Diagnosing problems of fine sediment delivery and transfer in a lowland catchment

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Abstract (150-250 words)

Fine sediment (here defined as fine sand, silt and clay) is a serious management problem in lowland rivers because of alterations to river channels, floodplains and the wider landscape. The multi-scale, complex and stochastic nature of sediment production, delivery and transport processes complicates the diagnosis of fine sediment sources, pathways and impacts. The hydromorphological assessment framework developed by the REFORM project offers a flexible approach to investigate fine sediment pressures. In this study, the framework was applied to a lowland river impacted by excess fine sediment (River Frome, Dorset, UK) to investigate likely sources and timing of sediment production, the segment-scale capacity of the river to transport sediment, and the reach-scale geomorphological response of the river. Land use mapping and agricultural census records suggest that intensive cultivation of cereals and high livestock numbers during the second half of the 20th century are the probable causes of fine sediment production and that a lack of any significant riparian buffer zone facilitates delivery of fine sediment to the river network. Sediment budget modelling indicates that transport capacities for gravel are low along the river, which is supported by field observations of compacted gravel/sand beds covered with algae. Analysis of historical maps reveals that the river has responded to the increase in fine sediment over the last 40-50 years with channel narrowing and an increase in sinuosity, as fine sediment is trapped and stabilised by aquatic vegetation in the channel margins. Interactions between hydrodynamic forces, sediment supply and vegetation are driving progressive adjustment of the River Frome, and are the key to its holistic future management.

Keywords: siltation, fluvial geomorphology, soil erosion, hydromorphology, channel change.

INTRODUCTION

Fine sediment is a natural component of rivers and is integral to their geomorphological and ecological functioning. However, humans have altered the quantity and quality of fine sediment in rivers (Owens et al. 2005) and it is now classified as a diffuse pollutant in Europe under the Water Framework Directive (WFD) (European Parliament 2000). More fine sediment is entering rivers, particularly lowland rivers in agricultural and urban settings, and this sediment is often contaminated with nutrients, heavy metals, organic pesticides and other pollutants (Owens et al. 2005). Once in rivers, fine sediment impacts directly on both the geomorphology and ecology, and also indirectly through complex interactions between the physical and biological components of river systems (Acornley and Sear 1999; Ballantine et al. 2009; Gurnell et al. 2006; Heppell et al. 2009; Jones et al. 2012; Sharley et al. 2008). In England, fine sediment is the fifth most common pressure on water bodies and is responsible for 12% of failures to reach good ecological status for WFD (Environment Agency 2013). Thus, the need to manage fine sediment is clear, but management is difficult and often prohibitively expensive to achieve once the sediment is in the river channel (Detzner et al. 2007; Hakstege 2007). Indeed the most sustainable solution is to reduce sediment production at source and to decrease connectivity between source areas and the river network as part of an integrated sediment risk management approach (Apitz 2012).

Although the study of erosion and transport of fine sediment has a relatively long history, the assessment of fine sediment pressures on rivers is still limited by the complexity and stochasticity of sediment transport processes and our ability to resolve its intrinsic spatial and temporal variability (Sear et al. 2010). Approaches such as soil erosion monitoring, sediment walkover surveys, sediment fingerprinting and sediment tracing have been developed to quantify sediment production, track sediment plumes during storm events, identify sediment sources based on sediment biogeochemical properties, and map pathways and quantify sediment flux (Guzmán et al. 2013; Walling 2013; Cooper et al. 2014). Whilst these approaches can provide valuable information for an assessment of fine sediment pressures, they require specialist knowledge and equipment and can be resource and time-intensive, thereby limiting the spatial scope of the studies and the timespans investigated. Consequently, an approach is needed that can be applied at a large-scale (i.e. catchment) to identify potential sediment sources, to identify changes over time in sediment production and delivery, and at small-scales (i.e. reach) to identify the geomorphological impacts of excess sediment within river systems.

The purpose of this paper is to demonstrate how a range of freely available datasets can be examined within the hierarchical framework proposed by the REFORM project (Gurnell et al. 2015, this volume) to investigate fine sediment pressures. The study focuses on a lowland river with a documented fine sediment problem, but for which gaps in our understanding remain. The hydromorphological assessment framework is used to fill these gaps by (i) identifying possible sediment sources and how they have changed over time at the catchment scale, (ii) the extent of riparian vegetation along river margins that could intercept delivery of fine sediment; (iii) by quantifying the transport capacity of the river at the segment scale to determine if sediment is likely to remain in the channel once it is delivered to it; and (iv) by quantifying geomorphological changes at the reach-scale to understand what impacts increased delivery of fine sediment has had on channel dimensions, planform and sediment characteristics. The assessment provides the necessary data to develop a conceptual model of the evolution of the river system which is used to predict how the system will respond in the future.

MATERIALS AND METHODS

THE STUDY CATCHMENT

The hierarchical framework (Gurnell et al., 2015) was applied to the River Frome in Dorset, southern England (Fig 1). The River Frome is a lowland gravel bed river protected under multiple UK and EU statutes for its species-rich aquatic plant communities and important river and floodplain habitats. Land use in the lowland catchment is predominantly agricultural with localised urban development concentrated in the middle and lower catchment around two small towns (Dorchester and Wareham). The landscape is characterised by low rolling

hills composed primarily of Cretaceous chalk in the upper catchment and Cainozoic marine deposits in the lower coastal plain. The chalk geology supports an unconfined aquifer in the upper and middle catchment which generates baseflow-dominated flows in the River Frome and its tributaries, driving a stable to superstable flow regime.

Lowland chalk rivers are particularly sensitive to increases in fine sediment loads. Their ecological communities are reliant on low turbidity levels and clean gravel beds, and their baseflow-dominated flow regimes and high width:depth ratio channels produce gentle flows with limited capacity to flush sediment once it deposits. For these systems, fine sediment is defined broadly and based on its functional impact on the ecology and hydrology of the river. It includes clay, silt and sand-sized particles, all of which are small enough to ingress into the channel bed and affect bed sediment size distributions, subsurface water flows and the benthic community. Increased fine sediment deposition within the River Frome has been noted over recent decades (Collins and Walling 2007a; Walling and Amos 1999), but little direct evidence exists to assess temporal trends in sediment loads or their impacts on channel plan or cross-sectional form.

The catchment and channel network were delineated into a hierarchy of spatial units following the REFORM framework (Gurnell et al., 2015). This initial step creates spatial units that are internally consistent in terms of their topography, geology, and land use (landscape units); valley setting and gradient (segment); and channel planform and longitudinal continuity (reach) which facilitates a process-based characterisation of hydromorphology at each scale. The 459 km^2 catchment was delineated into 3 landscape units, and the 66 km-long River Frome into 6 segments and 17 reaches (Fig 1). A combination of sediment budgeting and temporal analyses of land cover, agricultural production, and channel planform were used to investigate fine sediment production at the catchment scale, sediment delivery at the landscape unit scale, sediment transport at the segment scale, and the consequences of these sediment dynamics for channel planform at the reach scale.

