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Comparison of observed and DEM-driven field-to-river routing of flow from eroding fields in an arable lowland catchment

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Abstract

Field-to-river flow of runoff and sediment in a lowland arable catchment in the south of England is explored from both field and modelling perspectives. Routes observed to be taken by flow and sediment on five study areas include many interactions between flow and 'landscape elements' (LEs), including those (field boundaries, paths, roads) of anthropogenic origin. We satisfactorily replicated observed flow routes using a simple steepest-descent-with-overtopping model with a 5m DEM. This was unexpected, considering the narrowness of linear LEs such as paths and tracks. However LE attributes showed considerable sensitivity: changing just one attribute of a single LE-flow interaction notably altered the route taken by simulated flow, while changing other LE attributes notably affected synthetic hydrographs for flow reaching the river, suggesting similar impacts upon transported sediment reaching the river. Thus while simple steepest-descent and overtopping permits satisfactory replication of observed flow routes, it is likely that more explicit representation of LE-flow interactions is necessary in order to adequately capture the dynamics of field-to-river runoff and sediment transport, as must be done by catchment-scale erosion models. Doing so will enable such models to better represent runoff speed and volume, and the flux and size distribution of transported sediment, with the aim of overcoming broad limitations of such models as noted in earlier model validation studies. Finally, we consider the representation of some LE-flow interactions in several catchment-scale models, and discuss the ways in which such representation might be improved.

1. Introduction

The route taken by runoff and accompanying sediment, as it flows from an eroding field to a river, is determined by the flow's gravity-driven interaction with the earth's surface. Few soil erosion scientists would disagree with this statement. However, as in many scientific domains, the devil is in the details: here, in the phrase 'interaction with the earth's surface'. In an arable catchment, a field-oriented researcher may well see and describe a plethora of complex interactions between flow and those elements of the landscape encountered by the flow. A modeller must, of necessity, simplify; thus a modelled representation of the same catchment can focus only on a subset of the interactions noted by the field worker, and each interaction can only be relatively simply described. Neither viewpoint is more correct than the other.

However, few individuals possess both modelling skills and field-based expertise in erosion. As the range of techniques available to the field worker expands, and the complexity of models and associated technologies (e.g. GIS) increases, an ever smaller number of individuals are able to gain the skills needed to become competent in both domains. Thus there has been a recent tendency for field and modelling perspectives on soil erosion to drift apart. This drift has generated some contentious, even acrimonious, discussion (e.g. Evans and Boardman, 2016; Panagos et al., 2016) There is a corresponding need to reconcile these viewpoints if we are to make progress regarding the large gaps that still remain in our knowledge of soil erosion by water and its impacts: gaps in both process understanding (Kinnell, 2020) and management (Boardman and Vandaele, 2020; Boardman and Foster, 2021). Just as a house divided against itself cannot stand, a divided area of science cannot progress.

This study brings together field and modelling perspectives to explore field-to-river flow of runoff and sediment in a lowland arable catchment. The connectivity of sediment sources and sinks is the focus of much current research, in a range of geomorphological contexts (e.g. Turley et al., 2021; Uber et al., 2021; Wang N. et al., 2021). Yet few studies – in part because of the above-mentioned divide between field- and model-based researchers – explicitly compare observed and modelled routes of flow. We first discuss the interaction of this flow with 'landscape elements' (LEs), many of which are of anthropogenic origin. Next we compare – from the viewpoint of flow's interaction with LEs – the routes taken by flow as determined by field observation and as predicted by simple topography-driven modelling. We then consider the implications of LE-flow interaction for other attributes of field-to-river flow, and place our comparison in the wider context of catchment-scale erosion model validation studies. Finally we consider the implications for future attempts to better understand field-to-river movement of runoff and sediment, in a manner which brings together both field- and model-based perspectives.

1.1 Landscape elements and field-to-river movement of runoff and sediment in lowland arable catchments

In the long term, all hillslopes in temperate environments are fully connected to the wider hydrological system, by means of overland and sub-surface flow pathways (Chorley, 1978). Thus long-term hydrological connectivity (here considered to be "the internal linkages between runoff and sediment generation in upper parts of catchments and the receiving waters": Croke et al., 2005) is perfect, because all runoff which leaves any hillslope and is not lost to evaporation eventually finds its way to a permanent channel. The same is true for sediment, although there may be lengthy periods of within-catchment storage at long (10^2-10^6 yr) timescales (e.g. Schumm and Lichty, 1965; Trimble, 1983, 2012; Reid and Dunne, 2016). But from a shorter-term perspective, the within-catchment routing of runoff and associated sediment is greatly complicated by interactions with a variety of landscape elements (Table 1). The result is imperfect connectivity of overland flow and transported sediment over short to medium timescales: decidedly so, for the arable lowland catchments which are the focus of this study.

Mainly or wholly:	Barrier	Booster
Natural	• Soils with low erodibility (e.g. with high natural organic matter content) • Soils with high permeability • Low-gradient topography (< 2°) • Non-convergent planform topography • *Topographic depressions (sediment storage)* • High-density natural vegetation • Absence of pre-existing rill / gully network • Low drainage density of permanent channels • Natural flood management	• Soils with high erodibility (e.g. with low natural organic matter content) • Soils with low permeability • High-gradient topography (> 2°) • Convergent planform topography • Animal scrapes / burrows • Low-density natural vegetation • Pre-existing rill / gully network • High drainage density of permanent channels
Anthropogenic	• Non-arable land use (forest / grassland) • *Contour plough and drill across slope* • *Impermeable hedgerows / field boundaries* • Detention ponds / wetlands • Buffer strips / beetle banks (mid-field and edge of field) • Arable tramline disruption • Uncultivated field corners • Remove plough pan • *Mobile / permanent field edge barriers (e.g. straw bales / wicker fencing)* • Post-harvest compaction management / cover crops • *Path / road / railway / canal embankments* • Path / road runoff diversion / management	• Arable land use • Downslope cultivation / crop treatment • Soils with very high erodibility, due to agricultural practice (e.g. crusted soils, soils with very low organic matter content) • Permeable hedgerows / field boundaries / gateways • Development of plough pans • Arable wheelings and tramlines • No post-harvest compaction management / winter crop cover • Land drains / mole ploughing • Forest management tracks / thinning / logging operations • Paths / roads / sunken lanes • Ditches / culverts

Table 1. Landscape elements (LEs) commonly found in lowland arable catchments, categorised by origin and by effect on the connectivity of field-to-river flow. Italicized barrier LEs may become inoperative after some threshold is exceeded

Issues relating to the connectivity of the flow of runoff and sediment from source to a permanent channel – and so, by implication, to the detailed routing of such flow (e.g. Heckmann et al., 2018) – have recently been much debated in the geomorphological literature. Various themes are prominent: hillslope to channel connectivity in 'natural' or grazed environments (e.g. Harvey, 2002, 2012; Shook et al., 2021); alpine environments, which often involve debris flow activity (Berger et al., 2011; Cavalli et al., 2013; Croke et al., 2013; Heckman and Schwanghart, 2013; Turley et al., 2021); forested catchments and the role of roads and culverts (Galia et al., 2017); channel and floodplain relationships (Hooke, 2003; Sandercock and Hooke, 2011) and connectivity in semi-arid environments (Lesschen et al., 2009; Medeiros et al., 2010). Temperate lowland arable catchments have been somewhat neglected, though with some notable exceptions: Alder et al., 2015; Couturier et al., 2013; Gascuel-Odoux et al., 2009; Delmas et al., 2012; Sherriff et al., 2019; Souchere et al., 1998.

In such catchments, each LE encountered by field-to-river flow and transported sediment may be located within a spectrum which ranges from the wholly natural in origin (e.g. the planform convergence of coarse-scale topography) to the wholly anthropogenic (e.g. field boundaries, paths, roads, ditches and culverts). The importance of anthropogenic LEs in influencing the routing – and hence the connectivity – of flow in lowland urban catchments has long been recognised (e.g. Graf, 1977; McCuen, 1979; Emerson et al., 2005; Alder et al., 2015; Meierdiercks et al. 2017). We suggest that anthropogenic LEs are also important in non-urban lowland arable catchments.

The classic work of Trimble (1983), with its strong emphasis on sediment storage and release of sediment from storage sites, also focuses on this type of landscape. While Trimble does not use the terms specifically, connectivity and (dis)connectivity of sediment fluxes in an arable landscape are major themes of his study. Long-term issues of connectivity in similar landscapes are also addressed by Houben (2008) and Houben et al. (2009), and proposals to quantify connectivity are put forward by e.g. Borselli et al. (2008). Flow networks across an arable landscape are modelled, using map-derived data, by Gascuel-Odoux et al. (2009), who considered varying land uses and representations of field boundaries and roads in constructing networks of connectivity. Another example of this approach is the work of Steegen et al. (2001) in two small catchments in Belgium. These authors recognise the importance of road networks and the temporally variable patterns of land use and crop cover in influencing connectivity and therefore the export of sediment and phosphorus (cf. Gruszowski et al., 2003; Biddulph et al., 2017). Studies by Phillips et al. (1999a,b), Slattery et al. (2002) and Swiechowicz (2002) show considerable evidence that soil eroded on agricultural fields does not travel far, and is either stored within the field in ditches, as colluvial deposits in depressions, or at the margin of hillslopes and flood plains. In the UK, Evans (1990b) has shown that transport of soil beyond the field is related to texture, with fine-grained sediment more likely to exit the field. More recent work by Evans (2017) in the Wissey catchment, East Anglia, UK, shows the prevalence of runoff and wash even with little rilling on soils of low erodibility, thus transferring clay and fine silt-sized particles, nitrates, phosphorus and pesticides to ditches and streams even during low magnitude rainfall events. In some arable situations and locations most eroded material is stored, in others (such as our study area) anthropogenic modification of the landscape creates routes through which much eroded soil is moved to rivers.

Table 1 summarises, for temperate lowland arable catchments, the most common LEs and their impact upon field-to-river connectivity of runoff and associated sediment. Both within-field LEs, and LEs encountered after flow has left the field, are considered. However we do not attempt to identify the effects of tillage practices or crop type on soil loss (see Rickson 2014 for a discussion).

Some LEs, such as topographic gradient/planform convergence, are able both to both boost (i.e. enhance) connectivity and to form a barrier to connectivity. But others, such as field boundaries, can behave in a way which is too complex to be captured by a simple dichotomy. Open fences may have almost no effect on runoff, while ancient field boundaries may form an almost complete barrier to runoff except in the most extreme rainfall conditions. However the permeability of any field boundary becomes unimportant if flow passes through a gateway or gap in the field boundary. Hence changes to the physical location of gateways within a field may have a major effect on sediment delivery.

While all LEs listed in Table 1 may have been influenced to some extent by human activity – even natural streams may have had their course straightened – LEs such as roads, culverts, ditches and hedgerows are wholly anthropogenic in origin. In many parts of the UK they have been present since Mediaeval times (Hoskins, 1955) or even the Bronze Age (Bell, 2021). The only LE which, at most locations, is unlikely to have been much modified by human activity is the planform convergence and gradient of coarse-scale topography. But even for this there are exceptions. In some agricultural landscapes, contour ploughing and terracing significantly alter topography (although contour ploughing on steep slopes may increase erosion rates and enhance connectivity: Farahani et al. 2016). Large impoundments may also affect topography through longer term adjustments of the valley long profile and the preferential storage of sediment (Foster, 2010; Foster et al., 2019). Anthropogenic boosters and barriers in Table 1 include both the inadvertent (e.g. roads, tracks and sunken lanes) and the deliberate (e.g. farm ponds and buffer strips).

From the perspective of field-to-river movement of runoff and sediment, the most important LE other than attributes of coarse topography is the emergent development of a permanent drainage network (including, in some locations, now-dry valleys) which includes major river channels and floodplains. In low-stream-order catchments, floodplains are poorly developed and generally provide ineffective barriers between hillslopes and channels. In higher-order basins, floodplains occupy a greater proportion of the catchment and in their natural state constitute more effective barriers. However in many lowland catchments, connectivity has been enhanced by the construction of ditches and drains and/or the straightening of natural streams across the floodplain, which directly link hillslope fields to major rivers.

Interactions between LEs, and runoff and transported sediment, may vary greatly over time. This results in patterns of hydrological and sedimentological connectivity which shift both temporally and spatially (Wainwright et al., 2011). For example, field boundaries may be overtopped or leak only above a critical rainfall (amount / intensity) threshold while the role of ditches varies depending on whether they are clogged or have recently been cleared (e.g. Cappiella and Slattery 1999, Slattery et al., 2002). Breaks in connectivity, i.e. within-catchment sinks for runoff and sediment, may be created both by LEs which block flow (e.g. impermeable field boundaries, clogged ditches), and also by closed topographic depressions (within-catchment sinks or 'blind pits'). While closed topographic depressions can form long term sediment stores (e.g. Kołodyńska-Gawrysiak et al., 2017), in arable catchments they are often drained by culverts or other subsurface engineering works; these may vary in efficiency with time. Anthropological 'blind pits' include constructed farm ponds and wetlands, field edge or mid field buffer strips and beetle banks.

In addition to these within-system drivers, shifts in connectivity and routing also occur in response to external drivers such as the intensity and duration of rainfall, and economics and policy as they affect land use: this includes changes to land drainage, ditching practices, and implementation of sediment control measures such as buffer strips and edge-of-field sediment traps. Both internal and external drivers may operate to change flow connectivity and routing in a temporally smooth way, or in a temporally step-wise way (Thornes and Brunsden, 1977) when thresholds are crossed. Some LEs also have a 'memory': the permeability of field boundaries may depend not just on event runoff, but also on pre-event hydrological conditions. LE behaviour may even depend on runoff and sediment transport during more than one previous event (e.g. if trash has been deposited, blocking a culvert; or if earlier flow created a gap in a field boundary).

1.2 Implications of LE-flow interactions for flow routing

The above-discussed complexity of LE-flow interactions suggests considerable difficulty in reliably predicting the routes by which runoff and eroded sediment generated by a given rainfall event will leave fields and move to permanent watercourses. Prediction of a field's contribution of runoff and sediment to the catchment total is also made more difficult, since this contribution depends not just on the severity of erosion on the field, but also on the number and characteristics of the LEs which are encountered on its field-to-river flow path. Prediction of both routes and per-field contributions for multiple events, as is needed for long-term quantification, is even more challenging.

Thus from the perspective of LE-flow interactions, major problems are likely in reliably capturing the dynamics of within-catchment runoff and sediment movement (e.g. Sidle et al., 2017) in lowland arable catchments. Clearly, every catchment-scale erosion model, whether empirical or process-based, must be able to capture these dynamics. But since LE-flow interactions are described in – at best – an inconsistent way in such models (section 4.2), the obvious conclusion is that models should be incapable of producing good results, in the sense of an adequate match between observation and model output.

Yet catchment-scale erosion models have been, and are, capable of producing good results (section 4.1). This apparent conundrum led us to compare – with a focus on LE-flow interactions –

observed flow routing (section 2) with modelled flow routing, using the simplest possible approach (section 3).

