of LAPSUS is the lack of a realistic fluvial hydrology although first steps in that direction have been undertaken (Baartman et al., 2012b; van Gorp et al., 2014). This means that currently the model does not yield realistic sedimentology or morphology of floodplains. It does however simulate local fan morphology realistically but again without simulating sedimentological patterns. There are now attempts underway to use the more detailed, but also more parameter/input demanding Wainwright (2006) model for larger spatio-temporal scales using parallel processing PARALLEM (McGough et al., 2012). Unfortunately these attempts have not yielded realistic landscapes yet.

**Terrace records**

The 1-D FLUVER2 (Veldkamp and van Dijke, 1998; 2000) and Bogaart (2003a and b) models are both aiming at modelling longitudinal profile dynamics. FLUVER2 is more focused at the floodplain level and the effects of climate, tectonics and base level while the Bogaart et al. (2003a,b) model is more focused on climate change-related river channel dynamics. Both models are focused on fluvial terrace records, where FLUVER2 focuses more on terrace formation events along the whole longitudinal profile, while Bogaart et al. (2003a and b) focused more on river pattern change (meandering versus braiding) for a small stretch. Both models produce the potential events that may lead to terrace formation but both lack a realistic estimate of net terrace preservation due to the lack of a horizontal dimension. The LIMTER model (Veldkamp, 1992) —

more recently called TERRACE in (Viveen et al., 2014)— when combined with FLUVER2, can give some additional insight in the probability of terrace preservation and valley cross-sections. Unfortunately this model is, although spatially explicit is only partly numerical, not geographically explicit and conceptual (Veldkamp et al., 2002; Viveen et al., 2014).

### Delta records

The controls on river delta formation are not only driven by fluvial forces. Effects of wave reworking, wave and tide-induced currents and base level change also play a major role in delta formation. In addition to these afore mentioned external (allogenic) controls, deltas also respond to internal (autogenic) controls (Edmonds and Slingerland, 2010) such as avulsions and bifurcations. To understand, unravel and predict the complex deltaic stratigraphy there is an increasing use of process-based models that link hydrodynamics and sediment transport to better explain large and small-scale morphodynamics. These models are increasingly coupled to a stratigraphic module such that morphodynamics can be used to explain stratigraphic variability.

The open source Delft3D model (e.g. Geleynse et al., 2010, 2011; Hillen et al., 2014) put emphasis on 3D delta stratal records. The model has been developed in the engineering world over the past 30 years (Lesser et al, 2004; Roelvink, 2006), where many flume studies have contributed to the calibration of formulations included in the hydrodynamic modules and the sediment transport modules. For full details we refer to the Delft3D-FLOW manual. http://oss.deltares.nl/documents/183920/eeb97903-151a-49bf-a13a-54b616da47a9

### Catchment records

The CHILD model (Tucker et al., 2001; Tucker and Slingerland, 1997; http://csdms.colorado.edu/wiki/Model:Child ) simulates changes in topography in time and space under the influence of hillslope and fluvial processes. From this information, river long profiles, sediment fluxes and erosion rates can be derived. The model inputs are uplift rate and "climate" related rainfall models and inputs (Tucker and Bras, 2000). There are several options available for the fluvial and hillslope erosion laws. CHILD has been used for many different case studies with a wide range of spatio-temporal domains. For the FLAG community several applications are relevant. One study looks at how fluvial landscapes respond to climate change and to faulting for example to evaluate which long-term erosion laws best reproduce the channel geometry and the observed landscape response (Attal, et al, 2008). Another recent study looks at the effect of active normal faulting on channel long profiles and channel width record in the Central Apennines of Italy (Whittaker, et al., 2008). A large scale application of the CHILD model has been to study the effect of Late Pleistocene climate changes on the Rhine-Meuse catchment (Van Balen et al., 2010). The focus of this study was on the travel time of sediment pulses and on grain size sorting in this large catchment. The predictions were compared to inferences from the stratigraphic record in the downstream part. Model input consisted of an initial topography, various erodibility factors and a regolith layer with two different grain sizes and effective precipitation. For the topography a present-day DEM of the catchment was used. The effective precipitation was taken from a global circulation model. The results showed a considerable time-delay (several thousands of years) between climatic cause and sedimentary effect. This is partly blurred signal is due to the delayed arrival of separate sediment pulses that originate from the tributaries in the fluvial network.