SEDIMENT PRODUCTION - LAND COVER / USE

Changes in land cover and land use over time were investigated through the analysis of historical land cover maps, recent spatial land cover datasets and agricultural census records.

Scanned maps from the First Land Utilisation Survey of Britain (1:63,360 scale, 2 maps dated 1936 and 1943) were georeferenced in ArcGIS and land cover was classified using maximum likelihood classification. Recent changes in land cover were examined using the UK Countryside Survey digital land cover maps for 1990, 2000 and 2007 (1-km resolution) with thematic classes aggregated to match the first level of the Corine land cover dataset, a pan-European dataset recommend by REFORM (Gurnell et al., 2015). Changes in the area cover of land classes were investigated at the catchment scale as were the extent of riparian vegetation along the margins of the river network.

Agricultural statistics were obtained for the county of Dorset from the UK Department of Environment and Rural Affairs (DEFRA). To explore changes in land use that could impact soil and runoff production, the June agricultural census was used to track changes in the amount of arable land, permanent grasslands and rough pastures, as well as the number of livestock. Estimates are only available at the county scale, and are used to infer changes within the Frome catchment. This is a reasonable approach as the Frome catchment comprises a substantial portion of the county (18%) and elevation, land cover and land use are similar within the catchment and in the rest of Dorset.

SEDIMENT DELIVERY AND TRANSPORT – SEDIMENT BUDGETING

Long-term sediment transport monitoring data are not available for the River Frome. Therefore, a sediment budget was developed using the Sediment Impact Assessment Method (SIAM) within the 1-D hydraulic modelling package HEC-RAS (Little and Jonas, 2010). SIAM generates a simple sediment budget that identifies network-scale patterns in sediment accumulation or loss within the channel network. It is a 1-D sediment continuity model based on reach-averaged hydraulic and sediment information, and is intended as a screening

tool to assess the potential impacts of alternative sediment management options on downstream reaches. The model represents the River Frome as a single thread with a mixed sand/gravel bed, with river discharge based on the monitored flow duration curve, and fine sediment input originating from soil erosion. These simplifications were necessary because of a paucity of data to calibrate and validate the model. Consequently, the SIAM model is applied in an indicative manner wherein the available data are used to support the estimation of broad annual trends in the sediment budget.

The SIAM model has two components: a 1-D steady-state hydraulics model and a sediment characterisation. The hydraulics model was created using a river geometry file based on the stream network represented in the current Ordnance Survey map (1:2500 scale) and a mosaic of elevations from the ProfileDTM (10 m resolution) and LiDAR surveys. Channel cross sectional profiles were based initially on channel depth estimates from the UK Environment Agency's (EA) River Habitat Surveys, informed by local knowledge of bed configuration, and improved where engineering cross-sections were available from the EA. The steady state hydraulic data was obtained from 5 river gauging stations in the catchment, and extended to ungauged segments based on an empirical relationship between discharge and sub-catchment area for each discharge in the profile. The discharge profile was based on the flow duration curve: Q95 (67 days), Q70 (82days), Q50 (135 days), Q10 (65 days), Q2 (11 days), and Q1 (5 days). Sediment data included bed sediment size information extracted from River Habitat Surveys (EA) and Mean Trophic Rank Surveys (Centre for Ecology and Hydrology - CEH) and fine sediment input estimates from the Pan-European Soil Erosion Risk Assessment map (PESERA). PESERA is a pan-European model that predicts soil loss (t ha^{-1} yr^{-1}) at 1-km scale. A 500 m buffer around the river network was used to estimate annual delivery of fine sediment (t km^{-1} y^{-1}). Fine sediment derived from soil erosion was represented as clay/silt. The Yang sediment transport function was used, and additional sensitivity testing was conducted using the Meyer-Peter-Müller and Laursen (Copeland) equations. Model outputs were assessed based on the spatial pattern of bed sediment gain and loss in the channel network. No change in sediment storage was defined as 0 ± 5% of the min/max of sediment loss/gain for the model run.

Specific (i.e. unit) stream power was calculated using the median of the annual flood series (Qp$_{median}$ based on 15 minute flows) as $\omega = \rho gQS/b$, where ρ is the density of water (1000 kg m^{-3}), g is acceleration due to gravity (9.8m s^{-2}), Q is discharge (in m^3 s^{-1}), and S is slope (in m m^{-1}) and b is average channel width. Shear stress was estimated as $\tau = \rho gRS$, where R is the reach-averaged hydraulic radius estimated from reach-averaged channel width and depth (EA River Habitat Survey data).

REACH-SCALE CHANGES
Channel overlays from historical maps were used to examine changes in channel position, planform and width over time. Ordnance Survey (OS) large-scale maps were used throughout, which adopt a standard convention of the 'normal winter level' to define river channel edges (Harley, 1975). The OS MasterMap Topography layer was used to represent the current channel planform (here designated 2013), and large-scale (1:2500) historical OS maps were obtained for the years 1889 and 1960/1973 (date varies by reach). Some of the main channel in reach 1 was not included in this analysis because it was too narrow at one of the time points; at 1:2500 scale, OS maps only represent a river with two banklines if it is wider than 2 m. Positional accuracy of the Mastermap topography series is ±1.0 m in urban areas and ±2.5 m in rural areas, the second of which is comparable to the historical 1:2500 maps which have an absolute accuracy of ±2.8 m (Gurnell et al. 2003).

The historical maps were georeferenced to the current map in ArcGIS based on common landmarks (Grabowski and Gurnell 2014). All major and secondary channels of the main stem of the River Frome were digitised by reach for each time point. Channel area and length were quantified by reach and used to calculate reach-averaged channel width. Networks from different time points were overlaid to quantify the area of channels found in both time points (no change), areas that were channel in the first time point but land in the second (deposition) and area that was land in the first but channel in the second (erosion).

RESULTS

SEDIMENT PRODUCTION - LAND COVER / USE

The analysis of historical maps and datasets indicates that land cover in the River Frome catchment has changed little over the last 70 years (Fig 2). The catchment has historically been and remains dominated by agriculture. Agricultural surfaces have consistently covered almost 90% of the catchment area. No substantial change has occurred in the cover of forests or built-up (urban/suburban) areas; forest has covered 6-9% and built up areas 1-2% (though urban centres in the mid and lower catchment have grown in recent decades). The most notable change over time is the shift from pasture to arable land through the end of the 20th century. Furthermore, when floodplain land cover is investigated at the segment scale, riparian vegetation covers 32%, 35%, 10%, 5%, 8%, 10% of the floodplain area and the extent of river margins bordered by riparian trees or scrub is 42%, 30%, 27%, 9%, 18%, 21% in segments 1 to 6, respectively. This illustrates that apart from the headwaters (segments 1 and 2, Fig 1), riparian vegetation cover is low and very few river margins have any buffer of riparian vegetation that might intercept runoff and sediment transported from agricultural land.

At the county level, total agricultural area has remained unchanged over the past 100 years at approximately 2000 km^2, which encompasses approximately 75% of the area of Dorset (Fig 3a). The area of arable land fluctuated in the early 20th century, but increased to account for half of the agricultural area by the 1960s (Fig 3a). This temporal trend was mirrored by a decrease in the area of low-intensity agriculture (permanent grassland and rough pasture). County-level agricultural statistics also provide information on the total area of arable land under cultivation for different crop types (Fig 3b). The area of agricultural land under cultivation for cereals decreased during the early part of the 20th century, increased during World War II (WWII), and then increased dramatically in the late 20th century, first with barley production and then wheat. The area under root crops used for fodder decreased to zero over the first half of the 20th century, whereas potato cultivation was historically limited, but briefly peaked during WWII (Fig 3b). The increase in land use dedicated to cereal production over the later 20th century paralleled increases in crop yields. County level statistics for crop yields are not available, but country-level statistics show that the amount of wheat and barley produced per hectare of land increased dramatically from the 1930s (Fig 3d). Crop yields in the Frome catchment would have probably seen a similar trend, as the modernisation and intensification of agricultural practices would have been adopted over the entire country. The statistical data strongly suggest that the Frome catchment experienced not only an increase in the amount of land under tilled agriculture but a substantial intensification of production.

Finally, livestock numbers have also changed substantially over time in Dorset (Figure 3c). Sheep were the dominant livestock in the county in the early 1900s, but their numbers dropped over the first half of the century. Cattle numbers increased steadily over the 20th century and total livestock numbers reached a peak in 1995.

SEDIMENT DELIVERY AND TRANSPORT – SEDIMENT BUDGETING

The SIAM model predicts a net gain in bed sediment for the majority of the main stem of the River Frome (segments 2-6) and a net loss in bed sediment from the tributaries and segment 1. Transport potentials for the sand and gravel bed sediment are low in Segments 2-6, and are exceeded by the delivery of sediment from upstream segments and tributaries, resulting in a net gain of sediment within the river network. Sensitivity testing found a similar spatial pattern in sediment gain/loss regardless of the transport equation that was used, although higher sediment transport potentials for both sand and gravel were estimated when the Yang function was not applied.

The low transport capacity of the River Frome illustrated by the SIAM modelling results are unsurprising given the low specific stream power and shear stress for most of the length of the River Frome (Fig 4). Specific stream power is equal to or below 30 W m^{-2} at Qp$_{median}$ for the entire main stem of the River Frome except for reach 1 (45 W m^{-2}). Shear stress is approximately 30 N m^{-2} or less for all reaches except 1 and 4.

Overlays of the channel margins between different points in time give a good indication of the direction and magnitude of adjustment that has occurred. This type of analysis incorporates implicitly any changes that have occurred in channel width or length in addition to lateral migration. When the deposited and eroded areas are compared, it becomes clear that most reaches have shown a distinct and continuous reduction in channel area since 1889 (Fig 5a,b). These trends are likely to be robust, since the Ordnance Survey use a consistent definition of the channel boundary (the normal winter flow level), and interpretation of aerial imagery used the same definition. Such a definition can be robustly applied to the channels of the Frome, because of their typically steep (near-vertical) banks.

With the exception of several reaches which experienced large (apparently artificial) cut-offs, reach length and thus reach sinuosity has increased over time (Fig 5c,d). An increase in sinuosity was especially apparent in the second half of the 20th century (Fig 5d). As the number of channels was constant over time and channel lengths were stable or increasing, the decrease in channel area has been caused by a reduction in average channel widths. While no consistent change in width is detected between 1889 and 1960/75 (Fig 5e), channel narrowing is clearly evident over the last 40-50 years (Fig 5f). Out of the 17 reaches, 12 narrowed over this period, accounting for 69% of the total length of the main stem of the river. Although width reductions are small, on the order of 2 m or less, these translate to a 5-15% reduction in channel width. Over this period, channel widening was substantial only in reaches 2 (0.5 m, or 9%, increase in width) and 14 (2.8 m, or 14%, increase in width), and minor in the other 3 reaches, representing a 1-3% increase in width. Although the estimated reach-average channel narrowing is of a similar magnitude to potential errors in the map sources, the consistency of the changes observed along the gives confidence that genuine channel narrowing has occurred.

DISCUSSION

In this study, the hierarchical framework for hydromorphological assessment developed by the REFORM project was applied to a lowland river flowing through an agricultural catchment with a recognised fine sediment problem. The study demonstrates how a process-based framework can be used to develop a fuller picture of the problem by investigating each stage of the sediment transfer process: the source and timing of sediment production, delivery to and transport within the channel network, and the resulting impacts observed at the reach scale.

SEDIMENT PRODUCTION – LAND COVER/USE

This study found substantial shifts in agricultural land use practices starting in the middle of the 20th century which likely resulted in increased sediment production. The dominant land use in the agricultural catchment transitioned from pasture to arable land at this time, and was accompanied by a shift towards the intensive cultivation of cereals throughout the latter half of the century. These changes in agricultural land use were a result of government policies that promoted agricultural production during and following WWII and market forces that dictate crop prices (Angus et al. 2009). Over this period, an increased mechanisation of farming practices, improved crop varieties and an increased use of fertilisers dramatically improved yields (Fig. 3d), but some of these practices led to unintended soil loss consequences. More powerful tractors pull larger equipment, which are more efficiently and economically used on larger fields. The amalgamation of small fields into larger increases the length over which soil erosion operates and therefore intensifies rill and gully erosion (Leys et al. 2010). Heavier equipment is responsible for increased soil compaction on tramlines and more powerful tractors can plough against hillslope contours, aligning crop rows parallel to slope, both of which can increase surface run-off and intensify erosion (Deasy et al. 2009; Stevens and Quinton 2008). Furthermore, the relative lack of a zone of riparian vegetation bordering the river channel, means that connectivity between agricultural areas and the river network is high along the majority of the length of the main Frome.

The shift to intensive cereal cultivation in the latter 20th century is the most probable origin of recent fine sediment delivery to the River Frome. Soil erosion rates differ by crop types because of variations in the cover of above ground biomass, soil binding by roots, planting and harvesting techniques, and the timing of field operations in relation to precipitation patterns. Accordingly, UK government guidelines recommend that certain crops should not be grown on sites with high susceptibility to erosion, including autumn sown winter cereals, potatoes, sugar beets, field vegetables and forage maize (Boardman et al. 2009; Defra 2005). Whilst potatoes and maize have been or currently are cultivated in the Frome catchment, the predominance of cereals is readily apparent in the latter 20th century, a period which also corresponds with a shift in the timing of cereal sowing from spring to autumn. This change in practices means that fields are bare in autumn, at a time when rainfall intensity is greatest in this part of England (e.g. Gurnell and Midgley, 1993). Chambers et al. (2000) found that over 80% of erosion events in a large-scale field study in England and Wales occurred on land cropped with winter cereals.

Livestock production has also intensified and diversified over the second half of the 20th century and has likely contributed to increase fine sediment loads in the River Frome. Total livestock numbers increased steadily following WWII and changed from sheep- to cattle-dominated (Fig. 3c). Grazing influences vegetation cover and biomass, soil properties, and surface hydrology, which can increase the production and delivery of fine sediment to the channel (Bilotta et al. 2008; Bilotta et al. 2010; Trimble 1994; Trimble and Mendel 1995). Cattle accessing the river for drinking water (i.e. cow ramps) have been identified as a major source of bank degradation (i.e. poached river banks) and thus fine sediment input to rivers. The recent increase in the number of pigs may also be associated with an increase in outdoor breeding, which releases significant quantities of fine sediment (Evans 2004).

In combination, these land use changes suggest a trend of increased fine sediment production from the 1940s through to the end of the 20th century. While sediment fingerprinting studies have previously identified agricultural soils as the source of fine sediment in several lowland chalk rivers, they have only been able to estimate the relative net contributions (Collins and Walling 2007b; Walling and Amos 1999). For example a study on the nearby Pang/Lambourn catchment found that for fine sediment stored in the channel bed 19-35% originated from pastures and 31-55% from cultivated land (Collins and Walling 2007b). The present study corroborates this sediment fingerprinting research and in addition has identified the likely timing and agricultural land uses responsible for the increased delivery of fine sediment to the channel.

SEDIMENT DELIVERY AND TRANSPORT

The River Frome does not have long-term monitoring records of sediment transport, so a sediment budget modelling approach was used to estimate how the delivery of sediment from the catchment and upstream reaches would affect the spatial pattern of sediment gain/loss in the river network. The SIAM model estimated that most of the main stem of the river would gain bed sediment over a typical year. Low sediment transport capacities for gravel-sized sediment suggest that the river is unable to mobilise its gravel bed and that aggradation in reaches is primarily caused by the net deposition of sand delivered from upstream sources. Whilst the model does not predict deposition on silt and clay particles, it supports the argument that fine sediment, once it deposits and ingresses into the gravel-bed, is unlikely to be remobilised.

Although the SIAM model could be improved with additional calibration data, the results are consistent with research on critical erosion thresholds for non-cohesive sediment and field observations. Studies have suggested a specific stream power threshold of 30-35 W m^{-2} for gravel-bed rivers, above which erosional processes become dominate (Brookes 1987; Orr et al 2008; Bizzi and Lerner 2013). Specific stream power is equal to or below 30 W m^{-2} at Qp_{median} for all reaches except reach 1. Experimental work on incipient motion of uniform non-cohesive sediment has found that coarse sand (d_{50} = 2 mm) requires a critical shear stress of approximately 1 N m^{-2} while coarse gravel (d_{50} = 32 mm) requires a critical shear stress of approximately 30 N m^{-2} (Julien 2010). Reach-average shear stress is at or below 30 N m^{-2} for all reaches of the Frome except for 1 and 4. Consequently the gravel bed

is unlikely to be mobilised regularly in most of the River Frome. Sand may be mobilised, as shear stresses are greater than 1 N m^{-2} in all reaches, but once sand deposits in areas or at times of low flow and infiltrates into the gravel bed, it is unlikely to be remobilised. This conclusion is supported by field observations in many reaches of compacted gravels covered in algae, the smothering of gravels by silt and sand or accumulation of silt and sand within the margins of the river bed.

Finally, recall that the River Frome was modelled as a single-thread system based on the dimensions of the main channel, but it is actually anabranching in many reaches particularly in the middle and lower catchment. Therefore, flow velocities and unit stream powers would be substantially lower than estimated in the model because the total width of the multiple channels would be significantly wider than the single main channel, thereby reducing sediment transport potentials even further. Consequently, without the routine reworking of the gravel bed, the River Frome will continue to suffer from problems of persistent fine sediment storage.

REACH-SCALE CHANGES

The temporal analysis of channel position revealed that both channel area and width decreased along the majority of the River Frome over the last 40-50 years (Fig. 5). The channel narrowed by 5-15% along 69% of its length over this time period. This is in contrast to the earlier time period (1889-1960/75), when there was no consistent trend in channel area or width changes. Whilst the coarse temporal resolution of the analysis does not allow for precise estimation of the timing of narrowing, the results clearly indicate a correlation between channel narrowing and the adoption of agricultural practices that are known to increase soil loss in the second half of the 20th century. This link is supported by studies that have documented the deposition and stabilisation of fine sediment along channel margins that could produce channel narrowing.

Field studies of fine sediment transport and storage in chalk rivers have previously observed extensive fine sediment deposition within the channel, and particularly within stands of aquatic macrophytes (e.g. Cotton et al., 2006). The frequently high width:depth ratio of chalk rivers, their historically low suspended sediment concentrations, baseflow-dominated flow regime and the lack of significant riparian vegetation cover to shade the channel has created the ideal conditions for the establishment of aquatic macrophytes. Aquatic macrophytes interact with the flow of water and sediment, creating low flow velocity, low turbulence areas within the channel that promote sediment deposition and hinder the erosion of sediment deposits. Sediment storage has been noted in both submerged and emergent morphotypes, including the submerged *Ranunculus penicillatus ssp. pseudofluitans* and the emergent *Sparganium erectum*. Gurnell et al. (2006) found average depths of fine sediment deposited across the surface of the gravel bed at study sites in reaches 5 and 6 to vary greatly through time but with minimum and maximum reach average values of 0.2 cm and 4.0 cm. Surface accumulations were particularly high within emergent macrophyte stands where average depths of fine sediment varied from 3 to 4 cm in early spring to over 8 cm in August. Heppell et al. (2009) report that fine sediment storage varied between 11.6 and 66.8 kg m^{-2} at a site in Reach 4 in monthly measurements over a two year period. In this reach, the majority of this sediment was found within submerged macrophytes growing in the middle of the channel, particularly within patches of *Ranunculus* sp. The emergent macrophyte, *Sparganium erectum,* is also found widely along the River Frome. It has been shown from analysis of a national data set, that to achieve up to a 25% cover of *Sparganium erectum*, unit stream power at $Q_{pmedian}$ needs to fall below 60 W/m^2: above this value the species may be present but its abundance is lower and when stream power exceeds 100 W.m^2, its persistence at a particular location is probably too short for significant sediment accumulation (Gurnell et al., 2013). *S. erectum* tends to grow in dense stands, particularly towards the edges of the river bed, where it is particularly effective at trapping and retaining fine sediment and then stabilising it by sending rhizomes and roots into the freshly-accumulated sediments (Liffen et al., 2013). This process of sediment aggradation and stabilisation initiates the development of submerged shelves and emergent berms of vegetated fine sediment (Gurnell et al., 2013), which can be colonised by other plant species to evolve into benches and extensions of the bank profile (Gurnell 2014), so contributing to channel narrowing.