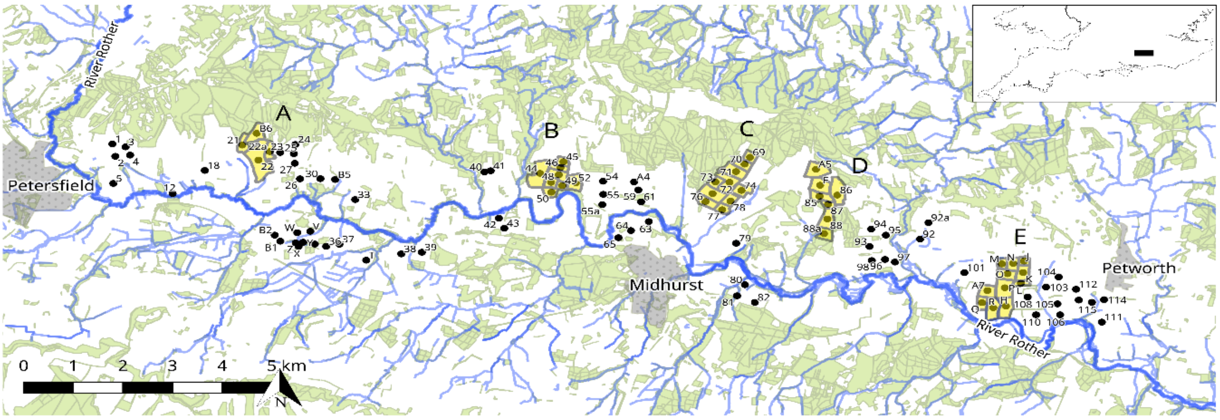


Figure 1 The study area: part of the catchment of the River Rother in southern England. The Rother flows from west to east. Woodland is green. Fields connected to the Rother are marked with dots, fields within the sample areas A-E are shaded yellow

2. Observed field-to-river routing in a study catchment

Our study catchment is that of the River Rother in the south of England (Figure 1 and Table 2). It is in the highest risk category for both sediment load and sediment accumulation in the national risk assessment analysis of Naura et al. (2016). The area with a history of erosion is close to the River Rother and is dominated by arable crops, with few areas of woodland, heathland or permanent grassland. Infiltration rates on these arable fields are low – either because of surface crusting or from the inability of subsoiling to break up shallow impermeable plough pans – thus generating surface runoff from rapidly saturated soils. Runoff can result from by both infiltration-excess and/or saturated conditions, depending on cultivation and harvesting techniques and time within the growing season. Hillslopes are therefore potential sources of runoff and sediment reaching the Rother, both because of the frequent failure of field boundaries to contain runoff, and because of post-1945 enlargement of fields by the removal of hedges (Boardman et al., 2009). A variety of LEs, mostly anthropogenic, are found within the catchment; many of which are commonly present in other lowland arable catchments. Land drains are however absent.

Area	342 km^2
Location	Mostly within the southern English counties of Hampshire and West Sussex, see Figure 1.
Climate	Temperate, with 910 mm average annual rainfall at Petworth, 1981-2016.
Geology and soils	Lower Greensand lithologies of Cretaceous age on which are developed well-drained sandy and coarse to fine sandy-loam soils which are at high risk of erosion (Jarvis et al., 1984; Evans, 1990a).
Topography	Altitude ranges from 10 to 160 m above sea level with generally gentle slopes (2-5°).
Current land use	36% grassland, 27% arable and horticulture, 30% woodland (Evans, 2019).
Past land use	Compared with the mid-1930s (LUS, 1935), 47 (29%) of currently arable fields were not then arable, a further 22 (13%) were only partly arable.
Crops grown	Cereals (39% of the total number of fields), maize (17%), grass (10%), vegetables and salad crops (8%) and asparagus (7%). Data for the summer of 2019.
Characteristics of arable fields	Median slope 3.3°, median size 9.5 ha. Typically separated by hedges or fences of varying permeability.
Impacts of erosion	Runoff from eroding arable fields results in off-site impacts: muddy flooding of property and pollution of freshwater systems (Boardman et al., 1994, 2009).

Table 2. Characteristics of the River Rother study catchment

2.1 Observed flow routes: methodology

We constructed a database of historically eroded fields from the late 1980s to the present. This utilised the maps of Guerra (1991) for the years 1987 and 1988 for the area around Rogate, and the maps of Shepheard (2003) for the year 2000, which were based on areas sampled from air photographs. Shepheard also mapped runoff from fields that impacted upon roads and watercourses. Google Earth images for 2001 and 2005, and for more recent years, were used to check and supplement these data (Boardman, 2016). In the years 2013, 2014 and 2015, Boardman (unpublished) carried out surveys of eroding fields in parts of the Rother valley. Since the summer of 2015 the same author has surveyed all fields with a history of erosion, recording land use and any erosion, at six-monthly intervals (Boardman et al., 2020). Erosion is estimated using the volumetric method described in Boardman and Evans (2020). The database consists of 194 fields for which there is evidence of erosion since 1987, all of which were arable at the time of erosion.

Field surveys were used to trace the pathways by which runoff and sediment leaves each field and potentially reaches the Rother. Flows were mapped after erosion events: Google Earth and air photographs were of value in this exercise. By ‘potentially’ we mean that at least once since 1987 there has been observation of, or inferred evidence of, runoff (usually with sediment) leaving the field; travelling either directly to the river, or to another field which is itself potentially connected to the river. We then chose five ‘sample areas’ (A to E) within the catchment in order to illustrate connectivity between fields and river.

2.2 Observed flow routes: results

Of the 194 fields with a history of recent erosion, 45 have been subject to field boundary changes in the period 1997 to 2009. Six of the fields had new boundaries (gains) and the rest were losses. These changes affect flows of water and sediment and therefore the routing of flow from fields to watercourses and the river. Field boundaries were classified as either ‘down slope’ or ‘across slope’, the latter being potentially more significant in terms of inhibiting connectivity. Across-slope boundaries had been removed from 23 fields between 1997 and 2009. Across-slope gains are minor, and new field boundaries tend to be inefficient as barriers to runoff until they are well established.

Runoff and erosion are frequent occurrences in the area with spreads of soil from farmers’ fields seen every year on major and minor roads. Major events in 2000 and 2006 are described in Boardman et al. (2009): it seems likely that, in those winters, almost all arable fields were bare or were planted with crops that were subject to significant and visible erosion and deposition. During the period 2015-2020, 103 fields showed visible evidence of erosion on at least one occasion, out of 188 fields monitored (55%).

Fields were also assessed in terms of their potential to increase connectivity (i.e. to act as boosters: Table 1) with fields downslope or to streams, ditches, roads, gateways and / or culverts linking to the river Rother. Fields directly connected to the main Rother were counted separately. In total, six different LEs depicted in Table 1 were identified and the number of fields connected by these LEs were counted in order to identify the most and least common LE connectivity occurrences in the database of surveyed fields. In several cases, connectivity was provided by more than one LE (e.g. both a permeable field boundary and a road), in which case both elements were counted. Of the 188 fields surveyed, 127 (68%) had clearly identified connectivity to a downslope field or LE. From these 127 fields, a total of 156 connectivity elements were identified. These are categorised in Figure 2.

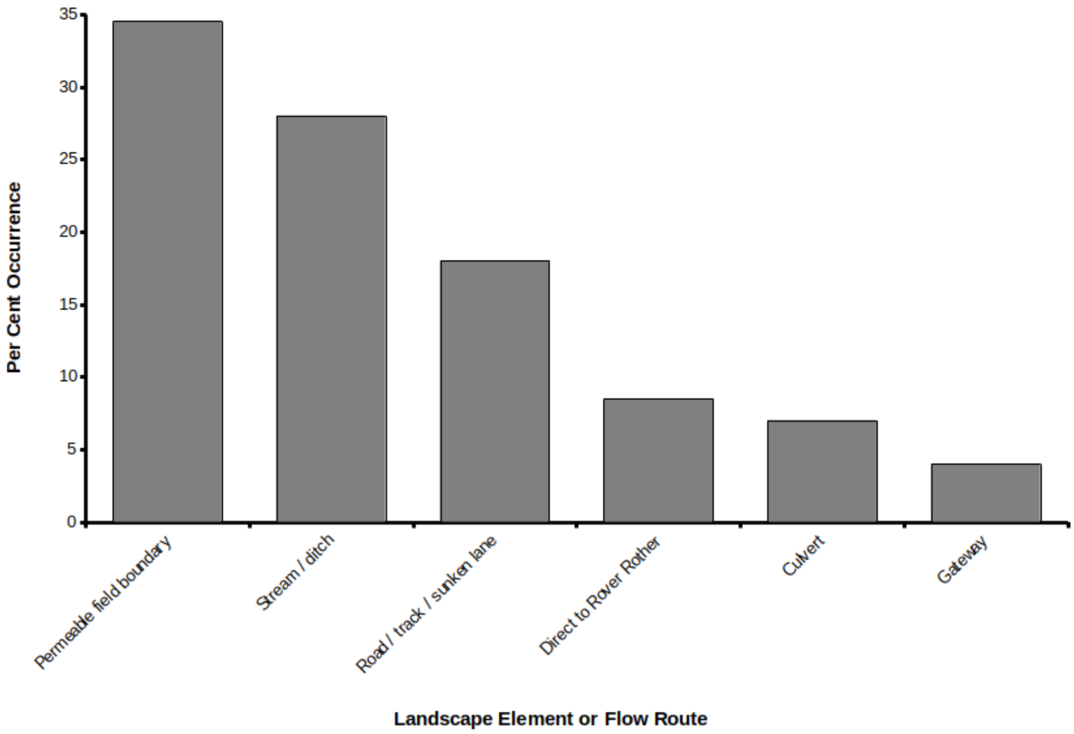
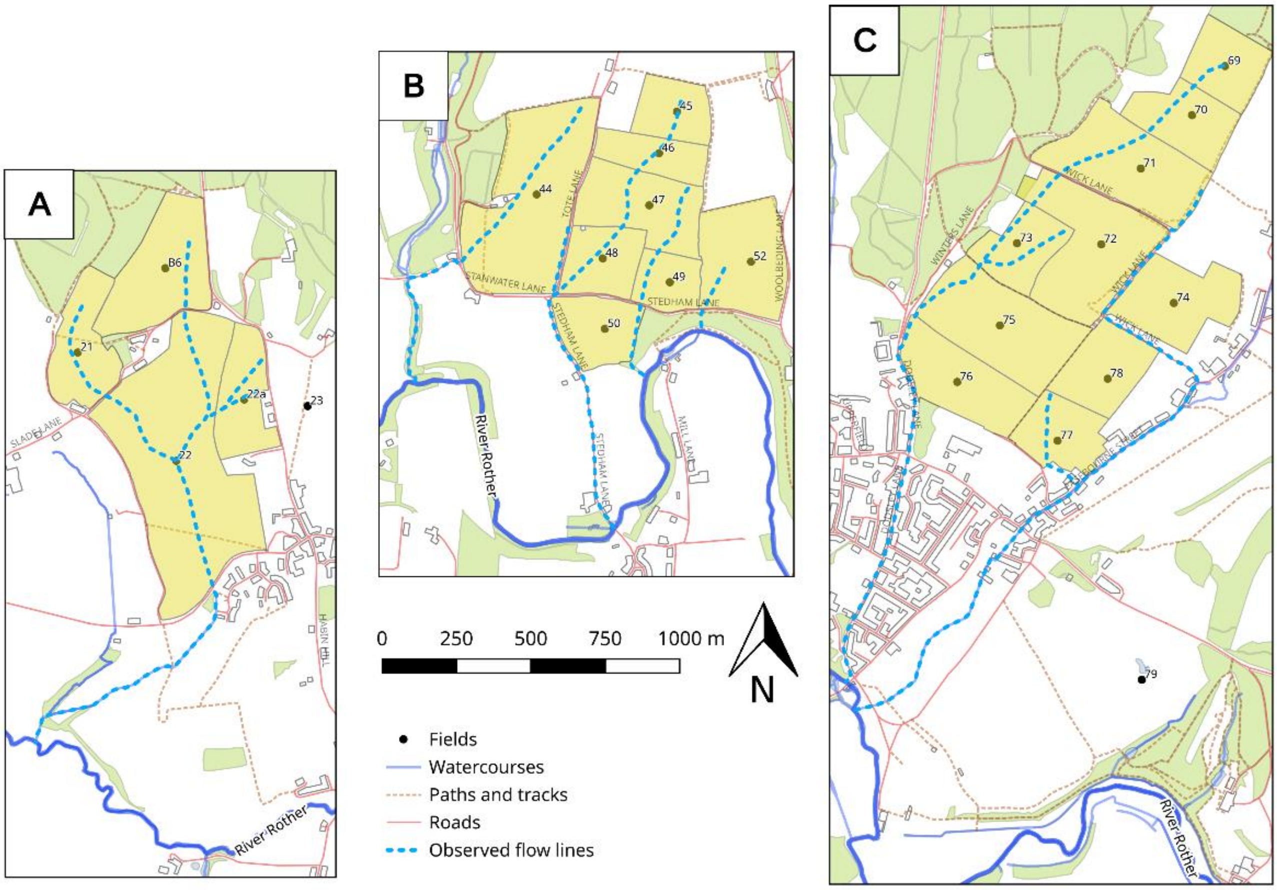


Figure 2. A categorisation of the anthropogenic landscape elements which boost connectivity in the study area


A
B
C
0
250
500
750
1000 m
N
Fields
Watercourses
Paths and tracks
Roads
Observed flow lines
River Rother
River Rother
River Rother

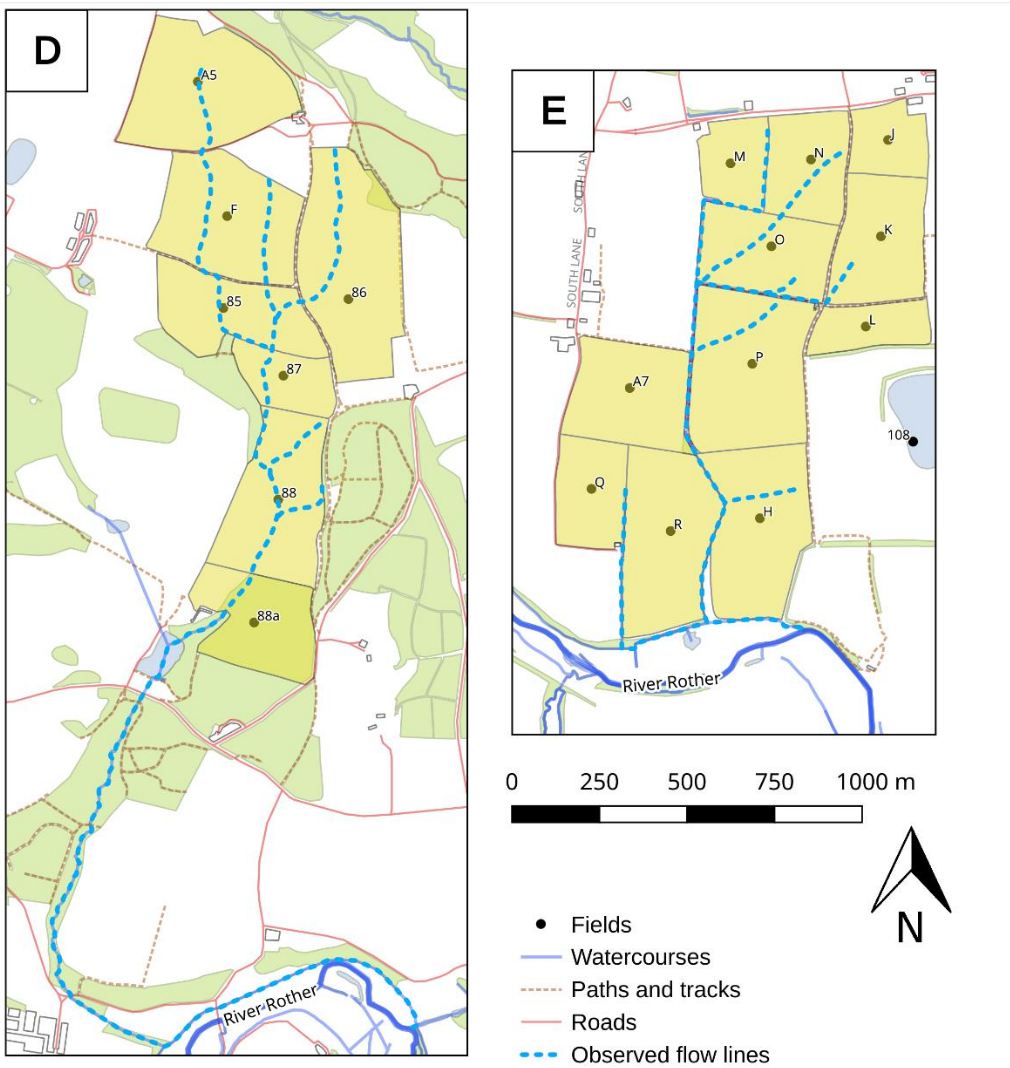


Figure 3. Observed flow routing in the five sample areas. (A) Adjacent to the village of Rogate, runoff generated on fields 21, 22a and 22 flows beneath the main A272 road via a drain to a permanent stream and then to the Rother. Runoff from 21 and B6 to 22 frequently crosses a minor road. (B) Runoff from a series of fields (45, 46, 47 and 48) passes through permeable hedge lines to reach the SW corner of field 48 where a retention pond overflows into a sunken lane, thence via Stedham Lane to the Rother at Stedham Bridge. Runoff from field 47 also reaches field 49, crosses Stedham Lane and thence via field 50 to the Rother. Runoff from field 52 exits the field in a drain and passes under Stedham Lane and thence to the Rother. (C) Flow from a long series of fields (69, 70, 71, 72, 73, 75 and 76) reaches the major road A286, travels along it for 1.3 km, and enters the river at the bridge over the Rother. (D) Runoff from fields A5, F, 85, 86, 87, 88, 88a reaches Benbow Pond which drains southwards via a culvert under the A272 to a permanent stream and thence to the Rother. (E) Runoff from fields N, M, O, P, A7, R and H travels by a series of well-maintained ditches to the stream that runs between fields R and H and thence to the Rother.