CAESAR (Coulthard et al., 2002; van de Wiel et al., 2007;) and the improved CAESAR-LISFLOOD (Coulthard et al., 2013) simulate topographical change due to water and sediment movement. There are some similarities with the SIBERIA model (Hancock et al., 2010). The model is focused on the hydrological dynamics and also produces surface and subsurface grainsize distributions. It operates on an event basis and is the only fluvial landscape model that produces detailed stratigraphy in the floodplain. Due to the use of higher resolution time series (rainfall or discharge) inputs can present computational challenges. CAESAR applications range over time scales from individual events up to 10 ka maximum. There have been many applications but only a few looking at longer term records that are especially relevant for the FLAG community. These have focused on the dominant role of climate over land use in affecting Holocene fluvial sediment records (Coulthard and Macklin, 2001). And, more recently, at how climatic signals may be more evident in sedimentary archives than tectonic signals over 10 ka and shorter timescales (Coulthard and Van de Wiel, 2013). Additionally, CAESAR has been used to explore the importance of nonlinear dynamics and floodplain dynamics in generating fluvial archives, notably how autogenic processes within drainage basins are capable of generating spurious signals in the sedimentary record (Coulthard and van de Wiel, 2007; 2010; 2012; Ziliani et al., 2013 ). The papers on nonlinear dynamics of sediment yields (Coulthard and Van De Wiel, 2007, 2013; Van De Wiel and Coulthard, 2010) are of direct relevance to the FLAG community for better understanding the formation of fluvial archives.

**Basin records**

The SELF-SIMILARITY DOWNSTREAM MODEL (Fedele and Paola, 2007; Duller et al., 2010; Whittaker et al., 2011) produces stratigraphic grain size trends as a function of tectonic subsidence and sediment supply variations at the whole basin level. It uses a self-similarity model for grain size fining, which was proposed in its current form by Fedele and Paola (2007). The model is a two-dimensional solution based on empirical observations that indicate that the grain size distributions of stream flow-dominated deposits are self-similar. For gravel grain sizes, this means that the mean and standard deviation of surface and subsurface sediments decrease at the same rate downstream (c.f. Paola et al., 1992; Paola and Seal, 1995; Duller et al., 2010; Whittaker et al., 2011). This approach is used to predict sedimentary grain sizes when sediment fluxes and tectonically-driven accommodation is known independently or estimated. The SELF-SIMILARITY DOWNSTREAM FINING MODEL has been applied to stream flow-dominated conglomerates in the Pobla Basin of the Spanish Pyrenees (Duller et al., 2010; Whittaker et al., 2011) and to understand systems such as the Fucino basin catchments in Italy (Armitage et al., 2011; Forzoni et al, 2014).

The ARMINTAGE-COUPLED CATCHMENT BASIN MODEL (Armitage et al., 2011; 2013) is focused on the translation of tectonic and climatic signals from source to sedimentary archives. It considers a small, frontal catchment and an alluvial fan which are separated by a vertical fault. The uplifted catchment is eroded and supplies a sediment discharge that is deposited within the basin. Erosion is mimicked by diffusive-concentrative hillslope and fluvial equations. Depositional architecture is calculated by a mass balance approach, assuming that no erosion occurs within the depositional fan. In the model, the apex boundary condition is free to move but with an imposed gradient continuity at the apex boundary. The slope of the fan is assumed to be constant. Therefore, at each time increment, a new depositional wedge is determined and selective deposition theory is used to estimate downstream stratigraphical grain size fining. The initial grain size signal is transformed downstream by selective deposition using an adapted version of self-similar solutions for downstream grain size trends. The ARMINTAGE-COUPLED CATCHMENT BASIN MODEL has recently been applied to understanding Eocene sediment routing in the Spanish Escanilla fluvial system (Armitage et al., 2015). The results demonstrate that an increase in catchment precipitation and tectonic uplift generates diagnostic patterns of downstream grain size fining and stratigraphic geometry. An increase in precipitation produces a transient and laterally extensive, coarse gravel sheet, whereas a change in tectonic uplift generates a more diverse suite of downstream grain size patterns and stratigraphic geometry.

