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

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Abstract

The development and application of numerical models to investigate fluvial sedimentary archives has increased during the last decades resulting in a sustained growth in the number of scientific publications with keywords, ‘fluvial models’, ‘fluvial process models’ and ‘fluvial numerical models’. In this context we compile and review the current contributions of numerical modelling to the understanding of fluvial archives. In particular, recent advances, current limitations, previous unexpected results and future perspectives are all discussed. Numerical modelling efforts have demonstrated that fluvial systems can display non-linear behaviour with often unexpected dynamics causing significant delay, amplification, attenuation or blurring of externally controlled signals in their simulated record. Numerical simulations have also

demonstrated that fluvial records can be generated by intrinsic dynamics without any change in external controls. Many other model applications demonstrate that fluvial archives, specifically of large fluvial systems, can be convincingly simulated as a function of the interplay of (palaeo) landscape properties and extrinsic climate, base level and crustal controls. All discussed models can, after some calibration, produce believable matches with real world systems suggesting that equifinality - where a given end state can be reached through many different pathways starting from different initial conditions and physical assumptions - plays an important role in fluvial records and their modelling. The overall future challenge lies in the development of new methodologies for a more independent validation of system dynamics and research strategies that allow the separation of intrinsic and extrinsic record signals using combined fieldwork and modelling.

Introduction

The establishment of Fluvial Archives Group (FLAG) in 1996 has led to important developments in the understanding of the long term development of fluvial systems. Key publications that have originated through FLAG, such as the works by Maddy et al., (2001), Bridgland and Westaway (2008, 2014), have clearly demonstrated that many large scale systems appear to have comparable records with similar external controls. Concurrently, the development of numerical fluvial landscape modelling has accelerated since the late 1990s with the increasing availability of computing facilities and the further development of model algorithms and code. Influential initial attempts focused on the terrestrial erosional processes of large basins aimed at understanding large-scale and long-term erosional dynamics (Howard, 1994; Whipple and Tucker, 1999). This contributed to important discussions about the influence of climate and crustal perturbations on the landscape, the non-linear feedback mechanisms that affect fluvial systems and new insights into the concept of steady-state topography (Whipple, 2001). Research linking the application and scaling of stream power equations, which had their origin in empirical process geomorphology, led to the first catchment evolution models (such as: SIBERIA, Willgoose et al., 1991; DRAINAL, Beaumont et al., 2000; DELIM, Howard, 1994; GOLEM, Tucker and Slingerland, 1997). Concurrently, Tetzlaff and Harbaugh (1989) aimed to simulate clastic sedimentation at the grain level in downstream sink areas. This latter simulation model produced relatively detailed (borehole) delta and marine stratigraphy that was used to support oil exploration efforts.

Initially the gap between these modelling efforts and fieldwork-based investigations was too large to be easily bridged. Available models were often too abstract to be directly linked to the typical fluvial records studied in outcrops and boreholes in the field. As a consequence, field studies remained focused on describing and interpreting fluvial records using a separate set of conceptual models. For instance, fluvial field observations have often been analysed in the context of their environmental, tectonic and sea (base) level change records (Bridgland and Westaway, 2008, 2014; Vandenberghe et al., 2003, 2008; Stokes et al., 2012). Such an approach typically assumes, either implicitly or explicitly, that fluvial records have formed under the direct or indirect influence of such external controls. It is a common approach within the Fluvial Archive Group (FLAG) publications (see http://tolu.giub.uni-bonn.de/herget/FLAG/). One specific numerical modelling approach that has been applied frequently within the FLAG special issues (e.g., Westaway, 2001, 2002, 2007) is based on the assumption that fluvial terrace records are primarily the product of feedbacks between climate change, surface processes, and crustal processes.

Most existing fluvial numerical process models use power laws derived from empirical relationships and all have unmeasurable parameters such as erodibility and effective viscosity, which are scale-dependent and which are difficult to relate to field observations (Lague, 2014). The available numerical models often have different objects or topics of study and consequently, they also have different scales of application, scale-dependent process choices and descriptions (Temme et al., 2011a; 2016). However, increasingly numerical models attempt to produce outputs, such as terrace and basin stratigraphy that can be more readily linked to field applications.

The aim of this perspective paper is to demonstrate and outline the current progress and developments in 'fluvial archive' model development, aided by a systematic keyword analysis of an established literature database (SCOPUS) (Table 1). Specifically, the developments in 'fluvial models' and 'numerical fluvial models' to model fluvial archives during the 20 years of the Fluvial Archive Group (FLAG) existence will be discussed.

This will be followed by a brief characterization of a range of papers which address the modelling of fluvial archives from both hillslope, catchment and basin perspectives. We describe the types of research problems addressed by these models, and we evaluate some of the key research challenges they raise.