Figure 3 shows spatial patterns of flow routing in the five sample areas (A to E) within the study catchment. In each sample area, one or more observed or inferred flow lines begins in a field, may pass through other fields, and either merges with other flow lines or terminates at the River Rother. Land use uphill from each sample area is non-arable. There is no run-on into the start-of-flowline fields from uphill i.e. each sample area is hydrologically a complete sub-catchment. Within-field portions of these observed flow paths do not consider the influence of tillage-created microtopography on flow direction.

For the fields depicted in Figure 3B we have direct observational evidence of flow to the river in the winter of 2006-7 (Boardman et al., 2009). Similarly, the fields shown in Figure 3C delivered muddy sediment to the river in 2014 (Boardman and Vandaele, 2015). For the three other sample areas, the potential connection is inferred, based on observation of erosion and runoff on all fields and the mapped routeways of flow toward the river. Thus there is greater certainty regarding the flow patterns identified in sequences 3B and 3C, and less certainty regarding the patterns in 3A, 3D, and 3E. However, we choose here to describe all five connectivity sequences as 'observed'.

Field or landscape element	Flow in?	Flow out?	Comment	Effectiveness as a conduit or generator of flow controlled by:	Can be identified from:	Usefulness in preventing runoff and sediment from entering river
Hillslope field, no flow from upslope	N	Y		Land use, gradient, soil surface characteristics	Map	Only if farmer willing to change land use, or to create barriers
Hillslope field, flow from upslope	Y	Y		Land use, gradient, soil surface characteristics	Map	Only if farmer willing to change land use, or to create barriers
Field boundary, fully permeable	Y	Y	Flow of any volume can cross	Nature of boundary	Field survey essential	Could be blocked
Field boundary, semi-permeable	Y	Y	Only flow above some threshold volume or depth can cross	Nature of boundary	Field survey essential	Could establish grass buffer strip
Ditch	Y	Y	Not usually marked on maps	Whether recently cleaned of sediment and vegetation	Field survey essential	Not useful
Stream	Y	Y	Always on map		Map	Not useful
Flow over road or track	Y	Y		Very effective	Field survey essential	Could be dammed (but this could lead toflooding)
Flow under road or track	Y	Y		Very effective	Field survey essential	Could be blocked (but this could lead to flooding)
Flow along road or track	Y	Y		Very effective	Field survey essential	Could be dammed, need to prevent flow onto road
Flood plain (or terrace) field	Y	Y	Low gradient, flow enters from upslope creating rills or ephemeral gully	Land use, soil surface characteristics	Map	Establish grassed area along former ephemeral gully
River	Y	N		N/A	Map	N/A

Table 3. Landscape elements in the five sample areas: an idealised sequence

Table 3 categorises LEs identified in the five sample areas, in an idealised field-to-river sequence. None of the flow paths in Figure 3 includes every element from Table 3.

3. Modelling the interaction between flow routing, topography, and landscape elements

Next, we compare the observed patterns of field-to-river flow routing on these five sample areas with simulated patterns, ideally making as few model-centric assumptions as possible. We constructed a GIS-based model ('FieldFlow') which is, conceptually, extremely simple. When run in 'topography only' mode, the model merely traces the field-to-river route taken by runoff by following the downhill line of steepest slope. Thus FieldFlow barely qualifies as a hydrological model; it has no erosion component. FieldFlow was built using Python 3.8.6 and QGIS 3.10.9; source code and some data are available at https://github.com/davefavismortlock/FieldFlow.

Role in FieldFlow	Used in FieldFlow mode	GIS Layer	Source	Type
Used in flow routing	'Topography only' and 'LE and topography'	DEM	OS Terrain 5 (horizontal resolution is 5 metres)	Raster
	'Topography only' and 'LE and topography'	Streams and river	OS MasterMap Water Network: watercourse links	Vector
	'LE and topography' only	Field boundaries	Hand digitized, from OS MasterMap 1:1000 raster data	Vector
	'LE and topography' only	Roads	OS VectorMap Local: road centrelines	Vector
	'LE and topography' only	Tracks and paths	Hand digitized, from OS MasterMap 1:1000 raster data	Vector
Visualisation only	'Topography only' and 'LE and topography'	Observed flow lines	Hand digitized	Vector
	'Topography only' and 'LE and topography'	Background	OS MasterMap 1:1000	Raster

Table 4. Data used by FieldFlow

Data used by FieldFlow are listed in Table 4. FieldFlow requires only two GIS layers in its ‘topography only’ mode: raster topography, plus a vector layer of permanent watercourses including, as a minimum, a target river. LEs – including field boundaries – are ignored. FieldFlow also displays other GIS layers for visualisation purposes. Our representation of topography was a readily available DEM (Table 4) with 5m horizontal resolution, not smoothed or processed in any way. The vector layer showing the centrelines of permanent watercourses was obtained from the same source.

For each sample area, FieldFlow was set up to trace flow only from those fields which have been observed to generate flow which reaches the Rother. For each of these fields, flow is assumed to begin at an arbitrarily-located single point within the field: the centroid of the raster cell of the DEM which is 0.75 of the way along a line joining the field’s centroid and the highest point on the field’s boundary. Flow is then simply routed downhill from cell to cell of the DEM (since within-field effects of tillage orientation are ignored) with the direction of cell-to-cell flow determined by selecting the steepest downhill path to the centroid of one of the eight adjacent raster cells.

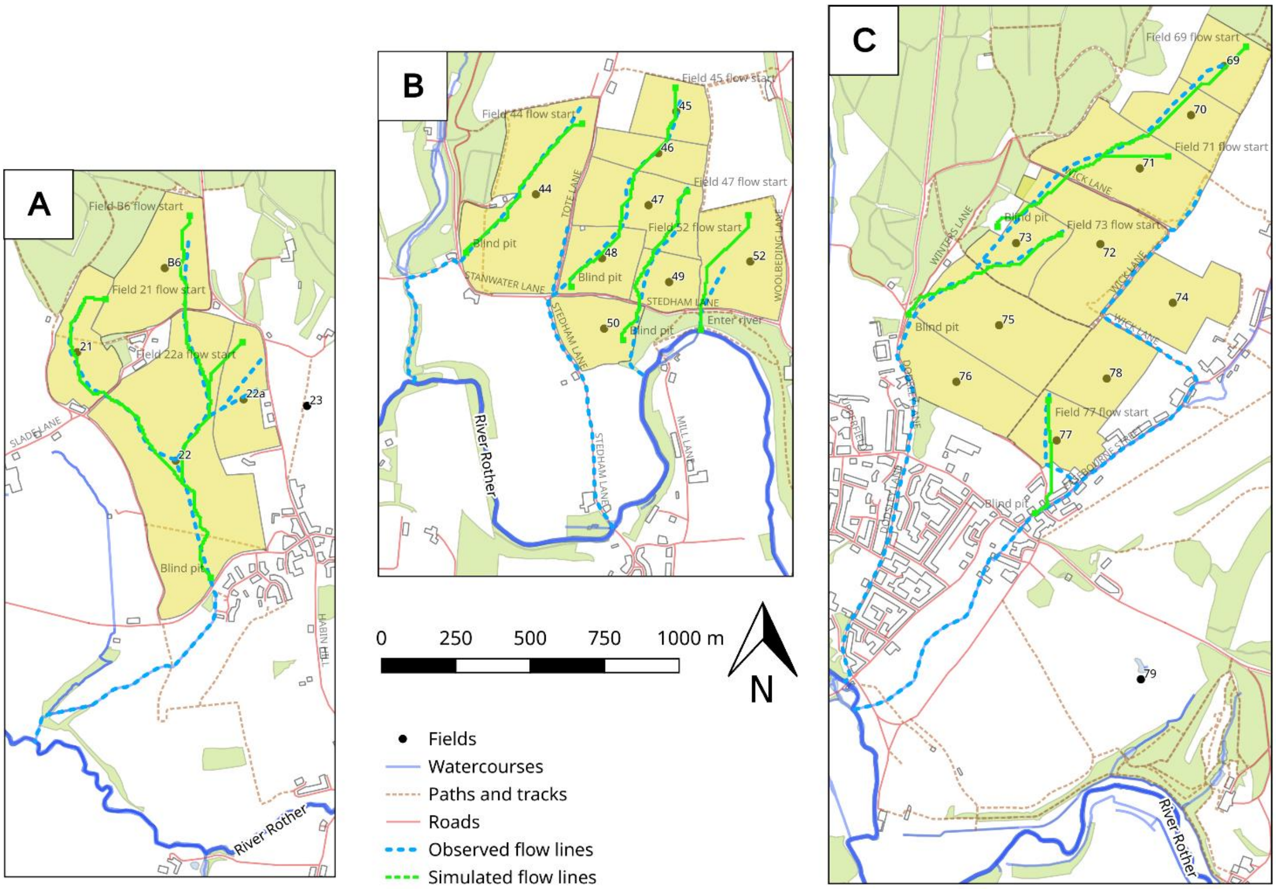
3.1 Topography-only simulations

Blind pits not filled

For the first set of topography-only simulations, downhill cell-to-cell flow is repeated until each flow path encounters either:

- the River Rother
- a flow path from another field
- a blind pit i.e. a cell where all adjacent cells are higher.

Results are shown in Figure 4 and summarised in Table 5.


A
B
C
Field B6 flow start
Field 21 flow start
Field 22a flow start
Blind pit
River Rother
Field 44 flow start
Field 45 flow start
Field 47 flow start
Field 52 flow start
Enter river
Field 69 flow start
Field 71 flow start
Field 73 flow start
Field 77 flow start
0 250 500 750 1000 m
N
Fields
Watercourses
Paths and tracks
Roads
Observed flow lines
Simulated flow lines

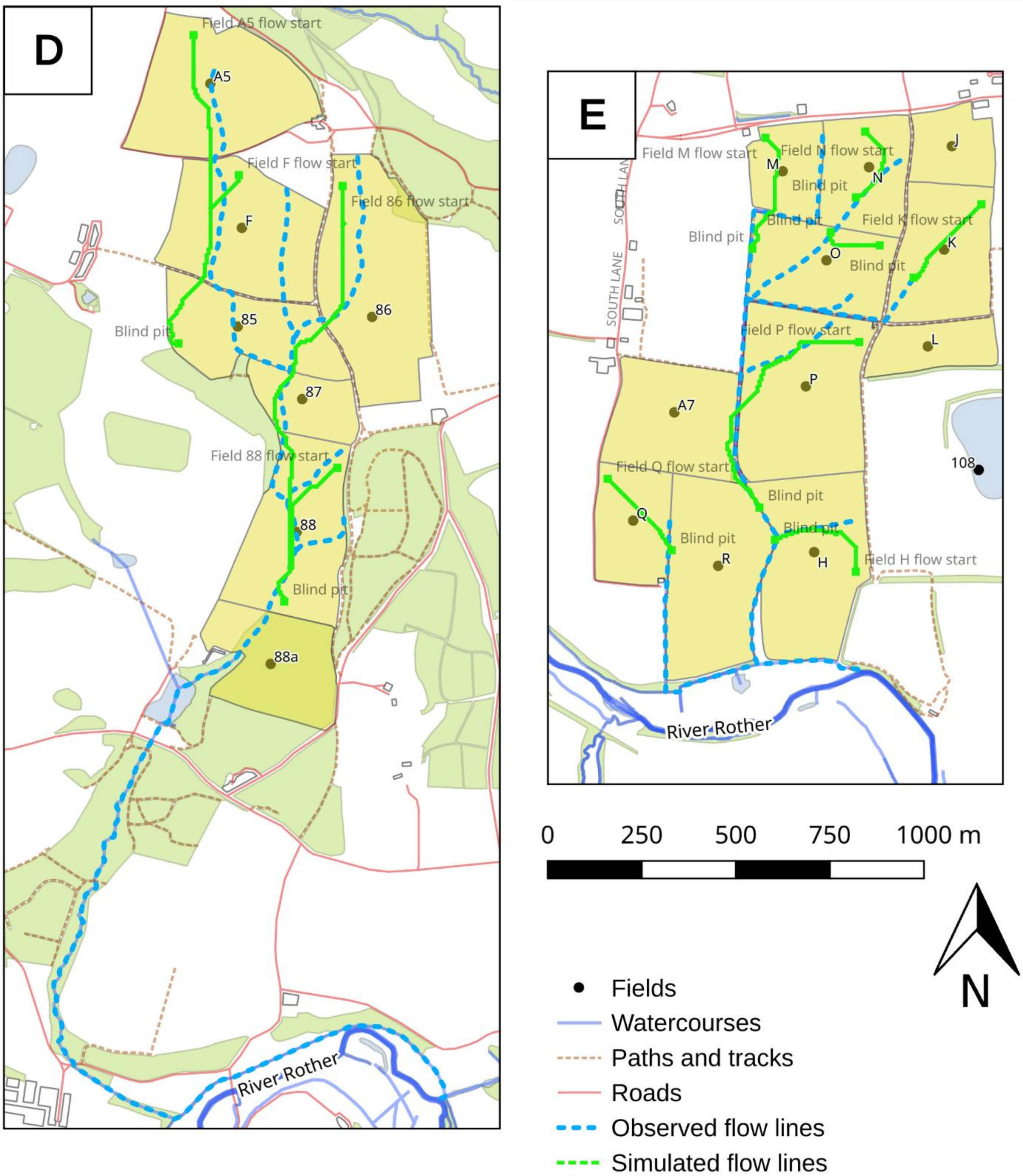


Figure 4. Simulated flow routing determined only by topography

Sample area	Number of fields generating flow	Number of flow lines reaching the River Rother		Similarity of observed/inferred flow lines and simulated flow lines
		Observed	Simulated	
A	3	1	0	Good apart from field 22a. Simulated flow lines merge then end in a blind pit
B	4	4	1	Generally OK. Three simulated flow lines each end in a blind pit
C	5	3	0	Good apart from field 79. All simulated flow lines either merge or end in a blind pit
D	4	1	0	Reasonably OK apart from flow from field F and flow from A5 and F in field 85. All simulated flow lines either merge or end in a blind pit
E	6	1	0	Only OK for field P. All simulated flow lines end in a blind pit

Table 5. Characteristics of simulated flow lines with routing determined only by topography

For all five sample areas, all simulated per-field flowlines – with one exception – either:

- end at blind pits, so that they fail to reach the Rother; or
- merge with flowlines from other fields, and so connect the source field to adjacent lower fields.

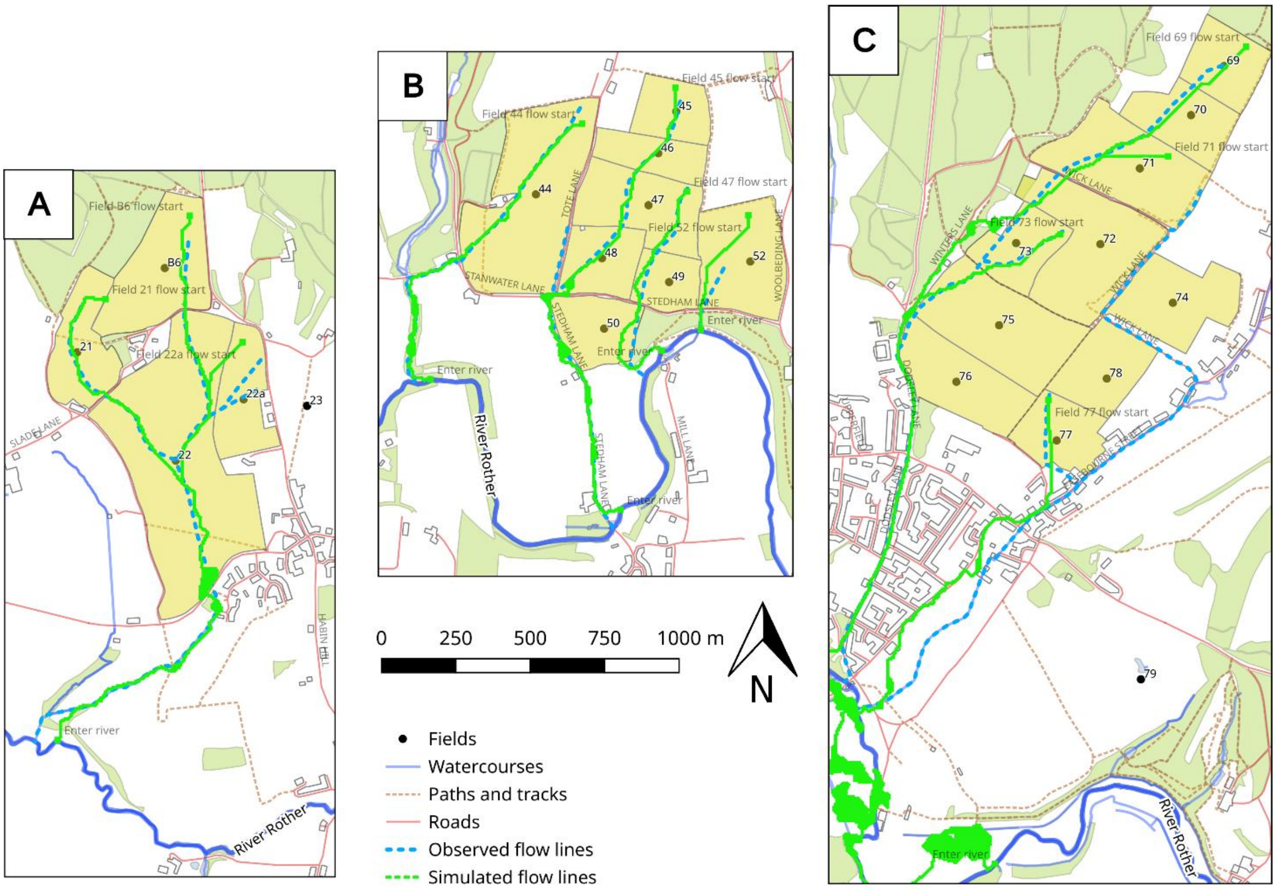
Simulated and observed flow routes are generally similar, although simulated flowlines are, because of the blind pit termination, shorter than their observed equivalents.

Thus for these five sample areas, a DEM with 5m resolution includes sufficient information to permit simple steepest-descent routing to generate a reasonable representation of observed flow routing: but only until flow hits a blind pit. Explicit representation of LEs is not necessary. It appears that the DEM used here possesses sufficient resolution to include representations of small elevation changes associated with LE-related features, such as depressions surrounding watercourses and ditches, and banks at field boundaries and along the edges of roads and tracks. Therefore these LEs, while not explicitly represented, still implicitly influence flow routing.

The major failing of this first set of simulations, however, is that almost all flowlines end in blind pits, great reducing connectivity to the Rother.

Blind pits overtopped

For the next set of topography-only simulations, blind pits are filled by overtopping. Now, when a flowline reaches a blind pit, the elevation of the water’s surface in the ponded area is incrementally increased until overtopping occurs and flow is again able to proceed downhill. Results are in Figure 5 and Table 6.


A
Field B6 flow start
B6
Field 21 flow start
21
Field 22a flow start
22a
23
22
SLADE LANE
Enter river
River Rother
B
Field 44 flow start
Field 45 flow start
45
46
44
Field 47 flow start
47
Field 52 flow start
48
52
49
STANWATER LANE
STEDHAM LANE
50
Enter river
Enter river
River Rother
Enter river
C
Field 69 flow start
69
70
Field 71 flow start
71
Field 73 flow start
73
72
74
75
76
78
Field 77 flow start
77
79
Enter river
River Rother
0 250 500 750 1000 m
N
Fields
Watercourses
Paths and tracks
Roads
Observed flow lines
Simulated flow lines

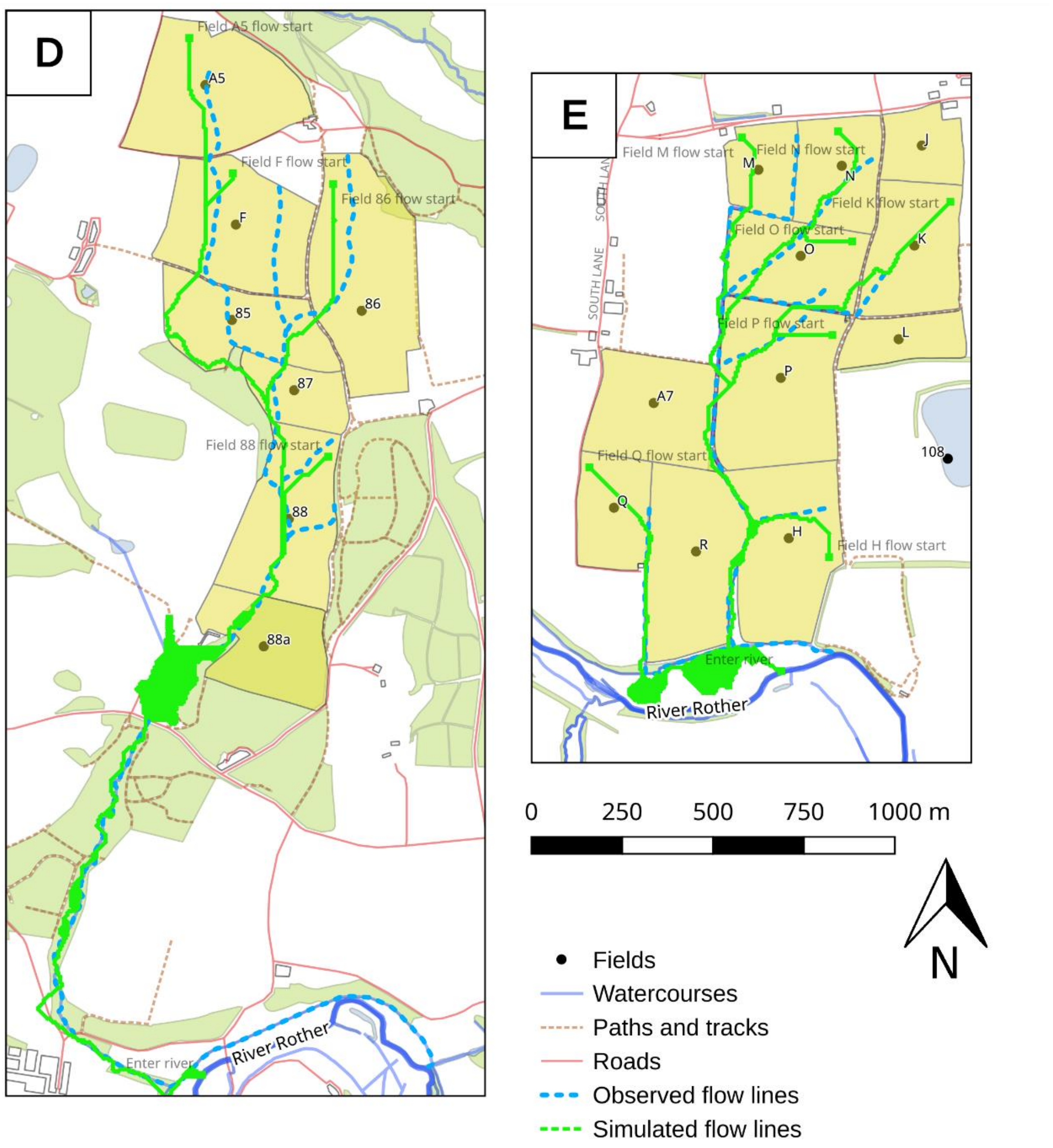


Figure 5. Simulated flow routing determined by topography, and with blind pits filled by overtopping

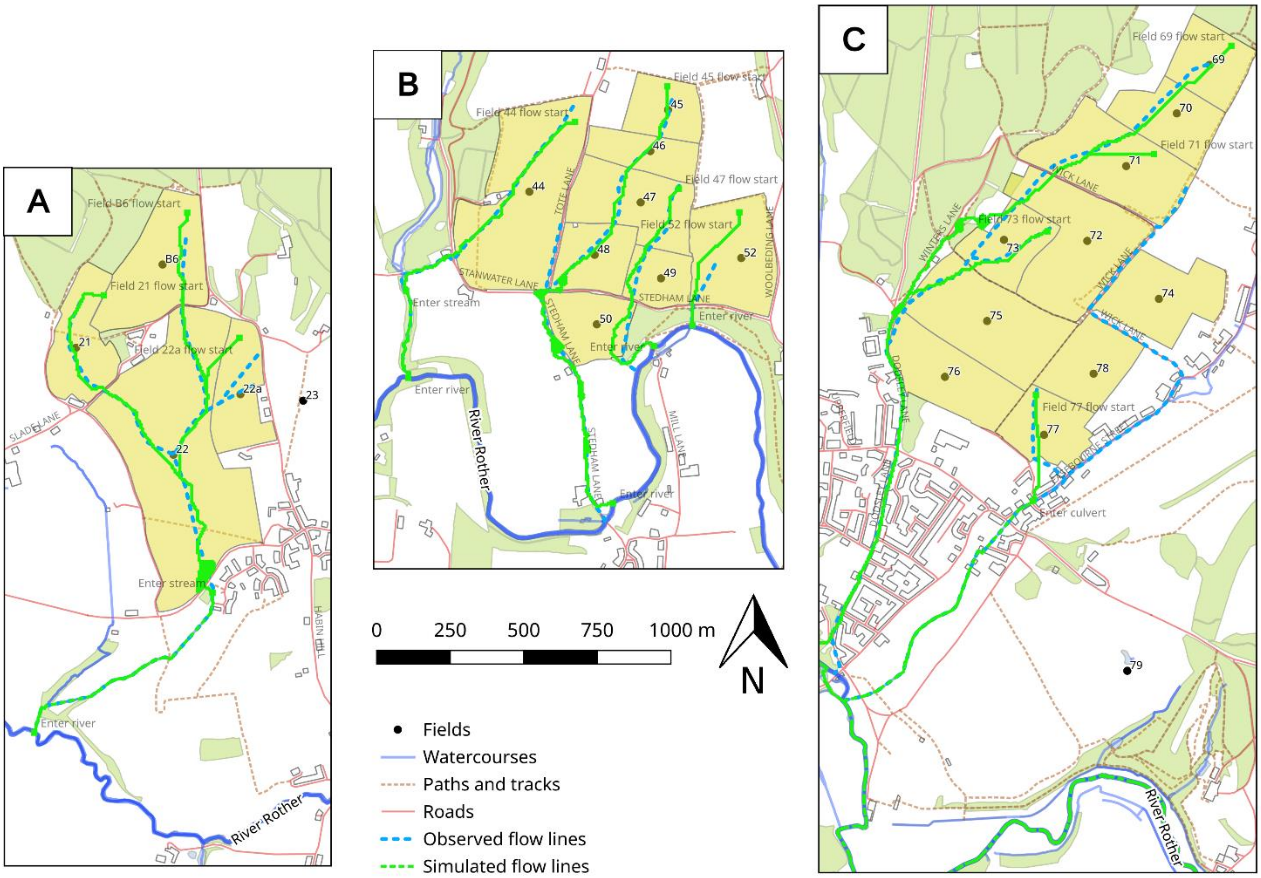
Sample area	Number of flow lines reaching the River Rother		Area of filled blind pits (m^2)	Maximum depth of overtopping needed (m)
	Observed	Simulated		
A	1	1	3125	0.5
B	4	4	5400	0.8
C	3	3	41125	1.1
D	1	1	23800	1.2
E	1	2	15600	0.2

Table 6. Characteristics of simulated flow lines with routing determined only by topography, and with blind pits filled by overtopping

Simulated runoff from every field now reaches the river. However the ponding necessary to overtop the blind pits (i.e. the area of the filled blind pit) is spatially quite extensive for areas C, D and E; and considerable depths of ponding (i.e. the depth of the blind pit) are needed to achieve overtopping on sample areas C and D. Downstream of overtopped blind pits, flowlines follow watercourses on all sample areas; on areas B and C, flow also follows roads. Again, it appears that flow direction is strongly influenced by the DEM's representation of elevation changes associated with these linear LEs.

Blind pits overtopped, flow into permanent watercourses

For the third set of topography-only simulations, if simulated flow is within 5m (an arbitrary value, chosen to be the same as the DEM's resolution) of a permanent watercourse, including ditches, then flow enters the watercourse. Flow then proceeds downstream until it reaches the Rother. Results are in Figure 6 and Table 7.