**Coupled Lithospheric and Surface denudation systems**

There are two models that simulate coupled lithospheric and surface denudation. The lower crustal flow model by Westaway (2002) and TISC (Garcia-Castellanos, 2003; Stange et al., 2014). The lower crustal flow model assumes lithospheric conditions combined with fluvial incisional rates typically derived from fluvial terrace records. There are several applications for most continents all suggesting a plausibility of the lower crustal flow mechanism (Westaway 2002; 2004; Westaway et al., 2002). The model can also explain the observed differences between fluvial staircases on old static continental cratons and young dynamic crusts (Bridgland and Westaway, 2008). However, lower crustal flow at this scale has never been directly demonstrated in these case studies and is not compatible with other estimates of visco-elastic properties of the lithosphere obtained from for example rheological modeling, basin modeling and glacio-isostasy studies. The observation that this model is able to fit any terrace record could be a result of equifinality. So without independent confirmation of the modelled processes no real validation of the modelling results is possible.

The TISC model is capable of combining landscape evolution with plan view lithospheric flexure (Garcia-Castellanos and Cloetingh, 2012). It can spatially predict the amounts of erosion and sediment accumulation, resulting in a redistribution of surface loads. Based on realistic (constrained) lithospheric rheological properties the model also gives rise to vertical motions that result from flexural isostatic compensation. TISC was recently applied to the Ebro river and its tributaries (Stange et al., 2014) and the results showed that isostatic motions do indeed contribute to the uplift required to explain river incision and terrace formation, but also that the largest amount of incision is probably caused by Quaternary uplift.

**Perceived limitations of the available models**

Every numerical model is a simplification of a real-world system based on many, often spatio-temporal, scale-dependent assumptions. The 1-D models that only describe the river profile dynamics all have as a main limitation that they lack the dimension crucial for realistically modelling river dynamics and the ability to model the preservation of older deposits. All models are scale-dependent regarding their settings and as a result, all require case-by-case calibration. This is most obvious in the choice of model processes and the description of the processes. Furthermore, all models have in common that they use unmeasurable, often lumped, parameters. The fluvial landscape models struggle with the initial relief/profile input. Because existing numerical models use forward-modelling approaches, they are sensitive to this initial input which is one of the most difficult input parameters to reconstruct. Initial relief is especially a key-sensitive input in the 2-D catchment and basin models (Stange et al., 2014; Van Gorp et al., 2016).

All models are facing the challenge to opt either for detailed process descriptions that are based on physics or to settle for a more or less simplified reduced complexity approach using empirical measurements and/or lumped proxy descriptions. The former models require long detailed times series as input, which are usually not available, while the latter type of models requires data input that cannot be measured directly, resulting in using proxies.

The more dimensions and/or processes in the model the more input data is required and the longer the run time. The reduced complexity models demand less input data and have relatively short run times, but they rely al lot on specific assumptions, making process validations almost impossible. This trade-off between complexity and feasibility is the underlying reason that no model is able to simulate detailed realistic landscapes over long time spans. So we are faced with the challenge that the theoretically best models are impossible to validate. Very often the downscaling of algorithms, proxies for model input, or stochastic approaches are used to bridge this gap.

Despite the fact that many models have limited process descriptions, such as the inability to cope with channel widening and avulsions, they all can be calibrated to existing fluvial records. But typically most calibrations and validation attempts are based on general catchment relationships. This issue touches upon the principle of equifinality. In complex systems a given end state can be reached through many different pathways starting from different initial conditions.
This may explain why most model applications are able to yield outputs that demonstrate a general match with the known field record.

