**Flood mitigation benefits**

There is growing evidence supporting the role of land cover to the mitigation of downstream flood risk. Key mechanisms by which the type of land cover can influence flood risk include the interception of rainfall and evapotranspiration, improved soil infiltration and reduced surface water runoff, and the slowing and interception of overland surface flow. Each of these mechanisms can increase the time and reduce the magnitude of downstream peak flows. Soil erosion is also highly influenced by land cover and can magnify the risk and/or cost of surface water flooding by reducing the effectiveness flood mitigation measures such as drainage ditches.

Estimates of flood mitigation service value for each grid cell derive from:

* Identifying potentially vulnerable areas (PVAs) defined as buildings at risk of flooding downstream from each grid cell
* Providing simple quantified scores of each cell’s contribution to mitigation of (i) overland flow, (ii) peak river flow, (iii) flood plain infiltration (iv) water course flow (v) soil loss and transportation

**Identifying potential vulnerable areas**

Potentially vulnerable areas (PVAs) were determined from where existing built-up areas, or areas assigned to an allocation zone, fell within Environment Agency flood risk zones for surface water or rivers/seas flooding corresponding to a risk greater than 0.1% per annum. A ‘PVA’ value was assigned to each of these cells equal to the percent of the cell that is built-up or assigned to an allocation zone (the latter given a constant 50% value).

**Estimating mitigation values**

To assist calculation, several different mechanisms by which landcover can mitigate the flood risk of potentially vulnerable areas are considered:

1. Mitigation of surface water runoff draining directly to a PVA.
2. Mitigation across the wider upstream catchment area that reduces the contribution of surface water runoff to peak river flows affecting PVAs.
3. Mitigation of flow velocity and improving soil infiltration across floodplain.
4. Mitigation of flow velocity along water courses – denser vegetation will generally slow flow along watercourses.
5. Mitigation of soil loss and transportation.

For (iii) and (iv) a constant value is applied according to whether a cell lies within a floodplain or along an open watercourse. For (i), (ii) and (iv) a varying score is estimated as described below.

*i. Mitigation on surface water runoff*

Only areas directly upslope of PVAs were considered to have a mitigating value on surface water flooding. Areas draining to a PVA along a permanent watercourse were *not* included (these are captured by ii below). The surface water flood mitigation potential of each cell *x* is calculated as:

*PV* = sum of the PVA value of all cells along the flow path from cell *x* that are vulnerable to SW flooding (>0.1% per annum). Flow path only extends as far as the first permanent watercourse downhill from cell (*ie* excludes river/stream flow).

*Rainfall* = rainfall erosivity (units) as a proxy of rainfall amount and intensity.

*SPR* = Standard Percent Runoff from soil HOST class (0 to 100%).

*SWmitig* is expressed as a normalised value between 0 and 100.

*ii. Mitigation of upstream catchment on river and stream peak flows*

The flood mitigation of a cell through its effect on downstream peak flow was calculated by estimating its contribution to peak flow to downstream river nodes prone to flooding. Each node was weighted by the sum of all nearby PVA cells.

The peak flood mitigation potential of each cell *x* (*Rmitig*) is calculated as:

*n* = the number of vulnerable downstream river nodes.

*CP* = contribution of cell *x* to the peak flow at node *i.*

*PV* = risk value at node *i*.

Rainfall = rainfall erosivity of cell *x.*

SPR = Standard Percent Runoff of cell *x*.

*Rmitig* was expressed as a normalised value between 0 and 100.

In terms of calculation, the following analytical steps were followed:

* The upstream catchment area for each PVA node was calculated from a hydrologically corrected DEM (see below) using a D8 flow direction method.
* All PVA cells were assigned to their nearest river/stream node (defined as a branch in the watercourse network) with the risk value of each node equal to the sum of the PVA values of assigned cells.
* The flow times of runoff from each cell to each downstream PVA node was calculated from the flow path and by applying modified Manning’s equation to estimate relative flow velocity for each cell, using Mannings coefficients for different landcover types as described in table \*.
* The contribution of each cell to peak flow at each PVA node is calculated by fitting a log-normal distribution to flow times, estimating the probability density function of this distribution, weighted by the maximum value of the function.