A
Field B6 flow start
B6
Field 21 flow start
21
Field 22a flow start
22a
23
22
SLADE LANE
Enter stream
HABIN HILL
Enter river
River Rother
B
Field 44 flow start
Field 45 flow start
45
46
44
TOTE LANE
47
Field 47 flow start
Field 52 flow start
48
52
49
STANWATER LANE
STEDHAM LANE
WOOLBEDING LANE
Enter stream
Enter river
50
Enter river
Enter river
River Rother
MILL LANE
Enter river
C
Field 69 flow start
69
70
Field 71 flow start
71
WICK LANE
Field 73 flow start
73
72
WINTERS LANE
74
75
76
78
Field 77 flow start
77
Enter culvert
79
River Rother
0
250
500
750
1000 m
N
Fields
Watercourses
Paths and tracks
Roads
Observed flow lines
Simulated flow lines

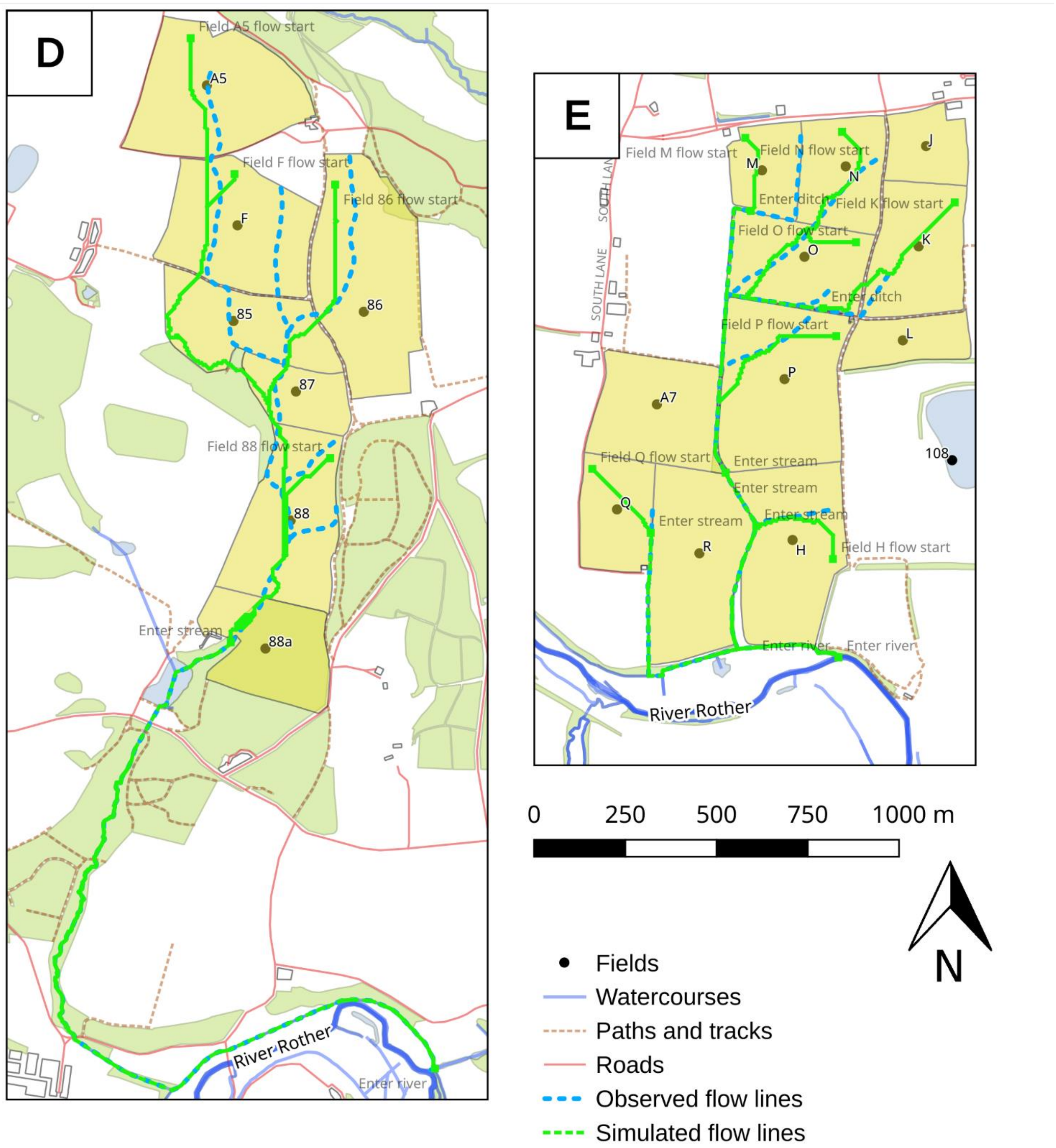


Figure 6. Simulated flow routing determined by topography, with blind pits filled by overtopping, and with flow routed into nearby permanent watercourses

Sample area	Number of flow lines that reach the Rother		Area of filled blind pits (m^2)	Maximum depth of ponding needed (m)
	Observed	Simulated		
A	1	1	2100	0.4
B	4	4	3725	0.8
C	3	3	2825	0.6
D	1	1	875	0.3
E	1	1	375	0.1

Table 7. Characteristics of flow lines when topography is considered, blind pits are filled by overtopping, and flow is routed into nearby permanent watercourses

On areas A to D flowlines differ little from previous results, however there are now no large along-stream areas of ponding. The maximum depth of ponding is lower (notably so on areas C and D). Which is gratifying, since field observation showed no evidence of extensive ponding (apart from sample area B where runoff leaves fields 48 and 49, due to detention structures). On area E, simulated and observed flowlines are now quite similar, with much of the flow now routed via ditches.

3.2 Topography-only simulations: discussion

These first simulations suggest an answer to the conundrum. For these five study areas, a DEM with adequate spatial resolution can, in conjunction with steepest-path flow, blind pit overtopping, and flow into nearby permanent watercourses, adequately replicate observed spatial patterns of flow routing. Therefore it is likely that a spatially-explicit catchment-scale erosion model, also assuming steepest-descent flow on a high-resolution DEM, with blind pits either overtopped or pre-filled (section 4.3), will achieve a similar result. So it is clear that model-based studies using this approach are capable of adequately replicating observed patterns of flow routing, without needing to consider the explicit effects of LEs on flow. Given that the resolution of the DEM used here is 5m, and the width of linear LEs (such as paths and minor roads) is notably smaller, this is a slightly surprising – but reassuring – result.

Note that FieldFlow, in the interests of simplicity, and because the focus of this study is post-field flow routing, makes an arbitrary assumption regarding the within-field location of the start of each flowline. Thus it ignores the effects of within-field tillage microtopography on flow direction. This results in obvious differences between the most upstream portions of observed and simulated flowlines. Since FieldFlow also assumes there to be only one starting point for flow within each field, secondary flowlines – where more than one observed flowline begins in a single field – are not simulated.

After flow has left the eroding field, the observed flowlines are not themselves free from error (Boardman et al., 2020). However, uncertainty may be expected to be lower where observed flow has clearly passed through a field boundary: it is gratifying that there is generally an excellent agreement between simulated and observed flowlines at such locations.

But despite the general similarity between observed and simulated flowlines, there are several problems which arise from our simple approach.

All blind pits were filled by overtopping. However some may have been artefacts (section 4.3). Filling non-artefactual (i.e. real) blind pits effectively smooths the DEM. One impact of this smoothing, for catchment-scale soil erosion models, is to artificially increase field-to-river flow speeds for those flowlines which pass through real-world blind pits, and to ignore deposition within the blind pit. Both of these will affect the characteristics – flux and size distribution – of sediment transported downstream from the pit. Also real-world blind pits in arable catchments are often drained via a culvert, ditch or other engineered structure. Such structures impose some threshold condition on flow speed and volume (Williams et al., 2019), which is ignored if the pit is simply filled. Ignoring this threshold condition also impacts the characteristics of sediment outflow from the pit.

Ignoring field boundaries, as we have done in these simulations, is equivalent to assuming them to be fully permeable. But as discussed in section 1, field boundaries may be impermeable or conditionally permeable; and permeability may vary with time, previous flow conditions, and from place to place along a field boundary. Thus ignoring field boundaries has major impacts on flow speed, volume, and sediment transport.

The first set of FieldFlow simulations (Figure 4) routed flow along linear LEs such as paths, roads and streams because of elevational changes (i.e. minor linear depressions) associated with these linear features, which were captured in the DEM. Such depressions are not necessarily present for every path, track, or road; or for streams enclosed by raised banks. If such depressions are not present in the DEM, then linear LEs are ignored when simulating flow routing. This can be clearly seen on area E, the only one of our study areas in which ditches are present. Here, ditches are too narrow to be represented in the 5m DEM, and so are ignored by the simulated flowlines (Figures 4E and 5E). The additional rule introduced in the third set of simulations, routing flow into a stream or ditch if with 5m of it, overcomes this problem (Figure 6E). Along-road or along-path flow has similar problems. Entrance or exit points determined by built infrastructure (e.g. a gap between houses), may well not be discernable from the DEM. When flow is routed onto a vector road or path, modelled provision must be made for it to encounter a blind pit. Streams and ditches drain downwards into a river, unlike vector paths and roads.

So while this simple modelling approach – steepest-path flow and blind-pit fill/overtopping – can, in conjunction with a suitable DEM, adequately reproduce spatial patterns of flow, it will fare less well:

- If there are LEs which are too small to be adequately captured by the DEM's resolution, and
- When simulating runoff speed and volume, and the flux and size distribution of transported sediment.

Thus it appears that for catchment-scale erosion models to adequately represent these characteristics of flow and sediment transport, more explicit within-model representation of those LEs which influence flow routing and characteristics is necessary: or at least, strongly desirable. This is the focus of the next section of this paper.

3.3 LE-and-topography simulations

To represent LEs and their attributes in a catchment-scale simulation of flow and erosion, a first requirement is some way of identifying which LEs are relevant, since not every ditch nor every part of a field boundary is involved in the journey of flow and sediment from field to river. A second requirement is to identify which attributes are necessary to describe each LE-flow interaction. FieldFlow has a second mode of operation which aims to assist with this. When run in its LE-and-topography mode, FieldFlow acts as a kind of 'pre-processor', highlighting the locations and nature of LE-flow interactions. Running FieldFlow in this mode is intended to be a kind of 'model reconnaissance', carried out to assist with gathering the input data needed to run a conventional spatially-explicit catchment-scale soil erosion model.

In this mode, FieldFlow requires additional GIS layers, each holding details of a single LE category (Table 4). As in the simple mode, FieldFlow traces a flowline from an arbitrary point within each connected field. Flow similarly moves downhill along the line of steepest slope until it merges with a pre-existing flowline; or if within 5m of a permanent watercourse, joins that watercourse. But additionally, in LE-and-topography mode:

- Each simulated flowline halts when it encounters any other LE (including blind pits). The user is then asked to supply information regarding this LE-flow interaction.
- The user must obtain this information, either from knowledge of the catchment, from remotely sensed data, or from a visit to the catchment. They then add this information to the FieldFlow input file, then re-run FieldFlow. This sequence is repeated until all simulated flowlines reach the river.

Attribute	Comment
LE 'inflow' spatial co-ordinate	An OS grid reference. This must be within 5m of the location of the LE-flow interaction previously reported by FieldFlow
LE type	From a list: 'boundary', 'culvert', 'track', 'road', and 'overtop'
Flow behaviour when flow encounters this LE	From a list: 'across', 'along', 'through' and 'overtop'
Short description of the location	E.g. 'On the south side of field 6'
An 'outflow' spatial co-ordinate for some categories of LE type and flow behaviour (e.g. 'field boundary' and 'across', 'culvert' and 'through', or 'overtop' and 'overtop'),	An OS grid reference

Table 8. The attributes required for a FieldFlow 'LE-flow interaction'

The information that is required for each LE-flow interaction depends on the LE and its attributes (Table 8). Most LE type/flow behaviour combinations require a user-specified outflow location: these include flow through a permeable field boundary, or flow crossing a path. Flow is then simply routed between the inflow location and the outflow location e.g. to the far side of the field boundary or path. A similar procedure is followed for flow which becomes trapped in a blind pit. If the blind pit is a real-world topographic depression, then the specified outflow location is either the end of the culvert (if the depression is drained), or a location just outside and downhill from the lowest point on the rim of the depression (if the depression is not drained, and so fills by overtopping).

However if the blind pit is known to be a DEM artefact, then the outflow location can be any point outside of and downhill from the blind pit.

LE type/flow behaviour combinations representing flow along a path or road, or a field boundary, do not require an outflow location. In these cases, FieldFlow routes flow downhill along the vector path, road, or field boundary until it either:

- Reaches the lowest point of the path, road, or field boundary (i.e. a blind pit on the path, road, or field boundary); the flowline then halts and the user is asked for information regarding this LE-flow interaction.
- Encounters a new LE. If the user has not already supplied information regarding this LE-flow interaction, then the flowline halts and the user is asked for this information. If the user has already supplied information for this LE-flow interaction (for example, for an observed exit point somewhere on the path, road or field boundary) then this is used to route the flow off the path, road or boundary.
- Encounters another flowline or enters a permanent watercourse.

When running FieldFlow in LE-and-topography mode, it is highly desirable to also have available (as we did) data regarding observed flow routes. In some cases there may be ambiguity regarding the direction of simulated flow: if this occurs, simulated flow should always follow the observed flow route. To achieve this sometimes requires the flow to be ‘forced’ to follow the observed route (Table 9).

When all simulated flowlines reach the river, the user has supplied information for all required LE-flow interactions. Data for each LE-flow interaction in the list (Table 9) may then used as input for the user’s chosen conventional spatially-explicit soil erosion model. Some LE-flow interactions will still require additional information gathering, beyond that required by FieldFlow: for example, the erosion model might require details of a threshold depth at a field boundary, below which flow is blocked.

*** TABLE 9

Sample Area	LE-flow interaction				Comparison with real-world field observation
	No.	LE	Interaction	Location	
A	1	Field boundary	Through	S edge of field B6	OK, through permeable hedge
	2	Road	Across	Slade Lane	OK
	3	Field boundary	Through	N edge of field 22	OK, ditch and bank overtopped
	4	Path	Across	Towards S end of field 22	OK
	5	Culvert	Through	Under road, S of field 22	OK
	6	Field boundary	Through	Between fields 22a and 22	OK, through permeable hedge
	7	Path	Across	In field 21	OK
	8	Field boundary	Through	SE edge of field 21	OK, through permeable hedge
	9	Road	Across	Slade Lane	OK
	10	Field boundary	Through	NW edge of field 22	OK, via gap in hedge
B	1	Field boundary	Through	Between fields 45 and 46	OK, via gap in hedge
	2	Field boundary	Through	Between fields 46 and 47	OK
	3	Field boundary	Through	Between fields 47 and 48	OK
	4	Blind pit	Overtop	In field 48	OK, is a small dam which is occasionally overtopped
	5	Road	Along	Onto Stedham Lane	OK
	6	Forced	-	To negotiate Stedham Lane junction	***
	7	Road	Along	South of Stedham Lane junction	*** Necessary because of the above
	8	Blind pit	Overtop	On road, by Meadowhills Cottage on Stedham Lane	OK, there is a slight change of gradient on the road here, but flow has been observed along this road
	9	Blind pit	Overtop	On road blind pit S of Meadowhills Cottage on Stedham Lane	OK, as above
	10	Road	Along	WSW along Stedham Lane	*** necessary because of the above
	11	Path	Across	E of former Talbots building	OK
	12	Blind pit	Overtop	S of former Talbots building	OK, overtops bund
	13	Field boundary	Through	SW edge of field 44	OK, via permeable hedge
	14	Road	Along	Stanwater Lane	OK
	15	Blind pit	Overtop	S of Stanwater Lane bend	***
	16	Road	Along	Stanwater Lane	*** Necessary because of the above
	17	Blind pit	Overtop	On Stanwater Lane, near stream	***
	18	Field boundary	Through	S edge of field 47	OK
	19	Road	Across	Stedham Lane	OK
	20	Field boundary	Through	N edge of field 50	OK
	21	Forced	-	To get flow moving S towards wood	***
	22	Field boundary	Through	E edge of field 50	OK
	23	Forced	-	To get flow moving S in wood	***
	24	Forced	-	To get flow moving SE in wood	***
	25	Field boundary	Through	S edge of field 52	OK
	26	Road	Across	Stedham Lane	OK, flow goes into culvert and under road
	27	Path	Across	In wood near Rother	OK, runoff from culvert discharged onto wooded slope

	28	Path	Across	Next to Rother	OK
C	1	Field boundary	Through	Between fields 69 and 70	OK
	2	Field boundary	Through	Between fields 70 and 71	OK
	3	Field boundary	Through	S edge of field 71	*** Google Earth images suggest flow to this point, then probably across Wick Lane and into field 72 but this has not been directly observed
	4	Road	Across	Wick Lane	*** As above
	5	Field boundary	Through	N edge of field 72	*** As above
	6	Field boundary	Through	Between fields 72 and 73	OK
	7	Field boundary	Along	W edge of field 73	OK
	8	Forced	-	Otherwise flows back to W boundary of field 73	***
	9	Field boundary	Through	S edge of field 73	OK, through thin part of generally thick hedge
	10	Path	Across	Between fields 73 and 75	OK
	11	Field boundary	Through	N edge of field 75	OK
	12	Field boundary	Along	W corner of field 75	OK
	13	Blind pit	Overtop	W corner of field 75	***
	14	Field boundary	Through	Between fields 75 and 76	OK, this is a very insubstantial boundary (grass strip)
	15	Field boundary	Along	NW corner of field 76	OK
	16	Blind pit	Overtop	W edge of field 76	***
	17	Road	Along	Dodsley Lane	OK
	18	Field boundary	Through	S edge of field 73	OK
	19	Path	Across	Between fields 73 and 75	OK
	20	Field boundary	Through	NE edge of field 75	OK
	21	Field boundary	Through	S edge of field 77	*** Flow route in the simulation is not really along Glaziers Lane but through housing area; requires further checking
	22	Road	Along	Glaziers Lane	OK
D	1	Field boundary	Through	S edge of field A5	OK
	2	Road	Across	Unmarked road	OK
	3	Field boundary	Through	N edge of field F	OK
	4	Field boundary	Through	S edge of field F	*** However the Google Earth image for 2013 shows flow straight across track
	5	Path	Along	To Love's Farm	OK
	6	Path	Leave	To Love's Farm	OK
	7	Field boundary	Through	N edge of field 85	*** Did not route flow via the eastern gully in Field F that then crosses into 85
	8	Forced	-	To get flow moving E at S end of field 85	***
	9	Field boundary	Along	S edge of field 85	OK
	10	Field boundary	Through	S edge of field 85	OK
	11	Field boundary	Through	S edge of field 87	OK
	12	Field boundary	Through	SW edge of field 86	OK
	13	Path	Across	Unmarked path	OK
	14	Field boundary	Through	NE edge of field 87	OK

