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Combining quantitative field and modelling approaches towards understanding landscape dynamics: an evolution of ideas spanning Jef Vandenberghe's research career

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Abstract

Geomorphology as a scientific discipline has underwent major developments since the mid 20th century. From its original descriptive nature aiming to understand landscape evolution, it developed towards a more process-based oriented discipline. To a large extent this evolution followed a quantitative approach whereby modelling becomes more and more important. A schism between applied or engineering geomorphology and system-based geomorphology aiming at understanding landscape change emerges in the 1950-1960's. Only at the end of the 20th century – early 21st century, integration of quantitative field-based approaches on longer term issues of landscape evolution with numerical modelling emerges. This is particularly true for the Holocene for which the importance of human impact on geomorphic processes and landforms became acknowledged. With respect to landscape evolution on much longer timescales, the development of tectonic geomorphology becomes apparent. In this paper, some evolution of ideas and trends within geomorphology with respect to understanding landscape dynamics are summarised and put into the career perspective of Jef Vandenberghe.

Keywords: quantitative geomorphology, numerical modelling, process geomorphology, Jef Vandenberghe, human impact, sediment dynamics

Introduction

During the second half of the 20th century, major developments in all scientific disciplines took place. This is also true for the interdisciplinary field of Geomorphology. Extensive reviews and opinions on the various trajectories within geomorphology have been made before (Brocklehurst, 2010; Church, 2005; Church, 2010; Keylock, 2010; Richards and Clifford, 2008; Summerfield, 2005). It is therefore not the aim of this paper to come up with an entirely new view on how geomorphology developed as a scientific discipline. Rather, in this paper some of the major evolutions in geomorphology of the last 50-60 years are sketched in view of Jef Vandenberghe's research career that started with his Geography studies in Leuven, Belgium during the late 1960's. As such it provides an overview on how the international changes within geomorphology have equally developed in the Low Countries. A synthesis of the main evolutions discussed in this paper is shown on Fig. 1.

1950's-1970's: the establishment of a new geomorphic paradigm

The apparent dichotomy in geomorphology as discussed for instance by Richards and Clifford (2008), whereby studies on long-term landform evolution are not linked to detailed local and short-term process studies, has many origins but one of the more important ones is the development of quantitative approaches in geomorphology. Although quantitative geomorphology originated in the 1940's and 1950's it remains at first stage rather descriptive as well: landforms and features in the landscape are now being measured and ordered but the quantitative description is largely being used to interpret the dominant processes shaping these landforms (see e.g. Doyle and Julian, 2005). The work by Robert Horton and Arthur Strahler on drainage basins in developing this new approach in geomorphology is widely known (Horton, 1945; Strahler, 1952) and within fluvial geomorphology the work by Luna Leopold and co-workers gave a further boost to this emerging discipline (Leopold and Maddock, 1953; Leopold

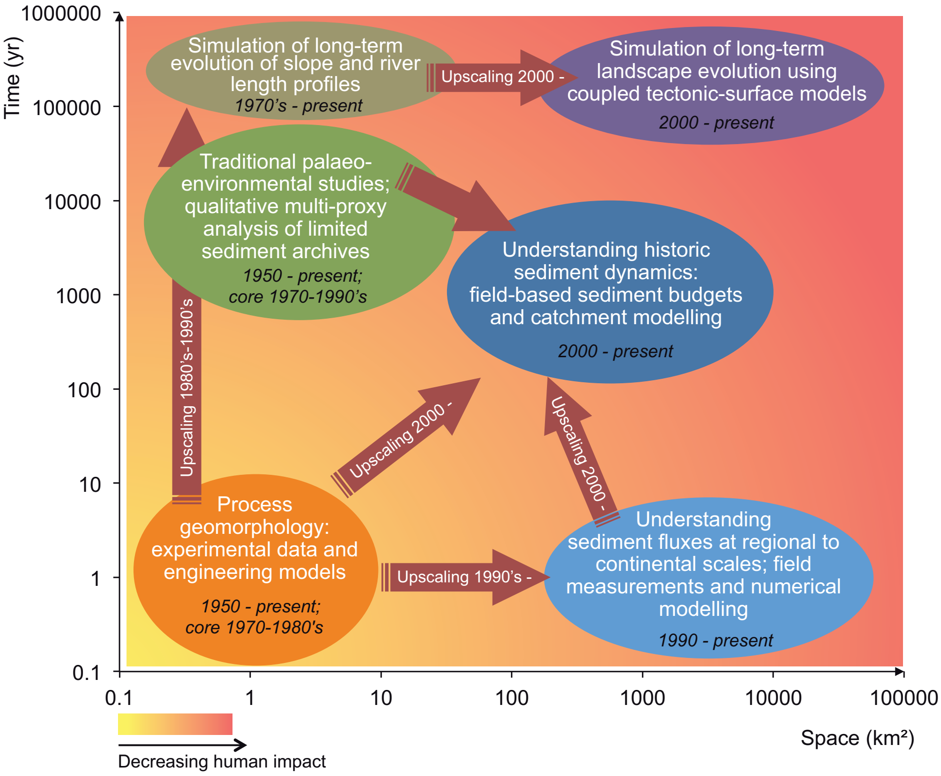


Fig. 1. Evolution of different research fields within geomorphology since the mid 20th century within a range of spatial and temporal scales. Text in italics refers to the time period during which each research field made most progress or when major evolution from one field to another took place. Background colour refers to the generalised importance of human impact on geomorphic processes.