Literature keywords search on 'fluvial models' in peer-reviewed publications

To characterize the developments in the field of fluvial modelling a literature search using the SCOPUS database was undertaken (See Fig. 1 and Table 1). An initial search extracted the publications with keywords 'Fluvial Model'. The keyword 'Quaternary', a focal period of FLAG research, was omitted because it reduced the total sample size to 405 papers from a total of 6639. The cumulative number of publications were plotted over time using five-year intervals (Fig. 1a). A consistent increase in publications with keywords 'Fluvial Model' is observed starting with a total of 461 publications before 1990 and cumulating to 6639 in August 2016 (Table 1). We subsequently made two subsets: 'Fluvial Process Model' and 'Fluvial Numerical Model'. Both are represented by less papers: 38.5% and 18.4% of the total 'Fluvial Model' group respectively. The 'Fluvial Process model' has a total of 148 publications before 1990 which increased up to 2557 in August 2016, while the even smaller subgroup of 'Fluvial Numerical Model' started with only 27 publications before 1990 and cumulated in 1222 in August 2016. We observe in Fig. 1b that the cumulative fraction of the 'Fluvial Model' papers using 'Numerical' as key word has steadily increased from 7% up to 18% in 2015. A similar, but weaker development can be observed for the 'Fluvial Process Model' group of papers, increasing from 30% up to 38%. This indicates that researchers publishing about fluvial models use now more frequently numerical models in their research. Although the fraction of numerical modelling seems to be increasing it still represents a minority of the fluvial model investigations (< 20%). Overall around 8% of the FLAG abstracts and special issue papers use some form of numerical modelling (Table 1b).

When we refine the key word groups by adding additional keywords we observe some additional trends (Table 1). A large proportion of the papers combine 'Fluvial Model' keywords with external controls such as ´environment´, ´climate´, ´sea level´, or ´base level´. Only a small fraction (maximum 3.2 %) of the fluvial model papers use key words related to intrinsic or nonlinear dynamics. The use of these keywords is more common in 'Numerical' papers, which may suggest that that numerical modelling makes researchers more aware of complex response dynamics and intrinsic versus extrinsic controls in fluvial systems.

An overview of numerical models used in Fluvial archive research

Because the review is aimed at the non-specialist in terms of numerical modelling, we have structured the numerical models according to the different depositional environments typically studied in the field. We distinguish: combined Hillslope/Fluvial records; Terrace records; Delta records; Catchment records; Basin records and finally a group of coupled models with a clear dynamic crustal component. We discuss the most relevant model contributions to support the understanding of fluvial archives over the last 20 years. We do not aim or claim to present a complete and exhaustive overview, nor will we go into detail about the specific model formulations as they have already been elaborately discussed in a recent overview publications, such as that of 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.

Hillslope/Fluvial records

Many headwater sediment records are often a mixture of 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 these types of records. The applications in regions such as 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 soil-hillslope records only and address mainly agriculture-related case studies spanning the last millennia when tillage-induced soil redistribution became an important process (Notebaert et al., 2011;

Haregeweyn et al., 2013). Both models were compared for a historical case study that demonstrated a similar performance in terms of generating plausible morphologies and colluvium records (Temme et al., 2011b). The challenge of LAPSUS and similar models such as the model of Wainwright (2006), lies in effectively coupling hillslope-channel dynamics. This determines the source-to-sink connectivity of the system and to what extent specific external drivers, such as large rainfall events, are registered in the long-term, downstream fluvial record (Savi et al., 2012; Michaelides and Wainwright, 2002; Bovy et al., 2016).

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) and 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., 2015). 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 detailed sedimentological patterns. There are also 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, 2000; Tebbens et al., 2000) and Bogaart et al. (2003a, 2003b) models both aim to model longitudinal profile dynamics. FLUVER2 is more focused at the floodplain level and on the effects of climate, active crustal deformation and base level interaction (Viveen et al., 2013) while the Bogaart et al. (2003a, 2003b) model is more concerned with climate change-related river channel dynamics. Both models attempt to simulate fluvial terrace records, however FLUVER2 focuses more on terrace formation events along the whole longitudinal profile. In contrast the model of Bogaart et al. (2003a, 2003b) focuses more on river pattern change (meandering versus braiding) for individual reaches. 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 lateral dimension. The LIMTER model (Veldkamp, 1992) — more recently called TERRACE in Viveen et al. (2014)— can give some additional insight into the probability of terrace preservation and the probability of valley cross-sections especially when combined with FLUVER2. Unfortunately this model is, although spatially explicit, only partly numerical with expert-based decision rules determining whether lateral and/or vertical erosion takes place (Veldkamp et al., 2002; Viveen et al., 2014).

Delta records

The controls on river delta formation are not driven exclusively by fluvial forces. The effects of wave reworking, wave and tide-induced currents, sediment transport mechanism, sediment properties (cohesive vs. non cohesive) and base level change also play a major role in delta formation. In addition to these aforementioned external (allogenic) controls, deltas also respond to internal (autogenic) controls (Karamitopoulos et al, 2014) such as channel 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 (Jerolmack and Paola, 2007; Van der Vegt et al, 2016). These models are increasingly coupled to a stratigraphical module such that morphodynamics can be used to explain stratigraphic variability.