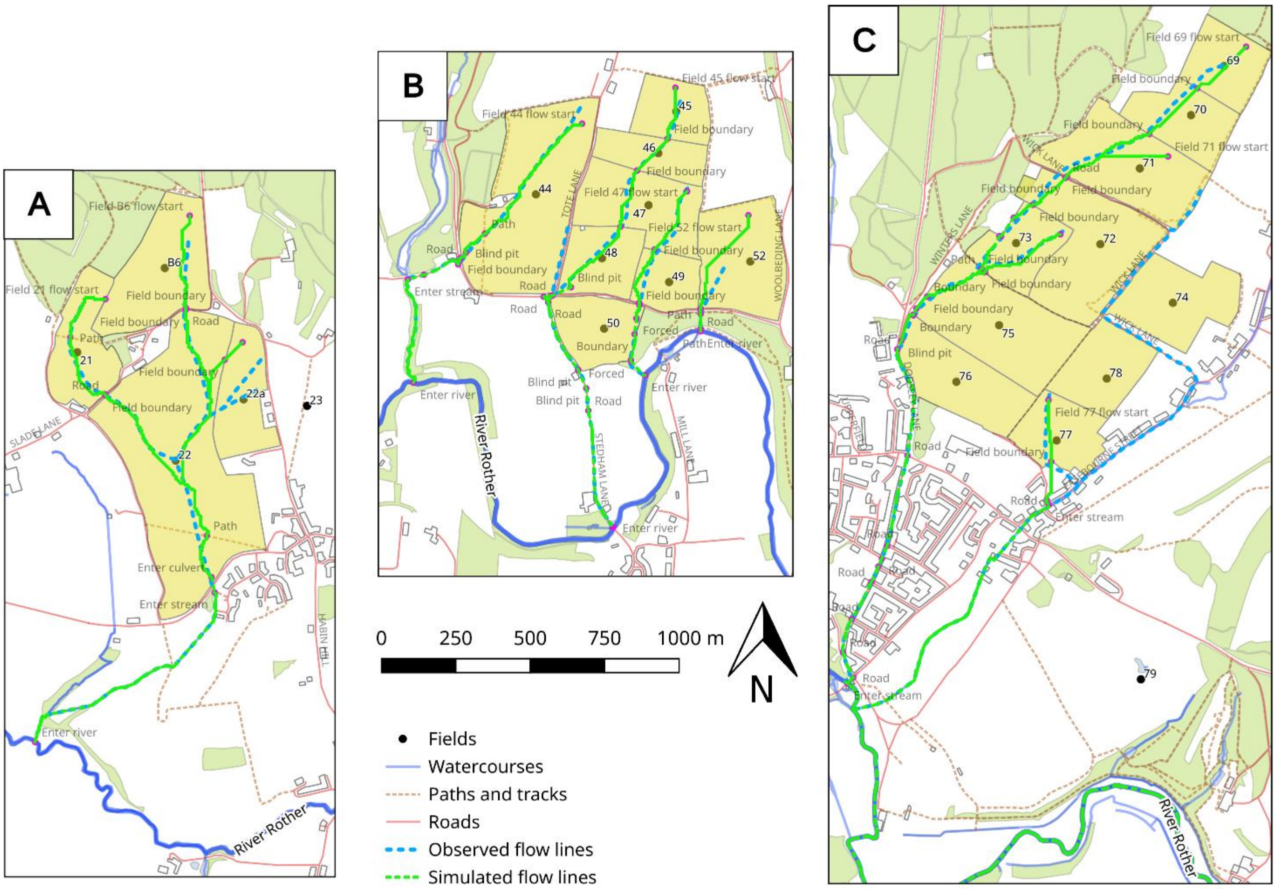
	15	Field boundary	Through	Between fields 85 and 87	OK
	16	Blind pit	Overtop	In field 88	***
	17	Field boundary	Through	Between fields 88 and 88a	OK
	18	Blind pit	Overtop	In field 88a	***
E	1	Field boundary	Along	S edge of field M	OK
	2	Blind pit	Overtop	In field N	***
	3	Field boundary	Through	S edge of field N	OK
	4	Blind pit	Overtop	First blind pit in field O	***
	5	Blind pit	Overtop	Second blind pit in field O	***
	6	Path	Across	Track to W of field P	OK
	7	Blind pit	Overtop	In field K	***
	8	Field boundary	Through	W edge of field K	OK
	9	Path	Across	Between fields K and O	OK
	10	Field boundary	Through	E edge of field O	OK

Table 9. A summary of the LE-flow interaction information used by FieldFlow to reproduce observed flow routes on the five sample areas. LE-flow interactions which are problematic or require further investigation are marked ***

FieldFlow was run in LE-and-topography mode for the sample areas (A to E). Readily available data was used for the vector roads layer, but it was necessary to hand-digitize data for the vector field boundaries and the vector paths (Table 4).

3.4 LE-and-topography mode simulations: results

Patterns of simulated flow are shown in Figure 7, and the LE-flow interactions on the sample areas are summarised in Table 10.


A
B
C
0
250
500
750
1000 m
N
Fields
Watercourses
Paths and tracks
Roads
Observed flow lines
Simulated flow lines

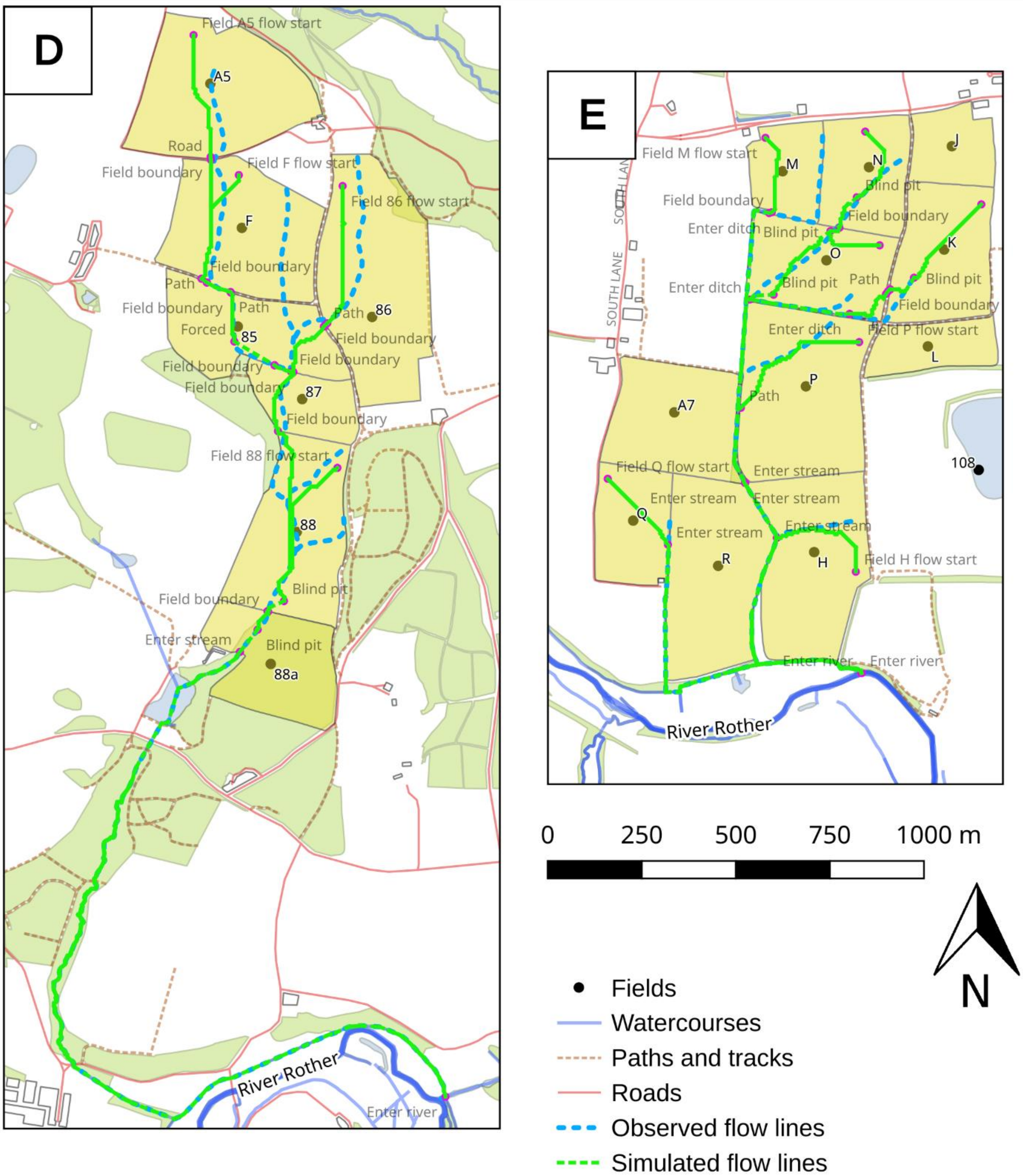


Figure 7. Simulated flow routing considering both topography and landscape elements

Sample area	Number of:			
	LE-flow interactions	Problematic LE-flow interaction	'Forced' LE-flow interactions	Blind pits
A	10	0	0	0
B	28	9	4	6
C	22	7	1	2
D	18	5	1	2
E	10	0	0	4

Table 10. Summary of LE-Flow interactions on the five sample areas

Sample area A was the most straightforward, having no problematic LE-flow interactions and no blind pits. Here flow direction is largely driven by topography, with simple LE-flow interactions (permeable field boundaries and flow across roads/tracks). But sample area B required data for more LE-flow interactions, and more of these LE-flow interactions proved troublesome. Forcing was needed to get simulated flow to follow the observed route at Stedham Lane road junction, and further downstream on Stedham Lane, and on Stanwater Lane. There were also problems with routing flow through a wood. Two blind pits (#4 and #12) exist in reality, all other blind pits are presumably artefacts. Sample area C was more straightforward, but forcing was required along one field edge (#8), two probably artefactual blind pits (#13 and #16). There was real-world ambiguity regarding flow at a field boundary (#3) and through a housing estate (#21). Sample area D was similar, with an unresolved routing problem at a field boundary (#7), two probably artefactual blind pits (#16 and #18), and real-world ambiguity regarding flow at a field boundary (#4). Area E generally fared well, with most flowlines routed via ditches, although flow needed to be forced out of four (possibly artefactual) blind pits.

3.5 LE-and-topography mode simulations: discussion

Obtaining the necessary data for most LE-flow interactions was straightforward, given our database of observational records. Still, a minority of LE-flow interactions proved troublesome. Problems arose due to blind pits on roads. These are probably artefactual: it is likely that inaccuracies in calculating elevations (especially on relatively flat sections of road) created these. The difficulty in correctly routing flow through woodland on sample area B, and at a field edge in sample area C, also probably result from inaccurate elevations. We had previously discovered some errors in the permanent watercourses GIS layer that were probably due to out-of-date source data. Interestingly, the simulations also threw up some examples of real-world ambiguity of flow, including some blind pits which may or may not be artefacts (areas D and E). These will be investigated further.

Note there is a choice regarding the level of detail, and hence the number of LE-flow interactions, specified. If, for example, flow travels first through a field boundary then across a road then through another field boundary, should this be encoded as three separate LE-flow interactions or as one composite LE-flow interaction? There can be no general answer. The detail input to the erosion model must depend both on the specifics of the LE-flow interactions (e.g. are either of the field boundaries only conditionally permeable?) and the specifics of the erosion model itself.

Another possible simplification, at first glance, is to specify LE-flow interaction attributes for the whole of a field boundary, rather than for just a point on the boundary. However, this risks being too general, by e.g. missing a hole in a hedge. And it must be remembered that while here we assumed all field boundaries to be either permeable or impermeable, real-world permeability is more nuanced.

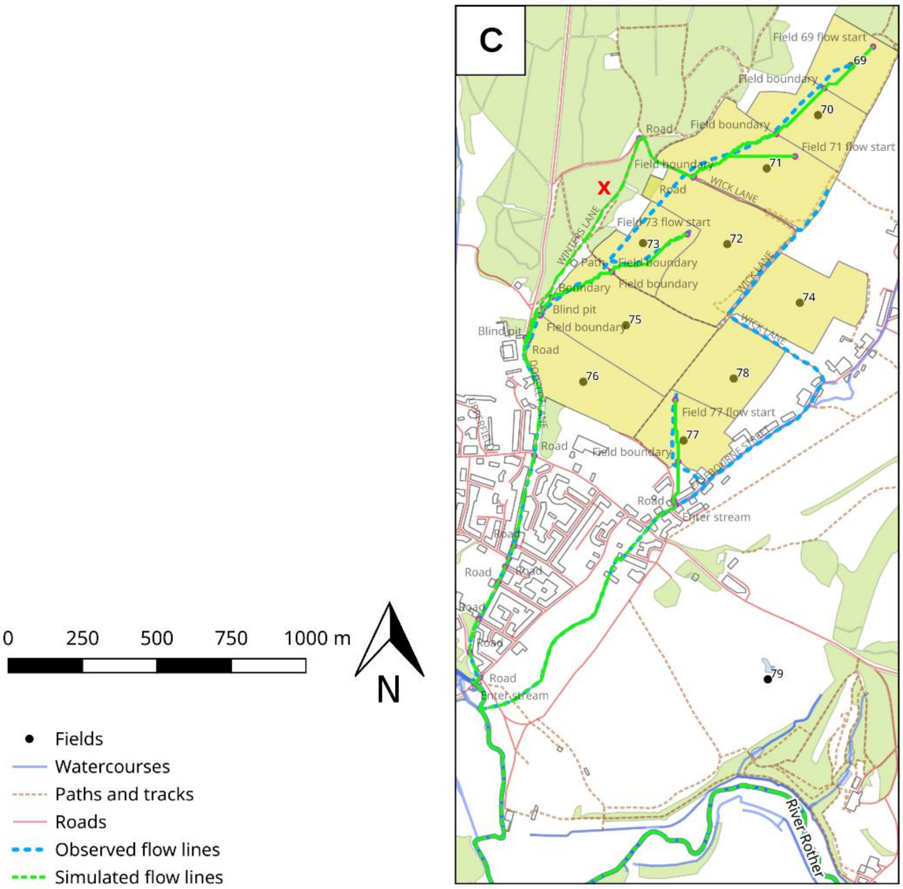


Figure 8. Simulated what-if flow routing considering topography and landscape elements, for sample area C only. Compare with Figure 7C. X in red indicates the changed flow route

3.6 Alternative flow routes

Next we investigate the sensitivity of LE-flow interactions. On occasion, changing a single attribute of an LE-flow interaction leads to a large change in flow routing. For sample area C, observed runoff originating in fields 69 and 71 passes through the permeable southern field boundary of field 72, crosses Wick Lane, then enters field 72 through its permeable northern boundary. If this field boundary is instead flagged as impermeable, then simulated flow takes a different route: first westward along Wick Lane then south along Winters Lane (Figure 8). Field observation suggests that this flow route is feasible, although not previously investigated.

3.7 Synthetic hydrographs

Finally, we demonstrate – albeit in a simplistic and crude way – the impacts of differing descriptions of a single class of linear LE, upon the temporal distribution of runoff reaching the Rother.

