# Water Environment Grant- Building Blocks:
# Hydrological Analysis to Prioritise Gully Block Locations
## Final Report

Dr David Milledge, Dr Salim Goudarzi (Newcastle University), and Dr Sam Dixon, contributing author (Moors for the Future Partnership)

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# Executive Summary

## Introduction

Moors for the Future Partnership (MFFP) has received grant funding from Natural England, under the Water Environment Grant (WEG) scheme for a 24 month project; *Building Blocks – next steps in gully blocking*. The project aims to improve biodiversity in the South Pennine Moors, through addressing the condition of the blanket bogs. The three project deliverables are:

- Installation of 7800 gully blocks
- Planting 400ha of sphagnum moss
- **Identifying the locations for the next 100,000 gully blocks.**

Newcastle University has worked in collaboration with MFFP to deliver point three above, to develop the approach and detailed methodology to determine the next 100,000 gully block locations.

## The need

Identifying 100,000 priority gully block locations in the South Pennine Moors Special Area of Conservation (SAC) will inform the next 10 to 20 years of moorland restoration. Working at this landscape scale, the gully blocking locations will need to be underpinned and validated using a robust hydrological methodology backed by scientific evidence allowing for a strategic and prioritised approach with the best hydrological outcome. The prioritised locations will be used by MFFP and their partners.

## Current prioritisation methods

Gully blocking locations have been informed by research with Natural England and by academic research such as Allott et al (2005) "Understanding Gully Blocking in Deep Peat". MFFP's current approach to prioritising gully blocking locations is through a 3 stage process, this includes:

- Examining physical characteristics of the moorland, including variables such as gully depth and elevation through flow pathways.
- Other factors such as, funding eligibility, opportunity to work in new geographical areas, existing landowner agreements in place.
- Ground truthing to confirm the specific locations and types of gully blocks to be installed, such as peat or stone.

The results often lead to a site by site approach. Given the scale of 100,000 gully blocks, a strategic and prioritised approach with the best hydrological outcomes will be needed.

## Hydrological objective

The objective of the study undertaken by Newcastle University was to:

***Identify and prioritise 100,000 gully block locations in the South Pennine Moors that will restore the hydrological regime towards that of an active blanket bog, with a view to moving the vegetative community towards favourable condition.***

In this context, restoration typically aims to restore hydrological function and vegetation cover (particularly active peat forming vegetation). There is a large and growing evidence base to suggest that gully blocking has a role to play in blanket peat restoration, moving the vegetative community back towards favourable condition.

## Technical summary

There is a strong connection between re-wetting and vegetation recovery and between the area of water ponded behind a gully block and the area of peat affected by re-wetting. Thus, prioritisation of gully block locations was based on maximising ponded area of water behind potential blocks; in other words, choosing block locations in such a way that they maximise the ponded area of water while minimising the number of blocks required to do so.

The weakest link of this work has been the available digital terrain model (DTM), because the majority of South Pennine SAC is covered by a DTM of 2 m resolution but derived from a coarser 5m resolution DTM. This results in considerable topographic smoothing, meaning that some details of the true gully/channel network are absent from the DTM. As a consequence, narrow moorland drainage grips are not captured within the elevation data and in some locations the predicted ponded areas are likely to be under- or over-estimations of the true value. Therefore, the calculated ponded areas should be used as an index of block performance for prioritising the block locations rather than as absolute area estimates. The Environment Agency plans to capture 1 m resolution elevation data for the whole of England by 2021. Updating the model outputs when such data becomes available would help address many of the complications observed throughout this report.

In light of the available DTM data, two very different methods of calculating ponded area were proposed to MFFP by NU; throughout this report, the two methods are referred to as ‘lower-bound’ and ‘upper-bound’ methods. The theoretical basis of the two methods are fundamentally different, thus the two results can be used to hedge against the DTM uncertainty, such that one method is chosen as the preferred model (‘lower-bound’ in this case) and the other is used to provide a secondary estimate of ponded area. This will be particularly useful when ranking the block locations in the South Pennine SAC in order to make a decision about which areas to block first.

The methodology optimises block locations to maximise average water table rise and pond area in a particular location. It does not account for flow interactions between blocks and therefore cannot provide any indication of the impact of blocks on gully discharge. As a result, the output cannot be used as a ranking of Natural Flood Management potential of the blocks.

## Outputs / Implementation

The projected model output will now not be constrained to a target number and will identify as many opportunities for gully blocking within the constraints of the data, identifying more than the initial 100,000 gully blocking locations. The output of the prioritised list of locations will be used to inform decision making when selecting sites/areas for restoration, as well as specific restoration works within a site. Furthermore, the results will improve the accuracy of future projects for estimation during the bidding process.

When selecting sites for restoration, the hydrological prioritisation forms only part of a wider selection criteria applied by MFFP within their wider programme of delivery. Other selection criteria applied to site selection includes:

- **Social:** e.g. not worked in the area/with the landowner before;
- **Technological:** e.g. supporting science & monitoring projects, advancing knowledge;
- **Environmental:** e.g. wild fire restoration, ecological and **hydrological**;
- **Economic:** e.g. funding availability, economies of scale;
- **Practicalities:** e.g. access, landowner permission.

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# Technical Summary

This report details the methodology developed by Newcastle University (NU) in collaboration with Moors for the Future Partnership (MFFP) to: ***identify and prioritise 100,000 gully block locations in the South Pennine Moors Special Area of Conservation (SAC) that will restore the hydrological regime towards that of an active blanket bog, with a view to moving the vegetative community towards favourable condition***. In this context restoration typically aims to restore hydrological function and vegetation cover (particularly active peat forming vegetation). There is a strong connection between re-wetting and vegetation recovery and between the area of water ponded behind a gully block and the area of peat affected by re-wetting. Thus, prioritisation of gully block locations was based on ponded area behind potential blocks. The report includes results from application of the methodology at four representative pilot study sites within the South Pennine Moors SAC. These results are used to explain methodological choices, evaluate model performance relative to existing block locations, and indicate what the method is (and is not) capable of providing, illustrated with examples from the study sites.

**Results**

The pilot study sites have motivated the following **methodological choices**: 1) Gullies are identified based on a spatially adaptive gully initiation threshold ranging from 600 $m^2$ to 1,200 $m^2$ and a fixed river channel initiation threshold of 20,000 $m^2$; 2) Gully block locations are optimised on predicted pond areas resulting from block installation; 3) Two methods of estimating pond area are used, the lower bound is used as the primary method to identify gully block locations and the upper bound as a secondary check on the predictions. 4) Gully blocks 10 m wide with a maximum block height of 0.5 m are used for the lower bound pond area calculation; 5) Gully blocks 0.25 m high are used for the upper bound pond area calculation.

**Outputs**

The methodology has identified nearly 2 million potential gully blocking locations across the South Pennine SAC, this represents an exhaustive search of the potential blocking locations within the constraints of the data. Each block location includes upper and lower bound estimates of pond area and pond volume, ranking or aggregation can then be performed on any of these properties allowing between or within region rankings to be calculated using GIS software. The boundaries used to calculate block benefit rankings can easily be changed depending upon what is required (e.g. water catchments, stewardship areas etc.). The output captures the hydrological effect of a particular block in terms of the area of ponded water that it would generate. This pond area is closely linked (in ground water theory) to both the area over which the block will raise water tables and the average water table rise. The block locations and attributes have been post-processed to generate spatially averaged pond area maps for both upper and lower bound pond areas. These averages are calculated over second order sub-catchments and expressed as a percentage pond area for each sub-catchment.

**The output is suitable for** applications where changes in water table or bog pool area resulting from blocks are the hydrological property of interest including: 1) large scale application such as: prioritising regions of the SAC, informing selection of sites/areas for restoration); 2) small scale application such as prioritising areas within a site or suggesting specific block locations; 3) improving future funding bids through more accurate estimation of capital works.

**Limitations**

The relatively coarse (5 metre resolution) underlying elevation data supplied by the Environment Agency means the topography in the model is unrealistically smooth. The methodology is tailored to best utilise this data. However, the realism of the methodology is somewhat reduced. This means that: 1) estimates of pond area and volume associated with each gully block **cannot be used as absolute area and volume estimates** (e.g. to calculate total water storage potential of gully blocks); 2) specific **block locations are unlikely to be correct to less than 10 metres**, meaning a site survey will still be required to finalise block locations; 3) moorland drainage ditches (i.e. grips), which are usually narrow (<5 m) are not captured within the elevation data, thus **the influence of grips on gully development is missed in the gully network map**.

The methodology optimises block locations to maximise average water table rise and pond area in a particular location. It does not account for flow interactions between blocks and therefore cannot provide any indication of the impact of blocks on gully discharge. As a result, the output **cannot be used as a ranking of Natural Flood Management potential** of the blocks.

Global gully network definition criteria result in over prediction of gully extent in some areas and under prediction of gully network extent in most areas. This is unavoidable without manual tuning (which would take excessive time for the full study area and beyond the scope of this project). As a result, **some gullies (particularly those that are smallest and nearest to the upper tips of the drainage network) are not identified in the gully network hence are not assessed for blocking**.

The lower bound pond area estimates are susceptible to overestimation bias where gullies coalesce into nearby river\gully channels, and also where the flow pathways not defined by the gully network (which is a model input) run close to blocking locations and are inadvertently blocked. A flag has been included in the block location data to indicate points that are suspected of suffering this bias. In these cases, the upper bound pond area estimate is expected to be a more accurate indicator of potential ponding and should be used to rank the blocks.

# 1 Introduction

## 1.1 The need

Identifying 100,000 priority gully block locations in the South Pennine Moors Special Area of Conservation (SAC) will inform the next 10 to 20 years of moorland restoration. Working at this landscape scale, the gully blocking locations will need to be underpinned and validated using a robust hydrological methodology backed by scientific evidence allowing for a strategic and prioritised approach with the best hydrological outcome. The prioritised locations will be used by MFFP and their partners at a strategic and site level.

## 1.2 MFFP current prioritisation methods

Gully blocking locations have been informed by research with Natural England, academic research such as Evans et al. (2005) and conservation works officers' experience. MFFP's current approach to prioritising gully blocking locations is through a 3 stage process, this includes:

1. Examining physical characteristics of the moorland, including variables such as gully depth and elevation through flow pathways.
2. Other factors, such as funding eligibility, opportunity to work in new geographical areas, existing landowner agreements in place.
3. Ground truthing to confirm the specific locations and types of gully blocks to be installed, such as peat or stone.

The results often lead to a site by site approach. Given the scale of 100,000 gully blocks, a strategic and prioritised approach with the best hydrological outcomes will be needed.

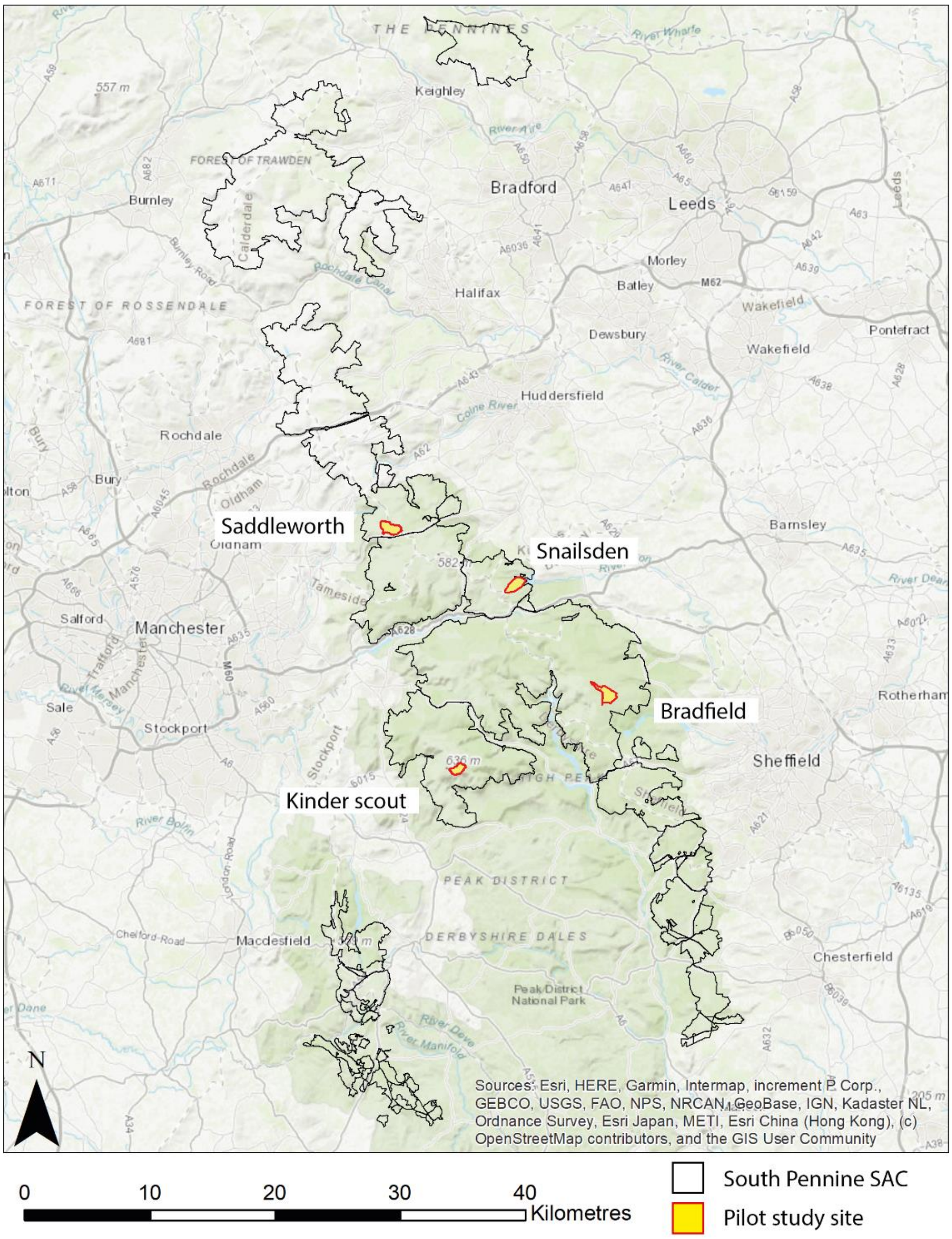
## 1.3 Current Literature

The blanket bogs of the Peak District are part of a UK resource which is globally restricted and hence of international importance for nature conservation. It includes the Habitats Directive priority habitat 'active' blanket bog, defined as 'still supporting a significant area of vegetation that is normally peat forming' (JNCC, 2011). Both the hydrological integrity and the vegetative community condition of the blanket bog habitat in the South Pennine SAC have been adversely affected by a range of factors (including historic air pollution, wild fires and land use / management practices), leading to areas of bare and eroding peat, gullying and piping, loss of peat forming species, lowered water tables and altered hydrology (Evans et al., 2005; JNCC, 2011). As a result, large areas of blanket bog are now classified as unfavourable condition.

In this context restoration typically aims to restore hydrological function and vegetation cover (particularly active peat forming vegetation – e.g. sphagnum mosses) (Anderson et al., 2009; Alderson et al., 2019). There is a large and growing evidence base to suggest that gully blocking has a role to play in blanket peat restoration, moving the vegetative community back towards favourable condition. In particular gully blocking can locally alter the hydrological regime towards that of an active blanket bog: reducing surface flow velocities and thus gully erosion, trapping eroded peat (Evans et al., 2005; Evans et al., 2006), increasing the number of bog pools (Beadle et al., 2015), and raising water tables (Dixon et al., 2014). Raising water tables is particularly important given the strong control of water table depth on both species composition through anoxia at depth and peat accumulation by retarding decomposers (Labadz et al., 2010, Price et al., 2003). These two characteristics feature strongly (along with hydrological regime itself) in the attributes of favourable condition for blanket bogs (Williams, 2006).

The effectiveness of gully blocking has been shown to depend not only on block design (e.g. Trotter et al., 2005) but also the location of the blocks (Holden et al., 2005; Parry et al., 2014). Therefore***, the objective of this project is: to identify and prioritise 100,000 gully block locations in the South***

***Pennine SAC (Fig 1) that will restore the hydrological regime towards that of an active blanket bog, with a view to moving the vegetative community towards favourable condition.***



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

*Fig 1: Map showing the South Pennine Moors* Special Area of Conservation *(SAC) with the locations of the four pilot study sites: Saddleworth, Snailsden, Bradfield and Kinder Scout.*

This final report documents the process of developing the set of gully block locations and ranks that are the primary output of the project. The aim of the report is primarily to explain what methodological choices have been made and why; and secondarily to provide a first indication of the strengths and weaknesses of the approach with respect to block performance prediction. To achieve this the report is structured to report results from the pilot study sites that were used to inform decisions taken jointly by MFFP and NU prior to full scale application of the agreed methodology.

Sections 2 and 3 of the report detail the rationale for gully block selection (Section 2) and explain how this was implemented (Section 3). Sections 4 and 5 introduce the four representative pilot study sites within the South Pennine SAC (Fig 1) at which the approach was tested (Section 4) and show results from these sites (Section 5). In Section 6 these results are used to explain methodological choices, evaluate model performance relative to existing block locations, and indicate what the method is (and is not) capable of providing, illustrated with examples from the study sites. Section 7 reports on full scale application of the methodology to the South Pennine SAC listing the methodological choices that were ultimately applied at this stage and describing the format of the final outputs. Section 8 concludes the report focussing on the implications of pilot study results for how the final set of gully block locations and ranks should be interpreted.

# 2 Rationale for gully selection

The focus of this piece of work is on restoration of the hydrological regime towards that of an active blanket bog. Thus, choice of gully block locations should concentrate on the relative significance of each potential block on the surrounding hydrological conditions (in terms of flow and saturation conditions), such that gully blocks that pond larger areas of water should be targeted first. This can be framed as an optimisation problem with the objective being to generate the largest ponding area with the least number of gully blocks.