and Wolman, 1957; Wolman and Leopold, 1957). However, by the 1960's this paradigm shift from descriptive or Davision geomorphology to quantitative geomorphology became more and more established and measurements of geomorphic and hydrological variables now form the basis for process understanding. Next to measuring geomorphic features in the field, experimental geomorphology provided an enormous amount of data upon which process interactions could be studied. The relations between drivers of geomorphic processes and the intensity of processes could now be quantified under controlled conditions. Hence, basic relations were established that predict amongst others the rate of erosion, sediment transport or discharge. This rapid expanding field of experimental geomorphology thus gave a further boost to process geomorphology studies upon which the first numerical modelling of geomorphic processes could build. Since both quantitative observations as well as experiments mostly focus on short-term timescales, the majority of modelling exercises is also oriented towards the prediction of contemporary process intensities. Often, such modelling approaches have direct engineering purposes. Typical examples are the hydraulic HEC model (HEC, 1968) and the Universal Soil Loss Equation or USLE to predict average erosion rates at the field plot scale (Wischmeier and Smith, 1960). In fact, these model approaches were built upon earlier quantitative field and experimental data, collected mostly by non-geomorphologists before World War II at agricultural or forestry experimental stations (Duley and Miller, 1923; Lentz et al., 1930) or by engineers (Meyer-Peter and Müller, 1948; Reynolds, 1883; Shields, 1936). The embracement of physical process understanding in quantitative geomorphology has led to the further development of applied geomorphology, thus leading away from the basic questions in the geomorphic discipline that relate to an understanding of how landscapes originate and develop (see also Church, 2005).

On the other hand, we also see in this time period the emergence of long-term geomorphic modelling approaches that are based on the mass conservation equation and that use a common transport law:

$$TC = kA^mS^n$$

With TC the transport capacity of the erosion process, k a constant reflecting land use, climatic, soil, etc conditions, A contributing drainage area, S the slope angle, whereas m and n are the area and slope exponents, respectively. Based on values for m and n from earlier empirical studies, Kirkby (1971) used this mathematical approach to simulate the impact of different erosion processes on hillslope form, thus suggesting that a quantitative description of hillslope morphology teaches us which processes were dominant on the long run. Ahnert (1970) came to the same conclusion but also added the variation of regolith thickness along a slope catena to the model. Nevertheless, the bulk of research papers on long-term landscape evolution remained rather descriptive in its nature.

It is in this context of changing trajectories in geomorphology that Jef Vandenberghe performed his Geography studies at KU Leuven in the late 1960's. The dichotomy in geomorphic approaches as seen in the United States and the UK is also reflected by the different expertises of the Physical Geography staff members in Leuven. Jef performed his doctoral studies under supervision of Frans Gullentops whose research at the time can best be described as a field-based approach to study landscape evolution during the Quaternary. Research methods included traditional geomorphic mapping, sediment coring, palynology as well as the application of geo-electric prospection methods (Gullentops, 1957; Gullentops, 1960; Gullentops et al., 1966; Mullenders and Gullentops, 1956; Mullenders and Gullentops, 1957; Mullenders et al., 1966; Vandenberghe, 1969). Although for that time innovative research methods were being used, for instance radiocarbon dating and palynology, most of the Quaternary research in Leuven remained, as in the rest of the world, rather descriptive. Jef's PhD (Vandenberghe, 1973) on the Geomorphology of the Southern Campine area in northern Belgium (published as Vandenberghe, 1977) is a typical example of this research field in Leuven. The same is true for the PhD of Paul De Smedt, also in 1973, on fluvial changes since the last pleniglacial in the confluence area of the Dijle and Demer Rivers in central Belgium (De Smedt, 1973). Jef Vandenberghe contributed to the fieldwork in the Dijle River floodplain and the analysis of changes in fluvial style of this river since the late Pleistocene became the topic of one of his first publications after taking the chair in Amsterdam in 1976 (Vandenberghe & De Smedt, 1979).

Meanwhile, Jan De Ploey embraced the new quantitative process geomorphology in Leuven in the late 1960's. His research focused on contemporary erosion process studies, mainly through experimental set-ups. Rainfall simulations, flume experiments as well as mechanical shear strength measurements were used to identify the main factors controlling rates of erosion under various conditions (e.g. De Ploey, 1971; De Ploey, 1974; De Ploey, 1977; De Ploey and Moeyersons, 1975; De Ploey and Savat, 1968). Although at the time no modelling of erosion processes was performed in Leuven, it was argued by the authors that the various empirical relations established through the experiments could be used to test and improve existing numerical or conceptual overland flow and erosion models (De Ploey et al., 1976). Although observations on contemporary process knowledge was also used by De Ploey and co-workers to reconsider landscape evolution during the Quaternary (De Ploey, 1977; Mucher and De Ploey, 1977), this feedback between process studies and long-term landscape evolution remained rather limited unlike for instance Kirkby (1971) and Ahnert (1970). In fact, there was almost no interaction between both schools in Leuven and the dichotomy in geomorphic approaches was deeply rooted.

1980's-1990's: development in isolation

The different research trajectories within geomorphology that originated after the Second World War further developed towards the end of the 20th century. This development in general took place in isolation, i.e. little co-operation or integration between the various research groups active in each of the trajectories could be observed. Nevertheless, major progress has been made in each field, as I will illustrate with three examples relevant for this contribution: an in-depth insight into fluvial response to intrinsic and external controls, numerical modelling of landscapes at long timescales, and a better understanding and modelling of contemporary hillslope erosion processes.

With respect to the first major achievement mentioned above, the work of Jef Vandenberghe as a Professor at the VU Amsterdam is of major importance. This work follows on the pioneering work in fluvial morphology of Luna Leopold and Gordan Wolman (see e.g. Leopold and Wolman, 1957; Wolman and Leopold, 1957), and the classic system approach by Stanley Schumm (1977). By gathering field data on fluvial systems from various regions and looking at much longer timescales (e.g. Bohncke et al., 1993; Kasse, 1995; Van Kolfschoten et al., 1993; Vandenberghe et al., 1994), Jef proposed his now widely accepted conceptual model (see e.g. Bell and Walker, 2005) on how river systems respond to external climatic perturbations (Vandenberghe, 1995), which recently has been refined (Vandenberghe, 2008). Although not a numerical model, it takes into account the various processes and process interactions taking place before, during and after major climatic transitions. As such, Jef and his group follow the process geomorphology approach towards understanding landscape evolution, however, with a major focus on field-based data gathering and not in a quantitative way.