*iii. Mitigation across floodplain*

The floodplain was defined as all cells upstream of a PVA that fell within a river or sea flood zone of 0.1% or higher. All floodplain cells were given a constant potential mitigation value,

*iv. Mitigation along watercourses*

All cells corresponding to an aboveground, open watercourses upstream of a PVA were given a constant potential mitigation value,

*v. Mitigation of soil loss*

Soil loss estimates estimated from the RUSLE2015 model (Panagos *et al* 2015) were used as the basis for this mitigation value, normalised to a value between 0 and 1.0.

**Application to prioritisation and opportunity mapping**

The combined flood mitigation potential, *FMP*, was calculated as:

*FMP* = (*SWmitig* + *Rmitig*) + ( (*SWmitig* + *Rmitig*)\*(*SLmitig*+*FPmitig*+*WCmitig*) )

With the resulting *FMP* normalised to between 0 and 100

FMP corresponds to a potential flood mitigation value of a cell. The combined effect of floodplain, riparian and soil loss mitigation mechanisms is limited to a theoretical maximum of twice the combined surface water interception and peak flow mitigation effects. In most cases the combined effect of these three factors will be less than that of the two primary factors *SWmitig* and *Rmitig*.

For **opportunity mapping** the potential flood mitigation values for cell *x* was calculated as:

*SLmitig* was calculated without consideration of existing landcover.

For **prioritisation mapping** the flood mitigation service value (*FMV*) of each cell *x* was estimated as:

*SLmitig*,was determined from the difference in soil loss under existing landcover and a baseline value.

*LC* = landcover flood mitigation value (0 to 1.0) from (i) cell habitat type and (ii) cell hedgerow lengths (normalised between 0 and 0.2) – see table below .

**Calculation of underlying layers**

Factors used in the calculation of flood mitigation values include:

**Soil Standard Percent Runoff:** estimates the % of rainfall that contributes to quick response runoff. High SPR soils are prone to rapid runoff or pathways to streams (*eg* naturally wet soils) and at risk of sealing/compaction. A SPR>25% is often associated with seasonally water-logged, flashy soils (Packman 2004). SPR was derived from the HOST value of soil layers (CEH data REF) at a resolution of 1km and then interpolated by a thin spline method using the surface elevation as an additional interpolation parameter.

Several methods (*eg* Forestry Commission Woodlands for Water mapping) have used SPR to identify priority areas for woodland creation with a revised SPR value of >50% (Broadmeadow et al, 2014) considered high priority area for flood risk management and used as a threshold for Countryside Stewardship grants to target the wettest soils (26.8% of England). However, it is recognized that woodland creation on the many soil associations with revised SPR values of <50% can also contribute to reducing flood risk management as a result of improved soil texture and enhanced soil infiltration.

**Rainfall erosivity:** was derived from ESDAC rainfall data (Panagos et al 2015 [10.1016/j.scitotenv.2015.01.008](http://www.sciencedirect.com/science/article/pii/S004896971500011X)) that provides a multi-annual average index that measures rainfall's kinetic energy and intensity. Various other sources of data are possible although unlikely to significantly affect the results. There is the possibility of including a canopy interception factor (eg higher for deciduous compared to broadleaf woodland) but this is considered included in the Landcover intercept values.

**Landcover flood mitigation values:** the habitat class and the sum of hedge lengths within each cell was used to derive a surface water intercept value between 0 and 1.0. Hedgerow mitigation was defined as a value between 0 and 0.2 based on the normalised sum of hedge lengths within the cell, which was added to the underlying landcover value (except for woodlands).

|  |  |
| --- | --- |
| **Landcover** | **Flood mitigation value (LC)** |
| Coniferous woodland | 1.0 |
| Broadleaf woodland | 0.85 |
| Semi-natural grassland | 0.2 +HRF |
| Wetland | 0.4 +HRF |
| Heath / Moor | 0.3+HRF |
| Inland Rock | 0 +HRF |
| Maritime cliff | 0.2 +HRF |
| Littoral Rock | 0 +HRF |
| Supralittoral sediment | 0.2 +HRF |
| Littoral sediment | 0.2 +HRF |
| Water | 0 +HRF |
| Arable | 0 +HRF |
| Improved grassland | 0.05 +HRF |
| Urban | 0 +HRF |
| HRF = Hedgerow factor | 0 to 0.2 |