## 2.1 Published prioritisation criteria

Existing published criteria for gully blocking locations are based on an analysis of South Pennine gully blocking shortly after installation (Evans et al., 2005) and a modelling analysis to assess change in flow paths following blocking (Holden et al., 2005). The latter study focussed on complete gully infilling which has subsequently been avoided for logistical, regulatory and health and safety reasons (MFFP, 2019). The former study made a number of recommendations based largely on observed block failure and recognising the difficulty of drawing conclusions only a short time after block installation. Evans et al. (2005) recommended that: gully slope should be <6°, block spacing should be greater than 0.7-2.8 m and less than 4 m, gully width should be ≤4 m, block height should be greater than 0.24 m for wood or stone and greater than 0.45 m for plastic piling; blocking should focus on headwaters <130 m from gully head and on bare peat areas since these are the greatest source of sediment supply.

The initial criteria described above were largely based on the assumption that the practice that Evans et al. (2005) observed of: ‘top to tail blocks’, where blocks were spaced so that the base of the upslope block was level with the top of the downslope pond was best practice. Their initial results did suggest that block failure was less likely in this case and that greater sediment accumulation and less scouring occurred (Evans et al., 2005). However, there is now a much larger body of experience on block construction so that failure is now only a minor concern. These results have also been misinterpreted in some cases as suggesting that if dams are spaced too widely the pressure from flow accumulation will be great and a dam will fail (Parry et al., 2014). This is unlikely since the force of the water on the block is controlled almost entirely by pond height and width, not discharge over the block.

## 2.2 New prioritisation criteria

Three important factors that do not feature in existing block location literature are the area of ponded water that the blocks will generate (Beadle et al., 2015), the area over which water tables should be raised and the average water table rise over that area (Dixon et al., 2014). These three criteria are central to the role of blocking in restoring the hydrological regime and thus to vegetation recovery (Labadz et al., 2010; Price et al., 2003; Williams, 2006). The new approach used here to prioritise gully block locations focuses on these criteria.

# 3 Methodology

This section summarises the methodology for extraction of potential locations for gully blocking in the South Pennine SAC, from the available topographic data. The methodology involves: construction of a Digital Terrain Model (DTM) from available LiDAR data; identification of the gully network; decomposition of the study area into sub-catchments; and optimisation of gully block locations.

## 3.1 Construction of Digital Terrain Model (DTM)

Any systematic prioritisation of block locations requires a high resolution DTM (Holden et al., 2005). LiDAR data of <2 m resolution is available for part of the study area but for the majority of the SAC the DTM is derived from 5 m resolution data, resampled to a 2 m resolution. A resolution of 5 m or less is essential to identify gullies but even 5 m data is unlikely to capture subtle topographic details of the gully and channel network. In those parts of the SAC that are covered by the 5 m data the block identification is unavoidably associated with considerable additional uncertainty. The implications of this uncertainty for data use are discussed in Section 6.5.

## 3.2 Identifying the gully network

### 3.2.1 Gully network identification using gully and channel thresholds

The most common and efficient way of defining the gully network for a given catchment is to set a minimum value for the upslope (i.e. catchment) area draining to any given cell, before that cell qualifies as a gully. This minimum value is the ‘gully threshold’. With increasing distance downstream gullies coalesce, and transition into perennial river channels. The transition from gully to river channel can also be identified based on an upslope area threshold referred to as the ‘channel threshold’. MFFP are not seeking to block these river channels. Thus, it is unnecessary to examine them as candidate blocking sites. Gullies are therefore defined as cells with an upslope area greater than the gully threshold and less than the channel threshold.

To calculate upslope area for each cell, the multiple flowpath routing algorithm of Quinn et al. (1991) was used to generate a Flow Accumulation Map (FAM). The FAM shows which group of cells drain to a particular point in a catchment. It uses an 8-direction flow algorithm to evaluate flow direction and proportion to each neighbouring cell (Schwanghart and Kuhn, 2010). Using the FAM the gully network is identified as cells with an upslope area greater than the gully threshold and less than the channel threshold (e.g. Lane and Milledge, 2012, Fig 2). The rationale for the chosen gully and channel thresholds is discussed in Section 6.1.

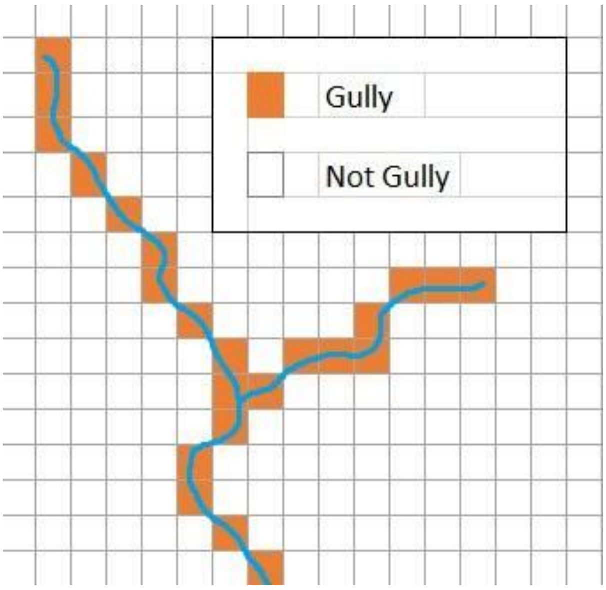


*Fig 2: Gridded gully network (credit: MFFP)*

### 3.2.2 Adaptive gully network identification

For small study areas (e.g. 1 km$^2$) the gully threshold can be tuned so that the predicted network captures the details of the gully network very well. However, natural differences in drainage density and differences in DTM resolution make it more difficult to find a single global (for the whole SAC) gully threshold that performs well everywhere. Different parts of the network will be affected differently depending on the true topography and flow pathways, meaning that a single-valued threshold approach will fail to identify some parts of the gully network.

To mitigate this effect, NU developed a variable (adaptive) threshold value such that cells further down the drainage network (i.e. closer to the outlet - ultimately the sea) require a higher threshold (i.e. larger catchment area) than those nearer the upper reaches of the network. This involves calculating the flow path length from each individual cell to the catchment outlet, then defining minimum and maximum thresholds (minThresh and maxThresh). The gully threshold value then varies linearly with distance between minThresh and maxThresh such that cells closest to the outlet get maxThresh and cells farthest from the outlet get the minThresh value. This allows smaller gullies at the top of the drainage network to be identified whilst minimising the issues associated with a low threshold (discussed in detail in Section 6.1).

## 3.3 Decomposition of the study site

The optimisation algorithm (described below) is very CPU and memory intensive and given the very large size of the DTM it is not possible to run it for the entire area at once. To alleviate that, the algorithm decomposes the study area into smaller segments and runs the optimisation separately for each segment. For this purpose, the entire SAC study area is gridded into squares of 1 km$^2$ (this is the largest area that could be modelled without further decomposition) and optimisation is then run for each segment. Once all individual square segments are optimised, without loss of accuracy, they are glued back together to form the SAC site map. As discussed in Section 5.1, channel and gully networks are identified using threshold values, meaning that, by cutting up the study site into smaller squares, the threshold values within each square would be different to the global threshold values (since the upslope areas would be changing). Therefore, in order for the gully and channel networks to be unaffected by this decomposition approach, the gully and channel networks were pre-calculated using the global values of minThresh and maxThresh for the entire SAC. These gully and channel network maps were then decomposed into 1 km$^2$ segments, each corresponding to the segments for which the optimisation was carried out. The resultant performance metrics (i.e. pond area and volume) are absolute (i.e. they are measured in terms of m$^2$ or m$^3$) so that this exercise has no impact on the prioritisation.

## 3.4 Optimisation algorithm for gully selection

### 3.4.1 Rationale for pond-area based optimisation

The project's objective was: *to identify gully block locations that will restore the hydrological regime towards that of an active blanket bog with a view to moving the vegetative community towards favourable condition*. Raising water tables is particularly important given the strong control of water table depth on both species composition and peat accumulation. Thus, choice of gully block location should concentrate on relative significance of each block on the surrounding flow and saturation conditions. Groundwater theory suggests that water tables will follow an approximately hyperbolic (i.e. dish shaped) profile set by the height of their nearest stream or pond and independent of surface topography. The change in water table height and the area over which this change occurs can be estimated given the hydraulic conductivity of the peat. Peat hydraulic conductivity is highly uncertain but because the relationship between pond height, and water table height is monotonic (i.e. if one increases the other cannot decrease) the relative increase in water table height is independent of the chosen hydraulic conductivity value. Thus, change in the area and average height of water table rise scales with average pond depth and area. ***On this basis pond area is used as the primary indicator of block impact and this area is maximised for each block.***

### 3.4.2 Upper and lower bound pond-area estimates

The algorithm calculates the pond area associated with a block based on two scenarios (Fig 3). Scenario (1) provides a best-case scenario (upper bound) for ponding, where the width of the dam can be extended as required so that water is forced to pond to the full gully block height, $H_b$ (Fig 3b). Scenario (2) provides a worst-case scenario (lower bound) for ponding, where it will not be possible to extend the width of the block as required to force the water to pond up to the block height, $H_b$. In this case the pond height is instead determined by the elevation of the adjacent cells (Fig 3c).

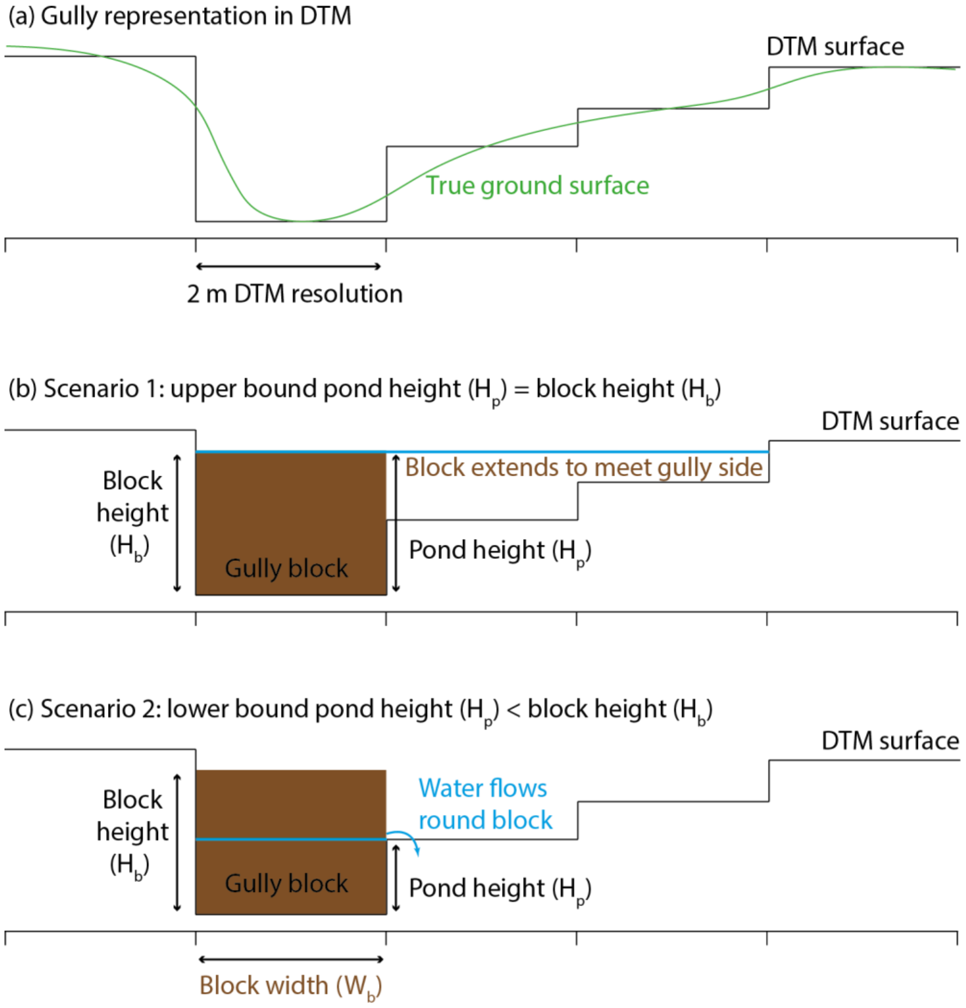


*Fig 3: cross section through a peat gully illustrating: a) the DTM representation of the true ground surface of a gully; b) scenario 1 where width is not limited so that pond height will be equal to block height but as a result the block may have a much larger width; c) scenario 2 where block width is defined as width $W_b$ and the pond height is then limited by the height of the neighbouring peat surface (in this case the cell to its right).*

In the lower bound method, block width is enforced while ponding height is determined by overspill around the block (Fig 3c). In the upper bound method, ponding height is enforced while block width is allowed to vary as required to maintain that pond height (Fig 3b). This might result in unrealistically wide blocks in the upper bound method. To mitigate this an additional requirement has been added that only cells that flow through the target cell are counted when calculating pond area and volume statistics.

Upper and lower scenarios provide two independent methods of estimating the pond area associated with blocking a particular location. Optimisation can only be performed on one of these estimates (i.e.

upper or lower bound method). Ultimately the lower bound was chosen as the preferred method. The performance of the different methods and the rationale for this choice are discussed in Sections 6.2 and 6.3. Although optimisation is performed using only one method (i.e. upper or lower bound) the other method is used to provide a second pond area estimate for each of the optimised block location.

### 3.4.3 Optimisation routine

The algorithm tests each cell in the gully network (the target cell) as a potential gully block location one-at-a-time by introducing individual gully blocks of a defined height ($H_b$), e.g. 0.5 m, and calculating the area of ponding as a consequence. The algorithm then ranks the gullies based on their generated ponding area while accounting for the interactions between gullies (e.g. if two neighbouring gully cells share ponding area, the better of the two is picked for gully-blocking). Locations that pond only a single cell (i.e. 4 $m^2$) are excluded as a candidate since these would result in every cell being allocated a block. As a result, the smallest recorded pond area for the method with which the optimisation was performed is two cells (i.e. 8 $m^2$). It is worth noting that this is only true when evaluating pond area using the method selected for optimisation. Therefore, it is possible for single cell ponds to appear when evaluating the same locations using the other method (e.g. for upper bound when optimisation has been performed with the lower bound or vice versa).

### 3.4.4 Outputs

The outputs of the optimisation are presented in the form of: 1) a shapefile of block locations where each point in the shapefile is associated with a set of attributes: the lower and upper bound pond areas (in units of [$m^2$]), the lower and upper bound pond volumes [$m^3$], the lower bound pond height [m]. This will enable MFFP to prioritise blocking locations across the full South Pennine SAC study area and to understand the relative difference in impact between one location and another. This is important because rank alone could mask very large or very small differences in block effectiveness. An example of the final outputs will be shown in section 7, where subsequent post-processing allows a map of percentage pond area (i.e. pond area as a fraction of total area) to be generated for spatially discrete segments of the study area. Results from pilot testing to choose the type and degree of aggregation for this spatial averaging are reported in Section 5.8, with the percentage pond area maps for the full South Pennine SAC shown in Section 7.

## 4 Pilot study sites

MFFP identified four pilot study sites at which to test and refine the methodology. Each site had an area of approximately 1 $km^2$ to allow application of the method without decomposition. Sites are all covered in blanket peat with varying degrees of gully erosion and re-vegetation/recovery. Topographic data at the Kinder Scout site (Fig 4c) is based on 2 m resolution data, at the other three sites it is resampled to 2 m from a 5 m resolution DTM. Gully blocking had not yet been undertaken at the Bradfield site (Fig 4d), at the other three sites at least some blocking had already been undertaken.

Apart from gully and channel initiation thresholds there are three additional choices involved in implementing the proposed methodology: 1) whether to use the upper or lower bound method to identify optimum block locations; 2) the maximum block height (relevant to the upper bound case); and 3) block width (relevant to the lower bound case).

The range of heights and widths to be tested were chosen based on MFFP's knowledge of existing gully and gully block properties. Block heights of 0.25 and 0.5 m were considered representative of typical gully blocks in the South Pennine SAC. Block widths greater than 2 m were considered to be rare but the DTM resolution imposed this as a minimum width thus initial tests were performed at this width. These early tests showed that the lower bound with 2 m width (i.e. a single cell) produced very poor results for situations where the underlying data was of 5 m resolution due to very severe topographic smoothing in the DTM. Since this represents the majority of the study area (see Fig 19) in collaboration with MFFP it was decided that widths of 6 and 10 m should be tested. Real gully blocks are not 10 or even 6 m wide but these artificially wide blocks were introduced to increase the ponding depth and prevent water flowing round the block edges. As a result, estimated pond areas and volumes cannot be interpreted in absolute terms. Instead, pond area should be considered an index of block performance.