Geomorphological change occurs slowly on the River Frome, reflecting the fact that it is a very low energy, baseflow-dominated river bounded by banks of erosion-resistant cohesive sediment. Nonetheless, the river appears to be responding progressively to the fine sediment that is being delivered to it as a result of human activities within the catchment. There have been no abrupt or dramatic adjustments to channel position or planform type, and river channel change is observed as a reduction in channel width, increased sinuosity and a fining of the bed sediment. The rate of change in channel area and width, and thus the amount of fine sediment retained, varies by reach (Fig 5), but it is unclear whether this is related to differences in the input of fine sediment, different lags in sediment delivery-transfer or different responses to the same delivery-transfer rates. So far, the river has been surprisingly resilient to the process changes to which it has been subject, at least in terms of its limited lateral dynamics and planform adjustment.

While it is difficult to identify a period in the recent past in Britain that is not significantly impacted by humans, we can hypothesise that prior to agriculture the gravel-bed River Frome would have been either single-thread sinuous / meandering or low energy anabranching and would have been flowing through a mosaic of wetland and wet woodland habitats (Fig 6a). Conversion of floodplains for pasture and arable land would have resulted in the loss of the natural floodplain vegetation and a reduction in woody riparian vegetation cover. Engineering of channels and floodplains from the Medieval period onwards saw the proliferation of weirs within the Frome river network to support water mills, the installation of sluice gates to control the flow of water, and the creation or modification of side channels to divert flow from the floodplain to the channel network, into water meadows and towards water mills (Lewin 2010). As was common in lowland rivers, the main channel would have also been straightened, widened and possibly deepened for a variety of purposes (e.g. land drainage, flood protection, etc.).

More recently, channels have narrowed and become more sinuous as aquatic plants trap and stabilise sediment in the margins, producing landforms (e.g. bars and benches) that aggrade over time to eventually fuse with the floodplain (Fig 6a,b). Under current land management and thus sustained fine sediment inputs, this process could be expected to continue until: (i) fine sediment loads decrease, (ii) the narrowing of the channel increases flow velocities sufficiently to reduce the establishment and survival of aquatic plants, or (iii) the growth of woody riparian vegetation shades out aquatic plants (however this would be accompanied by new wood-induced geomorphic processes) (Fig 6a). It is this interplay between fine sediment supply, river flows, and aquatic and riparian vegetation that is the key to understanding how the system has evolved over time and will respond to future management and climate change.

The preferred management option from a geomorphological perspective is to allow channel narrowing to continue until an equilibrium is reached, combined with a relaxation of riparian vegetation management. The fencing off of riparian areas from grazing will allow the re-establishment of herbaceous and woody vegetation. This increase in vegetation cover will help to reduce fine sediment delivery to the river from overland flow and promote the delivery of wood to the river channel which has been shown to induce geomorphic change. The narrowing of the channel will re-establish lateral connectivity in the system, by raising water levels, increase the frequency and extent of flooding and the deposition of fines on the floodplain, which is where fine sediment deposits in a natural system. Collaborative engagement with farmers and riparian land owners can minimise the potential negative impacts of these geomorphological changes by ensuring the protection of infrastructure and the promotion of flood tolerant agricultural land uses.

CONCLUSIONS

This study has demonstrated how a hierarchical framework for hydromorphological assessment can be used to develop a fuller understanding of pressures and their impacts on the river. The process-based approach has enabled us to identify the likely causes of increased sediment production in the river Frome catchment, to determine that transport capacities are too low to mobilise its gravel bed, and that this has resulted in changes

to channel width and sinuosity through an interaction with aquatic vegetation. The flexible nature of the framework allows the assessment to be developed further as additional data becomes available to help, for example, constrain the timing of increase sediment production or to elucidate the pathways, flux and temporal dynamics of sediment delivery to and within the channel

ACKNOWLEDGEMENTS

REFERENCES

Acornley RM, Sear DA (1999) Sediment transport and siltation of brown trout (Salmo trutta L.) spawning gravels in chalk streams. Hydrological Processes 13:447-458

Angus A, Burgess PJ, Morris J, Lingard J (2009) Agriculture and land use: Demand for and supply of agricultural commodities, characteristics of the farming and food industries, and implications for land use in the UK. Land Use Policy 26, Supplement 1:S230-S242

Apitz SE (2012) Conceptualizing the role of sediment in sustaining ecosystem services: Sediment-ecosystem regional assessment (SEcoRA). Science of The Total Environment 415:9-30

Ballantine DJ, Walling DE, Collins AL, Leeks GJL (2009) The content and storage of phosphorus in fine-grained channel bed sediment in contrasting lowland agricultural catchments in the UK. Geoderma 151:141-149

Bilotta GS et al. (2008) Rethinking the contribution of drained and undrained grasslands to sediment-related water quality problems. Journal of Environmental Quality 37:906-914. doi:10.2134/jeq2007.0457

Bilotta GS et al. (2010) Assessing catchment-scale erosion and yields of suspended solids from improved temperate grassland. Journal of Environmental Monitoring 12:731-739. doi:10.1039/b921584k

Bizzi S, Lerner DN (2013) The use of stream power as an indicator of channel sensitivity to erosion and deposition processes. River Research and Applications. doi: 10.1002/rra.2717

Boardman J, Shepheard ML, Walker E, Foster IDL (2009) Soil erosion and risk-assessment for on- and off-farm impacts: A test case using the Midhurst area, West Sussex, UK. Journal of Environmental Management 90:2578-2588. doi:10.1016/j.jenvman.2009.01.018

Brookes A (1987). The distribution and management of channelized streams in Denmark. Regulated Rivers 1: 3–16