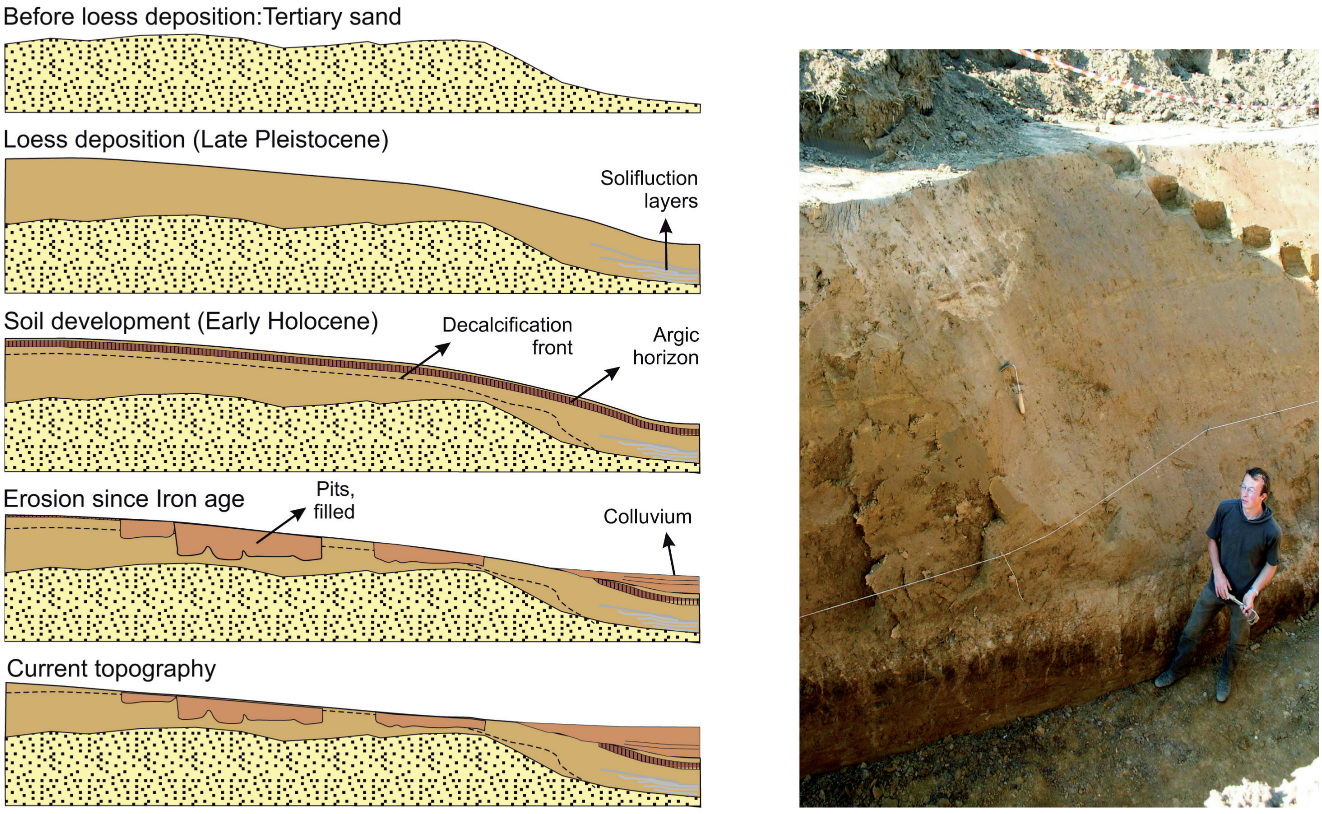
This is quite in contrast with the development of long-term landscape evolution models that build upon the pioneering work of Kirkby, Ahnert and others. Such modelling approaches vary from simulating catchment development at small spatial scales to channel growth models and bedrock incision models that are assumed to be applicable at regional to continental scales (e.g. Howard et al., 1994; Tucker and Slingerland, 1994; Willgoose et al., 1991). The rapid growth in the availability of global digital elevation models, although still with a coarse resolution in the 1990's, certainly gave a major boost towards this research field. Although most of these models were run on hypothetical catchments, thus lacking any field verification, these were most useful for identifying which parameters and controlling mechanism were most important in landscape development on the long run. Probably one of the most important contributions of such models is the Kooi and Beaumont (1996) paper. They could illustrate that, depending on the duration of tectonic pulses, landscapes may evolve according to either one of the three classical landscape evolution models, including the Davision concept of the geographical cycle. Thus, long-standing debates on how landscapes evolve on longer timescales were now being resolved through a simple numerical modelling approach.

The research in Leuven in this time period, first of all continues with experimental and field-based studies that aimed at a better understanding of the various water erosion processes operating at the plot and hillslope scale. Furthermore, quantification of the contemporary erosion processes is being made, i.e. limited to erosion following single rain events or a few years of rain events at maximum. It includes, amongst others, detailed studies on splash erosion (Poesen, 1986), interrill and rill erosion (Govers, 1991; Govers and Poesen, 1988) as well as gully erosion (Poesen et al., 1996) and sediment deposition by overland flow (Beuselinck et al., 2000). Through time, the spatial scale increased towards the size of entire catchments, thereby integrating all hillslope water erosion processes (Steegen et al., 2000; Vandaele and Poesen, 1995). Furthermore, more attention is also being paid towards the consequences of soil erosion (Verstraeten and Poesen, 1999) and the adaptation of soil conservation measures (De Ploey, 1988). Here, the research in Leuven more or less follows one of the trends in international research described above, namely the development of applied geomorphology. The fact that Jan De Ploey was one of the co-founders and first president of the European Society for Soil Conservation (1988) is another illustration of this development. On the other hand, much research also focused on the landscape scale and aimed to improve our knowledge on landscape development. For instance, Govers et al. (1996) showed that water erosion is the dominant process shaping the landscape at timescales of centuries to millennia, whilst more recently, tillage redistribution has become the dominant process. As such, geomorphology in Leuven did not choose between either the applied geomorphic approach or the traditional geomorphic questions with respect to the genesis and evolution of landscapes. In fact this is also reflected in the other field of research that further developed in Leuven in the 1990's, i.e. spatial modelling of geomorphic processes. Indeed, next to a better understanding and quantification of the erosion processes, the Leuven team also continued on the international trend towards modelling geomorphic processes. The enormous amount of field and experimental data on erosion and sediment transport processes gave a boost to the development, calibration and validation of relatively simple models. Most of these models can be considered to be on the bridge between pure 'engineering' models and 'geomorphic' models. I will not provide an overview of all model approaches developed, but rather give a selection pointing towards the broad character of model concepts. For instance, models that predict the location of ephemeral gullies in the landscape (Desmet et al., 1999) make use of thresholds within slope vs contributing area plots (S-A relationships) similar to the landscape approach by Montgomery and Dietrich (1992). In fact, the S-A relations all come back to the common transport law equation given above when considering steady-state incision and a mobile bed. Basic geomorphic expertise on how landscapes operate is also behind the factorial scoring model or FSM that predicts sediment export values for larger catchments (de Vente et al., 2006; Verstraeten et al., 2003). The main variables controlling sediment production and transport (lithology, topography, gully incisions, vegetation cover and shape) are rated and the product of each factor provides a score that is indicative of the sediment yield. In fact, such a lumped approach towards modelling catchment sediment export has also been postulated by Jan De Ploey in his erosion susceptibility model (Es) whereby he relates Es to the ratio between catchment wide denudation rate and the potential and kinetic energy input into the systems that steers the erosion processes (De Ploey, 1990; De Ploey et al., 1995). It can be seen as a synthesis of his work on individual erosion processes. Unfortunately, Jan deceased in 1992 and the Es-model was never fully developed. Probably the most important model development in Leuven is a suite of models that all follow the basics of the USLE-like approach. This model was adjusted to account for flow convergence such that it provides more realistic assessments of erosion rates in 2D landscapes (Desmet and Govers, 1996). This adjustment formed the basis for the WATEM/SEDEM model that predicts sediment fluxes from slopes to river channels and that is fully spatially distributed (Van Oost et al., 2000; Van Rompaey et al., 2001; Verstraeten et al., 2002). This model approach can and has been applied in an engineering fashion to simulate the impact of soil conservation management scenario's (Verstraeten et al., 2002) but one of its predecessors has also shown to correctly predict the spatial patterns of historic erosion and colluviation (Desmet and Govers, 1995).

21st century: towards more synergies again

During the first decade of the 21st century, a new trend towards increasing synergies between the various fields in geomorphology can be observed. This is in particular true with respect to understanding landscape evolution over timescales of several centuries up to several millennia. In this field of research, the blending of geomorphic process knowledge with quantitative field-based approaches provided a boost towards a better understanding on how landscapes react to human impact. In Leuven, a renewed interest in landscape evolution arose and although traditional field-based approaches that include detailed analysis of sedimentary archives at single observation points in the landscape are not excluded (Rommens et al., 2007) (Fig. 2a), the major focus is now on the full quantification of Holocene erosion depths, colluvial and alluvial storage through intensive coring programs (Notebaert et al., 2010; Rommens et al., 2005) (Fig. 3). This enabled, for the first time, the establishment of sediment budgets for small to intermediate river catchments spanning the entire Holocene (Notebaert et al., 2009; Verstraeten et al., 2009b). Sediment budget studies have been performed before and in other regions, however, their focus was either restricted to limited components of the sediment budget such as alluvial storage, or towards more recent time periods for which more detailed and accurate data exist (Abrahams and Marston, 1993 and references therein; Phillips, 1991; Trimble, 1999). The quantification of sediment sources and sinks in the Dijle catchment in central

Belgium has illustrated that even at the millennial time scale, around 40 to 50% of the eroded soil material is still stored on the slopes, with another 30 to 40% being stored in the floodplains. Similar studies from other catchments in western and Central Europe all point towards this large buffering effect (Fuchs et al., 2011; Hoffmann et al., 2007; Notebaert and Verstraeten, 2010; Stolz, 2011). Furthermore, a large database (n >100) of colluvial and fluvial sediment ages was obtained through C14 and OSL in order to obtain a timeframe of sedimentation rates (Notebaert et al., 2011a). Such a statistical analysis of large datasets on the timing of geomorphic processes during the Holocene has seen a major boost during the



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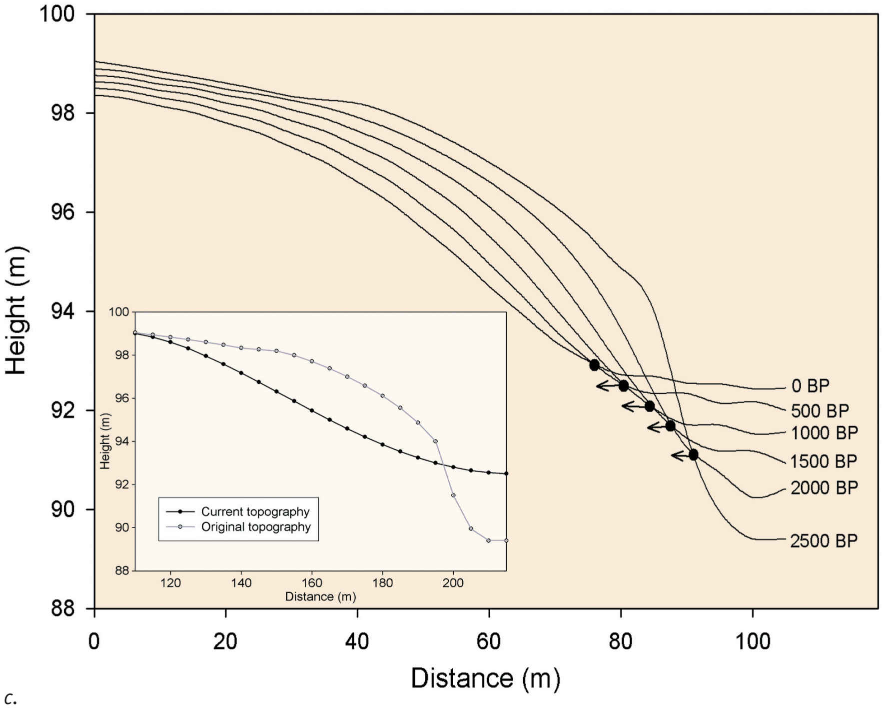


c.

Fig. 2. Reconstruction of the 2D landscape evolution during the Holocene along a slope catena in the Belgian Loess belt using a combined field and modelling approach. a. Landscape reconstruction based on soil stratigraphy mapped in a trench (after Rommens et al., 2007). b. Photograph showing 4 m colluvial deposits on top of the original Holocene Luvisol. First sediments on top of the soil profile were dated to the late Bronze Age - early Iron age (see Rommens et al., 2007). c. Results of modelling approach showing the evolution of the topography along the catena after 2500 years of continuous cultivation – the inset compares the measured original topography reconstructed in the trench (= model input 2500 BP) with the current measured topography. Note that the modelled topography at 0 BP corresponds with the original topography (after Peeters et al., 2008).

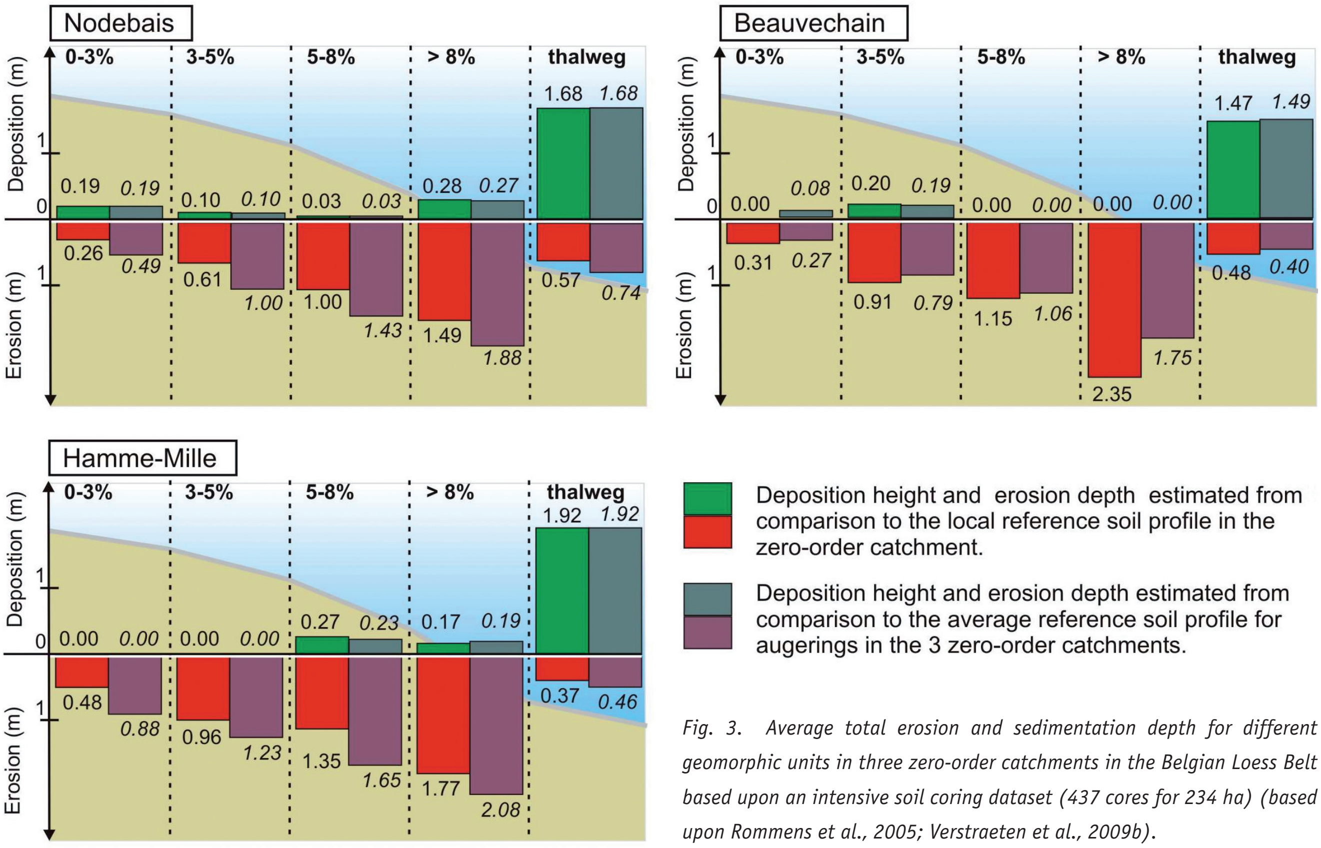


Fig. 3. Average total erosion and sedimentation depth for different geomorphic units in three zero-order catchments in the Belgian Loess Belt based upon an intensive soil coring dataset (437 cores for 234 ha) (based upon Rommens et al., 2005; Verstraeten et al., 2009b).