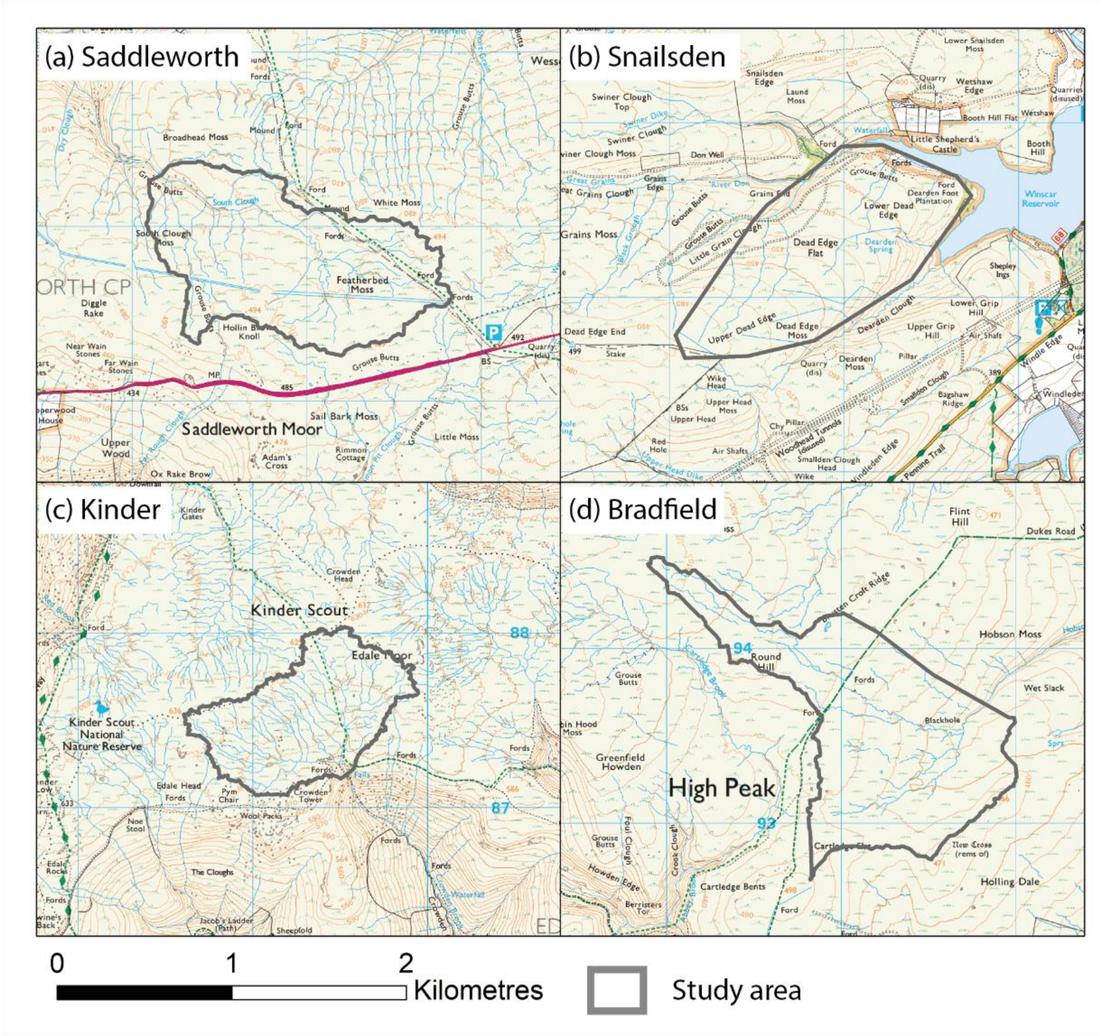


*Fig 4: Maps of the Bradfield, Saddleworth, Kinder Scout and Snailsden sites with shaded relief indicating the extent of the study sites. See Fig 1 for site locations within the South Pennine SAC.*

# 5 Pilot study Results

## 5.1 Channel and gully initiation thresholds

With increasing distance downstream, gullies coalesce and transition into perennial river channels. MFFP are not seeking to block these river channels. Thus, it is unnecessary to examine them as candidate blocking sites. Since the cost of identifying blocks in locations that are too far downstream to be suitable for blocking is small relative to the cost of missing potential blocking opportunities, a conservative channel initiation threshold of 20,000 $m^2$ was chosen. In this case a conservative threshold refers to a threshold that is more likely to mis-classify channels as gullies than to mis-classify gullies as channels to avoid missing possible blocking locations at the downstream end of the gully network.

It is beneficial to look for blocks as far up the gully network as possible thus as low a gully initiation threshold as possible is preferable. However, thresholds lower than 600 $m^2$ cause errors: indicated by the large patches of cells identified as gullies in Fig 5. These do not severely affect the methodology as the gully network is only used to identify which cells to test for blocking. However, there is both a prohibitive computational cost and an additional difficulty in interpreting outputs when the threshold is too low. Introducing the adaptive gully initiation threshold (described in Section 3.2.3) improves the identification of the gully network especially in the upper reaches of the network which are most relevant to this particular work. Comparing the network defined using an adaptive threshold (Fig 5d) with single-valued thresholds in the other panels (Fig 5a-c) the adaptive threshold reduces the 'gully patch' errors where multiple gullies appear to amalgamate while extending the network at its tips.

The gully initiation threshold for each study area was optimised to identify as many gullies as possible without generating large erroneous 'gully patches'. The resultant gully maps (Fig 6a,c,e,g) show a very wide range of gully density and gully network structure with the Kinder (Fig 6e) and Snailsden (Fig 6c) sites representing the highest- and lowest-density examples respectively. These gully networks would be the ideal basis for model application at each study site. However, since the analysis requires constant thresholds across the entire South Pennine SAC a second, global, optimisation was performed (Fig 6b, d, f, h).

Variability in gully density between sites decreases considerably when a global gully initiation threshold is used (Fig 6). There is a very small increase in density at Snailsden (Fig 6c-d), a slight reduction at Bradfield (Fig 6g-h) and Saddleworth (Fig 6a-b) and a very large reduction in density at Kinder (Fig 6e-f). These changes are expected given the differences between globally and locally optimised initiation values at these sites. However, they clearly demonstrate that the use of a single global parameter set without local calibration will result in reduced capability to identify blocks at the tips of the gully network for most sites. Alternative approaches that might allow local optimisation were considered but these would necessitate manual tuning of the gully threshold on a site by site basis and thus are not currently feasible for application to the full South Pennine SAC.

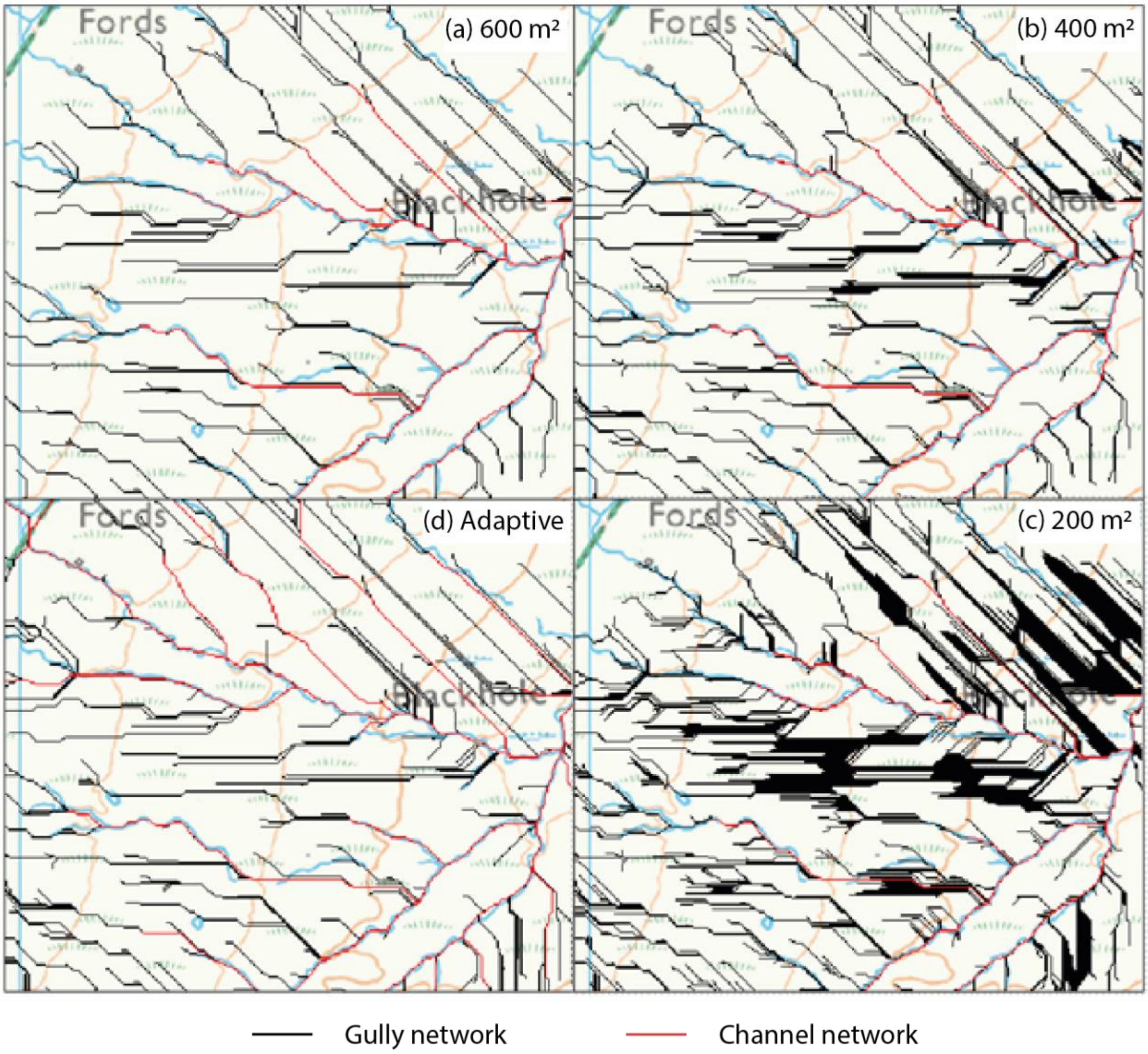


*Fig 5: Example gully (black) and channel (red) maps for part of the Bradfield study site. Clockwise from top left, gully thresholds are: a) 600 m$^2$, b) 400 m$^2$, c) 200 m$^2$; d) shows gullies identified using the spatially adaptive initiation thresholds for gullies and channels where gully threshold ranges from 200-600 m$^2$. Channel initiation thresholds are 20,000 m$^2$ throughout.*

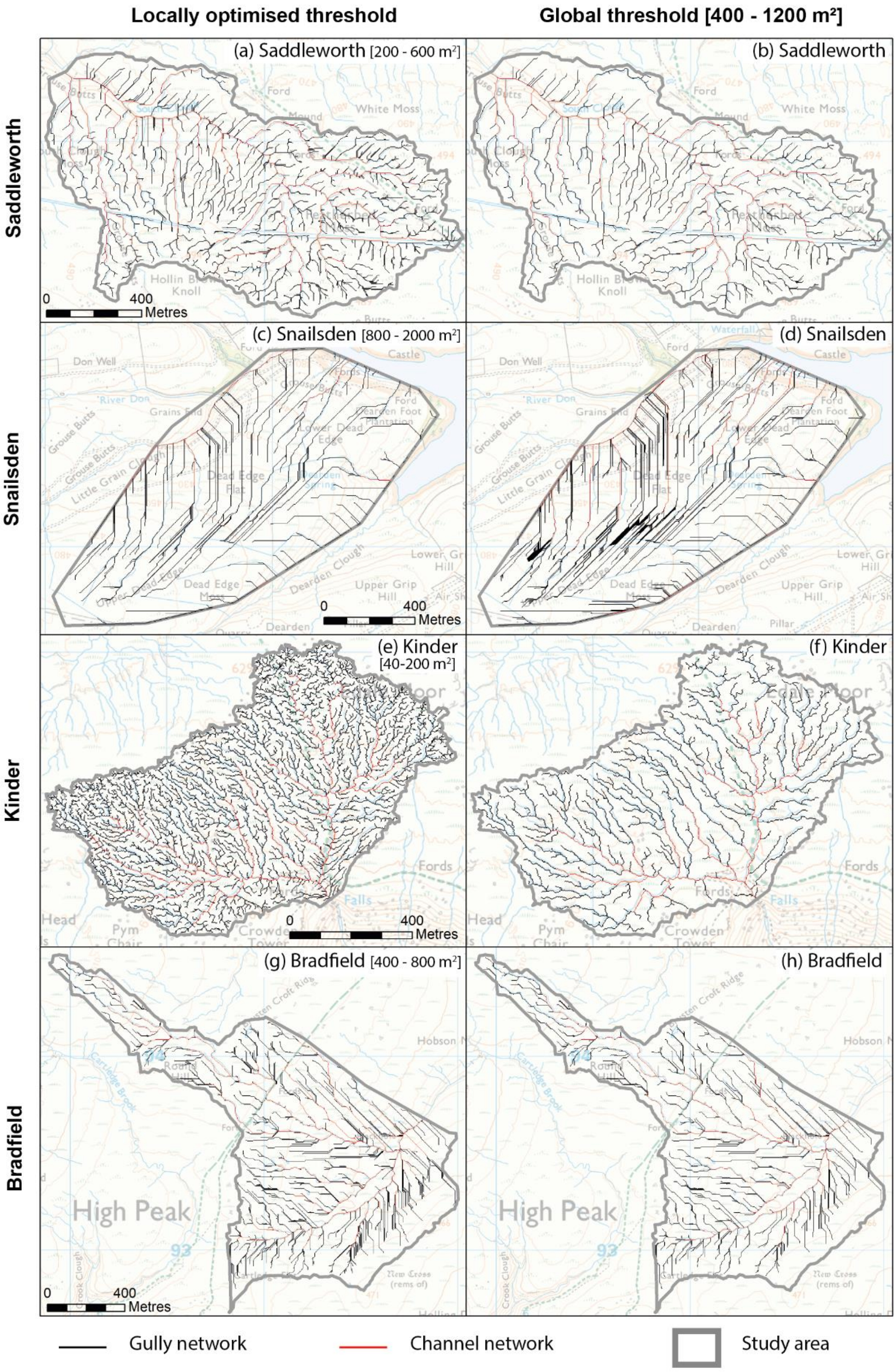


*Fig 6: Gully (black) and channel (red) maps using locally optimised gully initiation values in the left column of maps (threshold range, min-max in m$^2$, in square brackets) and global values in the right column.*

## 5.2 Block locations – Bradfield

Lower (Fig 7a-b) and upper (Fig 7c-d) bound maps are broadly comparable for the Bradfield site. The best blocks identified by both upper and lower bound methods are found in the west of the catchment towards the upper reaches of the gully network (Fig 7). In general, if a gully segment is not selected for blocking by the lower bound method, then it is identified as a poor block location by the upper bound method. The lower bound method identifies a number of very good block locations at the confluence between gullies and channels (Fig 7a-b). This effect is particularly pronounced for 10 m wide blocks (Fig 7b) and is due to blocking of the channel as well as the gully. Since this is unlikely to be possible in practice, these predicted blocks should be considered false positives.

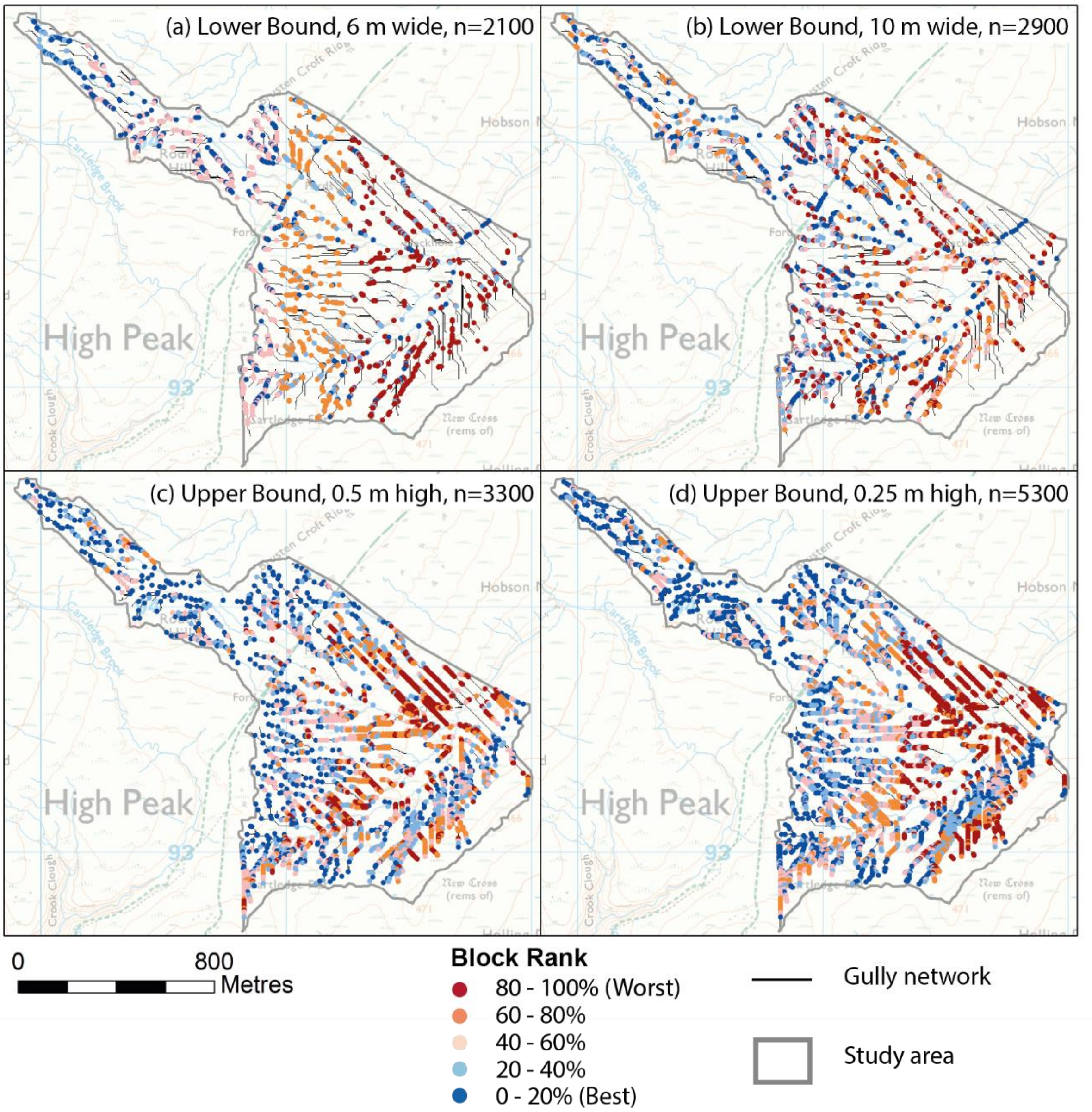


*Fig 7: relative rankings for Bradfield blocks based on pond area calculated using lower bound for a) 6 m and b) 10 m wide blocks; and upper bound c) 0.5 m and d) 0.25 m high blocks. Captions include numbers of blocks (given to 2 significant figures).*

For the lower bound method, more blocks are found using 10 m wide blocks (2,900) than 6 m wide blocks (2,100). This is because widening the blocks to 10 m decreases the number of gully locations at which a block would result in a pond area of less than 8 $m^2$, and thus be excluded as a candidate (see Section 3.4.3). These excluded locations are visible in the maps as segments of black line without any points. For the upper bound method, more blocks are found using 0.25 m tall blocks (5,300) than 0.5 m tall blocks (3,300). This increase in block numbers is caused by a reduction in the pond area behind each block, which frees up more space for new blocks (increasing the block density along gullies). The largest number of blocks are found using the upper bound method. The maximum pond depth returned in the lower bound method is 0.23 m for blocks 6 m wide (99% < 0.16 m) and 0.45 m for blocks 10 m wide (99% < 0.29 m). This indicates that the maps are insensitive to the choice of block height for block heights greater than 0.5 m.