The open source Delft3D model (e.g. Geleynse et al., 2010, 2011; Edmonds and Slingerland, 2010; Hillen et al., 2014) puts emphasis on 3D delta stratigraphical 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 numerical formulations included in the hydrodynamic and sediment transport components of the model.

Catchment records

The CHILD model (Tucker et al., 2001; Tucker and Slingerland, 1997) simulates changes in topography in time and space combining both 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 events (Tucker and Bras, 2000). Options have been proposed for both fluvial and hillslope erosion parameters, which have now been widely explored in the literature (e.g. Tucker and Whipple, 2002; Whipple and Tucker, 2002, Attal et al., 2008 amongst many). Consequently, CHILD has been used for many different case studies with a wide range of spatio-temporal domains. Several recent fluvial archive applications are particularly relevant: One study looks at how fluvial landscapes respond to climate change and to faulting 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 well-constrained active normal faulting on channel long-profiles and channel width in the Central Apennines of Italy (Whittaker et al., 2008). A large-scale application of the CHILD model has been developed to study the effect of Late Pleistocene climate changes on the Rhine-Meuse catchment (Van Balen et al., 2010). The focus of the latter 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 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) model simulate topographical change due to water and sediment movement. The model focuses on the hydrological dynamics with a high temporal resolution (event/sub event basis) and also produces surface and subsurface grain size distributions enabling the simulation of floodplain properties. Due to the use of higher resolution time series (rainfall or discharge) to simulate individual flood events, run times can be long. CAESAR applications range over time scales from individual events up to 10 ka maximum. However, only a few applications have focused on the long-term role of climate over land use in affecting Holocene, fluvial, sediment records (Coulthard and Macklin, 2001), and more recently, on how climatic signals may be more evident in sedimentary archives than signals resulting over shorter time scales from active crustal deformation (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, 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) and how basin response is linked to external and autogenic drivers are of direct relevance 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 crustal subsidence and sediment supply variations at the 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, as originally conceived, is two-dimensional and 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 accommodation space in response to active crustal deformation are known or estimated independently. 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). A new three dimensional version of the model has recently been applied to alluvial fans in eastern California to decode the effect of late Pleistocene to Holocene climate change on sediment fluxes in such source-to-sink systems (D’Arcy et al., 2016).

The ARMITAGE-COUPLED CATCHMENT BASIN MODEL (Armitage et al., 2011; 2013) is focused on the translation of crustal 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 sediment transport 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 vertically 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. A modified ARMITAGE-COUPLED CATCHMENT BASIN MODEL version with different domain and boundary conditions has recently been applied to understanding Eocene sediment routing in the Spanish Escanilla fluvial system (Armitage et al., 2015).

Coupled lithospheric and surface denudation systems

Many models have the aim of simulating coupled lithospheric and surface denudation (Kooi and Beaumont, 1994; Beaumont et al., 2000; Van der Beek and Bishop, 2003; Codilean et al., 2006; Wickert et al., 2013). The most recent overview (Van der Beek, 2013) reviews the coupling of surface process models to other numerical models, in particular those predicting tectonic motions in the lithosphere.

There are currently two modelling approaches that have been specifically used to understand fluvial terrace records in the context of lithospheric dynamics: the lower crustal flow model by Westaway (2001, 2002) and TISC (Garcia-Castellanos, 2002; Stange et al., 2016). It should be noted that these two models are based on different, partly incompatible, assumptions regarding the rheological behaviour of the Earth´s crust.

The lower crustal flow model (Westaway, 2001, 2002) calculates vertical crustal motions for continental crust with a mobile lower-crustal layer under conditions of isostatic equilibrium. It takes account of the effect of the non-steady-state conditions that develop within the crust as a result of changes in rates of surface processes (erosion or sedimentation). The model uses rates of surface processes before and after major climatic changes in the geological record such as the Mid Pleistocene Revolution (Mudelsee and Stattegger, 1997), and crustal properties such as crustal thickness, thickness of the mobile lower-crustal layer, and the effective viscosity of the mobile lower-crustal layer. The various lithospheric thickness parameters are constrained using geophysical studies based on seismic reflection profiles and heat flow measurements (e.g. Westaway, 2001). For the effective viscosity of the mobile, lower-crustal layer values are used that are based on the temperature at the base of this mobile layer and assumptions about is composition (Westaway, 1998). There are several applications for most continents all suggesting a plausibility of the lower crustal flow mechanism (Westaway 2002; Westaway et al., 2002). The model can also explain the observed differences between fluvial staircases on old, static, continental cratons and young, dynamic crusts (Westaway et al., 2003). An additional insight was the realization that in regions where the mobile lower crustal layer is thin (<~5 km) one observes alternations between uplift and subsidence rather than continuous uplift or subsidence (e.g. Westaway and Bridgland, 2014).