last decade (Dusar et al., 2012; Gregory et al., 2006; Hoffmann et al., 2009; Hoffmann et al., 2008; Macklin et al., 2006; Macklin & Lewin, 2003), although its validity has been questioned recently as well (Chiverrell et al., 2011). Nevertheless, the wealth of radiocarbon and luminescence dating made it possible to differentiate the sediment budget for the Dijle catchment in three major time periods, each with a different intensity of human impact (Fig. 4). The various quantitative field-based approaches in temperate Europe has thus shown not only that during the Holocene human impact has become the dominant factor controlling sediment dynamics – not climate – but also that the importance of colluvial and alluvial storage changes through time as is clearly shown for the Dijle catchment (Verstraeten et al., 2009b). Despite the high number of dated sediment units, the resolution of the sediment chronology remains limited, making it difficult to have a full understanding of the respective role climate and human impact have played, or to understand why sediment delivery ratio's change through time. These issues, however, can be resolved much easier through numerical modelling which enables to test various scenarios of climate and land use. Simple 2D and 3D versions of the WATEM/SEDEM model show that not only the patterns but also the average rates of erosion and sediment deposition at timescales of a few millennia can be correctly simulated when confronted with the quantitative field data, thus suggesting that a model that is built using contemporary process knowledge is valid when predicting longer term landscape evolution (Peeters et al., 2006; Peeters et al., 2008) (Fig. 2c). Confrontation of field data with different alternative modelling approaches also made clear that best results are obtained when using separate equations for erosion and sediment transport, which is in contrast to the majority of long-term landscape evolution models that are usually based on a single transport capacity equation. In fact, traditional landscape evolution models relying on only one approach may be valid to simulate catchment-wide climate or tectonic change but not the role of human impact during the Holocene as this impact may vary strongly in space (Temme et al., 2011).

Meanwhile, Jef's research group continued with a major research focus on fluvial processes and the impact of climate on these processes. However, modelling also emerged as an important tool in this group during the 21st century. Bogaart clearly showed how numerical models are able to simulate the changing behaviour of river channels at climate transitions (Bogaart et al., 2003a; Bogaart et al., 2003b; Bogaart et al., 2003c), similar to the conceptual model of Vandenberghe (1995), whilst Ward et al. (2007) now also focused on the impact of climate on Holocene flood hydrology of larger river systems. Also De Moor et al. (2008) turned their focus to the Holocene and their study in the Geul catchment is one of the first in Jef's research group that considered the role of human activity in shaping river morphologies. Keesstra et al. (Keesstra et al., 2005), moreover, studied the changes in river morphology for the Dragonja in Slovenia solely as a consequence of land use

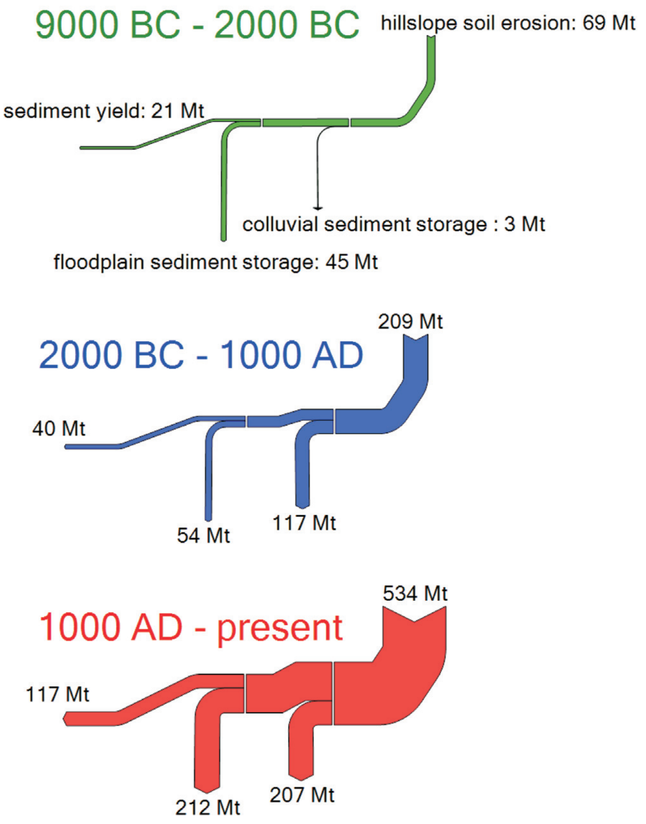
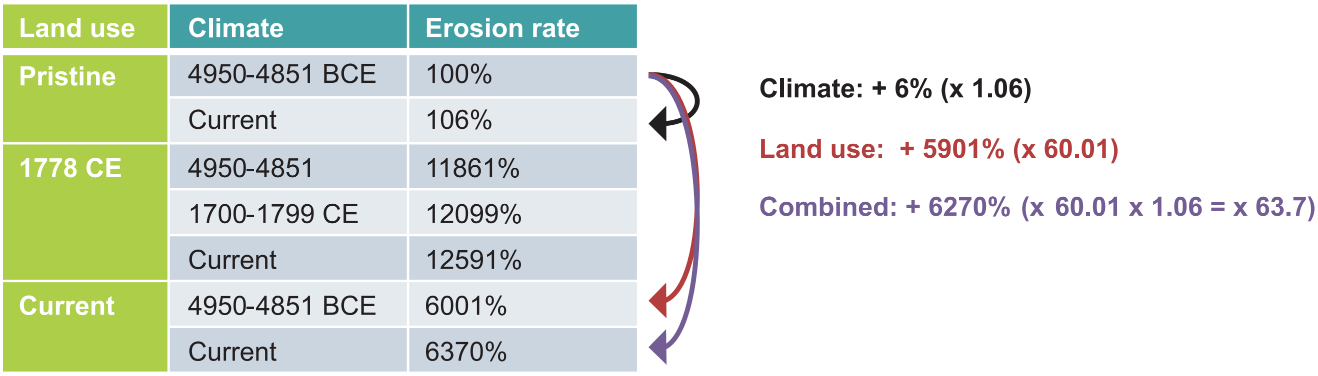