## 5.3 Block locations – Saddleworth

Upper and lower bound maps are broadly comparable (Fig 8). The best blocks identified by both lower (Fig 8a-b) and upper bound methods (Fig 8c-d) are found in the south of the catchment towards the upper reaches of the gully network. Steep valley sides along the main-stem near the outlet are either not identified as suitable for blocking (in the lower bound case) or are identified within the worst 20% of block locations (upper bound case). However, there are some clear synoptic scale spatial differences between methods: gullies in the south-east of the catchment that contain blocks classed within the worst 20% using the lower bound method (Fig 8a-b), have blocks classed within the best 20% by the upper bound method (Fig 8c-d). This is a result of the different assumptions on which the methods are based and will be amplified as a consequence of uncertainty in the topographic data. In cases where the upper and lower bound methods are in closer agreement one can be more confident in the predicted pond area. When the two methods disagree radically this suggests reduced confidence but is unable to provide any further information as to which method is more correct.

There is clear disagreement between upper and lower bound methods at the downstream end of gullies where they meet river channels (for example the main stem of the river in the northwest corner of the catchment, Fig 8). These locations are often identified by the lower bound method as some of the best block locations (Fig 8a-b) but are either not identified at all by the upper bound method or are at least not within the best 20% (Fig 8a-b). Again, this is due to blocking of the channel as well as the gully and, since this is unlikely to be possible in practice, these predicted blocks should be considered false positives.

For the lower bound method, slightly more blocks are found using 6 m wide blocks (3,700) than 10 m wide blocks (3,500). This is likely due to an increase in pond area behind 10m wide blocks reducing the available space for new blocks. The behaviour differs from the previous Bradfield example because here at Saddleworth relatively few gully blocks generate a pond area of < 8 $m^2$(which would result in exclusion), perhaps reflecting the different form of the gullies between these sites. For the upper bound method, more blocks are found using 0.25 m tall blocks (3,800) than 0.5 m tall blocks (2,800). Most blocks are found using the upper bound method. The pond depth returned in the lower bound method reaches 0.5 m for one of the 6 m wide blocks (99% < 0.34 m) and exceeds 0.5 m for seven of the 10 m wide blocks, though 99% are < 0.46 m deep. This indicates that the maps are only very weakly sensitive to the choice of block height for block heights greater than 0.5 m. I.e. <0.2% of the blocks are influenced by choice of maximum block height.

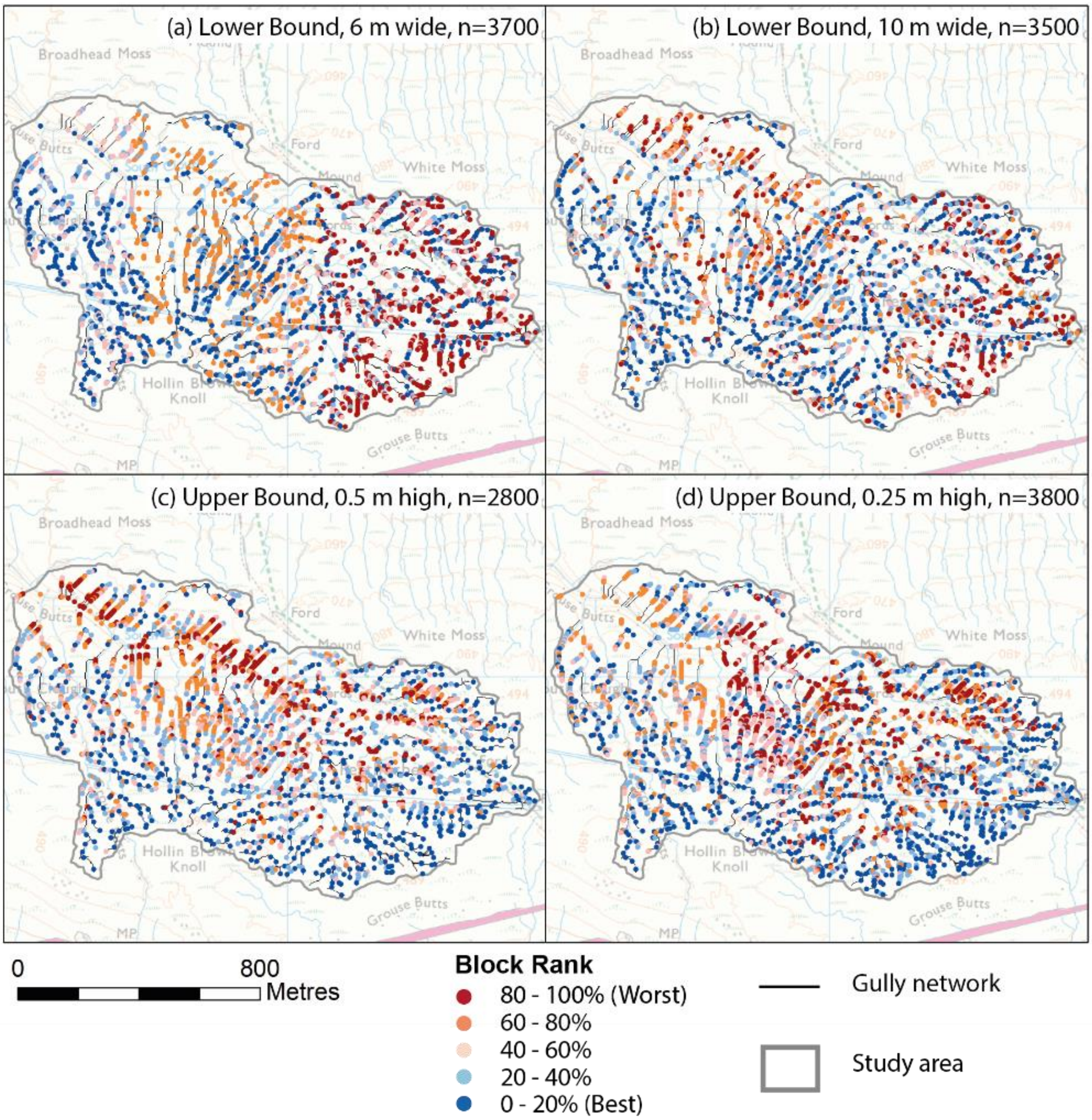


*Fig 8: relative rankings for Saddleworth blocks based on pond area calculated using lower bound for a) 6 m and b) 10 m wide blocks; and upper bound c) 0.5 m and d) 0.25 m high blocks. Captions include numbers of blocks (given to 2 s.f.).*

## 5.4 Block locations: Kinder

The pattern of gully block performance (in terms of ponding area) is extremely variable over very short length scales, resulting in a ‘salt and pepper’ appearance to the block maps with very good and very poor block locations interleafed down a single gully (Fig 9). Despite this variability, upper and lower bound maps remain broadly comparable. There are several bands of poor gully blocks running north-south across the map (probably related to gully slope). Clearest agreement is for the steep valley sides along the main-stem near the outlet where both methods identify locations suitable for blocking but both agree that they are in the worst 20% of block locations. Differences between upper and lower bound methods do exist, for example, in the northern most part of the catchment, but are difficult to identify given the extreme local variability in block performance. Within each method (upper or lower bound), differences in pond areas generated using different block height or width appear minor, with the primary effect being to alter the total numbers of blocks identified (Fig 9).

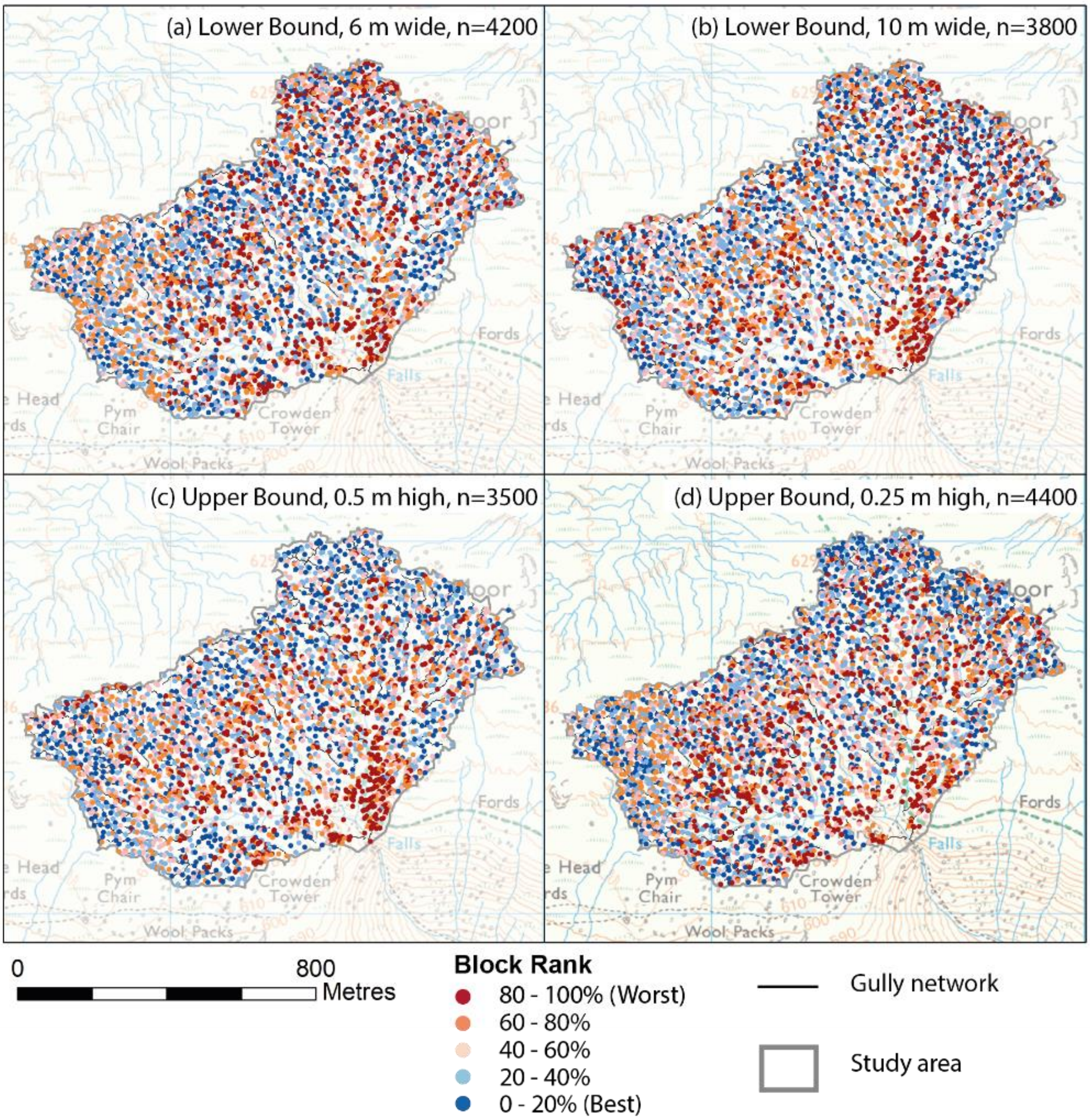


*Fig 9: relative rankings for Kinder blocks based on pond area calculated using lower bound for a) 6 m and b) 10 m wide blocks; and upper bound c) 0.5 m and d) 0.25 m high blocks. Captions include numbers of blocks (given to 2 s.f.).*

For the lower bound method, slightly more blocks are found using 6 m wide blocks (4,200) than 10 m wide blocks (3,800). This is consistent with Saddleworth but differs from Bradfield and Snailsden, likely reflecting the different form of the gullies and perhaps also their improved representation, given the higher resolution DTM data at this site. Larger pond areas generated in the 10 m case leads to fewer blocks required to pond the same overall area. For the upper bound method, more blocks are found using 0.25 m tall blocks (4,400) than 0.5 m tall blocks (3,500). Most blocks are found using the upper bound method but the differences both between different versions of the same method and between the different methods (i.e. upper vs lower bound) are much smaller than those at other sites. Again, this likely reflects the difference in gully morphology and underlying DTM data. The pond depth returned in the lower bound method exceeds 0.5 m for 301 of the 6 m wide blocks (i.e. 8%) and 445 of the 10 m wide blocks (i.e. 13%). This indicates that at this site the maps are at least somewhat sensitive to the choice of block height in this case.

## 5.5 Block locations – Snailsden

Upper and lower bound maps for Snailsden are broadly comparable (Fig 10). The best blocks identified by both upper and lower bound methods are found in the south-west of the catchment towards the upper reaches of the gully network. The steep slopes near the reservoir are either not identified as suitable for blocking (in the lower bound case) or are identified within the worst 20% of block locations (upper bound case).

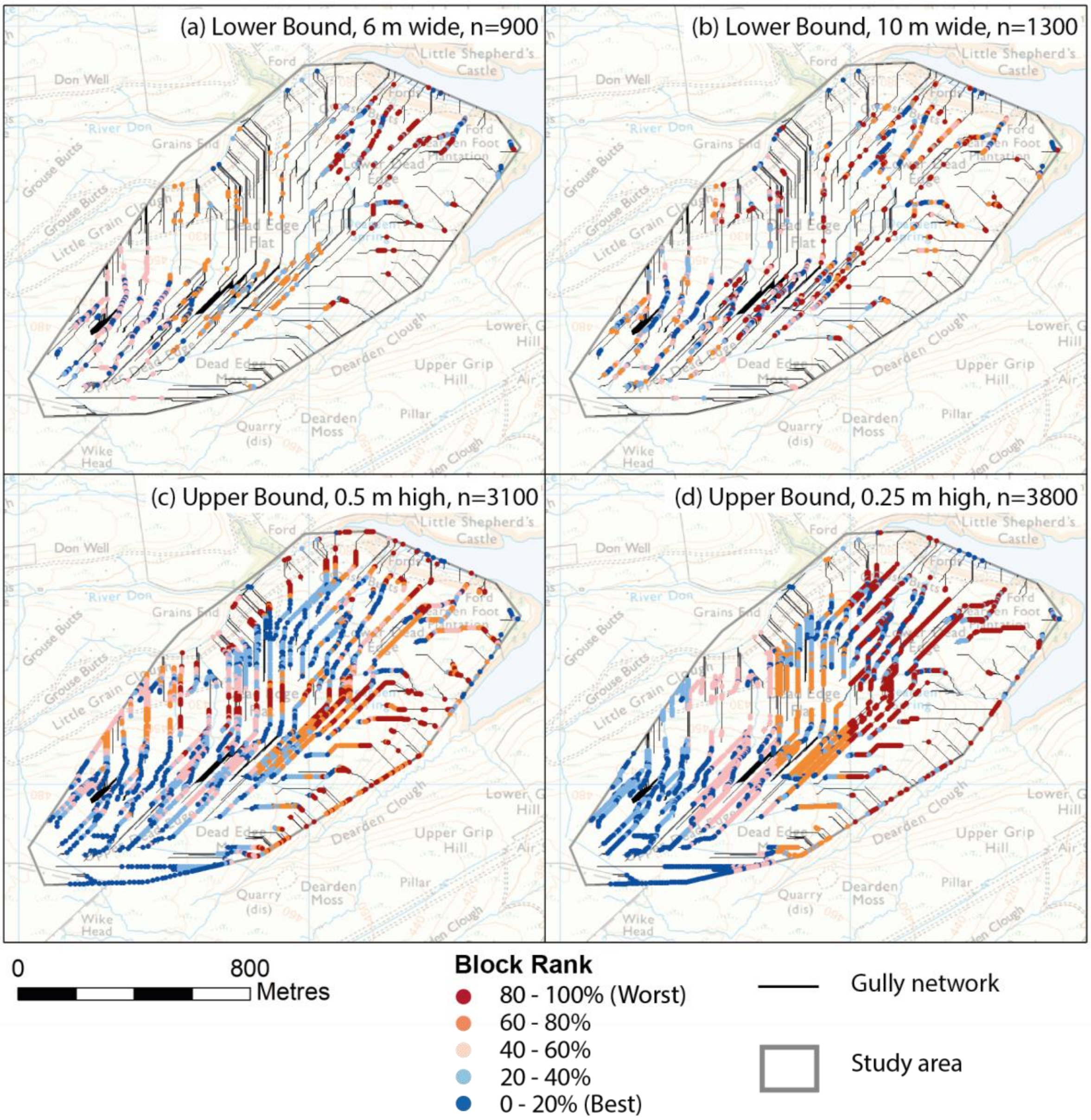


*Fig 10: relative rankings for Snailsden blocks based on pond area calculated using lower bound for a) 6 m and b) 10 m wide blocks; and upper bound c) 0.5 m and d) 0.25 m high blocks. Captions include numbers of blocks (given to 2 s.f.).*

However, there are some clear synoptic scale spatial differences between methods: gullies in the centre of the study area (just north of 'Dead Edge Flat') contain blocks classed within the best 20% or best 40% using the upper bound method, but have blocks classed within the worst 20% or worst 40% by the lower bound method (Fig 10). The differences are less severe when smaller blocks are used in the upper bound case (Fig 10d) and narrower blocks in the lower bound case (Fig 10a). Again, in cases where the upper and lower bound methods are in closer agreement one can be more confident in the predicted pond area. When the two methods disagree radically this suggests reduced confidence but is unable to provide any further information as to which method is more correct.

For the lower bound method, more blocks are found using 10 m wide blocks (1,300) than 6 m wide blocks (900). For the upper bound method, more blocks are found using 0.25 m tall blocks (3,800) than 0.5 m tall blocks (3,100). Most blocks are found using the upper bound method. The maximum pond depth returned in the lower bound method is 0.39 m for blocks 6 m wide (99% < 0.25 m) and 0.43 m for blocks 10 m wide (99% < 0.33 m). This indicates that the maps are insensitive to the choice of block height for block heights greater than 0.5 m.

## 5.6 Site by site differences – (global block ranking)

Using both upper and lower bound methods, on a global scale (where blocks are ranked globally), Kinder provides the largest number of good block locations (more cool colours in Fig 11; and see Table 1), followed by Saddleworth then Bradfield and Snailsden.

Snailsden appears a particularly poor candidate for gully blocking (Fig 11c-d) with the lowest number of blocks in every class, though the catchments are very similar in size (Table 1). The small number of total blocks reflects a lower drainage density than that of the other sites (e.g. Kinder) and a large number of single cell blocks, which have been excluded during optimisation. These single cell blocks likely reflect relatively steep slopes within the catchment (in the upper bound case) or smooth topography preventing ponding even behind 10 m wide blocks (in the lower bound case). Unlike other sites the DTM surface at Snailsden is extremely smooth. If this is a true representation of the ground surface then the site is likely to present relatively few gully blocking opportunities. However, if gullies at the site are small enough to be undetectable within the 5 m resolution DTM then the model's predictions for the site will be unreasonably pessimistic. This highlights the strong dependence of the model on the quality of the topographic input data.

Table 1 shows a large number of ponds with areas greater than 64 m$^2$ for all sites except Snailsden. Such large ponds are extremely unlikely in reality. These results highlight that pond areas should be treated as a relative index of ponding rather than an absolute estimate of expected pond area following blocking. The Kinder site, with its improved DTM data, is the only site at which pond area estimates might be expected to be reliable in absolute terms. However, even here there are a large number of large ponds (Fig 11e-f). Overestimation of pond area could be caused by: topographic smoothing (related to the DTM resolution), incorrect classification of river channels as gullies (due to a global channel initiation threshold) and undesirable blockage of river channels where wide gully blocks extend across both a gully and a river (only applicable to the lower bound method).

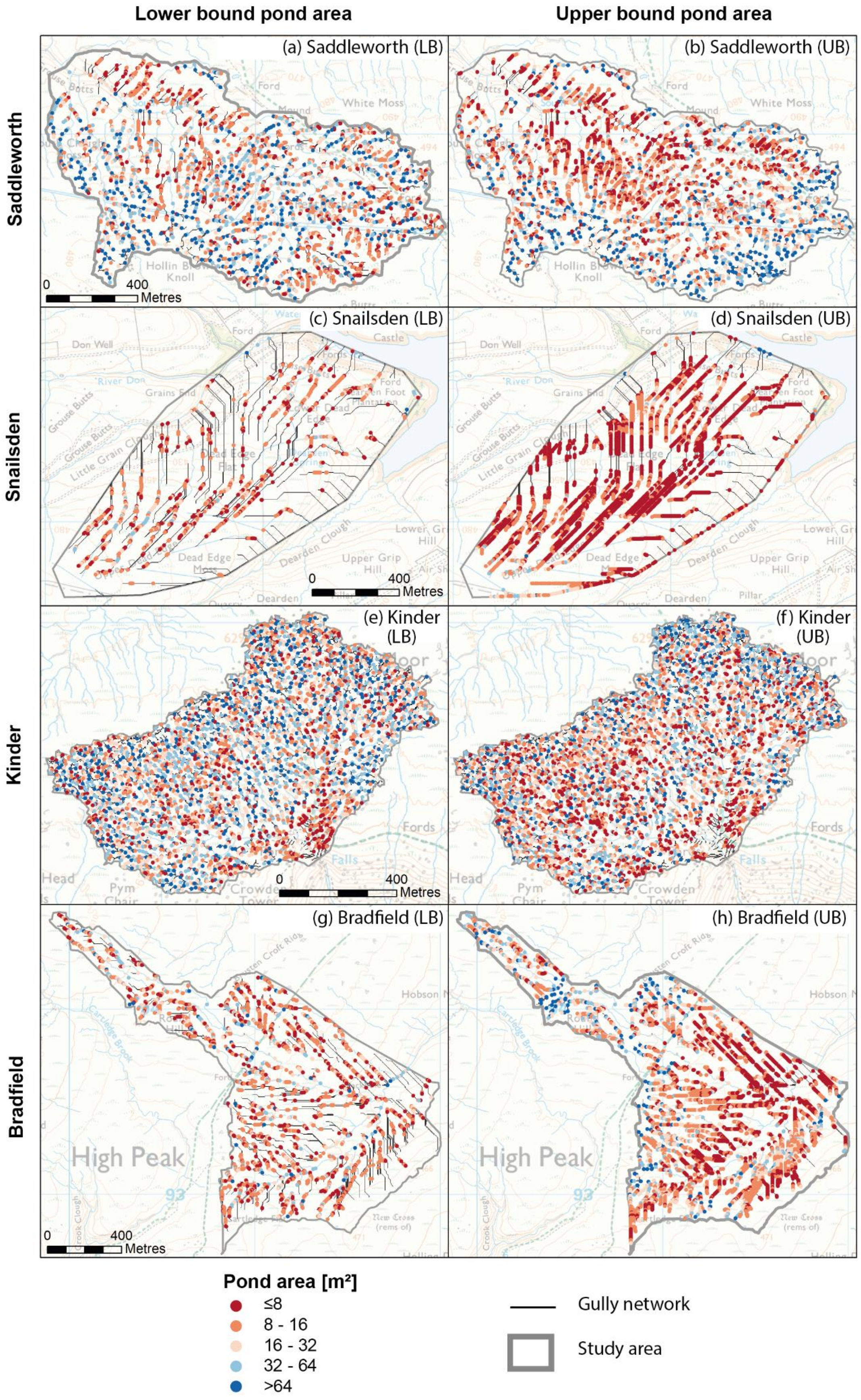


*Fig 11 Absolute pond area predictions for the four study areas using: upper bound method (0.25 m height) for maps in the left column and lower bound method (10 m width).*

| Pond | Kinder | | Saddleworth | | Snailsden | | Bradfield | |
|---|---|---|---|---|---|---|---|---|
| Area [m$^2$] | Lower | Upper | Lower | Upper | Lower | Upper | Lower | Upper |
| >64 | 565 | 453 | 408 | 368 | 3 | 9 | 52 | 183 |
| >32 | 1322 | 1218 | 851 | 709 | 5 | 34 | 179 | 483 |
| >16 | 2240 | 2269 | 1569 | 1411 | 281 | 227 | 703 | 1469 |
| >8 | 3216 | 3382 | 3002 | 2729 | 966 | 1140 | 2177 | 3552 |
| ≥8 | 3826 | 4385 | 3512 | 3842 | 1329 | 3820 | 2876 | 5327 |

*Table 1: number of ponds with a surface area [m$^2$] greater than the first column for each of the pilot sites and for lower and upper bound methods. Lower bound method uses blocks up to 0.5 m tall and 10 m wide, upper bound method uses blocks 0.25 m tall with no upper limit on width.*

## 5.7 Comparison with ground truthed data

The model is difficult to validate since its predicted pond areas cannot be interpreted in absolute terms. However, three of the four pilot study sites (Bradfield, Saddleworth and Kinder) have all experienced some past gully blocking by MFFP so that existing block locations are available at the sites. These block locations were not chosen purely hydrologically but also on the basis of landowner agreement, costing, accessibility for machinery, among other things. Therefore, we wouldn't expect a perfect match. However, comparison to existing block locations does give a general indication of the model's performance.

Results for the lower bound at 10 m width and upper bound at 0.25 m height are shown here because these are the models agreed upon in face to face meetings with MFFP. Where the model identifies a gully it generally also identifies block locations that are in good agreement with the observed locations. The three pilot study sites shown here (Kinder, Saddleworth and Snailsden) have radically different topographic form with: a dense dendritic (i.e. tree-like) network of gullies at Kinder; a sparser network of gullies at Saddleworth that remain clearly identifiable in the DTM; and a smooth flat topography across the majority of the Snailsden site. This explains both the different gully networks identified at these sites and the difficulty of identifying a single consistent gully threshold applicable to all sites.

### 5.7.1 Which sites does the model perform best at?

The model appears to agree particularly closely with the observed block distribution at Saddleworth (Fig 13), to agree fairly closely at Kinder (Fig 12) and to strongly disagree at Snailsden (Fig 14). This could reflect both the differences between gully selection methods and/or criteria; and between the available information on which these criteria were evaluated. For example, the model fails to identify a number of gullies that are clearly, though subtly, visible in the field. This difference is most striking at Snailsden, where a gully runs across the slope which is not visible in the DTM or the gully map derived from it.

### 5.7.2 How should the agreement between predicted and observed block locations be interpreted?

At the Kinder site (Fig 12), the granularity in predicted gully block performance makes it difficult to assess the level of agreement between predictions and observations. Blocking was undertaken for entire stretches of gully, and these almost always encompass the full range of predicted pond sizes. At the Saddleworth site (Fig 13), where the pond size pattern is less granular, an overall clustering of better and worse blocking locations emerges. Although this appears more desirable, it is likely an artefact of the smoother topographic data at the site. The granular pattern observed at the Kinder site (Fig 12) is likely to be more realistic.

The observed blocks at the Saddleworth site closely match the predicted pattern with the unblocked areas generally being those which are populated with ‘poor’ blocks in the predictions (Fig 13). The most prominent exceptions are the very good block locations (i.e. to result in very large ponds) predicted to be adjacent to river channels that do not match observed block locations. These are locations where the model has made an erroneously high pond area prediction because the gully block has extended across the river channel.

At the Snailsden site (Fig 14), there is also clear clustering of better and worse blocking locations, again this is likely an artefact of the smooth topographic data at the site. There is relatively little range in pond areas at this site and the pond areas are generally small relative to those associated with the best blocks from other sites. The observed blocks are not a good match to the predicted pattern (Fig 14). This is largely due to the model’s inability to identify the true gully network. The extent of the gully network is important because the model only looks to place blocks within the network so it will never find blocks in places it hasn’t identified as part of the network. The modelled gully network follows a different flow path to that which exists in reality. There are a number of places where the field mapped gullies run parallel to but do not overlap the modelled gullies. This is an unavoidable result of the low precision and resolution of the topographic data.

In other locations, the gully network overlaps with a mapped block location but that location is not identified by the model as a potential block location (Fig 14). This is due to the removal of potential blocks where pond area is less than 8 m$^2$ (i.e. only blocks that pond more than a single, 4 m$^2$, cell are shown on this map). Since true pond areas are almost certainly larger than 4 m$^2$ this suggests model error is to blame. This error is likely to be the result of the coarse (and therefore smoothed) representation of the topography in the DTM.

Finally, there are also some areas of relatively good agreement at the Snailsden site, particularly in the north-east of the study area (Fig 14), where gullies are more clearly defined close to the reservoir. These larger deeper gullies are both more clearly identifiable in the DTM and better suited to topographic analysis to estimate pond areas.

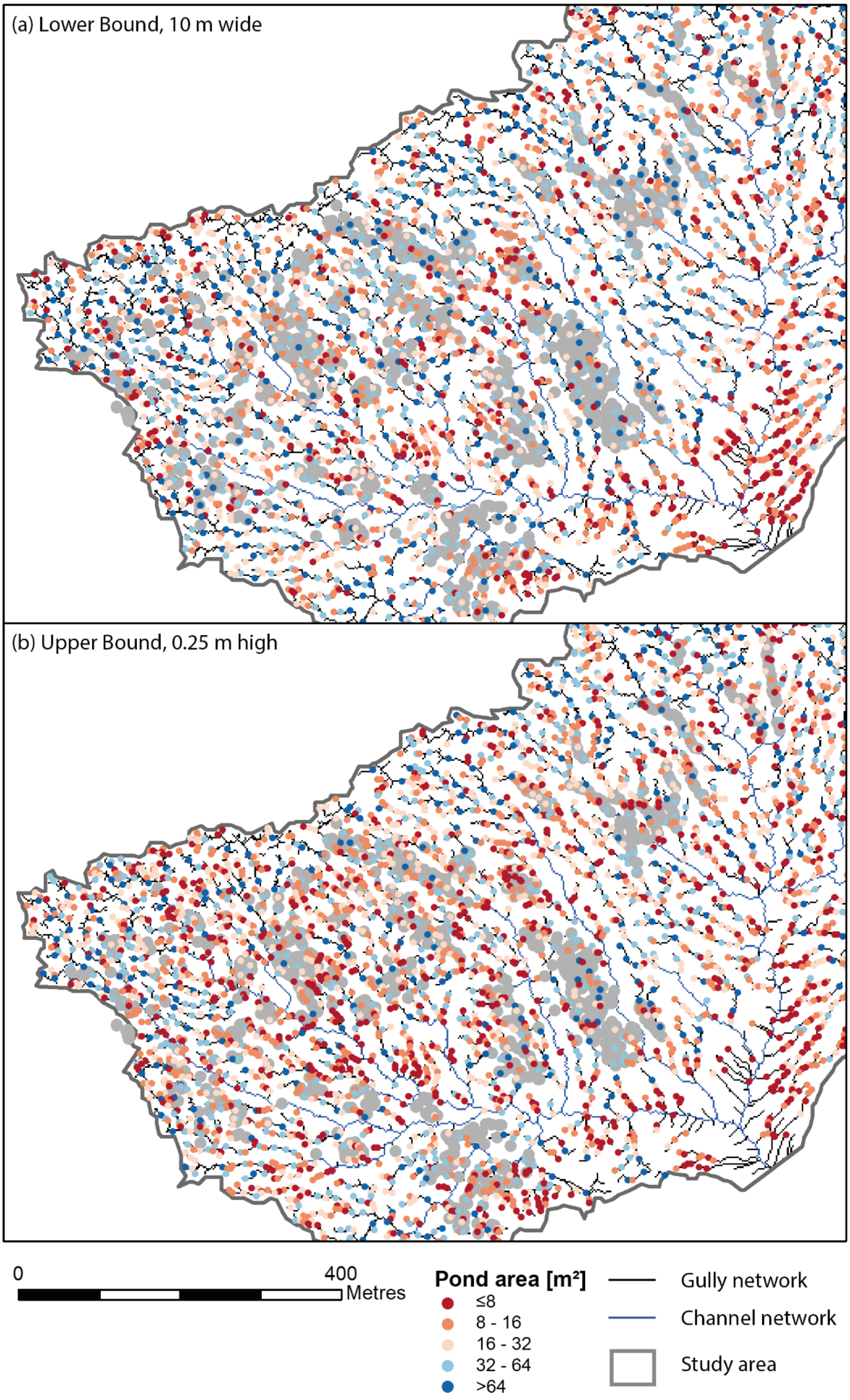


*Fig 12: Kinder - (a) lower bound (10 m width) and (b) upper bound (0.25 m height) block predictions compared against existing MFFP blocks (shown as large grey circles).*

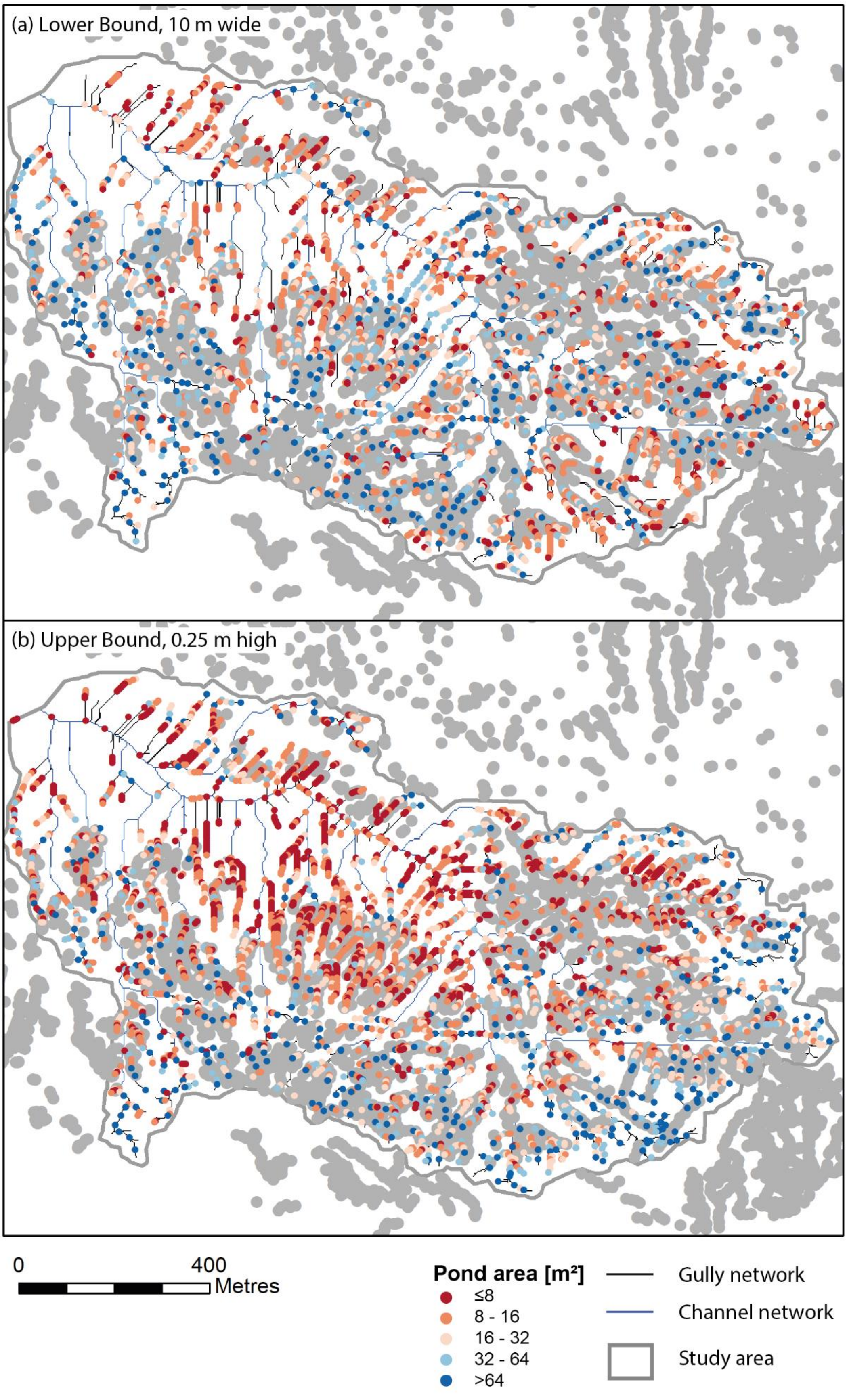


*Fig 13: Saddleworth - (a) lower bound (10 m width) and (b) upper bound (0.25 m height) block predictions compared against existing MFFP blocks (shown as large grey circles).*

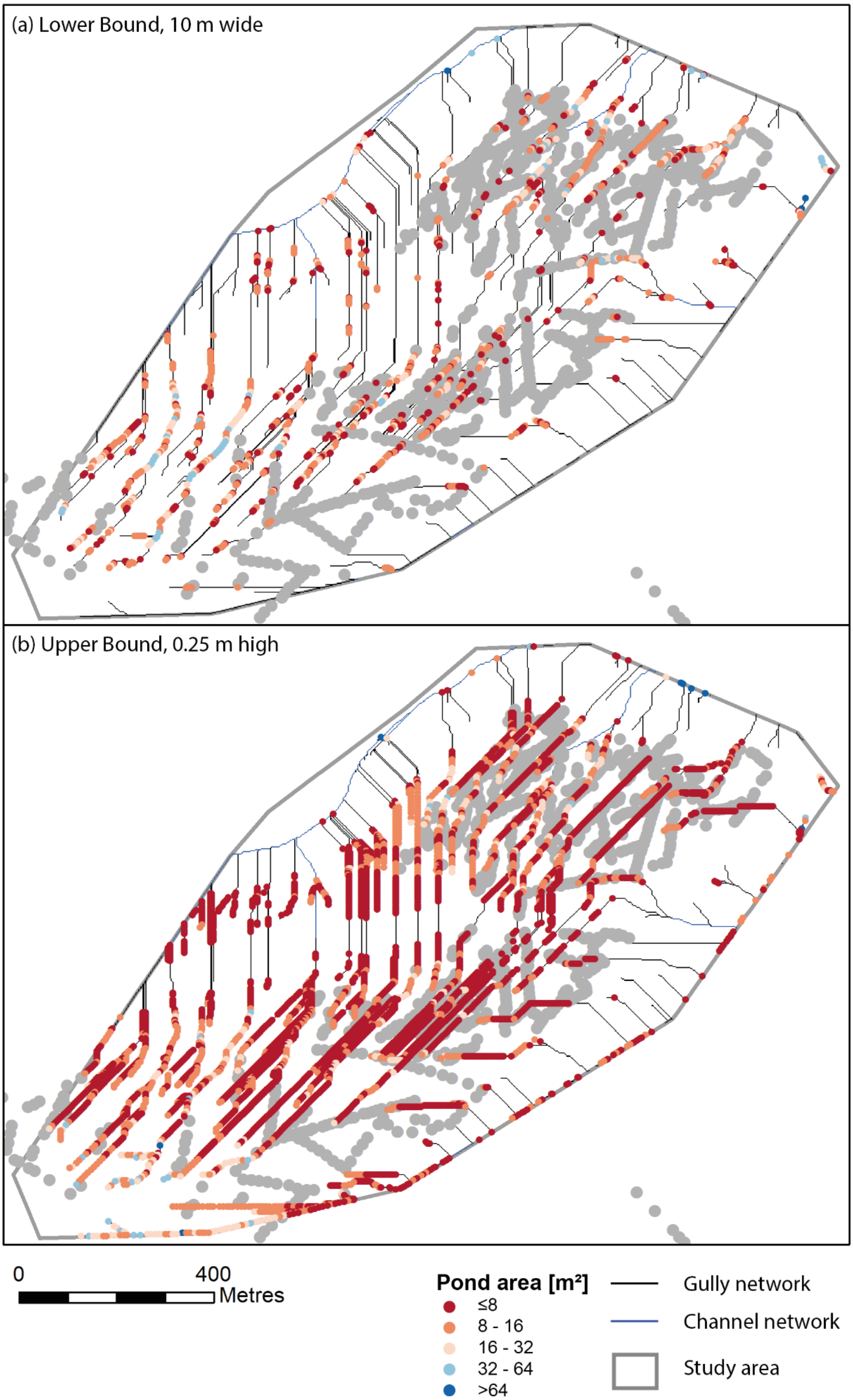


*Fig 14: Snailsden - (a) lower bound (10 m width) and (b) upper bound (0.25 m height) block predictions compared against existing MFFP blocks (shown as large grey circles).*

## 5.8 Spatial averaging to generalise gully blocking performance

Two different approaches have been tested to generate generalised gully block performance information. The first approach uses a gridded average, where the pond area for each block within a (coarse, >50 m resolution) grid cell is summed then divided by the area of each cell so that potential pond area can be expressed as a percentage of land surface area. In this case the resolution at which the averaging is performed is very tightly controlled and there is no variability in the spatial scale over which the averages are calculated for a given map. However, the boundaries of the units over which the average is calculated are arbitrary (i.e. they follow a grid pattern rather than catchment boundaries). Tests were performed for 100 m, 200 m and 400 m grids, with corresponding areas of 1, 4, and 16 hectares (Fig 15a-c). Of these the 200 m grid appears to offer the best trade-off between detail and noise reduction.

The second approach uses sub-catchment averaging, where sub-catchments are defined from the channel network by identifying confluences between channels and setting these as the downstream boundaries for each sub-catchment. In this case there is limited control over the resolution at which the averaging is performed and there is considerable variability in the spatial scale over which the averages are calculated for a given map.

However, the boundaries are hydrologically defined for the units over which the average is calculated. These boundaries do appear to offer improved aggregation providing more homogeneous units (i.e. more consistently 'good' or 'bad') relative to the uniform grids. Tests were performed for sub-catchments generated by defining catchment outlets at confluences of 1st, 2nd and 3rd order streams (with areas in the region of 0.05, 0.5, and 4 hectares (Fig 15d-f). Of these the 2nd order sub-catchment averaging was chosen by MFFP as that which offered the best trade-off between detail and noise reduction for an individual site (Fig 15e).

Gridded averages can be generated relatively easily in standard GIS software. However, their arbitrary boundaries are more difficult to interpret than a sub-catchment boundary and there is some indication that aggregation by sub-catchment reduces within unit variability. Thus, spatial averaging for the full South Pennine SAC was performed at the scale of 2nd order catchments (Fig 15e).

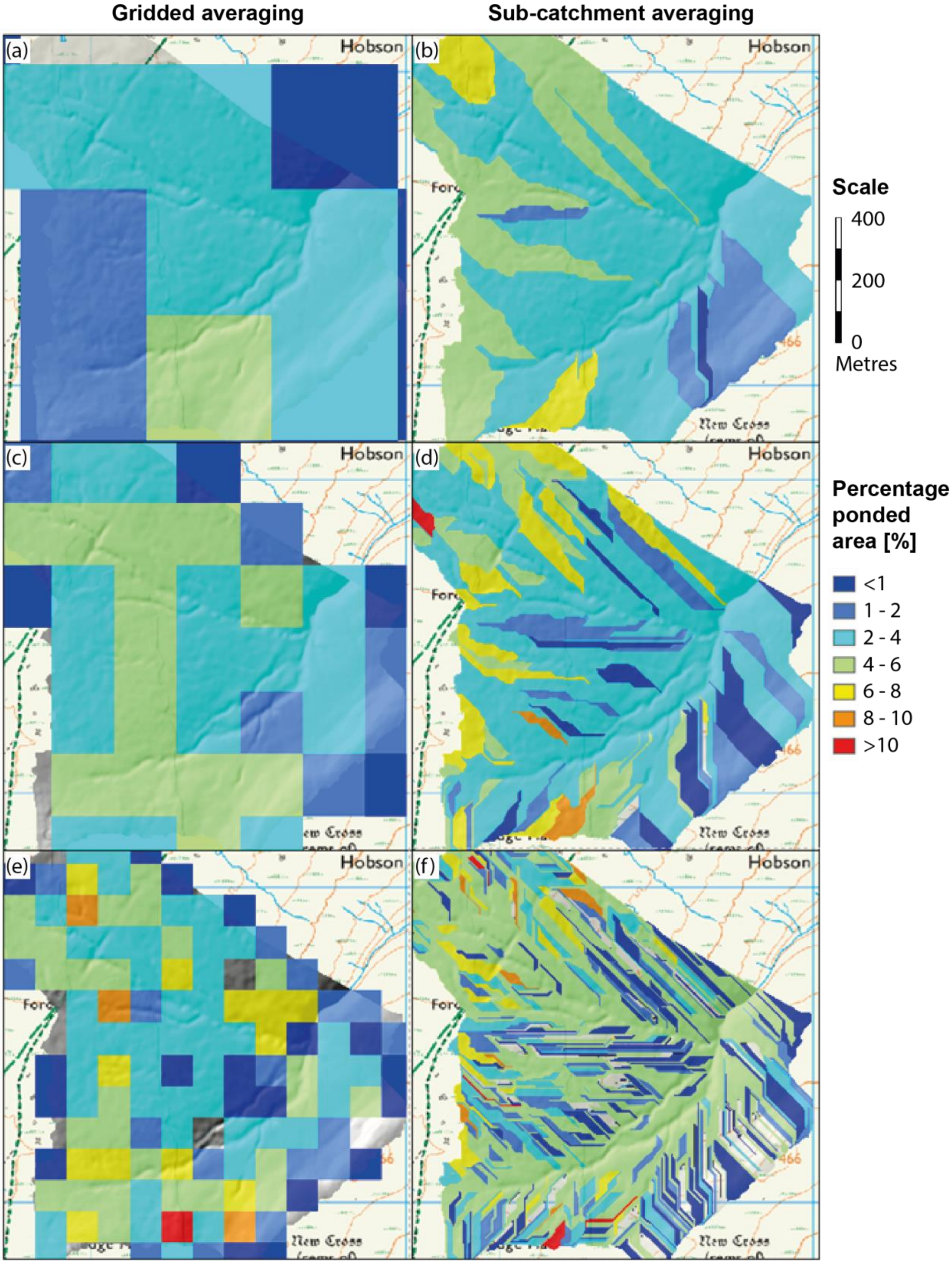


*Figure 15: spatially averaged percentage ponded area for lower bound (10 m width) at Bradfield. The left column shows gridded averages at: a) 400, c) 200 and e) 100 m resolution; the right column shows sub-catchment averages for: b) 3rd, d) 2nd, and f) 1st order catchments.*

# 6 Discussion

## 6.1 Choice of channel and gully initiation threshold

Channel and gully initiation thresholds control the candidate cells that are evaluated to identify best block locations. Field experience suggests that blocking locations near the tips of the gully network are often the most effective. Thus, searching for gully block locations as high up in the gully network as possible is clearly desirable. This requires that the gully network extends to smaller catchment areas (to ensure that the model looks at these locations). Gully networks are difficult to identify in 2 m DTMs when these DTMs have been derived from coarser 5 m data. Simply extending the network by reducing the threshold for gully initiation results in poor quality gully maps with many parallel 'false gullies' near the stream network. This is a symptom of planar slopes (where the gullies are not present in the topographic data). Introducing an adaptive gully initiation threshold based on distance from the sub-catchment outlet allows a more extensive gully network while avoiding most of the erroneous ‘gully patches’. There is a hard limit to how successful this can be though, since the subtle topography (and particularly the shallow, narrow gullies) at the top of the headwaters, are simply not present in the 5 m data. In addition, the gully network density varies considerably over the South Pennine SAC with some areas (e.g. Kinder) characterised by an extremely high drainage density and low gully initiation threshold while others (e.g. Snailsden) are characterised by extremely low drainage density and high gully initiation threshold. These differences are not resolved by an adaptive threshold but instead result in underestimates of gully network density at most sites (since the threshold must be set to avoid serious errors at the least dense sites). The adaptive gully initiation threshold has been parameterised to minimise this effect with adaptive initiation thresholds ranging from 400 m$^2$ to 1,200 m$^2$ giving best performance across the full range of pilot study sites. However, there is inevitable loss of performance related to this global application relative to a site by site calibration.

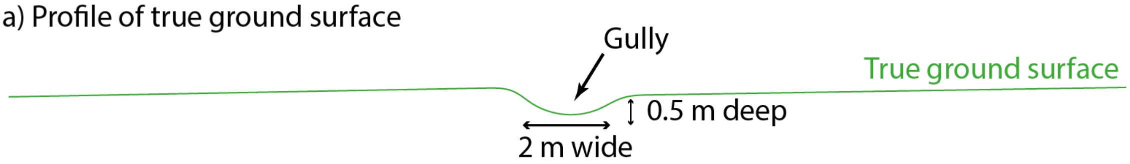
**Recommendation: use a spatially adaptive gully initiation threshold ranging from 400 m$^2$ to 1,200 m$^2$ and a fixed channel initiation threshold of 20,000 m$^2$.**

Global application of the gully mapping methodology revealed a large number of ‘gully patches’ using the 400-1,200 m$^2$ adaptive threshold, this reflects large areas of the SAC where the topography was smoother than at the Snailsden pilot site. The lower threshold for gully initiation was increased to reduce the number of ‘gully patches’ to an acceptable level. **The final thresholds used for gully mapping across the full South Pennine SAC were: 600 m$^2$ to 1,200 m$^2$.**

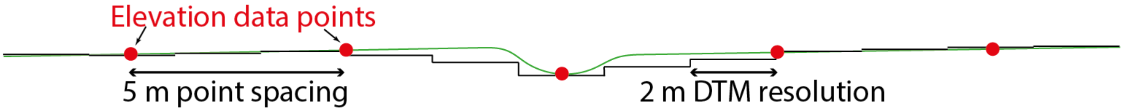
## 6.2 Lower bound method

The lower bound method has the strongest theoretical basis as an estimator of pond area because it is the closest approximation to the process of blocking a gully in reality. In a specified location the gully floor is raised by a block of defined width and height, water that would previously have flowed through that location ponds until it can spill round or over the block. However, the lower bound method is also most sensitive to uncertainty in the underlying topographic data. Systematic underestimation of pond size in the lower bound case is strongly related to topographic smoothing in the DTM. For example, if a real landscape has gullies that are 50 cm deep and 2 m wide spaced at 20 m intervals along contour (Fig 16a), these gullies would at best be represented as gentle swales 50 cm deep and 10 m wide (Fig 16b). In reality, water could pond to the full 50 cm depth (Fig 16c). However, in the example shown here, the lower bound method would predict ponding to a depth of only 40 cm behind a barrier 50 cm tall and 6 m wide because it would flow round the sides once it reached 40 cm deep. This is the best possible case scenario in terms of the topographic data since it assumes that elevations are sampled from the bottom of the gully. If the DTM is constructed from individual ray returns (as in photogrammetry or LiDAR) and the gully floor does not provide any returns, then the gully would be totally invisible and the profile would instead be entirely planar. If the DEM is constructed from an integrated return (as in InSAR) then the gully floor elevation will be an average elevation over the entire pixel in this case resulting in a gully depth of ~10 cm.

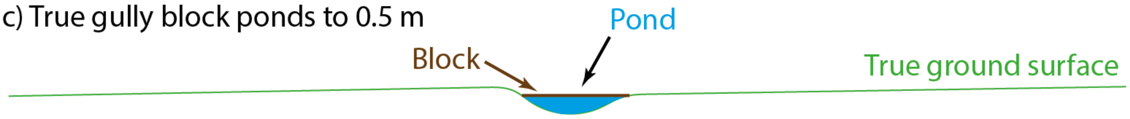
a) Profile of true ground surface



b) 2 m DTM from 5 m point spacing with a point at gully bottom



c) True gully block ponds to 0.5 m



d) Modelled 6 m wide 0.5 m high block ponds to 0.4 m

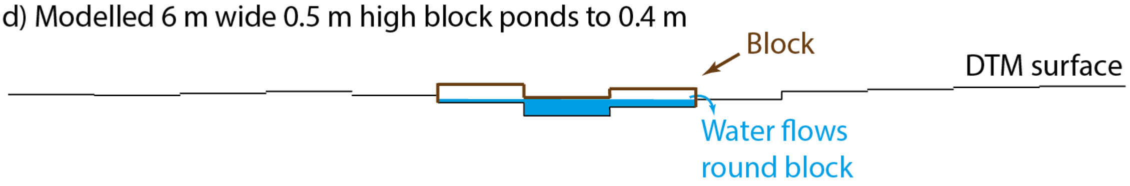


*Fig 16: Sketch cross section of a gully showing: a) the true ground surface in green, b) the elevation data derived from 5 m resolution photogrammetric DTM (red points) then re-interpolated to 2 m (black lines); c) the true gully block and resultant pond; and d) the gully block generated using the lower bound method with block height of 0.5 m and width of 6 m.*

A cross section running parallel to contours in the Bradfield study area from grid ref: 211,933 to 210,932 illustrates how subtle the gully topography is within the DTM (Fig 17). The y-axis for this profile is stretched for the purpose of illustration, elevation change is less than 1 m over the 140 m profile, but even after stretching the y-axis, the profile appears extremely smooth. It is difficult to pick out all but the largest gully (at a distance of about 100 m). This topographic smoothing explains both the disagreement between field observations of gully locations and the difficulty that the model has in estimating pond areas using the lower bound method. This smoothing is why the absolute values of area and volume have limited usability. Given the degree of smoothing, the model performs relatively well.

To mitigate the effect of smoothing in the lower bound method, the width of the gully blocks was extended. Real gully blocks are not 10 or even 6 m wide but these artificially wide blocks were introduced to increase the ponding depth and prevent water flowing round the block edges. The estimated pond areas and volumes are certainly not accurate and cannot be interpreted in absolute terms. However, pond area as an index of block performance is now better able to give relative indications of potential blocking locations.

Block widths of 2, 6 and 10 m were tested in the lower bound method. Where the underlying topographic data were of 5 m resolution blocks of 10 m width resulted in: 1) a larger number of candidate blocks; 2) better agreement between modelled and mapped block locations; and 3) modelled pond depths that were in closer agreement with those found in the field (though these were still much shallower than the observed ponds). On this basis a block width of 10 m was used for the lower bound method.

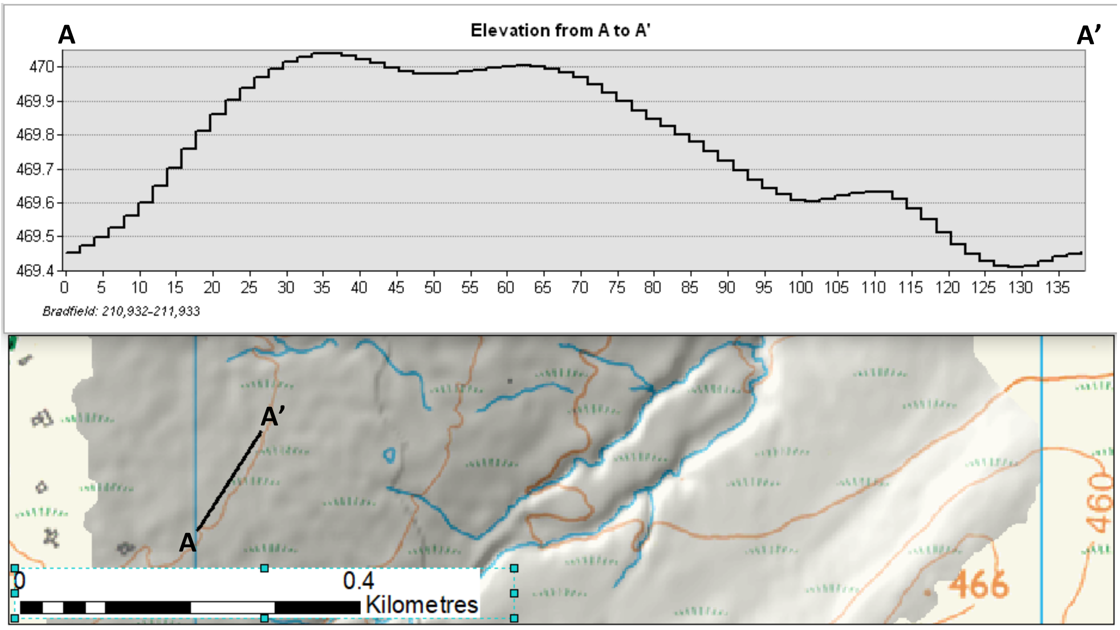


*Fig 17: a shaded relief map of part of the Bradfield study area and an elevation profile for the transect drawn on the map running from grid ref: 210,932 to 211,933.*

The maximum block height was set to 0.5 m and this is almost never reached when the underlying topographic data is 5 m (even for 10 m wide blocks). At the Kinder site, where the underlying topographic data are finer the maximum height is reached for approximately 10% of blocks reflecting the reduced smoothing at the site. On this basis a maximum block height of 0.5 m was used for the lower bound method.

Pond area is the most robust statistic with which to quantify block performance. This is because the alternative, pond volume, includes both pond area and pond depth, adding a second uncertain prediction and these uncertainties are likely to compound one another.

**Recommendation: use 10 m wide blocks with a maximum block height of 0.5 m and optimise on pond area.**

### 6.2.1 Lower bound and the 'channel issue'

Extending a block width beyond a single cell runs the risk of blocking multiple flow-lines with a single block. In the case that the extension runs into neighbouring gully or river channels then very large ponds can result (for example see Fig 18). This is a problem, because in this case, the generated pond area could include cells that are not in the upslope area of the target gully cell (central cell of a 5 cell wide block), meaning it is not clear how much of the calculated pond area is draining through the target cell and how much of it is due to undesirable blocking of neighbouring gullies/channels. In this report, this problem is referred to as the 'channel issue'. The channel-issue however, is not happening only at the gully-channel convergence, although that is the most obvious and severe location for it to occur. Channel-issue can occur at the gully-gully convergence or when two gullies are very close to one another (perhaps parallel) without converging, such that a block of 10m width can block both gullies. It is important to note, however, that since a global gully-threshold value was used, there will be a lot of smaller gullies that aren't identified in the gully-network which was input to the model (see section 5.1). When extending a block width to 10m, the gullies absent from the gully-network will still get blocked and contribute to pond area, even though they are not draining through the target block cell, causing lower-bound pond area becoming larger than upper-bound; which seems to be in violation of the principles of upper and lower bound methods described in section 3.4.2. However, note that the fundamental rule that lower-bound pond area will never exceed the upper bound's (as the names suggest) stops being a fundamental rule, when the block width is extended to more than one cell. Therefore, there has to be a way to filter out the abovementioned erroneous pond areas calculated by the lower-bound. This is described in Section 7.

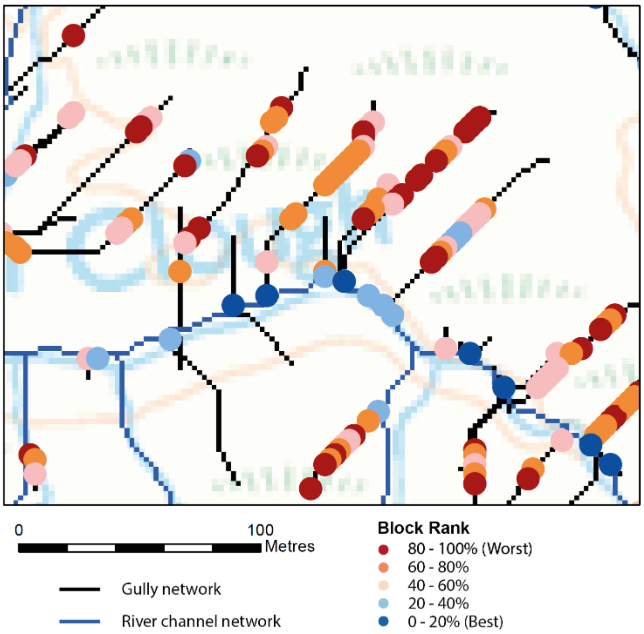


*Fig 18: gully block locations and ranks for part of the Saddleworth study site using the lower bound method with 10 m wide 0.5 m high blocks. The best blocks identified by the model in this figure are the result of wide gully blocks extending into the river channel causing large pond areas.*

## 6.3 Upper bound method

The upper bound method represents an alternative to the lower bound method for predicting best block locations. A weakness of the upper bound method is its assumption that water ponds to the height of the block independent of how wide the block must be to enable this (for example, in the profile shown in Fig 17 a 50 cm high block would be more than 140 m wide).

As with the lower bound method, estimates of pond area will not be accurate in absolute terms and as with the lower bound method, the error will increase with topographic smoothing (i.e. it will be most severe for lower resolution DTMs). However, the upper bound method is generally less sensitive to topographic smoothing than the lower bound method, particularly in terms of relative rankings. In addition, the upper bound method returned a larger sample of potential block locations (because it did not censor poor block locations) and, encouragingly, that the two methods produced broadly comparable patterns in terms of block performance.

The upper bound is most useful for identifying gullies or areas in which blocking will be most effective however, it is less effective as an indicator of numbers of blocks required within that region. This is because block spacing is set by pond size (such that two block locations share the least ponded area); and because pond sizes tend to be significantly larger in the upper than lower bound case the upper bound provides a minimum estimate for the number of blocks required. Decreasing block height generally increases the density of blocks (i.e. the number in the study area) whilst retaining a very similar pattern in terms of block performance. This is because it reduces the pond sizes and hence frees up more space for additional blocks. On this basis a block height of 0.25 m was used for the upper bound method so as to provide a more conservative estimate of the number of blocks needed for a given gully.

As with the lower bound method, pond area is likely to be the most robust performance metric given the additional uncertainty in pond depth (which is needed to calculate pond volume).

**Recommendation: use 0.25 m block height for upper bound and optimise on pond area**

## 6.4 Using the upper and lower bound methods in combination

The lower bound method will identify a gully block location as ‘good’ if: 1) a gully exists in that location; 2) the topographic gradient is gentle upslope of the location; and 3) the gully sides are clearly defined over a distance of 10 m (given the parameterisation of 10 m wide gullies). The upper bound method will identify a gully block location as ‘good’ if: 1) a gully exists in that location; and 2) the topographic gradient is gentle upslope of the location. There is no requirement for gully sides to be clearly defined in this method.

The lower bound method should be more accurate given topographic data capable of identifying gully geometries. Thus, the lower bound method is recommended as the primary method in locating gully blocks. However, the pilot results have demonstrated that this method tends to underestimate pond area when comparing with ‘like for like’ (10m wide with a maximum height of 0.5m) gully blocks in the field. However, when comparing model results with real world gully blocks the model tends to overestimate pond areas (note also that where the ‘channel issue’ occurs over-estimation is more likely; see section 6.2.1).The requirement for clearly-defined gully sides in identifying good block locations censors some locations that would be suitable for blocking. These locations will be characterised by narrow gullies or gullies that are shallow relative to the vegetation induced surface roughness. As a result, the upper bound method is recommended as a check on the lower bound predictions. In locations where both upper and lower bound agree, confidence in the block performance is high. In locations where the lower bound predicts no block or a block that performs poorly but the upper bound predicts a block that performs well this would indicate a location that should be treated with caution.

**Recommendation: use the lower bound method as the primary method with which to locate gully blocks and the upper bound method as a secondary check on these predictions (where agreement indicates a high degree of confidence, while poor lower-bound, but good upper-bound performance prompts further investigation).**

## 6.5 Impact of DTM resolution

The Kinder site was included as a pilot site to represent parts of the South Pennine SAC where native 2 m data are available. Predictions from the upper and lower bound methods converge at the Kinder site (i.e. the two methods predict similar block locations). This convergence is both expected and encouraging. Convergence of the predictions is expected because the methods have a theoretical basis in upper and lower bounds on pond area, thus as their predictions become more similar this indicates improved accuracy. Convergence of the predictions is encouraging, because it suggests that the model is performing well for this site where native 2 m data are available. Thus, in the small fraction of the South Pennine SAC where native 2 m data are available the impact of optimising the process for the resampled 5-to-2 m data will be fairly small (see Fig 19). Little is lost by setting up the methodology to attain best performance with the 5-to-2 m DTMs, much would be lost if the opposite approach was taken.

**Recommendation: design the methodology to maximise performance in areas where the 2 m DTM is generated by resampling 5 m data. Earlier specific recommendations reflect this choice.**

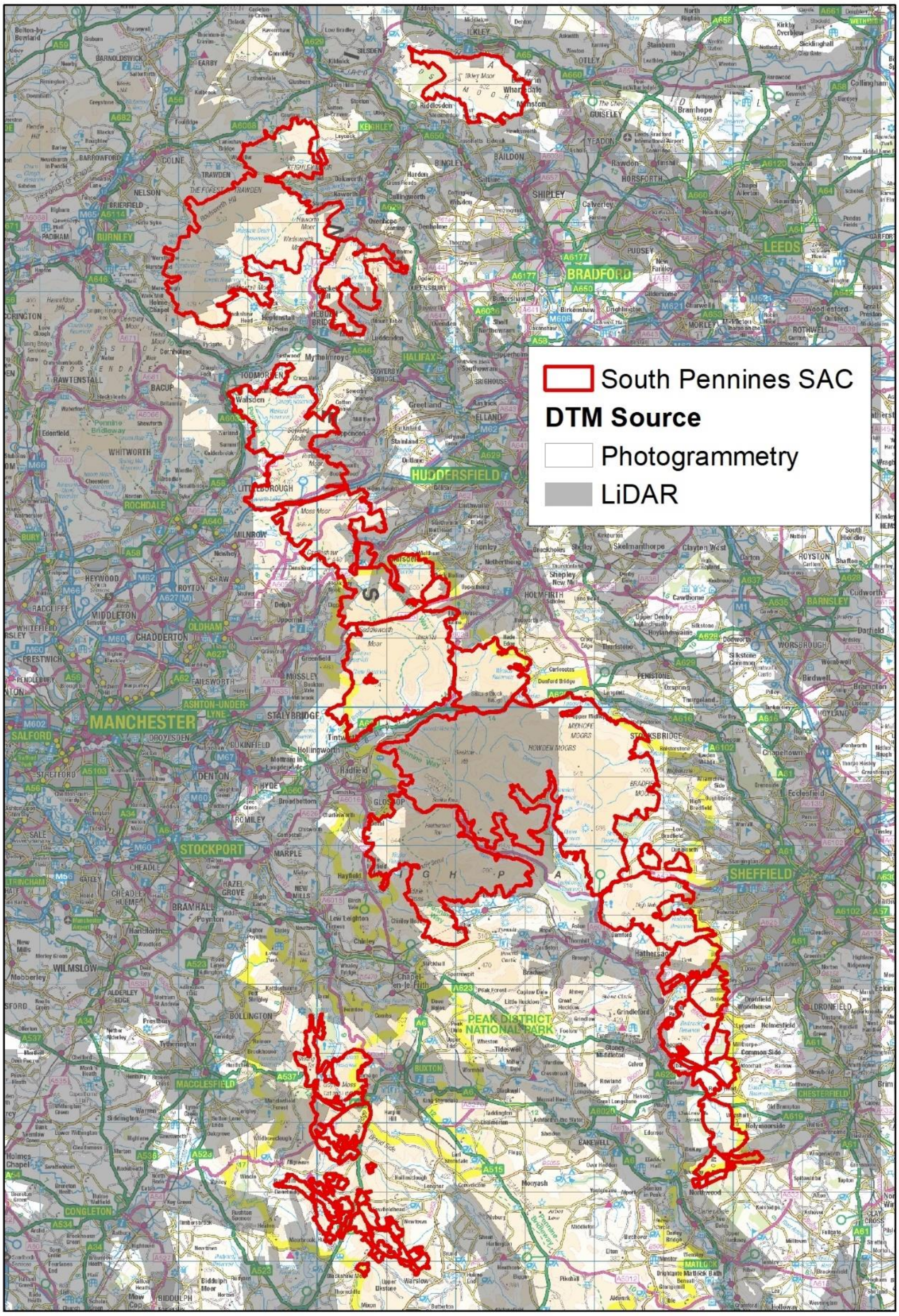


*Fig. 19: map of the South Pennine SAC showing the availability of 2 m LiDAR data.*

## 6.6 Interpreting block location and performance data

Application of the model to the full South Pennine SAC has provided a map of nearly 2 million potential block locations, which includes all block locations that pond an area greater than 8 $m^2$. As a result, a decision needs to be made about what is a worthwhile block. However, this is an operational decision that must be made in the context of: 1) the specific objectives of the user; and 2) the conditions at the site.

**Do not assume that the specific locations are correct to <10 resolution.** DTM resolution and topographic representation for most of the pilot studies is such that they will not be. Field judgement for specific locations remains the gold standard. In addition to existing rules routinely used by field surveyors that are focussed on feasibility and longevity of blocking in a location a 'rule of thumb' to identify best locations in the field might be: "maximise the length of gully segment that will contain standing water after blocking". To apply this operationally might involve siting the top of the next block such that it is at the same elevation as the base of the upstream block.

**Do not assume that the pond statistics: area, volume, maximum depth are true representations of the ponds that will be generated by blocking these locations in reality.** The extreme smoothing in the DTM means that pond depths tend to be underestimated and pond areas overestimated. The direction of the error in volume will differ depending on which effect dominates but it is clear that large errors in absolute values for depth, area and volume are the norm rather than the exception for these smoothed DTMs.

**Do not expect grips (i.e. moorland drainage) to be included within the gully network.** The gully identification method is extremely unlikely to identify grips or eroded grips. Gullies are identified on the basis of flow accumulation, which is highly sensitive to the representation of the topography within the DTM. Gullies formed by peat erosion due to surface flow generally run orthogonal to the contours (i.e. they follow the path of steepest descent) at a scale of tens of metres, with the micro-scale topography at the sub metre scale introducing only minor changes to the overall flow direction. Grips were typically dug across the slope (parallel to the contours) in order to divert surface and subsurface flow and drain the peat. As a result, there is a very large (up to 90°) divergence between the path of steepest descent at a scale of tens of metres and the path of steepest descent defined by the micro-scale topography (i.e. the grip). If this grip micro-topography is incompletely captured, flow will revert to the macro-scale path of steepest descent. Grips are typically less than 4 m wide thus they are typically invisible within a 5m or even 2 m resolution DTM. Where they are captured, they will only temporarily divert modelled flow until incomplete representation diverts the modelled flow downslope once again.

**Do not use the block rankings as an indicator of their flood management potential.** Block locations are optimised to maximise pond area this assumes impermeable blocks (so that water ponds behind then spills over them) and does not account flood wave behaviour. As a result, neither the block locations nor their associated rankings should not be interpreted in terms of flood management potential. Permeable blocks are likely to result in smaller and shallower ponds as these ponds will drain between rainfall events. The degree of permeability positively correlates with time-averaged pond area and depth thus more permeable blocks are expected to yield reduced benefits in terms of local water table rise.

# 7 Model outputs for the South Pennine SAC

On the basis of pilot study results and in consultation with MFFP the following choices were taken:

1) The lower bound method was used as the primary method with which to locate gully blocks. Optimisation of block locations was undertaken based on the lower bound. For the blocks identified in this optimisation, pond areas and volumes were calculated using the upper bound method as a secondary check.
2) For the upper bound, a block height of 0.25 m was used.
3) For the lower bound, 10 m wide blocks and a maximum block height of 0.5 m was used.
4) A spatially adaptive gully initiation threshold was used, ranging from 600 $m^2$ to 1,200 $m^2$ despite a narrower recommended range (400-1,200 $m^2$) in pilot testing because global application revealed a large number of 'gully patches' using the 400-1,200 $m^2$ adaptive threshold. This was due to large areas of the SAC where the topography was smoother than at the Snailsden pilot site. Thus, the lower threshold for gully initiation was increased to reduce the number of 'gully patches' to an acceptable level.
5) A fixed channel initiation threshold of 20,000 $m^2$ was used.

Examination of the model output for the full South Pennine SAC indicated that for some of the best ranking blocks, their very large lower bound pond area was due to the 'channel issue' (see 6.2.1), i.e., erroneously blocking of neighbouring gully/river channels. This was a consequence of artificially extending the width of gully blocks, which itself was a strategy developed to mitigate the topographic smoothing due to relatively coarse (5 m) topographic data.

Candidate blocks affected by channel-issue were identified as those blocks where the lower bound pond area exceeded the upper bound pond area and the lower bound pond depth was less than 0.25 m. The theoretical basis for upper and lower bound calculations (Section 3.4.2) dictates that the lower bound should never exceed the upper bound for blocks of the same geometry (width and height). However, during application of the two methods to the South Pennine case, the upper and lower bound methods were parameterised to differ both in terms of their width and their height. The lower bound method has a height of 0.5 m and a width of 10 m while the upper bound method has a height of 0.25 m and a width that is variable in order to ensure ponding to 0.25 m depth. However, the upper bound has the additional constraint that only cells that flow through the target cell (central cell of a 5 cell side block) can be included in the pond area. These differences in parameterisation mean that the upper and lower bound methods are no longer simulating exactly the same block geometries, and hence there can be cases where lower-bound pond area prediction exceeds the upper bound. The lower bound might exceed the upper bound because: 1) water ponds to a depth in excess of 0.25 m in the lower bound case; or 2) water ponds behind cells that do not flow through the target cell. The former should not be considered an error while the latter should. This is the basis for the post-processing rule to identify erroneously large lower bound pond estimates (lower bound area > upper bound area & lower bound depth < 0.25 m). **For candidate blocks flagged as affected by incorrect channel blocking, their final pond area (on which blocks were ranked) was defined as upper bound pond areas since these were considered more reliable in this case. For all other candidate blocks their final pond area was defined as the lower bound area.**

There are two outputs from this modelling study. The primary output is a georeferenced set of approximately 1,900,000 block locations optimised to maximise the lower bound pond area. Each block has a set of associated attributes (Fig. 20):

-**areaL**: the lower bound pond area in units of $m^2$

-**areaU**: the upper bound pond area in units of $m^2$

-**volL**: the lower bound pond volume in units of $m^3$

-**volU**: the upper bound pond volume in units of $m^3$

-**Hb**: the lower bound pond height in units of m

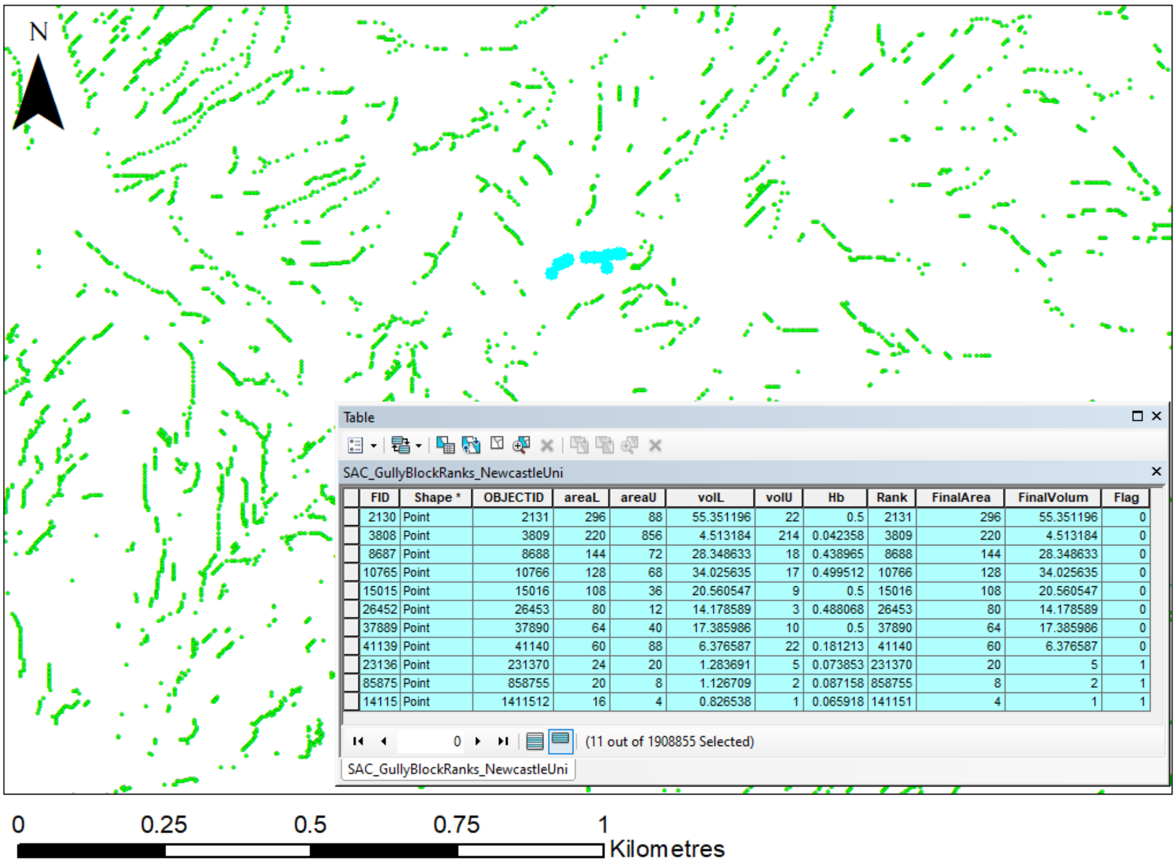
-**Rank**: the global rank for blocks within the South Pennine SAC in descending order of performance

-**FinalArea**: the area (in units of $m^2$) adjusted to minimise errors due to incorrect channel blocking

-**FinalVolum**: the volume (in units of $m^3$) associated with **FinalArea**

-**Flag**: a vector of zeros and ones where ones denote block locations affected by incorrect channel blocking (channel-issue)

Note that using these values, **FinalArea** (with which the final ranks have been generated) is calculated using: ***FinalArea = areaL * Flag + areaU * (1-Flag).***



| FID | Shape * | OBJECTID | areaL | areaU | volL | volU | Hb | Rank | FinalArea | FinalVolum | Flag |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2130 | Point | 2131 | 296 | 88 | 55.351196 | 22 | 0.5 | 2131 | 296 | 55.351196 | 0 |
| 3808 | Point | 3809 | 220 | 856 | 4.513184 | 214 | 0.042358 | 3809 | 220 | 4.513184 | 0 |
| 8687 | Point | 8688 | 144 | 72 | 28.348633 | 18 | 0.438965 | 8688 | 144 | 28.348633 | 0 |
| 10765 | Point | 10766 | 128 | 68 | 34.025635 | 17 | 0.499512 | 10766 | 128 | 34.025635 | 0 |
| 15015 | Point | 15016 | 108 | 36 | 20.560547 | 9 | 0.5 | 15016 | 108 | 20.560547 | 0 |
| 26452 | Point | 26453 | 80 | 12 | 14.178589 | 3 | 0.488068 | 26453 | 80 | 14.178589 | 0 |
| 37889 | Point | 37890 | 64 | 40 | 17.385986 | 10 | 0.5 | 37890 | 64 | 17.385986 | 0 |
| 41139 | Point | 41140 | 60 | 88 | 6.376587 | 22 | 0.181213 | 41140 | 60 | 6.376587 | 0 |
| 23136 | Point | 231370 | 24 | 20 | 1.283691 | 5 | 0.073853 | 231370 | 20 | 5 | 1 |
| 85875 | Point | 858755 | 20 | 8 | 1.126709 | 2 | 0.087158 | 858755 | 8 | 2 | 1 |
| 14115 | Point | 1411512 | 16 | 4 | 0.826538 | 1 | 0.065918 | 141151 | 4 | 1 | 1 |

0 (11 out of 1908855 Selected)

*Fig 20: example of block locations (green points) and their associated attributes (inset table). The Points highlighted in blue have their attributes listed in the table.*

In addition, a map showing the percentage pond per unit area (PPUA) of sub-sub-catchments (i.e., subcathcments of 2nd order stream) was generated to aid interpretation. This map, which uses the **FinalArea** described above, is shown in Fig 21. This map is helpful in trying to identify (based on model predictions) the areas of the SAC South Pennine that have a higher potential for generating ponded areas, and thus could be used as a tool to prioritise the implementation of gully blocks.

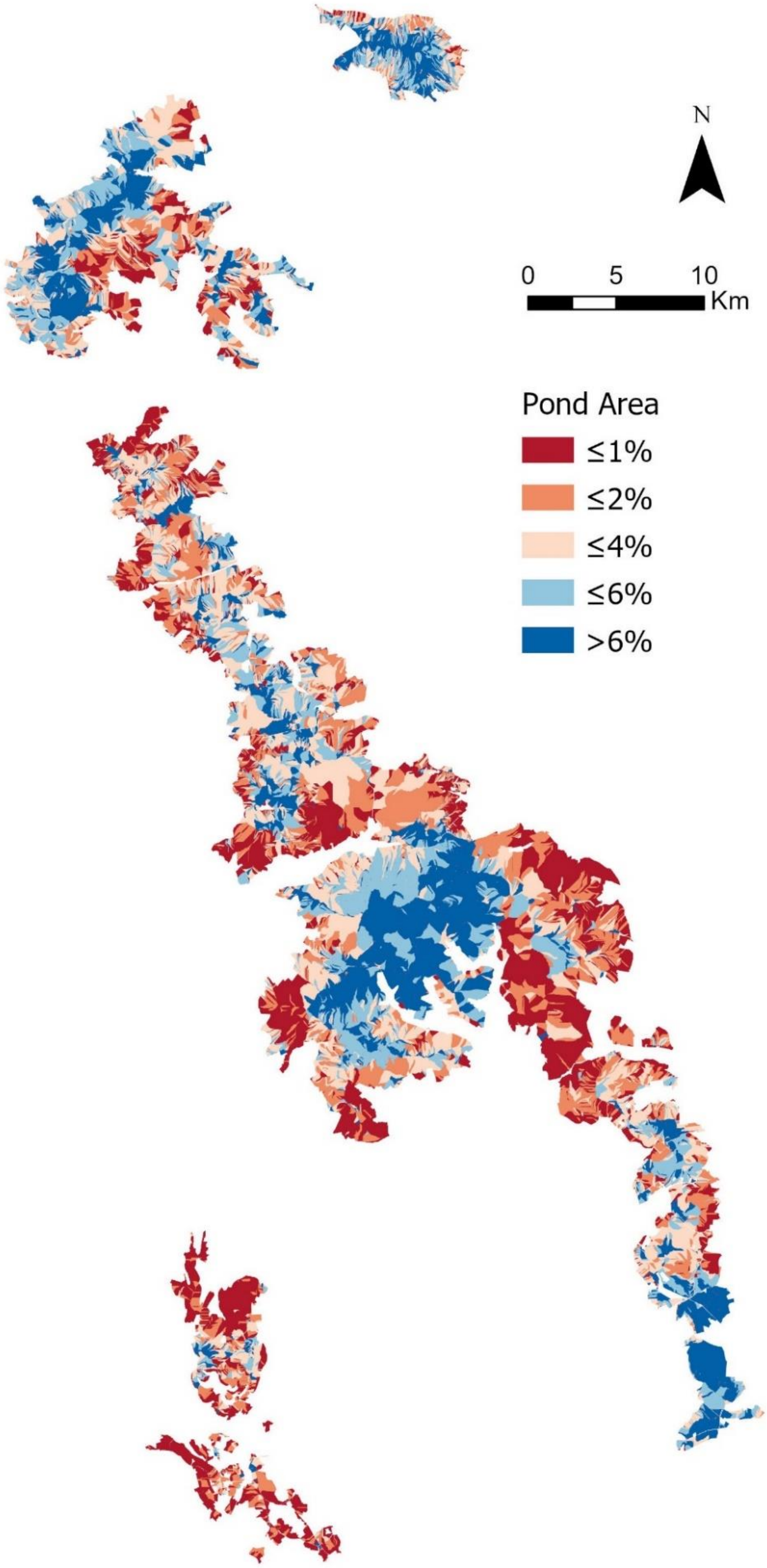


Fig 21: Percentage ponded area per unit area for the full South Pennine SAC using sub-catchment averaging and **FinalAreas** described in section 7.

# 8 Conclusions

Newcastle University (NU) in collaboration with MFFP have developed a methodology to: ***identify and prioritise 100,000 gully block locations that will restore the hydrological regime towards that of an active blanket bog, with a view to moving the vegetative community towards favourable condition***.

The methodology has been implemented across the South Pennine SAC to deliver a database of >100,000 potential gully block locations with an indication of the pond area and volume that would result from each block. This represents an exhaustive search of the potential blocking locations within the constraints of the data. Each block location includes upper and lower bound estimates of pond area and pond volume, ranking or aggregation can then be performed on any of these properties allowing between or within region rankings to be calculated using GIS software. The output captures the hydrological effect of a particular block in terms of the area of ponded water that it would generate. This pond area is closely linked (in ground water theory) to both the area over which the block will raise water tables and the average water table rise.

Results from this application and particularly from four representative pilot study sites within the SAC indicate that:

1) Global gully network definition results in over prediction of gully network extent in some areas and under prediction of gully network extent in most areas. This is unavoidable without manual tuning (which would require unreasonable processing time beyond the project's scope). However, errors can be reduced by using a spatially adaptive gully initiation threshold ranging from 600 $m^2$ to 1,200 $m^2$ and a fixed channel initiation threshold of 20,000 $m^2$. Even with this adaptive thresholding approach, some gullies (particularly those that are smallest and nearest to the tips of the drainage network) are missed and are therefore not assessed for blocking.

2) The relatively coarse (5 metre resolution) underlying elevation data supplied by the Environment Agency means the topography in the model is unrealistically smooth. This smoothing leads to errors in pond volume and area estimates. These errors can be reduced treating block width and height as tuneable parameters to enable reasonable pond area predictions in the presence of smoothed elevation data. However, the realism of the methodology is somewhat reduced. First, the resultant block geometries (i.e. 10 m wide, 0.5 m tall for lower bound and 0.25 m tall for upper bound) should not be taken as realistic block geometries since they have been used as tuning parameters. Second, estimates of pond area and volume associated with each gully block cannot be used as absolute area and volume estimates (e.g. to calculate total water storage potential of gully blocks). The pond areas are likely to be more accurate than their volumes (since both pond area and depth are uncertain), thus gully block locations are optimised on predicted pond areas (as opposed to volumes) resulting from block installation. Third, specific block locations are unlikely to be correct to less than 10 metres, meaning a site survey will still be required to finalise block locations. Finally, grips, which are usually narrow (<5 m) are not captured within the elevation data, thus the influence of grips on gully development is missed in the gully network map.

3) The methodology includes upper and lower bound estimates on pond area associated with a particular gully block location. The lower bound method has the strongest theoretical basis as an estimator of pond area but is also most sensitive to uncertainty in the underlying topographic data. Systematic underestimation of pond size in the lower bound case is strongly related to topographic smoothing in the DTM. The upper bound method is less sensitive to topographic uncertainty but contains the strict assumption that water ponds to the height of the block independent of how wide the block must be to enable this. The lower bound should be closer to the true pond area, given topographic data capable of identifying gully geometries, and will certainly be more conservative in estimating pond areas independent of topographic data quality. On this basis the lower bound should be used as the primary method for block identification and the upper bound as a secondary check on

the predictions. This check can be made easily because both lower and upper bound pond areas are included in the attributes for every potential block location in the list.

On the basis of the pilot study results the output block locations are expected to be suitable for: 1) applications where changes in water table or bog pool area resulting from blocks are the hydrological property of interest; 2) large scale application such as: prioritising regions of the SAC, informing selection of sites/areas for restoration); 3) small scale application such as: prioritising areas within a site or suggesting specific block locations; 4) improving the accuracy of future projects for estimation during the bidding process.

The output block locations are not suitable to inform Natural Flood Management without additional analysis. The methodology optimises block locations to maximise average water table rise and pond area in a particular location. It does not account for flow interactions between blocks and therefore cannot provide any indication of the impact of blocks on gully discharge. As a result, it cannot be used as a ranking of Flood Management potential of the blocks.

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