The 2-D spatial models are all struggling with either the coupling of hill slopes and fluvial channel dynamics, or with using scale-dependent power laws. There exists the tendency to incorporate more processes in the model, thereby increasing the degrees of freedom and making calibration easier knowing that equifinality will lead to plausible model results. Although more processes are incorporated, there are always more processes to be included. Studies have demonstrated that for example dynamic regolith production rates should be included because they have a significant effect on catchment-wide sediment delivery rates and landscape morphology (Tucker and Slingerland, 1997; Van Balen et al. 2010; Temme and Vanwalleghem, 2015). A related challenge is how to deal with boundary conditions such as tectonic and base level changes. One way is to make them an integral part of the model, but then the model becomes a complete, coupled earth system model, which makes validation of model results almost impossible.

## Surprises

Most model developers have had their share of surprises while developing and applying the models. Almost all have unexpected outcomes related to the non-linearity and delayed response of the modelled fluvial system. A common observation is that fluvial systems are usually not the simple environmental archives and records many field-oriented researchers consider them to be.

The spatial-temporal delay along a river profile may be expected but often signals start to interfere or they attenuate yielding unexpected records (Veldkamp and Tebbens, 2001). There are indications that nick points near the headwaters of large fluvial systems were original triggered many hundred thousands years age (Demoulin, 1998). A linear relationship between one external driver and observed fluvial record properties is rare. Many models and especially CAESAR indicate that a lot of signal shredding is taking place (Jerolmack and Paola, 2010; Van De Wiel and Coulthard, 2010). Modelling has demonstrated several times that many local records are the result of self-organizing behavior of the fluvial/slope system without any external environmental change (Van De Wiel and Coulthard, 2007; Coulthard and Van De Wiel, 2010; Schoorl et al., 2015; Forzoni et al., 2015). This insight is still not commonly shared with the field community. Most field records are still viewed as reflecting predominantly environmental changes (see special issues of FLAG). Most field-based researchers are probably aware of signal shredding and autogenic signals, but it is still too tempting to use simple causal relationships when interpreting fluvial records. The alternative is to consider the whole record to be autogenic thereby allowing no conclusions about the system controls at all. The biggest challenge for the modelling community is to convince field based researchers to consider model supported scenarios before making statements about causal relationships. For now, most field studies still link observed record changes almost exclusively to external changes in climate, tectonics or base level. Specifically the 2-D models have consequently demonstrated that river basins are always in a state if delayed response to external drivers, but at the same time they generate their own autogenic signals. The field community should focus more on how can we separate intrinsic from extrinsic record signals. Finally, modelling studies have also demonstrated that the external drivers of the fluvial system are not independent and that tectonics, climate and base level change are coupled drivers. They always have a combined, interfering impact in the fluvial records, thereby acknowledging that not every external change leaves a signal in the fluvial record.

The modelling applications have also demonstrated that some of the basic assumptions such as hydraulic scaling probably needs revisiting. A recent example is the importance of channel width in controlling how fluvial landscapes respond to tectonics. While many models typically assume hydraulic scaling, field and modelling data show that this assumption is not always valid (Attal et al., 2008). Whittaker et al. (2008) performed an experiment where rivers cutting across faults had a fixed channel width and an experiment where channels were allowed to vary dynamically with channel gradient. This made a big difference in to how landscapes recorded the imprint of tectonics.

Several model applications have demonstrated that despite the many degrees of freedom it is not always easy to calibrate to existing field records. On the other hand, some model developers indicate that they are surprised by the versatility of their models as they seem to work over a wide range of spatio-temporal scales. Other surprises are related to new insights about the key role of cohesive sediment on floodplain dynamics and deltaic channel pattern, and the role of sediment reworking in determining delta stratigraphy. Sometimes the surprise relates to the relative unimportance of a process such as tillage erosion which hardly supplies sediments to the fluvial system.