The TISC model is capable of combining landscape evolution with plan-view lithospheric flexure (Garcia-Castellanos and Cloetingh, 2012). It can predict the amounts of erosion and sediment accumulation, resulting in a spatial redistribution of surface loads. The surface process model comprises short-range, diffusive transport on hillslopes and long-range fluvial transport in the drainage network. The efficiency of linear, short-range diffusion is determined by effective precipitation, bedrock diffusivity and topographic gradient (Kooi and Beaumont, 1994). Long-range sediment transport in rivers depends on their sediment transport capacity (e.g. under-capacity transport model, (Van der Beek and Bishop, 2003), but other models are also available) that are proportional to mean water discharge and slope. Based on constrained rheological properties (effective elastic thickness) of the lithosphere, (e.g. based on basin modeling, glacio-isostasy, geodesy, etc) the model also predicts vertical lithospheric motions that result from lithospheric flexural isostatic compensation. TISC was recently applied to the Ebro river and its tributaries (Stange et al., 2016) and the results showed that isostatic motions do indeed contribute to the uplift required to explain river incision and terrace formation.

Limitations of the available models

Every numerical model is a simplification of a real-world system based on many assumptions and empirical relationships that are often spatio-temporal and scale-dependent. Because all models are scale-dependent regarding their settings, they will require case-by-case calibration (Oreskes et al., 1994; Sapozhnikov et al., 1998). This is most obvious in the choice of model processes and the numerical description of the processes (see classic work by Kirkby, 1971). Furthermore, all models have in common that they use unmeasurable, often lumped, parameters (Crisswell et al., 2016). The 1-D models that describe longitudinal river profile dynamics all lack the lateral dimension crucial for realistically modelling of the preservation of older deposits such as terraces (Langston et al., 2015; Veldkamp et al., 2016). Furthermore, all 2-D fluvial landscape models struggle with the initial relief/profile conditions (Stange et al., 2016; Van Gorp et al., 2014). This is related to the fact that existing numerical models use forward-modelling approaches, making them sensitive to initial input which is one of the most challenging input parameters to reconstruct (Van Gorp et al., 2016).

All numerical models use simplifications and some have been dubbed reduced complexity (Larsen et al., 2014), a catch-all phrase used to describe models using significant simplifications and often empirical measurements at the expense of more physics-based first principles methods (Temme et al., 2016). Designed more to look at relationships between processes, reduced complexity models demand less input data and have relatively short run times, but their reliance upon specific assumptions and simplifications can make their validation very difficult (Oreskes et al., 1994; Schoorl et al., 2014). This is representative of the trade-off between complexity and numerical simulation feasibility, which is one underlying reason that no model is able to simulate detailed realistic landscapes over long time spans. A technical approach to reduce run time is currently sought in parallel processing (McGough et al., 2012) and has been developed for versions of the CAESAR-Lisflood model. However, this technique also requires a complete recoding of existing models, discouraging its widespread adoption.

Despite the fact that many models have simplified empirical process descriptions, such as the inability to cope with channel widening and avulsions, they can all be calibrated to existing fluvial records (see Table 2). But typically most calibration and validation attempts are based on general catchment relationships and not on one to one comparisons (Ziliani et al., 2013). 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 and assumptions (Beven, 1996). This may explain why most model applications (see mentioned examples Table 2) are able to yield outputs that demonstrate a general match with the known field record (Nicholas and Quine, 2010).

The 2-D spatial models all struggle with either the coupling of hillslopes and fluvial channel dynamics, or with using scale-dependent power laws (Michaelides and Wainwright, 2002; Mayor et al., 2011; Lague, 2014). There is sometimes the tendency to 'improve' models by incorporating more processes in the model (Zolezzi et al., 2012), thereby increasing the degrees of freedom and making calibration easier, knowing that equifinality will lead to plausible model results. Before considering additional processes for a new model version, their relevance needs to be independently confirmed by field-based research. An example is the realization that dynamic regolith production rates should be included in landscape evolution modelling because they can have a significant effect on catchment-wide, sediment delivery rates and morphology (Van Balen et al. 2010; Temme and Vanwalleghem, 2015). In summary, additions to model complexity and processes will ultimately increase model uncertainty in addition to model plausibility. Useful models therefore represent a trade-off between simplification of reality and the ability to simulate dynamics as realistically as possible in such a way that outcomes can be confirmed by fieldwork (Briant et al., 2016).