Fig. 4. A time-differentiated sediment budget for the Dijle catchment showing the changing importance of colluvial and alluvial storage as well as sediment yield through time (based on Notebaert et al., 2011). For the first time period, without major human impact, hillslope sediment delivery is near maximal with almost no colluvial deposits but with floodplain deposition. In a second time period spanning the early agricultural expansions in the Bronze Age, Iron Age and Roman Period, colluvial deposits become important and hillslope sediment delivery declines due to limited slope-channel coupling. During the last 1000 years, agricultural is so dominant in the landscape that slopes-channel coupling increases again and slopes as well as floodplains now trap huge quantities of eroded soil material.

changes. Thus, the research in physical geography at the VU evolved from field-based studies of long-term fluvial activity under changing climate conditions towards field-based studies of Holocene fluvial dynamics under anthropogenic impact on the one hand, and modelling focusing on hydrological/fluvial processes on the other hand.

This broadening of the scope in Jef's group thus took place during a period where research in physical geography at KU Leuven evolved from contemporary erosion studies and modelling towards Holocene catchment sediment dynamics again through field-based studies and modelling. As such, the research of both groups evolved in such a way that it opened several opportunities for integration. Modelling expertise on historic hillslope soil erosion was combined with field-based expertise in alluvial stratigraphy to develop a Late-Holocene sediment budget for the Geul catchment (de Moor and Verstraeten, 2008), or to better understand river channel changes for the Dragonja (Keesstra et al., 2009). Experience with palaeoclimate and palaeohydrology modelling was in turn coupled with land use modelling tools and soil erosion models to simulate the changes in sediment fluxes for the Meuse catchment following land use and climate change during the Holocene and in the near future (Ward et al., 2009). The same approach was repeated for the Dijle catchment (Notebaert et al., 2011b) further illustrating that changing rates of hillslope sediment delivery closely follow the evolution in land use and are hardly impacted by climate (Fig. 5). As such, the modelling approach confirms the conclusions made from the field-based studies, yet the role of climatic events that could not be resolved through the field work can be largely rejected by the modelling. The combination of the soil erosion model developed in Leuven with the hydrology model of the VU has also shown, both for the Dijle and the Meuse catchment, that human and climatic impact on sediment transport and flood frequency is different for the period before the major Industrialisation process in the 19th century compared to expected trends for the 21st century. Where erosion, sediment transport and flood frequency increased during the course of the Holocene because of an increase in deforestation and agriculture, opposite trends can be projected for the coming century. Indeed, under a warming climate, rainfall intensities may increase and the rapid increase of urbanising areas further increased the risk to flooding. On the other hand, decreased acreage of arable land due to urbanisation and reforestation further protects the soil against erosion and sediment transport is likely to decrease (Notebaert et al., 2011b; Ward et al., 2009).

The embracement of quantitative field-based and numerical modeling approaches into landscape evolution studies is not only restricted to the Holocene. Also with respect to long-term landscape evolution models an increasing coupling with quantitative field and experimental data can be observed. Whereas the earlier landscape evolution models where mostly applied on theoretical landscapes (see e.g. Kooi and Beaumont, 1996 referred to above), model outcomes are more and more compared to reality. Recently, an increasing number of experimental set-ups with rainfall simulators are being used to study the erosion and sedimentation processes in uplifting mountain ranges or drainage network evolution in tectonically active regions (Graveleau and Dominguez, 2008; Hancock and Willgoose, 2002; Hasbargen and Paola, 2000; Turowski et al., 2006). Furthermore, recent advances in dating methods have made it possible get a better control on the chronology of landscape evolution that was hitherto not achievable (Duller, 2004; Gosse and Phillips, 2001; Reiners and Brandon, 2006). The application of cosmogenic radionuclides now also makes it possible to infer long-term catchment wide erosion rates that can be used for model validation (e.g. Schaller et al., 2001). Particularly of importance in explaining the boost of research on landscape evolution models is the ever increasing



Land use	Climate	Erosion rate
Pristine	4950-4851 BCE	100%
	Current	106%
1778 CE	4950-4851	11861%
	1700-1799 CE	12099%
	Current	12591%
Current	4950-4851 BCE	6001%
	Current	6370%

Climate: + 6% (x 1.06)

Land use: + 5901% (x 60.01)

Combined: + 6270% (x 60.01 x 1.06 = x 63.7)

Fig. 5. Modelled sensitivity of erosion in the Dijle catchment due to climate and land use changes during the Holocene (after Notebaert et al., 2011b). Results of the WATEM/SEDEM model show that changes in climate between the pristine Mid-Holocene environment and the present are only responsible for a 6% increase.

availability of digital elevation models spanning nearly the entire globe (first GTOPO30, than SRTM global dataset and now also the ASTER-GDEM) and at smaller spatial units the development of high-resolution LIDAR imagery. Finally, during the last decade the increase in computing power facilities made it possible to simulate more complex and thus realistic landscapes. All these developments led to a new boost in the study of long-term landscape evolution that closely examines the link between tectonics and geomorphology (Bishop, 2007; Brocklehurst, 2010; Burbank and Anderson, 2001; Summerfield, 2000).