Longer time span applications have demonstrated that some time-specific, high-magnitude, low-frequency events (landslides, earthquakes, volcanic eruptions) can have a long lasting effect on the fluvial record (van Gorp et al., 2016). Probably also, the contrary happens as large events occur with no long-lasting impact at all

## **What is needed to advance modelling efforts (future plans)**

Typically, modellers want more data and bigger and faster computers. But there are also concrete steps proposed to advance the relevance of numerical models in understanding fluvial archives.

There is a clear demand for a new type (strategy of using) of case studies. A compendium of field sites is needed in which a high resolution stratigraphy is available – i.e. well dated in time and space and where sedimentation rates are high and sedimentation budgets are closed. These areas can be used as model development reference areas.

In order to involve the field community more in the model development it is suggested to develop user-friendly tools to increase the user group. A good example of a general overview of many existing models is found at https://csdms.colorado.edu/wiki/Model_download_portal , where many earth scientific models are grouped and documented. What may be lacking are simple demo-versions demonstrating to field-oriented researchers some key issues such as the effects of non-linearity, signal shredding and intrinsic vs extrinsic dynamic. Figure 1 is a first attempt to illustrate why linear correlations between climate and fluvial records are unlikely. Two model outcomes the intrinsic and extrinsic driven erosion/deposition dynamics illustrate this principle. On the other hand, modellers need to be more included in the collection of field data. In fact one could argue that the terms modeling community and field community should become obsolete, as they need to be one and same community. Real progress can only be made when these two fields are better integrated.

It is also proposed that combining and linking existing models and their concepts might advance our insights. An obvious idea is to recommend ensemble forecasts (similar to the climate modelling community), where different models are used to explore a range of simulated outcomes. The main challenge will be systematically dealing with the different spatio-temporal scaling effects and basic model assumptions. Of course there is the call for adding more processes in the existing models or to generate new additional information that can be used to calibrate and validate the models. As mentioned earlier, one general weak component of many models is the lateral migration and widening of the active riverbed.

It is the ultimate goal to reproduce realistic landscapes for well-studied case studies. New type of applications related to the prediction of gold deposits and archeology will test the robustness of the models in different ways. Another step is to have the models producing relevant field-related outputs such as stratigraphical records and calculated $^{10}$Be erosion rates. One might even speculate to predict the degree of bleaching of sand grains, as a relevant fluvial record property.

There is also a clear need to target specific field studies to investigate landscape connectivity such as hillslope-channel coupling and decoupling in more detail. This will help to separate intrinsic self-organizing phenomena from extrinsic controlled record properties. Ultimately we want to understand how the records were formed, and to try to infer the relevant climate and other external drivers. It may be for example that the frequency of threshold surpassing storms is the key property that is registered in fluvial records. So that raises the twin question of how to incorporate this into models (i.e. what level of complexity to use) and of course, the extent to which we can reconstruct the historical fluvial record to test model outputs.

## Conclusions

Quaternary numerical fluvial system modelling is still a long way from reproducing real-world fluvial landscapes. The current models have proven beyond any doubt that to understand fluvial archives we are dealing with non-linear systems with often surprising and unforeseen dynamics that cause significant external signal shredding. The modelling efforts have demonstrated that fluvial archives are not only controlled by the interplay of (palaeo) landscape properties, climate, base level and tectonics, but also by self-organizing, intrinsic dynamics generating autogenic signals. The effect of external signal shredding is observed by all models but they can produce convincing matches with real-world systems after some calibration efforts. Currently the modelling community is using different scale-dependent process choices and descriptions. Future research direction are sought to improve models with nested model assemblies, new field studies, and measures that give additional information for model parametrization and calibration. In general we recommend that the fieldwork community avoids using simplistic, often linear, hypothetical models in their reconstructions, and that they profit more from the insights derived from numerical process modelling. The overall success of the FLAG community lies in its ability to separate intrinsic from extrinsic record signals using both fieldwork and modelling approaches.