Unexpected results from modelling exercises

Almost all models have unexpected outcomes related to the non-linearity and delayed response of the modelled fluvial system (Coulthard and Van De Wiel, 2007, 2012; Forzoni et al., 2014; Geach et al., 2015) . For instance, there are indications that knickpoints near the headwaters of large fluvial systems were originally triggered many thousands of years ago (Demoulin, 1998;

Beckers et al., 2015). A common observation is that fluvial systems are usually not the simple environmental archives that many conceptual models consider them to be (Vandenberghe, 2003; 2008). Modelling efforts in fact demonstrate that a spatio-temporal delay of erosion and sedimentation events along a river profile should be expected (Whittaker and Boulton, 2012). Often external controls start to interact, causing blurring of signals due to amplification or attenuation effects causing unexpected fluvial record properties (Veldkamp and Tebbens, 2001; Forzoni et al., 2014). Even a linear relationship between one external driver and observed fluvial record properties is rare. Many models and especially catchment and basin models (see Table 2) indicate that substantial signal modification (Van De Wiel and Coulthard, 2010) can (and does) take place. This blurring of environmental signals by sediment transport is thought to be driven by ubiquitous thresholds in the transport system, by autogenic behaviours, and by system noise (Jerolmack and Paola, 2010). For instance, Jerolmack and Paola (2010) suggested that external signals are shredded when their time and amplitude scales fall within the ranges of the morphodynamic disturbance, making smaller systems more sensitive to this shredding effect. Modelling has also demonstrated that simulated fluvial records can be the result of self-organizing behaviour of the fluvial/slope system without any external environmental change (Van De Wiel and Coulthard, 2007; Coulthard and Van De Wiel, 2013; Schoorl et al., 2014; Forzoni et al., 2015). This insight is still *not* commonly applied when interpreting fluvial records. Most field records are still viewed and interpreted via a cause and effect framework, where external changes in climate, active crustal deformation or base level control fluvial records (See for example many papers in special issues of FLAG, http://tolu.giub.uni-bonn.de/herget/FLAG/). It seems that this approach has some validity for large river systems (Bridgland and Westaway, 2008, 2014) but certainly for smaller more local systems it is a feasible alternative to consider the whole observed record to be autogenic thereby allowing no conclusions about system controls at all. Current 2-D models (See Table 2) have clearly demonstrated that river basins are always in a state of delayed response to external drivers, and always generate their own autogenic signals. These intrinsic dynamics seem especially relevant in smaller systems (Coulthard and Van de Wiel, 2013; Schoorl et al., 2014). It is therefore highly relevant to focus more on how we can separate intrinsic from extrinsic record signals.

Finally, we know that the external drivers of the fluvial system are not independent and that active crustal deformation, climate and base level change can act as coupled drivers (See examples Westaway, 2001, 2002; Stange et al., 2016). They can affect fluvial records in combination, which means that we have to acknowledge that not every external change leaves its own independent evidence in the fluvial record. All these insights combined imply that it would be exceptional to find simple, causal relationships reflected in the fluvial archive. This insight is illustrated by field studies where such causal relationships become less obvious when more independent age control of the fluvial record is obtained (Maddy et al., 2005; 2016).

Numerical modelling has also demonstrated that some of the basic assumptions about river behaviour, such as hydraulic scaling, probably need revisiting (Attal et al., 2011). A recent example is the importance of channel width in controlling how fluvial landscapes respond to active crustal deformation. While many models typically assume hydraulic scaling, field and modelling data show that this assumption is not always valid (Whittaker et al., 2007; Whittaker et al., 2008). Attal 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 significant difference in how simulated landscapes record the imprint of active crustal deformation activity.

Several model applications have demonstrated that despite the many degrees of freedom it is not always easy to calibrate to existing field records (Baartman et al., 2012b; Geleynse et al., 2010). On the other hand, some models surprise by their versatility as they seem to work over a wide range of spatio-temporal scales (Coulthard et al., 2002; Temme et al., 2009; van der Vegt et al 2016). However, recent work suggests that model 'calibration' may at best only be site specific and may require re-calibration for changing climates (Coulthard and Skinner, 2016) and other factors. Other unexpected results are related to new insights in the key role of initially unconsidered factors such as the role of cohesive sediment and sediment transport mechanism on floodplain dynamics and deltaic channel pattern, or the role of sediment reworking in determining delta stratigraphy (Edmonds and Slingerland, 2010; Hillen et al., 2014; van der Vegt et al 2016). Additional unforeseen outcomes relate either to the relative unimportance of a considered process such as tillage erosion (Baartman et al., 2012a) or the long-lasting effects in the fluvial record due to a temporary local base level change as a result of lava damming (Van Gorp et al., 2013; 2016).

What is needed to advance modelling efforts (future plans)

If we want to use existing numerical models in a more effective way we need them to be more realistic – to a certain degree. One way to achieve this is by developing an ensemble of field sites where a high resolution stratigraphy is available – i.e. stratigraphy that is well dated in time and space, and where sedimentation rates can be accurately reconstructed and sedimentation budgets are closed. Within such reference areas existing models can be tested, calibrated, compared and further developed.