**Table \*:** Flood mitigation values for landcover

It is recognized that these values reflect a range of different mechanisms by which landcover can mitigate downstream flooding. The effect of landcover on surface water and channel flow is integrated directly into the calculation of contribution to peaks through the Manning’s coefficient.

**Contribution to peak:**  the contribution of each cell of a digital elevation dataset to peak flow is calculated by fitting a log-normal distribution to flow times, estimating the probability density function (pdf) of this distribution, weighted by the maximum value of the pdf. Manning's equation is used to calculate flow velocity across all cells of a digital elevation model.

**Manning’s roughness coefficients**: used in the Manning’s formula to calculate flow in open channels, the values describe the resistance of land cover to water flow. The formula is adapted as an estimate of overland as well a channel flow in determining the contribution of cells to peak flow.

|  |  |
| --- | --- |
| **Landcover** | **Manning’s Roughness Coefficient** |
| Coniferous woodland | 0.12 |
| Broadleaf woodland | 0.12 |
| Semi-natural grassland | 0.03 + HRF |
| Wetland | 0.05 + HRF |
| Heath / Moor | 0.05 + HRF |
| Inland Rock | 0.01 |
| Maritime cliff | 0.03 + HRF |
| Littoral Rock | 0.01 |
| Supralittoral sediment | 0.03 |
| Littoral sediment | 0.05 |
| Water (lake/estuary) | 0.04 |
| Arable | 0.02 + HRF |
| Improved grassland | 0.02 + HRF |
| Urban | 0.02 + HRF |
| HRF = Hedgerow factor | 0 to 0.02 |
| Permanent watercourse | 0.035 |

**Soil erosion** estimates were calculated following the RUSLE2016 model described by Panaglos et al (2015) (also used in the calculation of water quality benefits).

**Hydrologically-corrected digital elevation model**: was used for the determination of peak flow catchment areas in ii. The hydrological elevation model was calculated by correcting the original DEM using stream burning (Saunders 1999) the open river network (Ordnance Survey OpenRivers data) followed by single cell pit raising (to level of closest neighbouring cell) using Whitebox (2018) GIS tools. Permanent streams, defined as all areas with a flow accumulation greater than 100 upstream cells, were then extracted and these were found to closely match know stream networks (OS Mastermap watercourses). Remaining no-flow cells in the corrected DEM were found to be restricted to coastal edges.

Without correction, flow paths will not always correspond to known watercourses due to artefacts of the DEM, particularly at lower resolutions. Typical artefacts include narrow streams and drainage channels, as well as river flow under other terrain features such as road and rail bridges.