Despite the fact that quantitative and numerical modeling approaches are now being used in understanding landscape evolution at both long-term (i.e. Plio-Pleistocene) and mid-term (i.e. Holocene) temporal scales, there remains a major gap between the research communities. Research on long-term landscape evolution traditionally focuses on the respective role climate and tectonics has played. Both natural forcing factors have been used in the past to understand Holocene landscape dynamics as well. However, during the last two decades, growing evidence has pointed to the overwhelming anthropogenic impact on late Holocene landscape dynamics (Messerli et al., 2000; Syvitski and Milliman, 2007). The increasing number of palaeo-environmental studies that focus on the role humans have played in landscape evolution point to the rise of a new paradigm into geomorphology: humans as geomorphic agents (Hooke, 2000; Montgomery, 2007). The dominance of humans in controlling late Holocene sediment dynamics also made those modeling approaches that intend to simulate these landscape dynamics different from long-term landscape evolution models. For instance, the aforementioned WATEM/SEDEM model partly incorporates an adapted version of the Universal Soil Loss Equation that is mainly used to simulate the impact of changes in land use practices on local soil loss. In landscapes with a long history of human impact such as the northwestern European Loess Belt, it is therefore not surprising that the WATEM/SEDEM is capable of correctly simulating landscape evolution for the last few thousand years (e.g. Notebaert et al., 2011b; Peeters et al., 2006; Peeters et al., 2008). Long-term landscape evolution models, though, are not developed to simulate the impact of changing anthropogenic land cover conditions. Nevertheless, a few studies have combined information on long-term landscape dynamics and short-term anthropogenic driven geomorphic processes (Syvitski and Milliman, 2007; Vanacker et al., 2007; Wilkinson and McElroy, 2007). What is still missing is a comprehensive model approach that is able to incorporate all possible forcing mechanisms (climate, tectonics, land use change, human impact in all its forms) and this at various temporal and spatial scales. Such a unified model approach that can simulate landscape evolution under any given conditions can be considered the Holy Grail in Geomorphology.

Conclusions

Geomorphology as a scientific discipline has seen a major evolution since the mid of the 20th century. One of the main aspects of this evolution is the development of quantitative approaches as well as numerical modelling techniques. Quantitative field-based approaches have generated large datasets that were used to develop, calibrate and validate numerical models of contemporary sediment dynamics. It is mainly contemporary process knowledge derived from actual field measurements and experimental data that led to the development of these models. In recent years, these modelling approaches have been applied successfully to understand historical fluxes of sediment as well. Again this was made possible through a quantitative (r)evolution in the study of palaeo-landscapes. These developments led to a narrowing of the apparent schism between process geomorphology and descriptive palaeo-environmental studies. The increasing awareness that human impact has become the major driver of landscape change throughout the Holocene in palaeo-environmental research has certainly facilitated this coupling of contemporary processes and studies of landscape evolution. As such, the apparent shift of quantitative geomorphology towards engineering studies, away from long-standing questions in geomorphology on landscape genesis and evolution, and which has by some been seen as a threat to geographical geomorphology (Church, 2005), is no longer a major concern. Also within the study of long-term landscape evolution (>million years), a quantitative and modelling revolution has taken place over the last few decades. The schism between quantitative geomorphology on the one hand and traditional geomorphology on the other, which lasted for decades in the second half of the 21st century, has now been replaced by the emergence of two new large paradigms in geomorphology, i.e. tectonic geomorphology and humans as geomorphic agents, the latter being part of the larger research domain on human-environment interactions. Both research domains are applying quantitative and numerical modelling approaches, yet at different timescales. These new paradigms do find their origin to a certain extent in the various curricula in which geomorphology is taught. It is certainly not surprising to note that tectonic geomorphology mainly has emerged in the US where geomorphology has (and still is) mainly been taught in Geology programs. On the other hand, the emergence of anthropogenic geomorphology is mainly seen in the UK and the rest of Europe where geomorphology is often taught in the broader discipline of Geography that encompasses both physical and human geography. Remarkable in this respect is that in Leuven, where a broad Geography curriculum exists, much more attention has been paid to the role of humans in geomorphology. On the other hand, the focus of Jef's research in Amsterdam on understanding the role climate and tectonics have played in long-term landscape evolution may well arise from the fact that in the Netherlands Physical Geography has long been a separate study program with close links to Geology, but without a major introduction in Human and Social Geography.

Although quantitative and numerical modelling approaches have made major progress over the last few decades, this is not sufficient to fully understand past landscape dynamics. The various model outcomes for the Dijle catchment discussed above do show that still major uncertainties with respect to sediment transport and the role of humans therein exist for time periods with a limited intensity of land use. It is, for instance, unclear to what extent early human impact in the Neolithic has already impacted river channel behaviour and floodplain sedimentation rates. Which thresholds needed to be crossed before all components of a catchment's sediment budget, including the larger river floodplains, react to human disturbance in the catchment? How important is the intensity, quality and spatial patterns of human induced land use change on controlling sediment fluxes? Neither the quantitative sediment budget approach, nor the modelling approach, is able to answer this research question in full. Amongst other reasons, especially the lack of detailed and precise chronologies of sediment dynamics and human impact relates to this problem (Verstraeten et al., 2009a). Ongoing research, jointly carried out by Jef's research group and that of the author, therefore applies 'traditional' palynology (Broothaerts et al., 2012), yet in such a way that in the near future a quantitative pollen-analytical approach using numerical pollen dispersal models will be used to fine-tune the historical land use maps that were up till now used in the geomorphic process models. It is the combination of traditional field-based approaches with spatial modelling techniques that allows us to further enhance our knowledge on past (and present) landscape evolution. Calibration and validation of models, which is crucial in any model approach, requires that extensive data on real-world landscapes are being collected.

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