In order to involve non-specialists in the numerical modelling debate they need to have access to demos and animations that illustrate the specific intrinsic fluvial dynamics and related signal amplification, attenuation, delay and shredding. There are already websites giving a general overview of many existing models. At the website of the Community Surface Dynamics Modelling System, https://csdms.colorado.edu/wiki/Model_download_portal for example, many Earth scientific models are grouped and documented. What is still lacking are simple illustrations of specific principles as discussed above. Figure 1 is a first simple attempt to illustrate why linear correlations between climate and fluvial records are not always likely. Assuming complete preservation, a typical correlation can be made using the Vandenberghe (2003) model on the timing of cold stage deposition using an existing climate curve (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 in timing and magnitude from the original climate curves. As a result, the interpretations using this curve demonstrate some deviations in depositional history for the older units. When the intrinsically driven erosion/deposition curve is included, even more deviations can be observed. Given that fluvial systems are non-linear and display a mix of intrinsic and extrinsic dynamics, the more realistic interpretations seem to be made when we take nonlinear, intrinsic behaviour into account. This behaviour cannot be determined from the field record, but requires supporting numerical model simulations (Briant et al., 2016).

One implication of tighter integration of numerical modelling with fieldwork is to allow numerical modelling to guide fieldwork. A very first attempt to guide future sampling in the

Allier system was recently made by Veldkamp et al. (2016) using a calibrated and quasi validated FLUVER2 model.

It is also proposed that combining and linking existing models and their concepts might advance our insights (Temme et al., 2011a). An obvious idea is to develop ensemble forecasts where different models are used to explore a range of simulated outcomes, as is done in climatology and hydrology (Saleh et al., 2016; Coulthard et al., 2013). Another key area of work is to integrate “upstream” and “downstream” perspectives of fluvial systems incorporating both the source catchment and the depositional sink (e.g. Forzoni et al., 2014). The main challenge in both these cases, and more widely, will be to systematically deal with the different spatio-temporal scaling effects and basic model assumptions.

The ultimate goal of work in this area is to provide an improved understanding of the controls and dynamics of fluvial systems. However, numerical models are only one means to achieve this goal. One way to bring the numerical models closer to fieldwork is to modify them to produce additional, relevant and measurable field-related outputs such as stratigraphical records, grain size distributions, calculated ^{10}Be erosion rates (Schaller et al., 2002; 2004) or OSL inventories. There is also a clear need to target specific field studies to investigate in more detail landscape connectivity such as hillslope-channel coupling and decoupling in more detail because this mechanism will determine whether there exists a source-sink relationship in a given fluvial record (Savi et al., 2012). Such field studies help to identify intrinsic self-organization as a threshold related phenomenon (Michaelides and Wainwright, 2002), distinct from extrinsically controlled properties of fluvial records (Faulkner, 2008). Ultimately we want to understand how the records were formed and to try to infer the relevant environmental and other external drivers.

Conclusions

Numerical models have been increasingly developed and used to unlock the fluvial archive during the last decades, much of this work having been undertaken under the auspices of FLAG. Numerical modelling efforts have demonstrated that fluvial systems can display non-linear behaviour with often surprising and unforeseen dynamic effects causing significant delay, amplification, attenuation or shredding of external control signals in their simulated record.

Numerical models have also demonstrated that fluvial records can be generated by intrinsic dynamics without any change in external controls. Many other model applications demonstrate that fluvial archives, specifically of large fluvial systems, can be convincingly simulated as a function of the interplay of (palaeo) landscape properties and extrinsic climate, base level and crustal controls. All discussed models can, after some calibration, produce convincing matches with real world systems suggesting that equifinality plays an important role in fluvial records and its modelling (Nicholas and Quine, 2010). The overall future challenge lies in the development of new methodologies for independent validation of system dynamics and research strategies that allow the separation of intrinsic and extrinsic record signals using combined fieldwork and modelling.

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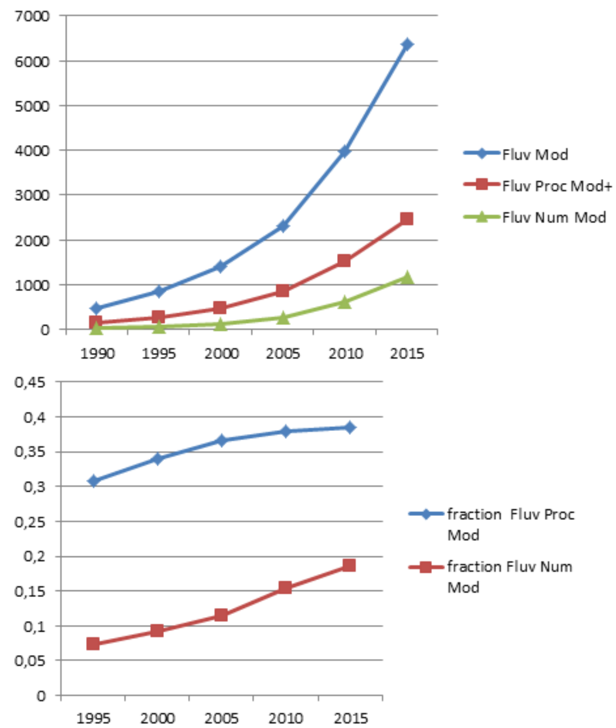