Rainfall/flow speed scenario	Runoff		Relative flow speed along:				
	Duration	Peak	Ephemeral gully	Permanent watercourse	River Rother	Path or track	Road
Baseline	1.0	1.0	1.0	1.2	1.5	0.8	0.9
High intensity rainfall	0.25	4.0	1.0	1.2	1.5	0.8	0.9
Slow flow along roads and paths	1.0	1.0	1.0	1.2	1.5	0.4	0.5
Slow flow along roads and paths and high intensity rainfall	0.25	4.0	1.0	1.2	1.5	0.4	0.5

Table 11. Synthetic hydrographs: runoff and flow parameters (arbitrary units) for the four rainfall/flow speed scenarios

We construct, for each of the runoff-generating fields on sample sites A to E, a synthetic (triangular) hydrograph with a given duration and peak (in arbitrary units: Table 11). We assume that runoff commences simultaneously on every runoff-producing field, and that the volume of runoff leaving the field is proportional to the field's area. We then develop two LE-related scenarios, with flowlines handled differently in each. For the 'LEs-ignored' scenario, every portion of every flowline is assigned to one of only three categories: 'permanent watercourse', or 'River Rother', with the remainder of each flowline categorised as ephemeral gully (cf. Figure 6 in Boardman et al. 2020). For the 'LEs-considered' scenario, two additional flowline categories – 'path or track' and 'road' – are used. By measuring the length of flow line in each category, and assigning an arbitrary relative flow speed for each category (Table 11), we constructed a hydrograph for each flowline, for the point in the Rother where the furthest downstream flowline for that sample area enters. Per-flowline hydrographs were then summed, to give a hydrograph for all off-field runoff entering the Rother for that sample area (Figure 9, 'baseline' results).

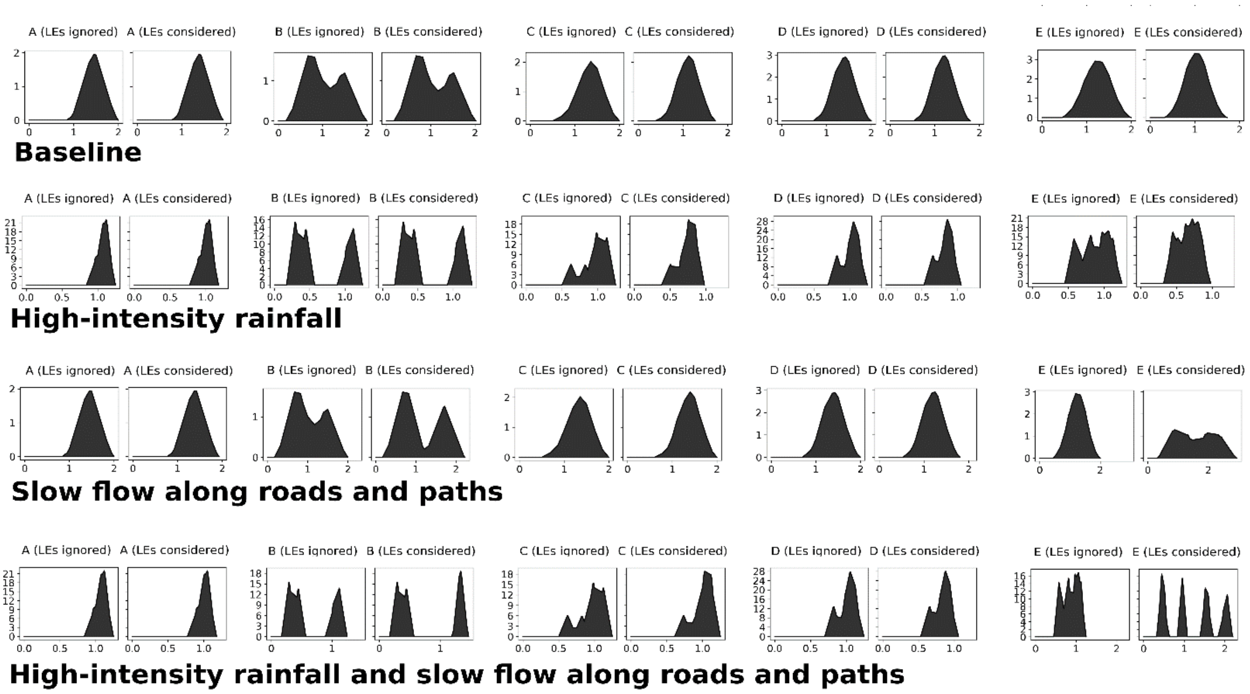


Figure 9. Synthetic hydrographs for flow entering the River Rother from (left to right) sample areas A to E. These compare hydrographs for two ways of representing linear LEs (roads and paths), under four scenarios: baseline, high-intensity rainfall, slow flow along roads and paths, and high-intensity rainfall and slow flow along roads and paths

Baseline

Sample area LEs	A ignored	A considered	B ignored	B considered	C ignored	C considered	D ignored	D considered	E ignored	E considere
N peaks	1	1	2	2	1	1	1	1	1	1
Peak flow	1.9	1.9	1.6	1.6	2.0	2.2	2.9	3.0	2.9	3.3
Peak flow time	1.5	1.4	0.7	0.7	1.4	1.1	1.4	1.2	1.2	1.0

High-intensity rainfall

Sample area LEs	A ignored	A considered	B ignored	B considered	C ignored	C considered	D ignored	D considered	E ignored	E considere
N peaks	1	1	3	3	4	2	2	2	5	5
Peak flow	22.0	22.0	15.4	15.4	15.4	19.3	27.7	28.7	16.9	20.7
Peak flow time	1.1	1.1	0.3	0.3	1.0	0.8	1.1	0.9	1.1	0.7

Slow flow along roads and paths

Sample area LEs	A ignored	A considered	B ignored	B considered	C ignored	C considered	D ignored	D considered	E ignored	E considere
N peaks	1	1	2	2	1	1	1	1	1	2
Peak flow	1.9	1.9	1.6	1.6	2.0	2.2	2.9	2.9	2.9	1.3
Peak flow time	1.5	1.4	0.7	0.7	1.4	1.4	1.4	1.3	1.2	0.9

High-intensity rainfall and slow flow along roads and paths

Sample area LEs	A ignored	A considered	B ignored	B considered	C ignored	C considered	D ignored	D considered	E ignored	E considere
N peaks	1	1	3	3	4	2	2	2	4	4
Peak flow	22.0	22.0	15.4	18.6	15.4	18.9	27.7	28.0	16.9	16.6
Peak flow time	1.1	1.1	0.3	1.3	1.0	1.0	1.1	0.9	1.1	0.5

Table 12. Synthetic hydrographs: results (arbitrary units) for the four rainfall/flow speed scenarios

Three further scenarios, this time considering rainfall rate and flow speed on roads and paths, were constructed. Hydrographs for the ‘high-intensity rainfall’ scenario assume the same volume of rainfall as the ‘baseline’ runs, but a higher rainfall intensity; hydrographs for the ‘slow flow along roads and paths’ scenario assume lower relative flow speeds on paths and roads, while hydrographs for the ‘slow flow along roads and paths and high intensity rainfall’ scenario assume both higher intensity rainfall and lower flow speeds on paths and roads (Figure 9 and Tables 11 and 12).

With higher-intensity rainfall, all hydrographs have higher peaks and are of shorter duration, compared with the baseline hydrographs. Slower flow on roads and paths accentuates the differences between the ‘LEs ignored’ and ‘LEs considered’ scenarios. For sample area A, flow reaching the Rother always results in a single peak: ‘LEs ignored’ and ‘LEs considered’ hydrographs are identical because there is no along-path or along-road flow. For area B, flowlines enter the Rother at several locations. Rother hydrographs have two peaks, which are distinct and further separated in time for the higher intensity results. Along-road flow here results in minor differences between the shape and spacing of the peaks for ‘LEs ignored’ and ‘LEs considered’ scenarios. Sample area C has more along-road flow, so the Rother hydrographs for ‘LEs ignored’ and ‘LEs considered’ always differ. There are multiple peaks for the two higher intensity rainfall results . Area D has little along-path flow so the Rother hydrographs for ‘LEs ignored’ and ‘LEs considered’ are almost identical; again, multiple peaks appear for the higher rainfall intensities. On area E, along-path flow causes the Rother hydrographs for ‘LEs ignored’ and ‘LEs considered’ to differ, strongly so for the higher rainfall intensity results (which also produce multiple peaks).

The extent of along-road and along-path flow in a sample area thus drives the difference between ‘LEs ignored’ and ‘LEs considered’ Rother hydrographs. Differences become more marked for the higher intensity scenarios, and for the scenarios which assume a greater contrast between flow speed on paths and roads. It is clear that, even in this crude exercise, considering or ignoring only a single category of LE-flow interactions (i.e. paths and roads) noticeably impacts the temporal distribution of runoff reaching the Rother.

While we have not been able to consider transported sediment here, sedigraphs are very commonly sensitively dependent upon hydrographs. It is likely, therefore, that sedigraphs would show similar, probably even greater, changes as a result of ignoring or considering only this single category of LE-flow interactions. Thus it is also to be expected that ignoring or considering these LEs in a conventional erosion model will have similarly noticeable impacts upon the hydrology, and also the characteristics of transported sediment, reaching the river.

4 Implications for catchment-scale erosion models

4.1 Quantitative evaluation of erosion models

The quantitative prediction of soil erosion, and hence the beginning of soil erosion modelling as a tool to advance understanding of this area of science, began over 75 years ago (Laflen and Flanagan, 2013), with the first generally useful models developed during the 1960s. Another 30 years passed before the first quantitative comparative evaluations of erosion models. The IGBP-GCTE (International Geosphere Biosphere Programme - Global Change and Terrestrial Ecosystems) Soil Erosion Network (Ingram et al., 1996) model reviews focused first on field-scale models (Favis-Mortlock, 1998), then on catchment-scale models (Jetten et al., 1999), with a third exercise evaluating catchment-scale models for simulating impacts of major climate and land use change (Nearing et al., 2005). All three were pragmatically-oriented validation studies which assessed models by comparing model outputs with real-world measurements. Alternative, but more theoretical, approaches to model review may classify models by structure or approach (e.g. Merritt et al., 2003; Brazier, 2004; Aksoy and Kavvas, 2005; Jetten and Favis-Mortlock, 2006; Deb and Shukla, 2011; Raza et al., 2021), by geospatial characteristics (Karydas et al., 2014), or by approach to connectivity (Baartman et al., 2020), or bibliographically (Alewell et al., 2019).

Jetten et al. (1999) used data (10 x 10m raster maps showing elevation, land use, soil type and surface drainage) for a 41.5 ha intensively-farmed catchment in the Netherlands. By today's standards, this is rather coarse-scale data. Even so, this study found that catchment-scale erosion models are capable of a good agreement with observations for estimates of runoff and sediment discharge at the catchment outlet. Runoff totals are usually better predicted than runoff peaks, and both are better predicted than sediment discharge. Both field-scale and catchment-scale GCTE studies (Boardman and Favis-Mortlock, 1998; Jetten et al., 1999) found calibration to be either essential or strongly desirable. A similar conclusion was reached by Jetten et al. (2003). Calibration is, essentially, a way of compensating for model inadequacies. Jetten et al. (1999) found that calibration is most effective when the events to be estimated lie within the range of calibration events; to do this is problematic if models are used to represent novel conditions, such as changed climate or land use (Favis-Mortlock et al., 1996). Jetten et al. (1999) also found that when the aim is to identify within-catchment hotspots which are the main source of runoff and sediment, then the same models, with the same data, generally perform less well. A similar result was found by Starkloff and Stolte (2014). Such model inadequacy is a problem for e.g. catchment managers who wish to identify candidate locations for interventions to ameliorate riverine pollution.

The GCTE model validation studies were carried out around twenty years ago, but are still useful in highlighting those broad areas of model inadequacy which future models must address. Subsequently, development of erosion models has been incremental rather than explosive (Favis-Mortlock et al., 2001; Boardman, 2006). There have been impressive improvements in the quality and availability of spatial data (e.g. 1m resolution LIDAR imagery), and in GIS technology. These advances have not just aided the visualisation of model results; they have made it possible to tightly couple GIS, spatial data, and catchment-scale models e.g. AnnAGNPS (USDA-NRCS, 2020), GeoWEPP (Renschler, 2003), OpenLISEM (Jetten, 2017), SWAT (USDA-ARS, 2020) to create user-friendly decision support systems that are now widely used by catchment managers and others. These achievements are real and should not be denigrated. However, 'a dog in a dress is still a dog'. Flow routing in current spatially-explicit catchment-scale erosion models still – just as it did twenty years ago – is driven largely (if not wholly) by the interaction between gravity-driven flow and a representation of topography (a DEM). As the first part of this paper has shown, where flow encounters LEs such as field boundaries or tracks, then more detailed representations are essential.

4.2 Representation of LEs in catchment-scale erosion models

Our results – both from field observations and from a simple model – show that in our study area, LEs play a vital role in conveying runoff and sediment from eroding fields to a river. It is reasonable to assume that LEs are of importance in other, similar lowland arable catchments. A DEM of sufficiently high resolution, in combination with a simple steepest-descent approach to flow routing plus blind pit filling or overtopping, can do a good job of replicating observed spatial patterns of field-to-river flow. But to properly capture the effects of LE-flow interactions on runoff (and, by inference, on sediment characteristics), it appears necessary to explicitly represent these LE-flow interactions in catchment-scale erosion models. LEs are, however, not always directly represented in such models. Table 13 summarises the representation of five categories of LE-flow interactions (these include both within-field LEs, and LEs encountered after flow has left the field) in a selection of spatially-explicit catchment-scale soil erosion models.

Model	Reference(s)	Spatial discretization of catchment, as used for flow routing	Erosion modelling approach	Modelled representation of landscape element-flow interaction				
				Along-furrow flow represented?	Temporal and spatial variability of field boundary permeability considered?	Within-ditch deposition?	Flow interaction with path, track or road?	Along-talweg flow on field (or terrace) can create an ephemeral gully?
AnnAGNPS (Annual version of the AGricultural Non-Point Source model)	Young et al. 1989, USDA-NRCS, 2020	'Amorphous grid' and cells (a)	Empirical (RUSLE)	No	No	No	No	Yes
ANSWERS-2000 (Areal Nonpoint Source Watershed Environment Response Simulation model)	Beasley et al. 1980, Bouraoui and Dillaha 1996	DEM cells	Rill and interrill (energy flux)	No	No	No	No	No
Erosion-3D	Schmidt 1991, Németová et al., 2020	DEM cells	Rill and interrill (momentum flux)	Yes (b)	Partly	Yes	Yes	No
GeoWEPP	Flanagan and Nearing 1995, Renschler 2003, GeoWEPP 2020	Representative profile for each field (a)	Rill and interrill (energy flux)	No	Only indirectly and only in specific cases	No	Indirectly only	No
MEFIDIS (Modelo de Erosão FÍsico e DIStribuído)	Nunes et al. 2005	DEM cells	Rill and interrill (energy flux)	No	Partly	No	No	No
OpenLISEM (Open-source version of the Limburg Soil Erosion Model)	De Roo et al. 1996, Jetten 2017	DEM cells	Rill erosion only (energy flux)	No	Partly	Yes	Partly	Yes
SCIMAP	Lane et al. 2009, SCIMAP 2020	DEM cells	Risk-based	No	No (c)	No	No (c)	No (c)
STREAM (Sealing and Transfer by Runoff and Erosion related to Agricultural	Cerdan et al. 2002, Couturier et al. 2013	DEM cells	Interrill, rill, and gully (empirical)	Yes	Partly	No	Partly	Yes
STREAM (Sealing and Transfer by Runoff and Erosion related to Agricultural Management)	Cerdan et al. 2002, Couturier et al. 2013	DEM cells	Interrill, rill, and gully (empirical)	Yes	Partly	No	Partly	Yes
SWAT (Soil and Water Assessment Tool) (d)	Arnold and Fohrer 2005, Neitsch et al. 2011, USDA-ARS 2020	Homogenous 'Hydrological Response Units' (e)	Empirical (MUSLE or USLE)	No	Partly	No	No	No

Table 13. The representation of five landscape elements by a selection of spatially-explicit catchment-scale soil erosion models. See text for details. (a) Constructed using a version of TOPAZ (Garbrecht and Martz, 1997). (b) Erosion 3D now has a module which can calculate the transition of runoff due to overtopping of furrow ridges. (c) Could be implicitly included as a change to a risk weighting in this risk-based model. (d) SWAT has mostly been applied to large catchments, for which it is reasonable to lump Hydrological Response Units (HRUs) within a subcatchment and to not simulate processes from edge-of-field to the subcatchment outlet. (e) A recent development of SWAT (SWAT+: Bieger et al, 2016) has added the capability to route flow between HRUs, a representation of interaction between channel flooding and the flood plain subcatchment (Sun et al., 2016), and gully headcut and growth (Allen et al., 2018). As with SWAT, the intended usage of SWAT+ is large catchments.