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Figure 1

Illustration of challenges of fluvial records interpretation, assuming general preservation within a terrace record, with and without using models. An existing climate record (example is temperature (red) and precipitation (blue) deviations over the last 150 ka (Guiot et al., 1989; 1993) is given at the left hand side. Typically a cold stage correlation is made (see green arrows). When this climate curve is modelled into an externally driven fluvial erosion/deposition curve using the FLUVER2 model a curve (purple curve, right hand side) is created that already deviates from the original climate curves. As a result the interpretations using this curve (see blue arrows) correlating depositional events to sedimentary units, deviations can be observed for the other units. When the intrinsic erosion/deposition curve is used even more stronger deviations can be observed (see red arrows). Given the fact that we know that fluvial systems are non-linear and display a mix of intrinsic and extrinsic dynamics, the most correct interpretations can only be made using numerical models.

## Appendix I

In order to allow for a systematic review on modelling contributions to FLAG, I have developed a set of questions and info request to standardize your contributions. I will focus on the applications to real world archives and not dive into the model specifics, that has been done before. Please submit your own personal views and opinions. There is no need for consensus.

1. Name:
2. What do you consider your most relevant modelling contributions (can be both model development as model application papers) towards unraveling fluvial archives (please list key publications not older than 20 years here)?
3. What model did you use and in which key publications are the principles and formulations of the model version you used/developed described?
4. Please list all case studies explored with the model (location, extent in both space and time)
5. What are the key external drivers (inputs) of the model?
6. What are the key outputs of the model?
7. Are there systematical sensitivity analyses performed? Please list the publications
8. How was the model calibrated? (this might be case study specific)
9. How was the model performance (either behavior, validation?) evaluated
10. What do you consider the main limitation(s) of your model (Exercise)?
11. Where there surprises as a result of the modelling exercise?
12. What do you consider the main contribution of your modelling exercise to unraveling the fluvial archive (new insights etc)?
13. What is needed to advance your modelling efforts (not only stating more data but please specify your explicit needs)?
14. What are your modeling plans for the nearby future in the context of FLAG

**Table**

| Model name | Key papers | Inputs | Outputs | Number of relevant Fluvial archive applications | Website: |
|---|---|---|---|---|---|
| CHILD 2D landscape evolution model TIN based model | (Tucker et al., 2001) | Topography, uplift rate – "climate" – there are a range of rainfall models and inputs, including stochastic distributions, bedrock strength/erodibility and a choice of different fluvial and hillslope erosion laws | Changing topography in time and space. From this, river long profiles, sediment fluxes, erosion rates can be derived. | (Attal, et al, 2008) effect of active normal faulting on channel long profiles and channel width record. Central Apennines of Italy (Whittaker, et al., 2008). Van Balen et al., 2010 (effect of climate change on sediment fluxes and grain size sorting (Rhine-Meuse rivers) | http://csdms.colorado.edu/wiki/Model:CHILD |
| FLUVER2 1D longitudinal nodal model | (Veldkamp and van Dijke, 2000) | Initial longitudinal profile, Precipitation and temperature curve, Tectonic movement rates, base level curve | Profile evolutions maps, Sediment fluxes, vertical floodplain dynamics | Allier - Loire in France (Veldkamp et al., 2016), The Meuse in the Netherlands (Tebbens et al., 2000), the Aller (Weser tributary) in Germany (Veldkamp et al., 2002), the Guadalhorce in southern Spain (Schoorl and Veldkamp, 2003), the Thames in England (Stemerdink et al., 2010), the Miño in Portugal and Spain (Viveen et al., 2013), and the Tabernas in south-eastern Spain (Geach et al., 2015). | http://www.wageningenur.nl/en/Expertise-Services/Chair-groups/Environmental-Sciences/Soil-Geography-and-Landscape-Group/Research/FLUVER2.htm |
| CAESAR Grid based model focused on | (van de Wiel et al., 2007), (Coulthard et al., 2013) | Topography (DEM), Climate (precipitation time series), Grainsize, | time series of water and sediment at catchment outlet, | Records of UK Holocene river activity (Coulthard and Macklin, 2001); Importance of location of fluvial archive within drainage | http://www.coulthard.org.uk/CAESAR.html and |

| | | | | | |
|---|---|---|---|---|---|
| landscape and floodplain dynamics | | Land cover (reflected in hydrology). | DEM's of surface at whatever time required, Surface and subsurface grainsize | basin (Coulthard et al., 2005); Role of non linear processes in generating false alluvial archive signals (Coulthard and Van de Wiel, 2007; 2010). | http://www.coulthard.org.uk/CAESARLisflood.html |
| LAPSUS (2002) Grid based landscape model focused on hill slope dynamics | (Schoorl et al., 2000; 2002) | altitude (DEM), rainfall (climate), tectonics, lithology (erodibility, infiltration) | timeseries of: DEMs, maps of erosion, sedimentation, discharge, data on mean erosion – sedimentation rates for locations, areas, zones at any time t during simulation. | Schoorl and Veldkamp, 2001 (Dynamic landscape, potential for sediment mixing, spatial distributed erodibility)<br>Schoorl et al 2014 (Sediment trains, locations of erosion and sedimentation (Terraces) changing locations under equal conditions, preservation potential, possible autogenous terraces etc )<br>Claessens et al. 2006 coupling landslides through the river network to a sediment archive<br>Temme et al., 2009;<br>Baartman et al 2012a en 2012b<br>Van Gorp 2013, 2014, 2016 | http://www.lapsusmodel.nl |
| SELF-SIMILARITY DOWNSTREAM FINING MODEL | Duller et al., 2010, Whittaker, et al., 2011 (developed from Fedele & Paola, 2007, JGR) | Sediment flux, spatial distribution of accommodation, grain size in the supply. | Spatial distribution of mean grain size in the deposit, standard deviation of grain sizes | Parsons et al., 2012, JGSL; Michael et al., 2013, JofG; Michael et al., 2014 GSA Bulletin, all in Spanish Pyrenees, D'Arcy et al., 2016, Sedimentology, in press, Death Valley). | http://www.imperial.ac.uk/people/a.whittaker; |
| COUPLED CATCHMENT BASIN MODEL | (Armitage et al., 2011, 2013) | *Catchment:* length, size, hillslope diffusivity, rainfall parameter, non-linear fluvial transport co- | Long profile evolution in time and space; sediment flux in time and space, stratigraphic output of | Armitage et al., 2015, JSR, - Spanish Pyrenees; Allen et al., 2015; JofG, Italy. | http://www.ipgp.fr/en/user/584 |

| | | | | | |
|---|---|---|---|---|---|
| | | efficient, erosion exponent, n, *Basin:* subsidence/uplift rate in time and space; sediment flux from catchment output, above, grain size estimate. | volumes and sedimentary grain sizes. | | |
| Delft3D | Lesser et al., 2004; Roelvink 2006, Geleynse et al 2010, 2011 | Topography, bathymetry, fluvial discharge, sediment concentrations, wave climate, tidal regime. | Topography, bathymetry, stratigraphy, hydrodynamic information in time (flow velocity, sediment transport rates, deposition rates, erosion rates) | Geleynse et al 2010, 2011, Hillen et al 2014 | http://oss.deltares.nl/web/delft3d |
| TISC | Stange et al. (2014) | Initial topography, erodibility, precipitation | Changing topography in time and space. From this, river long profiles, sediment fluxes, erosion rates can be derived.<br>+<br>Plan view flexural isostatic subsidence and uplift | The Ebro river sytem (Pyrenees and Ebro Basin) | https://sites.google.com/site/daniggcc/publications |

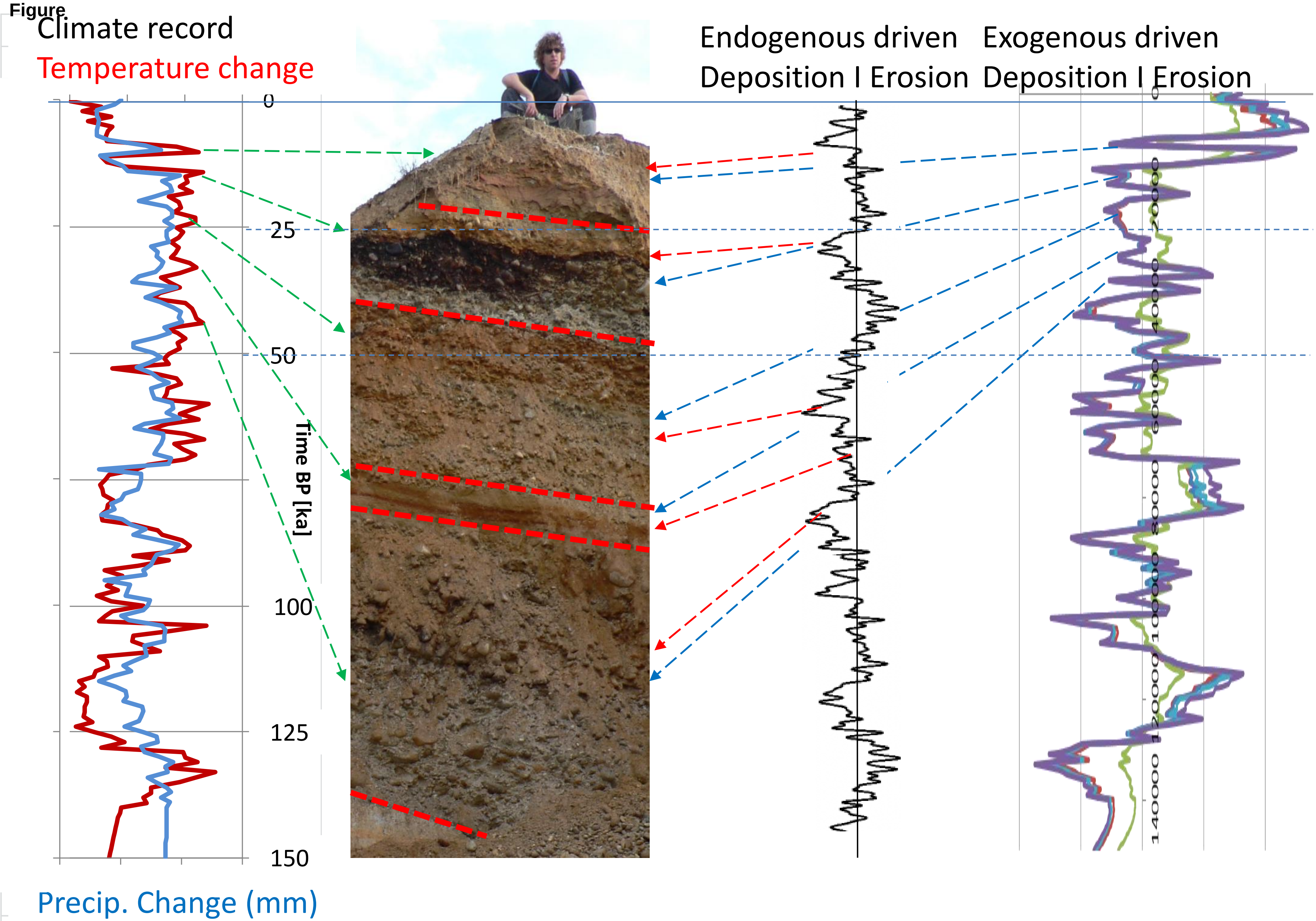
Figure
Climate record
Temperature change
Endogenous driven
Deposition I Erosion
Exogenous driven
Deposition I Erosion
0
25
50
100
125
150
Time BP [ka]
Precip. Change (mm)

Figure 1