Fig 1. Upper graph a: number of scientific publications cummulative in time with specific key words. Lower graph b: fraction of process models and numerical models of the 'Fluvial Model' group (source: SCOPUS data base August 2016)

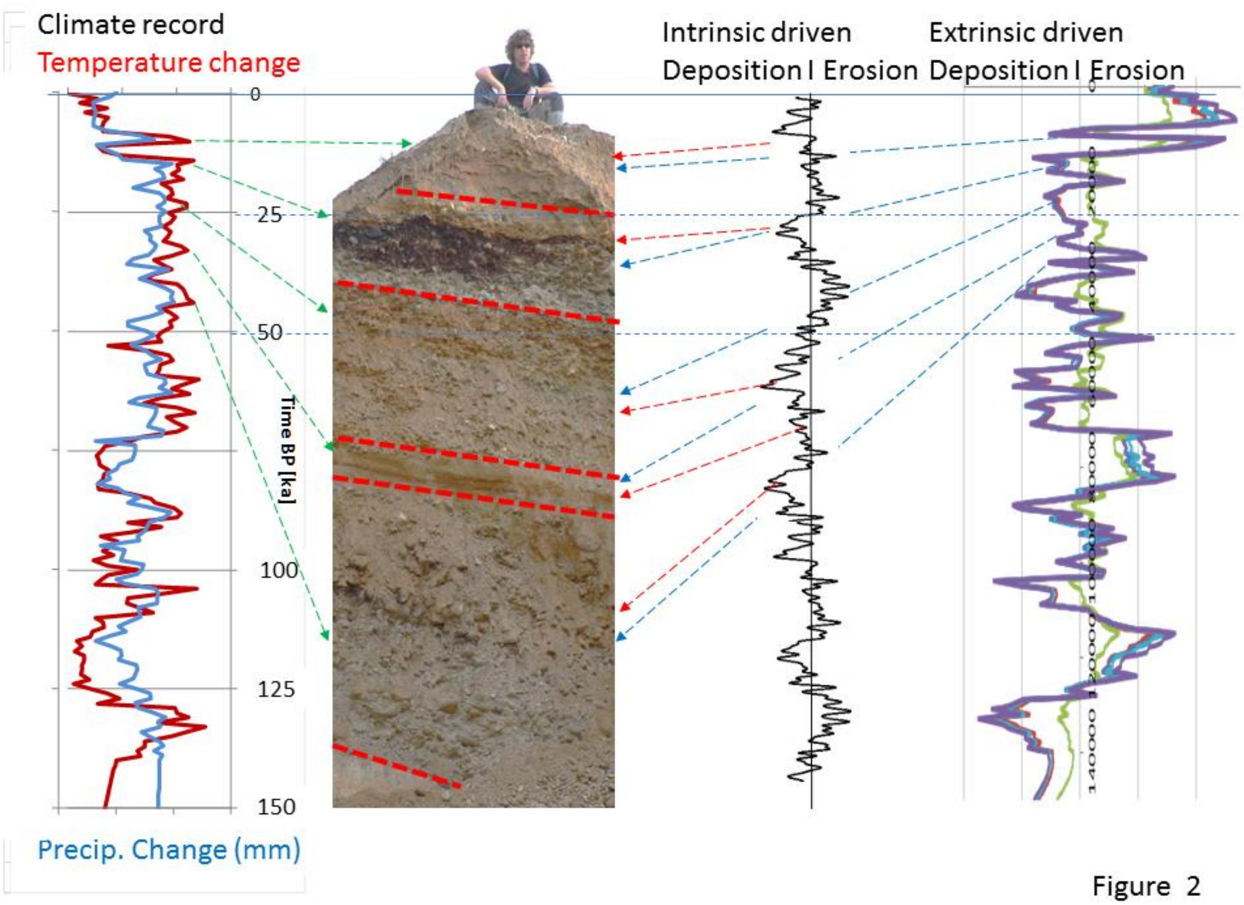

Figure 2.

An existing climate record for France (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. This climate curve is remodeled into an externally driven fluvial erosion/deposition curve using the FLUVER2 model a curve (purple curve, right hand side, (see Veldkamp et al., 2016)). As a result the interpretations using this curve (see blue arrows), correlating depositional events to sedimentary units, demonstrates some deviations especially for the older units. When the intrinsically driven erosion/deposition curve is calculated even more deviations can be observed (see red arrows).

Table 1a: Key words:	Fluvial Model	Fluvial Process Model (38.5% of fluvial model group)	Fluvial Numerical Model (18.4% of fluvial model group)
	6639	2557	1222
+ Control	1121 (16.9%)	480 (18.8%)	203 (16.6%)
+ Environment	1454 (21.9%)	593 (23.2%)	220 (18.0%)
+ Climate	864 (13.0%)	372 (14.5%)	137 (11.2%)
+ Tectonic	804 (12.1%)	320 (12.5%)	123 (10.0%)
+ Sea Level	501 (7.5%)	179 (7.0%)	82 (6.7%)
+ Base Level	319 (4.8%)	123 (4.8%)	47 (3.8%)
+ Non linear	87 (1.3%)	42 (1.6%)	39 (3.2%)
+ Intrinsic	53 (0.8%)	30 (1.2%)	16 (1.3%)

Table 1b:	17 FLAG dedicated special issues	FLAG meeting abstracts, last six meetings
Total papers/abstracts considered	187	276
Dedicated to modelling	16 (8.5%)	26 (9.4%)

Table 1a: Inventory of publications in SCOPUS data base using keywords. Three main groups of key words. ‘Fluvial Model’, ‘Fluvial Process Model’, ‘Fluvial Numerical Model’. The + key words are added to these three groups individually. Numbers indicate number of all publications in data base (August 2016), ercentages indicate share within each main group.

Table 1b: counted papers and abstracts in FLAG dedicated special issues and Abstracts of last six FLAG meetings. See http://tolu.giub.uni-bonn.de/herget/FLAG/ for documentation.

Model name	Key papers	Inputs	Outputs	Relevant Fluvial archive applications cited in main text	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. (Whittaker, et al., 2008): Central Apennines of Italy (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	(Tebbens et al., 2000): Meuse river in the Netherlands. (Veldkamp et al., 2002): Aller river (Weser tributary) in Germany, (Viveen et al., 2013): Miño river in Portugal and Spain (Geach et al., 2015): Tabernas river in south-eastern Spain (Veldkamp et al., 2016): Allier - Loire river in France	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 landscape and floodplain dynamics	Van de Wiel et al., 2007, Coulthard et al., 2013.	Topography (DEM), Climate (precipitation time series), Grainsize, Land cover (reflected in hydrology).	time series of water and sediment at catchment outlet, DEM's of surface at whatever time required, Surface and subsurface grainsize	(Coulthard et al, 2002): Records of UK Holocene river activity (Coulthard et al., 2005): Importance of location of fluvial archive within drainage basin. (Coulthard and Van de Wiel, 2007; 2013): Role of non linear processes in generating false alluvial archive signals	http://www.coulthard.org.uk/CAESAR.html and 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 et al., 2014): Intrinsic sediment pulses, changing locations of erosion and sedimentation causing autogenous terraces . (Claessens et al. 2006): coupling landslides through the river network to a sediment archive. (Temme and Veldkamp, 2009): Late Pleistocene colluvial record South Africa (Baartman et al 2012a, 2012b): Late Pleistocene colluvial record South Spain with historical tillage translocation. (Van Gorp 2013, 2015): spatial temporal effects on fluvial landscape development due to lava damming (western Anatolia).	http://www.lapsusmodel.nl
SELF-SIMILARITY DOWNSTREAM FINING MODEL	Duller et al., 2010. (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	(Whittaker, et al., 2011): downstream trends in stratigraphic grain-size as a function of tectonic subsidence and sediment supply (D'Arcy et al., 2016): Pleistocene to Recent climate-driven sediment fluxes and grain size changes.	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-efficient, erosion exponent, n, *Basin:* subsidence/uplift rate in time and space; sediment flux from catchment output, above, grain size estimate.	Long profile evolution in time and space; sediment flux in time and space, stratigraphic output of volumes and sedimentary grain sizes.	(Armitage et al., 2015): application - Spanish Pyrenees.	http://www.ipgp.fr/en/user/584
Delft3D	Lesser et al., 2004; Roelvink 2006,.	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): Controls on river delta formation	http://oss.deltares.nl/web/delft3d
Lower Crustal Flow Model	Westaway, 1998, 2002.	Estimated rates of surface processes, crustal properties such as crustal thickness, thickness of the mobile lower-crustal layer, and the effective viscosity of the mobile lower-crustal layer.	Predicted rates vertical crustal motion. It provides age predictions for fluvial terraces and as stresses at depth within the crust, rates of flow within the mobile lower-crustal layer, etc, but these quantities are not directly observable.	(Westaway, 2004): application Loire/Seine Trance (Westaway et al., 2002): Application Thames UK (Westaway et al., 2003): Application India (Westaway and Bridgland, 2014): global synthesis of applications.	Not available
TISC	Garcia-	Initial topography, erodibility,	Changing topography in	(Stange et al. , 2016): The Ebro river sytem	https://sites.google.

	Castellanos and Cloetingh, 2012.	precipitation, effective elastic thickness distribution for lithospheric flexural isostatic compensation calculations	time and space. From this, river long profiles, sediment fluxes, erosion rates can be derived. + Plan view flexural isostatic subsidence and uplift	(Pyrenees and Ebro Basin)	com/site/daniggcc/ publications