The choice of models in Table 13 is somewhat arbitrary. Wide usage (i.e. the number of published applications) of a model was a positive factor in our choice, as was some familiarity with the model. We chose to omit ‘experimental’ versions of a model, and models which derived from an earlier model e.g. LandSoil (Ciampalini et al. 2012), which is based upon the STREAM model (Cerdan et al., 2002). The LE-flow interaction categories of Table 13 are discussed in more detail below.

Within-field along-furrow flow represented? Any model can in principle – given a DEM with very high resolution (< 10 cm) – consider within-field flow along tillage furrows. But only Erosion 3D and STREAM attempt to represent the specifics of along-furrow flow i.e. overtopping and breakthrough (Takken et al., 2001; 2002).

Temporal and spatial variability of field boundary permeability considered? Similarly, given a DEM of sufficient resolution (< 1 m), any model will acknowledge a hedge or fence and will route flow along it (or if so instructed, through it). Erosion 3D, OpenLisem, MEFIDIS, STREAM and SWAT explicitly represent field boundaries, while other models (e.g. GeoWEPP) also have the capability of representing certain kinds of field boundary e.g. buffer strips. Also, many models permit user-specified within-catchment sinks (which may be called impoundments, ponds, sedimentary basins, potholes, basins etc.): within-catchment deposition at field boundaries could be indirectly (but crudely) represented this way. However, none of the models in Table 13 are capable of easily representing the kind of spatially- and temporally-variable permeability of field boundaries which we have observed in our study area.

Within-ditch deposition? Most models can simulate within-ditch deposition if the ditch is included in a network of permanent channels. However this approach treats the ditch as if it were a low-order stream i.e. it does not specifically consider the flow conditions that lead to the build-up of vegetation and sediment that we have observed in agricultural ditches, nor does it permit a ditch to be specified as clogged or recently cleared.

Flow interaction with path, track or road? Given a DEM of sufficient resolution (< 1 m), any model can consider the impact of elevation change associated with a path or track, and route flow along or across it. OpenLISEM can explicitly represent flow along or across roads, but not under roads via culverts. Erosion 3D is capable of calculating flow over barriers such as street kerbs. For other models (e.g. GeoWEPP) the impacts of a track or road on flow may be represented indirectly, e.g. by means of the land use and soil input layers. But no model considered can represent the full range of effects of along-path infrastructure – such as gutters, culverts, drains, and surrounding buildings – on flow, as in our study area.

Along-talweg flow on field (or terrace) can create an ephemeral gully? Any model can represent an ephemeral gully if this is added to the network of permanent channels. Doing this is however logically incorrect if the ephemeral gully does not exist prior to the modelled rainfall event; it also ignores hydrological differences between ephemeral gullies and low-order streams.

An objection to Table 13 is that the influence of any LE on modelled flow routing may be represented indirectly by simply changing some input parameter value(s). For example, one effect of blocked and conditionally permeable field boundaries is to reduce the proportion of runoff and eroded sediment which reaches the catchment outlet. Fine tuning parameters for within-catchment infiltration and sediment storage may allow reproduction of this effect in terms of simulated values at the catchment outlet. However, this would be a case of “the right answer for the wrong reason” (Favis-Mortlock et al., 2001). Such epistemologically flawed approaches should be avoided if model results are to be robust, i.e. are expected to realistically represent even partially unknown situations.

In summary, Table 13 shows that these models represent the interactions between LE and flow in an inconsistent way. Some models – often the most recently developed – represent more of these interactions, but no model considers them all; and no model is capable of representing the temporal and spatial variability in LE attributes that we have observed in our study area.

4.3 Blind pits and flow routing in catchment-scale models

Blind pits are a category of LE which requires separate consideration. The DEMs used as input to catchment-scale erosion models have usually undergone some smoothing procedure (Hancock, 2008) in order to remove closed depressions within the DEM, i.e. areas (usually relatively small), which have no downhill connection to the catchment outlet. Removal of blind pits ensures that all points within the DEM are hydrologically connected to the catchment outlet (Barnes et al., 2014). There are two reasons for removing blind pits from a DEM. The first is that some blind pits may be artefacts, introduced during DEM creation. The second is that the kinematic flow approach to flow routing, commonly used in catchment-scale erosion models, requires a fully-connected DEM (e.g. Bout and Jetten, 2018). It is not easy, however, to distinguish between real and artefactual blind pits in DEMs (Callaghan and Wickert, 2019). If DEM smoothing pre-infills any real-world blind pits, this has the undesirable effect of artificially increasing the connectivity of the DEM (Yu and Harbor, 2019) and increasing field-to-river flow speeds (i.e. decreasing travel times) for flowlines which pass through these filled blind pits.

5 Discussion

5.1 The importance of LE-flow interactions for field-to-river flow in arable catchments

In our lowland arable study area, LE-flow interactions have a major role in determining both the spatial patterns of field-to-river flow of runoff and sediment, and the characteristics of runoff and sediment delivered to the river (section 2). It seems likely that this is also true for arable catchments elsewhere: including, for example, the catchment in a hilly loess area in the south of the Netherlands which was used for the IGBP-GCTE evaluation of catchment-scale models (Jetten et al., 1999); see below. Indeed, LE-flow interactions are probably important in any anthropogenic landscape where the topography/flow network has been modified at a scale less than the resolution of a DEM, including urban areas with a surface water ditch drainage network (cf. Michalek et al., 2021; Wang L. et al., 2021).

We found that flow lines can be simulated with good agreement to observed data, using a simple steepest-descent flow routing approach plus blind pit overtopping on a 5m DEM (section 3.1). However, we infer that the impacts of LE-flow interactions on runoff volume and speed, and on associated sediment flux and size distributions, cannot be adequately captured by any such simple approach. Indeed, some LE-flow interactions are highly sensitive, so that a small change in the characteristics of a single LE can have a large impact on flow routing (section 3.6) and hence the temporal distribution of flow (section 3.7). Current spatially-explicit catchment-scale soil erosion model describe LE-flow interactions in an inconsistent manner (section 4.2). In particular, no model is capable of representing the temporal and spatial variability in LE attributes that we have observed in our study area.

5.2 Model deficiencies and modelled representations of LE-flow interactions

Our findings suggest that deficiencies in the representation of LE-flow interactions in catchment-scale erosion models can help to explain the following conclusions drawn from the IGBP-GCTE evaluation of catchment-scale models (Jetten et al., 1999).

Runoff totals are better predicted than runoff peaks: runoff peaks will be strongly impacted if flow passes through a conditionally-permeable field boundary, or overtops a non-artefactual blind pit, or overtops road-side infrastructure.

Both runoff totals and runoff peaks are better predicted than sediment discharge: decreasing flow speeds at e.g. the above-mentioned LEs will sensitively give rise to within-catchment deposition.

Calibration is either essential or strongly desirable: since calibration is in effect a method of compensating for model inadequacy, it is likely that improved, more explicit, representation of LE-flow interactions will decrease the need for compensatory calibration.

These deficiencies must be addressed if catchment-scale erosion models are to transcend the general limitations found in e.g. the GCTE model evaluation study (section 4.1). Therefore representations of LEs, and of LE-flow interactions, within erosion models will need to be improved. What is needed for such improvements is of course model-specific. However, it may be generally helpful, with regard to linear LEs such as paths and roads, if erosion models were able to make use of vector representations of these LEs (section 3.3).

Nonetheless, gathering the data need for more explicit representation of LE-flow interactions may not be easy or cheap (see below). While remote sensing may be useful, field observation appears to be the only way of gathering data for some LE-flow interactions (Table 3). In section 3.4, we suggest an approach which may help to identify which LE-flow interactions are relevant for a given catchment.

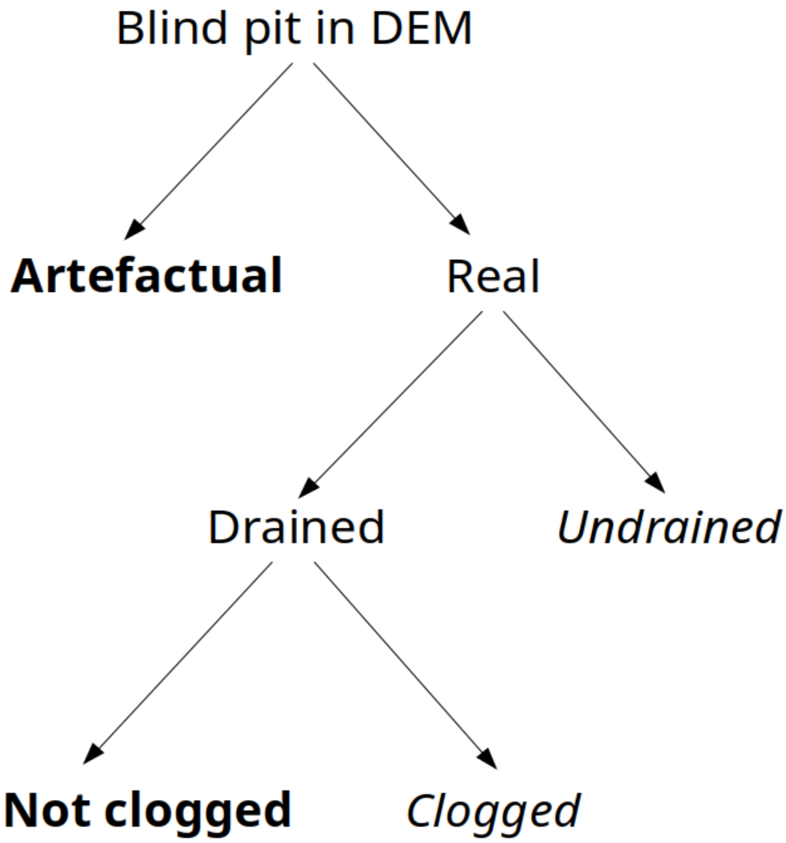


Figure 10. A typology of blind pits

Improved simulations necessitate an end to the common practice of automatically pre-filling all blind pits in the DEM (section 4.3; cf. Shook et al., 2021 and Wang N. et al., 2021). Blind pits may be handled considering the typology shown in Figure 10. Each blind pit must first be checked to ascertain whether it is an artefact of DEM creation. This may require field survey. If the pit is artefactual, then it can be pre-filled. If the pit is real but not drained, then the erosion model can simulate this by overtopping; if drained then the model must be able to represent flow via culvert or via ditch (Boardman and Foster, 2021).

Similarly, improved simulations require future models to be able to represent conditionally variable flow through field boundaries, with ponding and possible overtopping when flow is below the threshold (cf. Cossart et al., 2018). Permeability may also vary with time, previous flow conditions, and from place to place along the boundary. As shown in section 3.6, changing the permeability of even a single field boundary can have a considerable effect on flow routing. Simulations will also require explicit representation of linear LEs such as paths and roads. As has been noted by urban runoff modellers (e.g. Dai et al., 2019; Cao et al., 2020; Kim et al., 2020), flow routes which are controlled by built infrastructure (e.g. exit points for along-path or along-road flow) may well be impossible to detect except in a DEM with resolution < 1m. Subsurface flow (e.g. by culverts) cannot be determined from any DEM (Hänsel et al., 2019). Ditches must also be explicitly mapped, if they are not already mapped as permanent watercourses. Where observed flow routes are available (i.e. in 'known' situations rather than hypothetical scenarios) then mapping these is invaluable – possibly essential – for checking model results. Again, acquiring these data may require field survey, ideally during or immediately after heavy rainfall. Drone photography (e.g.

Kaiser et al., 2018) may be very helpful, although vegetation obscuring vertical or lateral lines of sight can be problematic.

5.3 How necessary are field data?

Data collected in the field are fundamental to the modelling components of this study. Acquisition of these data were reasonably straightforward for us because of our detailed observational database, but we do not under-estimate the amount of work involved. Thus obvious questions are "Is it worth it? How necessary are these field data?". For any particular catchment, the answer is of course unknown. We suggest that the only way to provide an answer is, after considering the aims of the study, to make the attempt (cf. Gascuel-Odoux et al., 2011; Mahoney et al., 2018; Baartman et al., 2020).

In any scientific endeavour there is always a balance between greater detail and improved results, but improvement in results may not justify the extra work involved in providing the extra detail. Rather, simpler and more complex modelling approaches can co-exist, as Pope (2000, p92) says:

> "In the historical development of a scientific field of inquiry, it is usual for there to be a succession of models proposed to describe the phenomenon being studied. Often [...] the early models are simple, but are subsequently found to be lacking both in physical content and in predictive accuracy. Later models may be superior in physical content and predictive accuracy, but lack simplicity. In spite of their flaws, it is valuable to have an appreciation for the early, simple models. One reason is that the behaviour implied by the models may be determined by simple reasoning or simple analysis, as opposed to the numerical solutions usually required for complex models. Second, the simple models can provide a reference against which the phenomena being studied – and also more complex models – can be compared."

5.4 Field and modelling perspectives

Finally, with reference to the need to reconcile field and modelling perspectives mentioned in section 1, the authors of this study comprise both field workers (JB and IF) and a modeller (DFM). It is not always easy to rise above the differences in expectation and terminoloy, and the unspoken assumptions which underpin each perspective ("It requires a very unusual mind to undertake the analysis of the obvious": Whitehead, 1925), but doing so was fruitful. It was a matter of surprise to all of us that observed flow routes could be adequately replicated by a simple steepest-descent model on a 5m DEM. The modeller found the variety and complexity of observed LE-flow interactions in the study area to be both surprising and somewhat daunting; and the field workers were surprised to note the sensitivity of LE-flow interaction, such that changing just one attribute of this interaction resulted in a major (and plausible) change in flow routing. Surprise is a valuable result in any scientific study: indeed, it has been said that "the way to do research is to attack the facts at the point of greatest astonishment" (Green, 1976). We suggest that, despite the difficulties regarding expectations, terminology, and underlying assumptions, this kind of field-modelling collaboration is essential for the future of soil erosion research.

6 Conclusions

We have explored field-to-river flow of runoff and sediment in a lowland arable catchment in the south of England, from both field and modelling perspectives. We began by mapping observed routes taken by flow and sediment on five study areas. These include a considerable number of interactions between flow and LEs, including many (field boundaries, paths, roads) of anthropogenic origin. A simple steepest-descent model with overtopping of blind pits, using a 5m DEM, was able to replicate the observed flow routes reasonably well: somewhat to our surprise, given the narrowness of linear LEs such as paths and tracks. However on one area, changing just one attribute of a single LE-flow interaction notably altered the route taken by simulated flow. For all areas, changing LE attributes had strong impact upon synthetic hydrographs for flow reaching the river; suggesting equally strong impacts upon transported sediment reaching the river. We conclude, therefore, that while simple steepest-descent and overtopping can work adequately in terms of replicating flow routes, more explicit representation of LE-flow interactions is necessary to enable catchment-scale erosion models to better represent runoff speed and volume, and the flux and size distribution of transported sediment; and so to overcome the broad limitations of such models as noted in earlier model validation studies. We then consider the representation of some LE-flow interactions in several catchment-scale models, and discuss the ways in which such models might, in future, better represent LE-flow interactions.

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