Chambers BJ, Garwood TWD, Unwin RJ (2000) Controlling soil water erosion and phosphorus losses from arable land in England and Wales. Journal of Environmental Quality 29:145-150

Collins AL, Walling DE (2007a) Fine-grained bed sediment storage within the main channel systems of the Frome and Piddle catchments, Dorset, UK. Hydrological Processes 21:1448-1459

Collins AL, Walling DE (2007b) The storage and provenance of fine sediment on the channel bed of two contrasting lowland permeable catchments, UK. River Research and Applications 23:429-450

Cooper RJ, Krueger T, Hiscock KM, Rawlins BG (2014) High-temporal resolution fluvial sediment source fingerprinting with uncertainty: a Bayesian approach. Earth Surface Processes and Landforms. doi:10.1002/esp.3621

Cotton JA, Wharton G, Bass JAB, Heppell CM, Wotton RS (2006) The effects of seasonal changes to in-stream vegetation cover on flow patterns and sediment accumulation. Geomorphology **77**:320–334

Deasy C, Quinton JN, Silgram M, Bailey AP, Jackson B, Stevens CJ (2009) Mitigation options for sediment and phosphorus loss from winter-sown arable crops. Journal of Environmental Quality 38:2121-2130. doi:10.2134/jeq2009.0028

Detzner HD, Hakstege AL, Hamer K, Pallemans I (2007) Overview on treatment and disposal options, In: Bortone G, Palumbo L (eds.) Sustainable Management of Sediment Resources, V. 2, Elsevier, Oxford, pp 59-67

Defra (2005) Controlling soil erosion: A manual for the assessment and management of agricultural land at risk of water erosion in lowland England. Department for Environment Food and Rural Affairs, UK. http://archive.defra.gov.uk/environment/quality/land/soil/documents/soilerosion-lowlandmanual.pdf. Accessed on 31 December 2014

Environment Agency (2013) Evidence Summary - Sediment, Evidence for significant water management issues, http://www.geostore.com/environmentagency/Sediment_Evidence_Summary_v2_1_external.pdf. Accessed on 31 December 2014

European Parliament (2000) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 : establishing a framework for Community action in the field of water policy. Brussels, Belgium

Evans R (2004) Outdoor pigs and flooding: an English case study. Soil Use and Management 20:178-181. doi:10.1079/sum2004248

Grabowski RC, Gurnell AM (2014) Characterizing geomorphological change to support sustainable river restoration and management. WIREs Water 1:483-512. doi:10.1002/wat2.1037

Gurnell AM (2014) Plants as river system engineers. Earth Surface Processes and Landforms 39:4-25

Gurnell AM, Midgley P (1993) Estimating variations in catchment erosion and sediment yield over a 50 year period: A GIS approach. British Hydrological Society Fourth National Symposium. 5.1-5.7

Gurnell AM, O'Hare MT, O'Hare JM, Scarlett P, Liffen TMR (2013) The geomorphological context and impact of the linear emergent macrophyte, *Sparganium erectum* L.: a statistical analysis of observations from British rivers. Earth Surface Processes and Landforms 38 1869-1880

Gurnell AM, Peiry J-L, Petts GE (2003) Using historical data in fluvial geomorphology. In: Kondolf GM, Piegay H (eds) Tools in fluvial geomorphology. J. Wiley, Chichester, pp 77 - 101

Gurnell AM, van Oosterhout MP, de Vlieger B, Goodson JM (2006) Reach-scale interactions between aquatic plants and physical habitat: River Frome, Dorset River. Research and Applications 22:667-680

Guzmán G, Quinton J, Nearing M, Mabit L, Gómez J (2013) Sediment tracers in water erosion studies: current approaches and challenges. J Soil Sediment 13:816-833. doi:10.1007/s11368-013-0659-5

Hakstege AL (2007) Description of the Available Technology for Treatment and Disposal of Dredged Material, In: Bortone G, Palumbo L (eds.) Sustainable Management of Sediment Resources, V. 2, Elsevier, Oxford, pp 68-118

Harley JB (1975) Ordnance surevy maps: a descriptive manual. Southampton, Ordnance Survey

Heppell CM, Wharton G, Cotton JAC, Bass JAB, Roberts SE (2009) Sediment storage in the shallow hyporheic of lowland vegetated river reaches. Hydrological Processes 23:2239-2251

Jones JI, Collins AL, Naden PS, Sear DA (2012) The relationship between fine sediment and macrophytes in rivers. River Research and Applications 28:1006-1018. doi: 10.1002/Rra.1486

Julien PY (2010) Erosion and sedimentation, 2nd edn. Cambridge University Press, Cambridge ; New York

Lewin J (2010) Medieval environmental impacts and feedbacks: The lowland floodplains of England and Wales. Geoarchaeology 25:267-311. doi: 10.1002/Gea.20308

Leys A, Govers G, Gillijns K, Berckmoes E, Takken I (2010) Scale effects on runoff and erosion losses from arable land under conservation and conventional tillage: The role of residue cover. J Hydrol 390:143-154. doi:10.1016/j.jhydrol.2010.06.034

Liffen T, Gurnell AM, O'Hare MT (2013) Profiling the below ground biomass of an emergent macrophyte using an adapted ingrowth core method. Aquatic Botany 110: 97-102

Little C, Jonas N (2010) Sediment impact analysis methods (SIAM): Overview of model capabilities, applications, and limitations. 2nd Joint Federal Interagency Conference: Las Vegas, NV, USA

Orr HG, Large ARG, Newson MD, Walsh CL (2008) A predictive typology for characterising hydromorphology. Geomorphology 100: 32–40.

Owens PN et al. (2005) Fine-grained sediment in river systems: Environmental significance and management issues. River Research and Applications 21:693-717

Sear DA, Newson MD, Thorne CR (2010) Guidebook of applied fluvial geomorphology.Thomas Telford, London

Sharley DJ, Hoffmann AA, Pettigrove V (2008) Effects of sediment quality on macroinvertebrates in the Sunraysia region of the Murray-Darling Rivers, Australia. Environ Pollut 156:689-698 doi: 10.1016/j.envpol.2008.06.014

Stevens CJ, Quinton JN (2008) Investigating source areas of eroded sediments transported in concentrated overland flow using rare earth element tracers. Catena 74:31-36. doi:10.1016/j.catena.2008.01.002

Trimble SW (1994) Erosional effects of cattle on streambanks in Tennessee, USA. Earth Surface Processes and Landforms 19:451-464. doi: 10.1002/esp.3290190506

Trimble SW, Mendel AC (1995) The cow as a geomorphic agent - a critical review. Geomorphology 13:233-253. doi: 10.1016/0169-555x(95)00028-4

Walling DE (2013) The evolution of sediment source fingerprinting investigations in fluvial systems. J Soil Sediment 13:1658-1675. doi: 10.1007/s11368-013-0767-2

Walling DE, Amos CM (1999) Source, storage and mobilisation of fine sediment in a chalk stream system. Hydrological Processes 13:323-340

Figure 1 – The River Frome catchment is delineated into 3 landscape units based on elevation, geology and land cover/use (L1 to L3), 6 segments based on valley setting and major tributary confluences (S1 to S6) and 17 reaches based on planform and longitudinal discontinuity (e.g. major weirs – indicated as open rectangles).
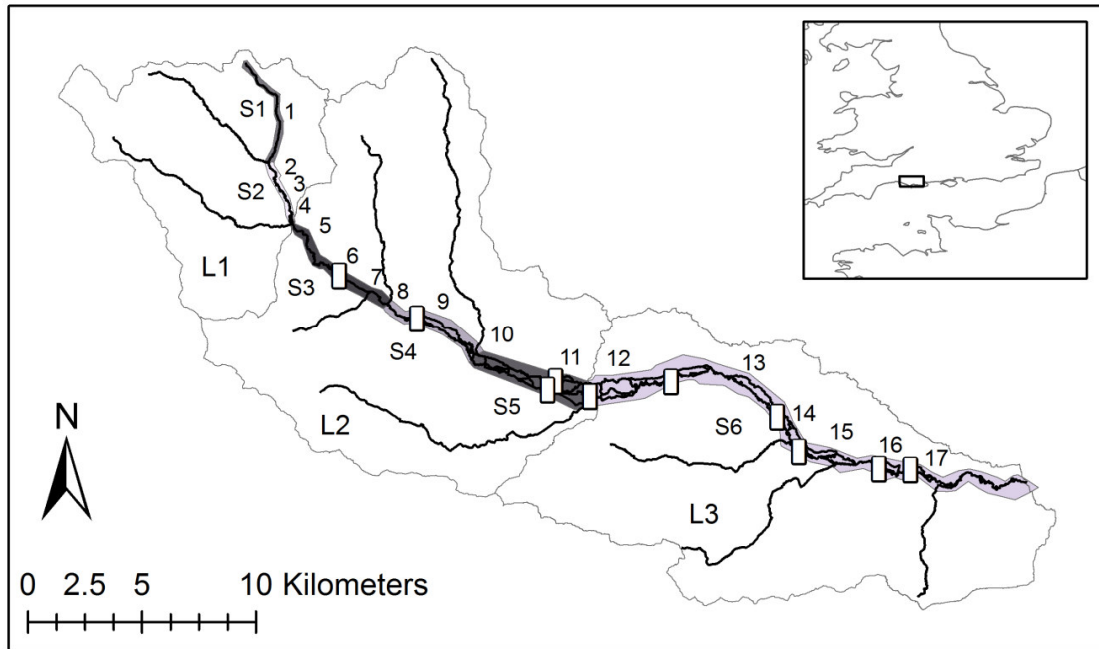

Figure 2 – Change in land cover based on the First Land Utilisation Survey (1940) and UK Countryside Surveys (1990, 2000, 2007)
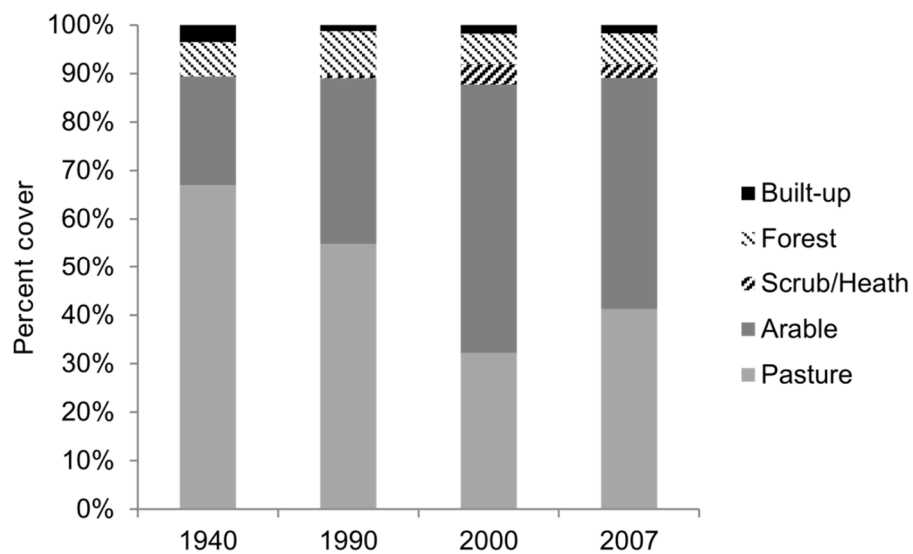
Figure 3 Agricultural land use for the county of Dorset over the last century by (a) area of land under different land use types, (b) area of arable land under different crop types, (c) livestock numbers for cattle, sheep and pigs. (d) Area of arable land cultivated and yields for wheat for England and Wales.
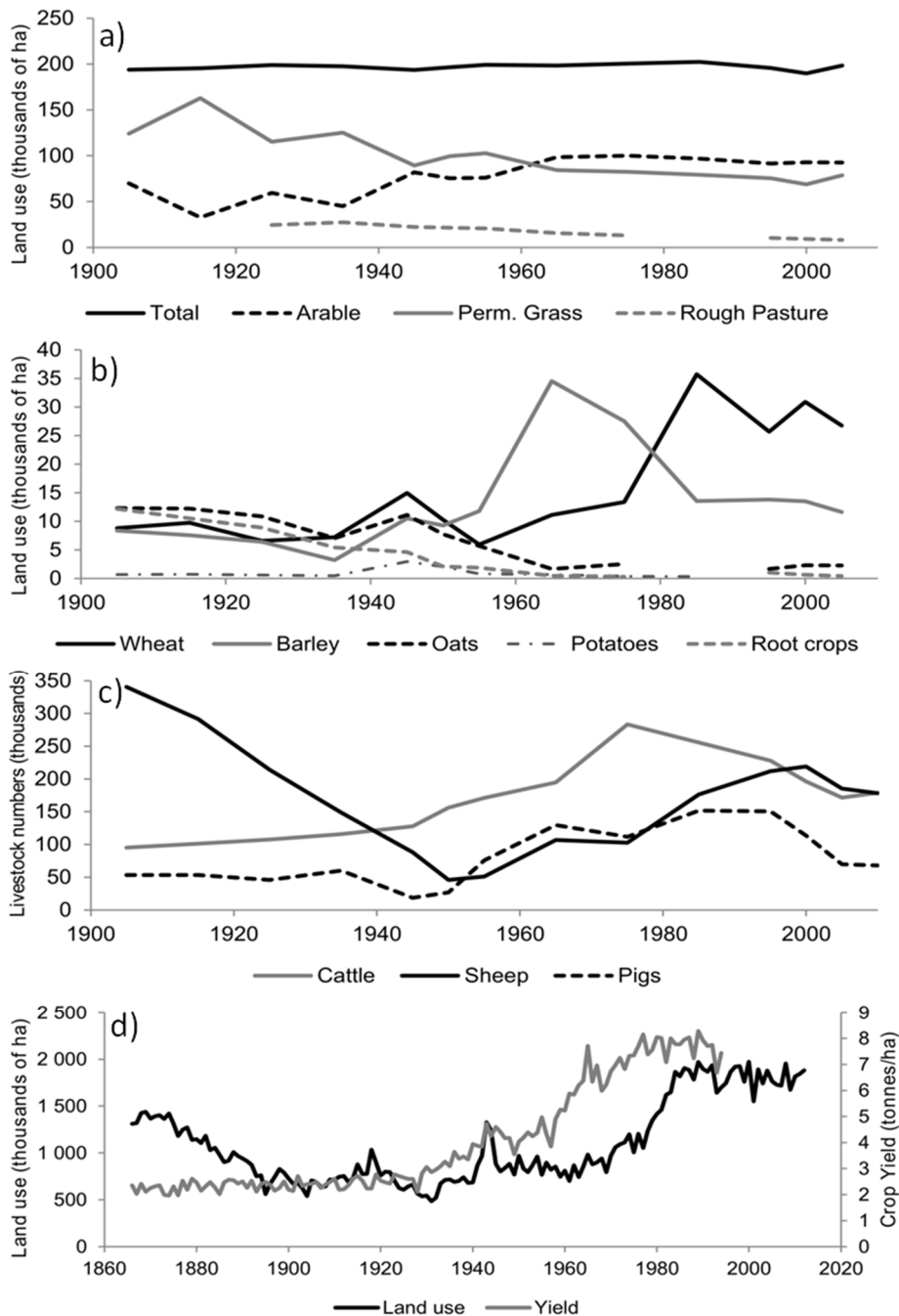
Figure 4 Average specific stream power and shear stress for the 17 reaches of the River Frome
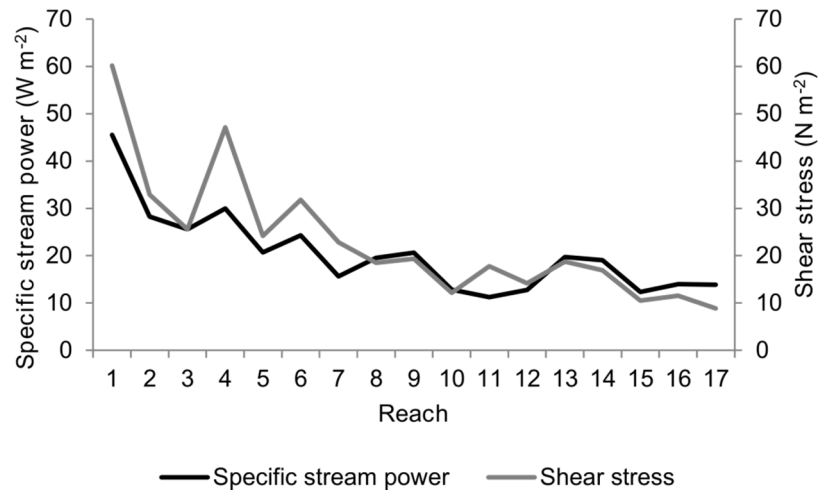

Figure 5 Changes in channel (a,b) area, (c,d) length and (e,f) width for the River Frome by reach for the periods (a,c,e) 1889-1960/75 and (b,d,f) 1960/75-2013.
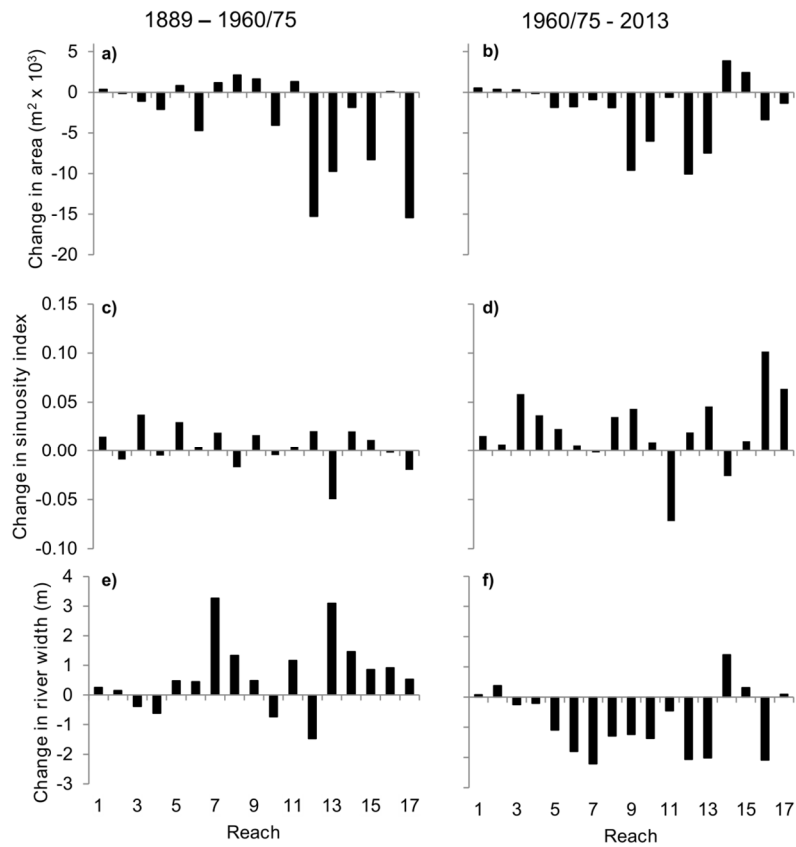
Figure 6. (a) Conceptual diagrams of the changes in channel form and floodplain and aquatic vegetation over time in cross-section (top) and plan (bottom) views. The "past" scenario represents a time period prior to intensive agriculture. The "future" scenario assumes current management practices plus a relaxation of riparian vegetation maintenance/grazing. (b) A short section of the River Frome within reach 6 showing narrowing, increasing sinuosity and landform development within the channel, which was probably mainly initiated by the growth of Sparganium erectum at the edges of the river bed.