**Methodological limitations and issues**

* Potential Vulnerable Areas (and underlying Environment Agency flood zones): take no account of 'Areas Benefitting from Flood Protection' or 'Flood Storage Areas'.
* Alternative or additional data that could be used to define and weight PVAs might include information on infrastructure, such as main road and rail lengths within flood zones.
* Effect of normalisation will be to reduce the influence of outliers and extreme values.
* There is an argument for imposing a more explicit simplification of the service estimate by, for example, applying a simple scoring system (eg 0-3 according to a zero, low, medium, high effect defined by quantiles) for each of the key mechanisms contributing to flood mitigation.
* The effect of land management practices (for example ploughing regimes and orientation) are excluded.
* Contributions to peak flow are used to weight flood mitigation values on the basis that these are the areas where landcover change (whether removel of existing landcover or habitat creation) is most likely to affect downstream peak flow. However, the method cannot fully capture the interdependence of landcover effects (or changes) across a catchment area. The weighting is best interpreted as an indication of where medium-scale landcover change could provide flood mitigation value.
* Hedgerows: could act as a break to overland flow or as a channel to redirect that flow. The importance of hedgerows to reduce overland flow is difficult to estimate. The current hedgerow lengths per cell used are based on all hedges, whereas a better measure may be a weighted length according to hedge orientation relative to flow direction.
* Watercourse characteristics affecting flow velocity for the calculation of contributions to peak are not taken into account. For example, width indications given in OS Mastermap water network layer could be used to estimate channel dimensions.
* Soil HOST data was downscaled from 1km raster to 100m raster. An alternative source of data is the Soilscape data derived from the National Soil Inventory Data (LandIS: <http://www.landis.org.uk> ) to derive SPR or other suitable values at finer resolution. In most cases however, this data is itself interpolated from underlying data of a similar resolution as that used by the CEH HOST data.
* Effect of soil transport on flood mitigation is complex – in certain cases the blocking of drainage channels could mitigate downstream floodrisk.
* The hydrological DEM used enforces flow from lakes and reservoirs. An alternative approach would to consider reservoir and lake catchment areas as excluded from the river network in terms of flood risk and mitigation, assuming flow from these water bodies is fully controlled.
* Rapid Reaction Catchments – these are defined by the Environment Agency on the basis of time to peak flow and potential risk to life and properties.

**Main Data Inputs**

* OS Terrain 50m. Ordnance Survey 2016. https://www.ordnancesurvey.co.uk/business-and-government/products/terrain-50.html
* OS OpenRivers. Ordnance Survey 2016. <https://www.ordnancesurvey.co.uk/business-and-government/products/os-open-rivers.html>
* ERCCIS Hedges and Field Boundaries Project hedges layer. ERCCIS. [erccis@cornwallwildlifetrust.org.uk](mailto:erccis@cornwallwildlifetrust.org.uk)
* Risk of Flooding from Rivers and Sea v1.7. Environment Agency 2017. <https://data.gov.uk/dataset/bad20199-6d39-4aad-8564-26a46778fd94/risk-of-flooding-from-rivers-and-sea>
* Risk of Flooding Surface Water – Extent. Environment Agency 2013. <https://data.gov.uk/dataset/1f3d6e13-40f1-4d12-99de-77132bc19c47/risk-of-flooding-from-surface-water-extent-0-1-percent-annual-chance>
* National Receptor Database. Environment Agency 2017. <https://data.gov.uk/dataset/0eda736c-b85b-4ad4-a308-6fe5fbd08dc8/national-receptor-dataset-afa171>
* Soil HOST classes. CEH. <https://www.ceh.ac.uk/services/hydrology-soil-types-1km-grid>
* Soil Loss by Water Erosion in Europe. ESDAC. <https://esdac.jrc.ec.europa.eu/content/soil-erosion-water-rusle2015>
* Land Cover Map 2015 v1.2. CEH 2017. <https://eip.ceh.ac.uk/lcm/lcmdata>

**References**

Nisbet, T., Silgram, M., Shah, N., Morrow, K., and Broadmeadow, S. (2011) Woodland for Water: Woodland measures for meeting Water Framework Directive objectives. Forest Research Monograph, 4, Forest Research, Surrey, 156ppP

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, .C. 2015. [The new assessment of soil loss by water erosion in Europe](http://www.sciencedirect.com/science/article/pii/S1462901115300654). Environmental Science & Policy. **54**: 438-447. DOI: 10.1016/j.envsci.2015.08.012

Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., Tadic, M.P., Michaelides, S., Hrabalíková, M., Olsen, P., Aalto, J., Lakatos, M., Rymszewicz, A., Dumitrescu, A., Beguería, S., Alewell, C. [Rainfall erosivity in Europe](http://www.sciencedirect.com/science/article/pii/S004896971500011X). Sci Total Environ. **511** : 801-814.

Lindsay JB 2018 WhiteboxTools Version 0.11 <http://www.uoguelph.ca/~hydrogeo/Whitebox/>

Saunders, W., 1999, July. Preparation of DEMs for use in environmental modeling analysis. In *ESRI User Conference* (pp. 24-30).

Manning’s coefficients:

* <https://www.engineeringtoolbox.com/mannings-roughness-d_799.html>
* <http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm>