Landscape and Urban Planning 234 (2023) 104737

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Hydrological assessment of urban Nature-Based Solutions for urban planning using Ecosystem Service toolkit applications

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HIGHLIGHTS

- ANaRM is a simple ecosystem service model for NBS effects on flood hydrology.
- Validated model provides realistic flood peak estimates across an urban catchment.
- Ponds are most effective for reducing peak flow in channels and fluvial flooding.
- LUC and SuDS reduce localized runoff, peak flow and pluvial flooding.
- Sensitivity analysis to key NBS/runoff parameters, code and user guide provided.

ABSTRACT

Ecosystem Service (ES) toolkits are increasingly used to quantify and visualize the benefits gained from Nature-based-solutions (NBS) but modules for hydrology are often absent, or if present they lack meaningful hydrological functionality or validation. This leads to gaps in the evidence base required by decision makers. To bridge the gap between such limitations and more complex hydrological models this paper presents a hydrologically based NBS model compatible with spatial ES toolkits. The approach ‘Adapted Nature-based-solutions Rational Method’ (ANaRM) is based on the Rational Method, widely used in hydrology. We apply this model to the city of Birmingham, England, to validate its performance and to analyse the effects of different NBS scenarios.

The validated ANaRM model provided robust estimates of peak flow using design storm rainfall. It proved capable of simulating the hydrological effects of NBS such as land use change from urban to green, or installation of SuDS and ponds. Results suggest ponds are found most effective for achieving peak flow reduction in channels and are the best option for mitigating fluvial flooding downstream. Reduction in localised runoff and pluvial flooding is best achieved by converting impervious surfaces such as buildings, hardstanding and roads to green solutions such as green roofs, permeable pavements and greenspace. This paper highlights the importance of considering the spatial effects of urban NBS on hydrology, and that these can be captured with relatively simple modelling approaches such as ANaRM. Its ease of use means it suits any level of user looking to represent the flood mitigation aspect of NBS spatially and has high potential as part of any ES toolkit focused on representing the spatial effects of NBS on ecosystem services.

1. Introduction

Urbanisation poses a significant flooding threat globally through changes to natural hydrological functioning. As permeable surfaces are converted to sealed impervious surfaces or buildings, rainfall is unable to infiltrate to soils below and runoff increases. In urban areas, localised storage in soils and small depressions is limited, and attenuation of any runoff is reduced. Natural drainage through soil and via sinuous streams is replaced by artificial storm drainage systems that capture runoff efficiently and speed up conveyance from developed areas. Taken together, this can result in raised peak flows during storms and greater risk of localised and downstream fluvial flooding (Miller & Hutchins, 2017). This is exacerbated by climate changes driving more intense storm rainfall (Arnell et al., 2015; IPCC, 2022), which can further exceed the design capacity of drainage systems and lead to surface water flooding (Arnbjerg-Nielsen et al., 2013). To mitigate the effects of storm rainfall on local surface water and downstream fluvial flooding, new urban developments are routinely being fitted with urban Nature-Based-Solutions (NBS). NBS are defined as “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address

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https://doi.org/10.1016/j.landurbplan.2023.104737
Received 9 September 2022; Received in revised form 13 February 2023; Accepted 27 February 2023

societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016). For flood mitigation in urban areas, they usually take the form of Sustainable Drainage Systems (SuDS), also known as Low Impact Development (LID). These aim to maintain and restore more natural flows of water through the urban environment and provide local aquatic habitats. Source control measures capture rainfall at its first contact with a surface. For example, green roofs replace impervious building footprints with vegetation and growing media, which can both store and attenuate runoff, reducing runoff volumes and peak flow rates. (Stovin et al., 2012). Likewise, permeable paving replaces asphalt and concrete hardstanding such as roads, parking and pavements with a system capable of enhanced infiltration and sub-surface storage – reducing surface water flooding and inputs to storm drainage (Marchioni & Becciu, 2015). By contrast, storage measures are designed to capture water, with attenuation ponds of varying size and type providing localised storage of runoff from upstream drainage areas, reducing the peak flow and delaying the movement of runoff volumes downstream (Woods Ballard et al., 2015). The hydrological benefits from such NBS measures are locally reduced runoff and pluvial flooding (from rainfall) alongside attenuation and reductions of downstream fluvial flooding (from rivers) (CIWEM, 2010).

Ecosystem Service (ES) toolkits are becoming widely used to quantify and visualize ecosystem services. Traditional hydrological tools provide detailed hydrological process representation whereas ecosystem services tools are more accessible to non-experts and can represent a diversity of ecosystem services in the urban environment (Vigerstol & Aukema, 2011). However, ES toolkits often lack hydrological modules. Where hydrological aspects are incorporated, the simplest approaches use mapping of impervious and pervious surfaces as a proxy for hydrological impacts. For example, the GISP model (Meerow, 2019) identifies priority areas for Green Infrastructure (GI) based on estimates of percentage imperviousness for each spatial unit, and applies this simple index to three coastal mega cities. A slightly more complex approach involves mapping opportunities for GI based on multiple criteria and linking this to needs, used in the SSANTO toolkit (Kuller et al., 2019). More hydrologically relevant ES toolkits consider runoff production as a function of land use and/or soil type, for example InVEST (Tallis & Polasky, 2009). InVEST includes a stormwater management module based on runoff coefficients, which runs gridded at an annual scale (Hamel et al., 2021), an Urban Flood Mitigation module (used by Kadaverugu et al. 2021) based on the Curve Number method and intended for event use, and the InVEST Seasonal Water Yield Model (Redhead et al. 2016), which is the only module to include routing but is more focused on large mixed-use rural catchments. However, while being one of the most widely used ES models within hydrology (Ochoa & Urbina-Cardona, 2017) there is no single module capable of modelling the hydrological routing of design-storm event peak flows in small urbanised catchments – these being the typical areas of interest when considering SuDS.

The missing factor in many ES toolkits is a link between spatially isolated pixel runoff and a hydrological network. Studies and toolkits incorporating such spatial hydrology rely upon relatively complex hydrological models. Semi-distributed models such as Long-Term Hydrologic Impact Assessment-Low Impact Development (L-THIA-LID), Soil Water Assessment Tool (SWAT) and the Storm Water Management Model (SWMM) model a catchment's sub-catchments as lumped systems with one outlet, SWMM being widely applied as it includes LID functions (Qiu et al., 2019). Fully distributed models (grid-based) provide time-series of flow across a gridded network. One example that explicitly represents NBS/LID is Multi-Hydro (Alves de Souza et al., 2018) but it is not openly accessible. One of the most advanced and openly available ES focused hydrological models is the i-tree Hydro model, a vegetation-specific urban hydrological model that routes runoff into the channel network (Yang & Endreny, 2013). The user interface is simpler than many hydrological models, and it has been widely applied, from assessing greenspace in China (Song et al. 2020) to green roofs in Colombia (Bautista & Peña-Guzmán, 2019). However, it is semi-distributed, requires hydro-metrological data, and does not integrate with other ES toolkits.

The use of more hydrologically sound and representative functions represents a challenge for ES toolkit users (Vigerstol & Aukema, 2011). The skills and experience required to deploy detailed data-intensive and process-orientated models can be demanding (Van Oijstaeijen et al., 2020). Data needs are much greater for hydrological models, as is the time required for data preparation and model set-up (Lüke & Hack, 2017). Related to the above is the need from decision makers, particularly non-academic, for relatively simple ES toolkits that require little specialist knowledge to run on readily available datasets within some form of simple user interface (Ochoa & Urbina-Cardona, 2017). Examples that identify optimal NBS scenarios for flood risk are appearing (e.g. Quagliolo et al. 2022) that link decision making to models such as InVEST through Multicriteria Decision Analysis, but expert judgement is required to be able to link such elements. This incompatibility between user and model/tool suggests a gap in ES assessment research for a simple framework that can produce hydrologically relevant outputs while remaining compatible with the constraints listed above.

A possible bridge explored in this paper is to utilise a relatively simple but hydrologically sound method for estimating flow and to adapt it for deriving gridded outputs and incorporating NBS effects. Given the constraints listed, and acknowledging that there is a need for outputs that are both indicative of peak flows and can be validated, the most suitable method identified was the widely applied Rational Method (Hydraulic Research Limited, 1981). This method is noted in the (English) Environment Agency's (EA) review of methods for estimating flood peaks in small catchments (EA, 2012) as being suited towards small urban/impermeable catchments and data-poor applications, and is included in national and regional guidance worldwide.

The Rational Method was developed well before the NBS concept was conceived, with a focus on estimation of peak flows for individual points in small urban catchments. However, there is scope for developing a gridded application by treating each grid cell as spatially independent, and incorporating NBS as extra land cover classes. The Rational Method does not represent the effects of waterbodies for attenuating floods. One potential solution for this aspect is to incorporate the UK Flood Estimation Handbook (FEH) (IoH, 1999) catchment descriptor 'Flood Attenuation by Reservoirs and Lakes' index (*FARL*) (Bayliss, 1999). This index has the benefit that it only requires information on the outlet location and surface area of waterbodies, which can be derived entirely from a DEM. Taken together, these provide the opportunity to develop an adaptation of the Rational Method as an urban flood-focused ES modelling tool.

The aim of this paper is therefore to develop and test a gridded hydrologically based NBS model compatible with spatial ES toolkits, and to use this new model to analyse the effects of different NBS scenarios. To achieve this, we set four main objectives. First, the model framework is spatially representative of hydrological systems and validated against robust data. Second, the model can represent the effects of key urban NBS on peak flows. Third, the model parameters are stress tested in a sensitivity analysis to see how this could affect results. Fourth, the modelling approach is tested and validated – here using an urban catchment in Birmingham, UK. The model is designed to be applicable to cities globally and the integration potential of the proposed model for ES toolkits will also be considered.

2. Method

2.1. Study area

The River Rea catchment (Fig. 1) contains a predominantly suburban area of south-west Birmingham, a major city in the West Midlands region and second largest city in the United Kingdom by population.

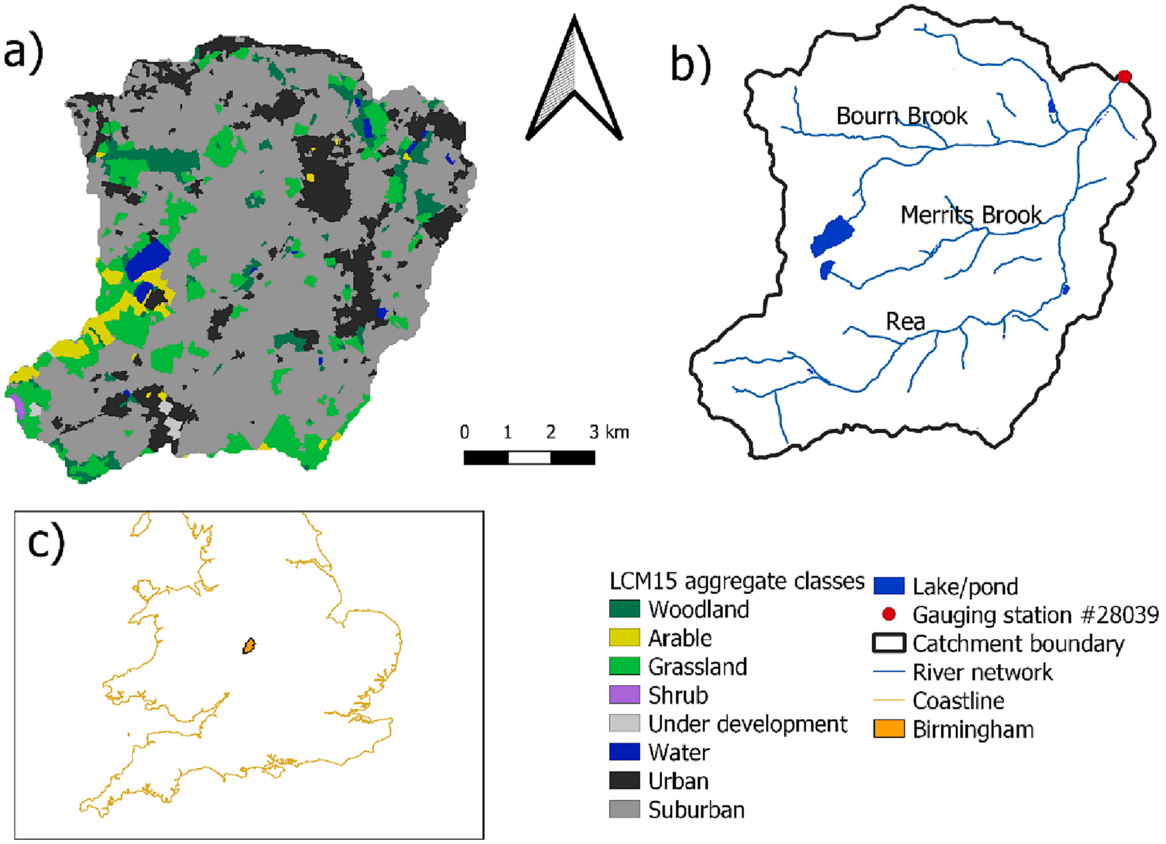

Fig. 1. Study catchment - Rea at Calthorpe Park: a) catchment land cover using aggregated classes from UK Land Cover Map 2015, b) catchment hydrology indicating the EA gauging station, Rea, main tributaries and waterbodies, c) location of Birmingham administrative area in the Midlands region of Great Britain.

Bounded by the Environment Agency (EA) gauging station (NRFA #28039) at Calthorpe Park, this 74 km^2 catchment has predominantly clay soils and drains approximately one quarter of the Birmingham City area (Fig. 2). The Rea forms the main river in the catchment, with two tributaries: the Bourn Brook drains one of the only large natural areas in the catchment and contains a large reservoir; Merrits Brook drains a smaller central area and contains a large wastewater treatment facility. The relatively small size and high urbanisation level of this catchment provide a highly suitable test bed for the application of this modelling approach.

3. Model set-up and application

3.1. Adapting the Rational Method for gridded catchment application

The Rational Method is a simple equation (HRL, 1981) linking peak discharge to catchment area, upstream land cover and mean rainfall intensity for a storm of a given return period via,

$$Q_p = 0.278CiA \tag{1}$$

where Q_P is peak discharge in cubic metres per second, C is a dimensionless coefficient linked to land cover, i is the average storm rainfall intensity in millimetres per hour, A is the contributing catchment area in square kilometres, and the numerical factor of $0.278 = 10^3/60^2$ arises during conversion from base SI units. The coefficient C is a combination of two values: C_V is the runoff coefficient, and C_R is a dimensionless routing coefficient recommended to be set to 1.30 (HRL, 1981). C_V at any location is affected by the type of land cover upstream and can be considered a representative value for the area-weighted mean runoff coefficient of all land cover types upstream. Although guidance often limits this method to small catchments with short (sub-hourly) concentration times (HRL, 1981), it has been applied to catchments up to 250 km^2 (Pilgrim et al., 1987).

Equation (1) does not include flood attenuation effects from ponds or other retention features. Assuming waterbodies produce 100% runoff, then, according to eq. (1), they would actually increase flood peaks. To rectify this, we multiply the peak discharge by an additional factor, *FARL*, that captures attenuation effects using a value ranging between 1 (no attenuation) and 0 (complete attenuation). We retain the FEH form of *FARL* (Bayliss, 1999) (also see SI).

Based on the above considerations, the final equation for the peak discharge is

$$Q_P = 0.278 \times 1.3 \times C_V iA \times FARL^{\theta}, \tag{2}$$

where peak discharge, Q_P, is measured in cubic metres per second, rainfall intensity, i, in millimetres per hour (here determined as the mean hourly rainfall over the design storm event duration), area, A, in square kilometres, and $\theta = 3.445$ (Kjeldsen et al., 2008). Equation (2), and its gridded application across a catchment of interest, is herein termed the Adapted Nature-based-solutions Rational Method (ANaRM).

3.2. Input data

The open access ESA WorldCover (Zanaga et al., 2021) was identified as a suitable global dataset depicting land cover meeting model objectives. Comparison to aerial imagery and mapping indicated that tree cover was greatly overestimated and roads and buildings missing. To address this, a new dataset was compiled that enabled urban-scale mapping of buildings, roads and trees (see SI for detail). This resulted in an augmented land cover dataset for the Rea catchment, herein termed the ‘augmented land cover’ dataset, with a total of nine land cover classes (Fig. 2), of proportional coverage from 0.5% to 34.6%

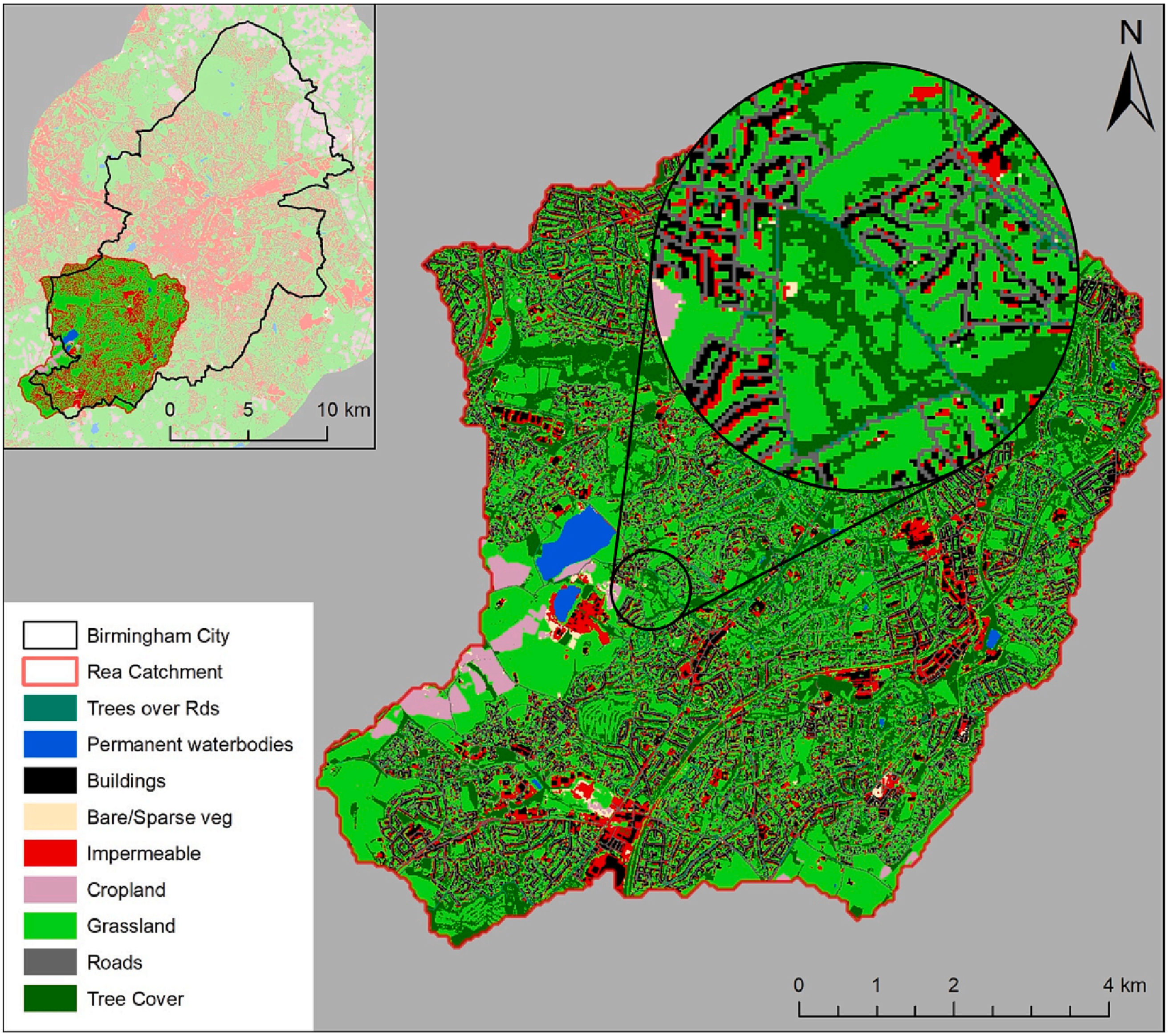

Fig. 2. Landcover of the Rea, based on ESA WorldCover, and augmented using other spatial datasets for trees (Street Trees Layer, Open Street Map), roads (OS Open Roads), and for buildings (Ordnance Survey VectorMap District). Map shows location of Rea catchment within Birmingham City administrative boundary (top left insert), and the updated land cover data for the catchment (main), with a zoomed region (circular insert) to show detail, including the "trees over roads" class (details and references in SI).

Table 1
Land cover classes and percentage cover for Rea catchment in the BASE (baseline) scenario.

Class	Description	Coverage
1	Tree Cover	19.0%
2	Roads	10.1%
3	Grassland	34.6%
4	Cropland	3.1%
5	Impermeable	12.2%
6	Bare/Sparse veg	0.6%
7	Building	18.2%
8	Permanent waterbodies	0.5%
9	Trees over Roads	1.7%

(Table 1).

The FEH13 depth-duration-frequency (DDF) model (Stewart et al., 2013) was used to provide rainfall intensity to ANaRM as it provides an industry standard means for estimating design rainfalls, easily accessible through the FEH Web Service (https://fehweb.ceh.ac.uk). The catchment's critical duration was estimated at 12.5 h using ReFH 2 methodology, and the depth of the 12.5-hour 10-year (10% AEP) event was estimated at 44.23 mm, resulting in a mean rainfall intensity, i, of 3.54 mm/hour.

The volumetric runoff coefficient C_V is defined as the proportion of rainfall that subsequently becomes surface runoff and enters the storm drainage system (Volume 4 of the Wallingford Procedure: HRL, 1981). A range of values are reported over time, across literature (Dunne and Leopold, 1978; Young et al., 2009), engineering reports/tables (ASCE, 1996), and software (SWMM, SCS-CN). An indicative set of runoff coefficients suitable for an urbanised catchment application of the rational method is provided in Table 2.

Indicative values for the two source control SuDS/NBS considered in this study – permeable pavement and green roof – come from literature. For green roofs, reported runoff reductions per event range from 0 to 100% (Stovin et al. 2012; Fassman-Beck et al. 2016; Akther et al. 2018). A typical 60% conversion of storm rainfall to runoff ($C_V = 0.6$) over a

Table 2

Runoff coefficient (C_V) values for the selected land cover classes and additional NBS classes (italics). High C_V values will be used by default.

Land cover class	C_V (Low)	C_V (High)
1 - Tree	0.05	0.50
2 – Road	0.70	0.91
3 – Grassland	0.12	0.42
4 – Cropland	0.08	0.72
5 – Impermeable	0.50	0.89
6 – Bare/sparse veg	0.10	0.50
7 - Building	0.75	0.95
8 – Water	1.00	1.00
9 – Trees over Roads	0.50	0.80
10 – Permeable pavement	0.00	0.40
11 – Green Roof	0.00	0.60

single rare event in a temperate oceanic climate is consistent with the studies assessed. Marchioni & Becciu (2015) undertook a synthetic review of experimental results for permeable paving in urban areas across wider literature, and found that runoff coefficients vary considerably (0.00–0.45) based on type and location and that 0.40 is an appropriate C_V value for most storm cases.

Digital Elevation Model (DEM) data are used to derive the hydrological pathways within the study area. Data at 10-metre resolution were obtained from the NextMap Elevation dataset for Great Britain (Intermap Technologies, 2007). Elevations across the study area range from 106 to 305 mAOD.

3.3. ANaRM model and code operation

The geospatial input datasets described above are used as inputs to code producing gridded estimates of peak flows, based on eq. (2), throughout the model domain. The code is written in the R programming language and is available with example data as "ANaRM" on GitHub (JRWallbank/ANaRM). It operates in two stages, using the inputs described and following a process both detailed in the SI. Stage 1 estimates peak flows for a baseline scenario, herein termed 'BASE', that represents current catchment land cover and conditions. Stage 2 estimates peak flows for an adjusted land cover scenario (see NBS Scenarios) that includes NBS, herein termed 'GREEN'. In both the default BASE and GREEN scenarios, we apply the high C_V values in Table 2, to plausibly represent the level of runoff generation during a more extreme storm event – such as the 1 in 10-year event considered here. Running ANaRM produces two main gridded output files of peak flow: Q_P (BASE), and Q_P (GREEN). A gridded output representing the ratio Q_P (BASE) / Q_P (GREEN) is also produced, alongside tabulated Q_P values for any user-specified coordinates in the network.

3.4. Model validation

The BASE grid of peak flows is used to validate the model function. To facilitate both validation and spatial assessment of NBS effects, eight peak flow 'checkpoints', in addition to the outlet at station #28039, were identified across the hydrological network (Fig. 3). For model validation, we utilise a combination of UK hydro-meteorological gauged data and industry standard flood models. The Flood Estimation Handbook provides two independent methods to estimate peak flows associated with flood events of specified AEP: a statistical method (Kjeldsen et al., 2008), implemented through WINFAP 5 software, and a rainfall-runoff method (Kjeldsen, 2007; Wallingford HydroSolutions, 2019), implemented through ReFH 2 software. Details are included in the SI.

3.5. NBS scenarios

To model the potential effect of urban NBS, three types of conversion were applied to develop a comparative NBS scenario, termed 'GREEN' (Table 3). Suitable areas of homogeneous land cover were identified in the augmented land cover mapping (Fig. 2) and used to derive polygons for applying the conversions (Fig. 3). Conversion 1 involved land use change (LUC) and was applied to small but intensely developed urbanised areas, converting impervious surfaces, excluding roads and buildings, across roughly 1% of the total catchment area, to greenspace – generally large areas of hardstanding such as car parks/industry. Conversion 2 took a multi-SuDS approach to larger areas of mixed land use and involved the following conversions: i) building to green roof, ii) road to permeable paving, and iii) built to permeable paving -

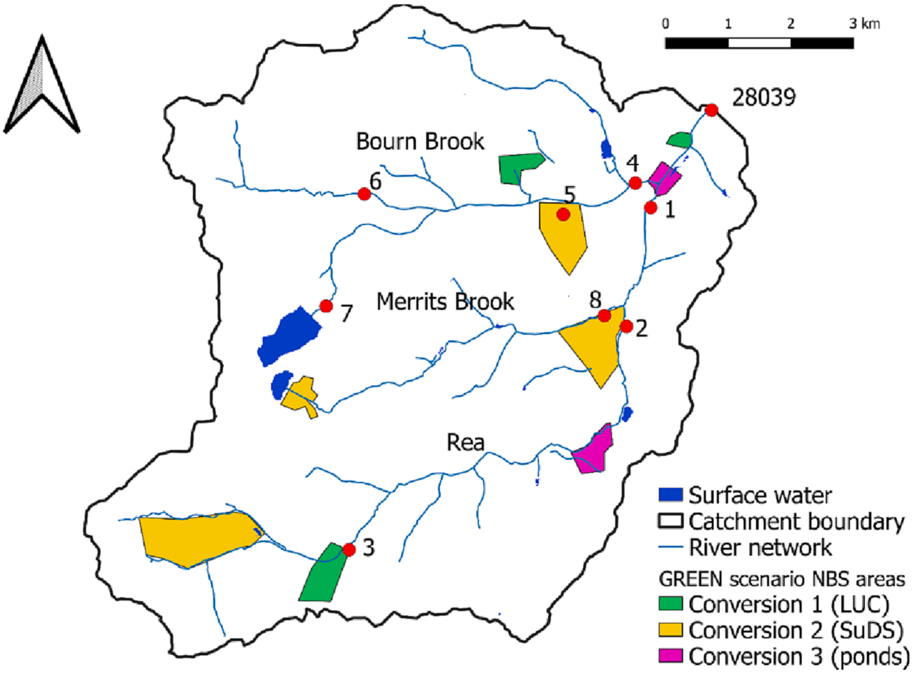

Fig. 3. Conversion areas for urban NBS in the GREEN scenario and selected peak flow checkpoints (marked as red circles with associated location code). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
GREEN scenario conversions and spatial coverage with detail on the classes converted from the BASE scenario: respective runoff coefficient (C_V) values are italicised.

BASE	GREEN
Conversion 1 – Convert impervious areas to greenspace (LUC)	
Total area 0.73 km^2 (1% of Rea catchment)	
Built – *0.89*	Greenspace – *0.42*
Conversion 2 – Multi SuDS conversion of mixed urban areas (SuDS)	
Total area 2.73 km^2 (3.7% of Rea catchment)	
Road – *0.91*	Permeable Pavement – *0.4*
Building – *0.95*	Green Roof – *0.6*
Built – *0.89*	Permeable Pavement – *0.4*
Conversion 3 – Convert greenspace to attenuation ponds (Ponds)	
Total area 0.44 km^2 (0.6% of Rea catchment)	
Open greenspace	2 × large online Ponds

converting 3.7% of total catchment area. Conversion 3 involved converting two large undeveloped areas of continuous greenspace along main river channels to new attenuation ponds – 0.6% of total catchment area. Polygons representing these areas were rasterised to identify the area of each new waterbody and its most downstream point on the hydrological drainage network. It was not possible to alter the C_V grid as the underlying flow direction grid would require adjustment for each new waterbody. All spatial processing of land cover for the GREEN scenarios was undertaken in ArcGIS, details in SI.

To assess NBS effectiveness between scenarios, the associated grid of Q_P ratios between the GREEN and BASE (Q_P (GREEN) / Q_P (BASE) – 100%) scenarios is used. This provides a spatially explicit means of assessing the hydrological effects of NBS converted in the GREEN scenario, with respect to BASE scenario conditions. This approach allows identification of locations where the effects are greatest and the degree to which they are diluted downstream.

3.6. Model sensitivity testing

The use of relatively high C_V values for urban land cover, and a *FARL* coefficient derived mainly from large reservoirs in large catchments, represents plausibly high conditions for generating significant runoff and peak flow attenuation. To test the model sensitivity to these two key elements of parameterisation, and how the model could respond to differing antecedent conditions, the model is also run under two additional setups for comparison to the default parameters:

1. **Low** – lowering runoff fractions while retaining high attenuation effectively reduces peak flows compared to the validated BASE model. The use of low C_V values mimics drier antecedent conditions, the effect being that surfaces are able to store a greater fraction of the rainfall. C_V values representing this lower estimate of runoff for each class are taken from Table 2.
2. **High** – retaining high runoff fractions while lowering attenuation effectively increases peak flows compared to the validated BASE model. Reducing the influence of *FARL* results in less attenuation from water bodies and thus an increase in modelled peak flows downstream. For *FARL*, the power $\theta = 3.445$ applied to *FARL* (eq. (2) is replaced with a lower power of $\theta = 2.627$ taken from recalibration of the FEH *QMED* regression equation for small catchments up to 40 km^2.

Model sensitivity to rainfall intensity is not assessed but is considered in the discussion.

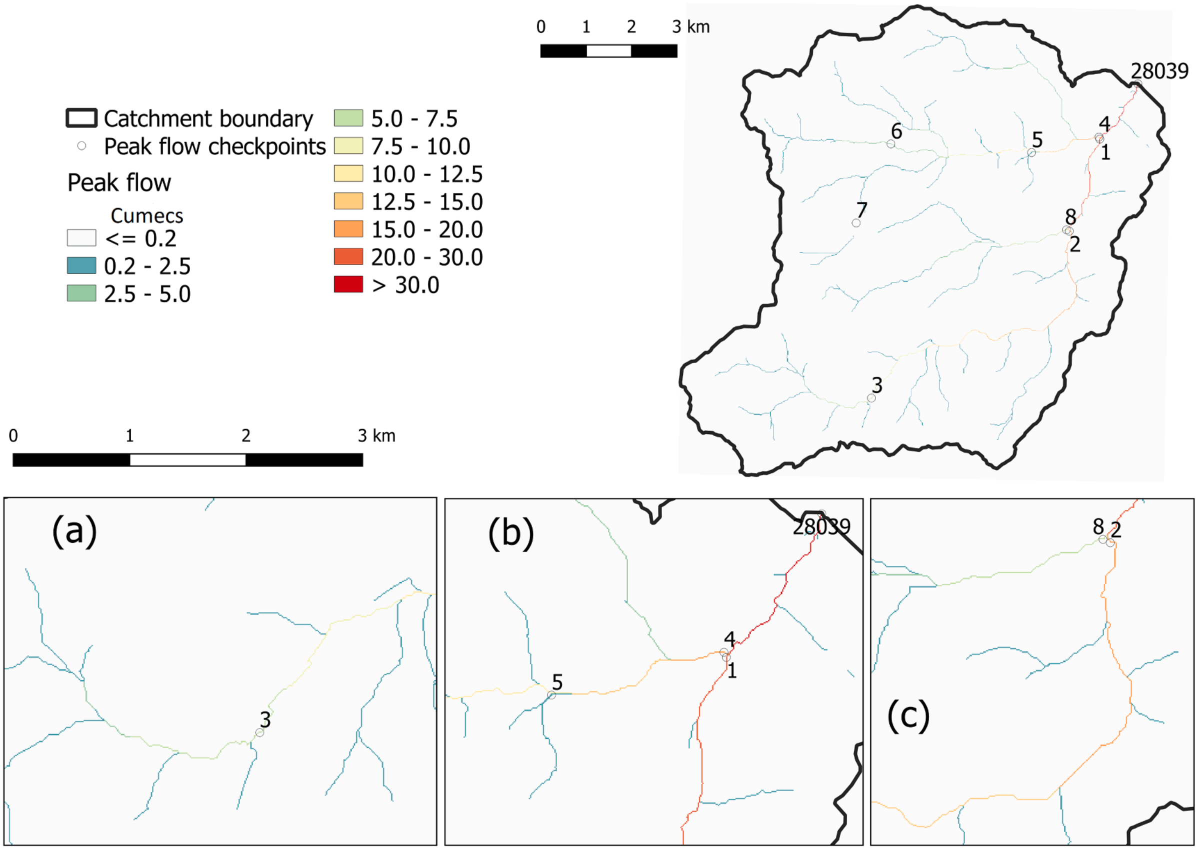

Fig. 4. BASE model peak flow grids for the Rea catchment (#28039) - with insets a-c highlighting changes across certain reaches, confluences and checkpoints.

4. Results

4.1. Baseline model and validation

The gridded peak flow values from the BASE scenario are shown in Fig. 4. Peak flow values are close to zero in most grid cells, but increase as the network passes downstream, with tributary and confluence effects clearly represented (Fig. 4a-c). This demonstrates that application of the Rational Method in a gridded and spatially consistent form along a hydrological network is a valid approach for the ANaRM model.

Peak flow validation across the network compared ANaRM modelled peak flow values against values derived from industry standard hydrological models at all nine checkpoints, and additionally from at-site observations at station 28,039 (Table 4). At the outlet (28039), the WINFAP enhanced statistical (EnhSS) estimate is within 10% of our ANaRM estimate. This is the site at which we have the highest confidence in any FEH estimate, as the EnhSS estimate makes considerable use of actual gauged data at that site. At the eight other sites, ANaRM estimates are occasionally very well-matched to FEH estimates (3, 6) and occasionally less so (8). A serious discrepancy between ReFH2 and ANaRM below Bourn reservoir (7), is expected, as ReFH 2 does not model attenuation from water bodies. Applying the ratio of EnhSS to ungauged WINFAP estimates at the two largest subcatchments (1, 4) gives higher peak flow estimates that are closer to ANaRM. While the differing suitability of the ANaRM and FEH methods for urban catchments complicates comparison, the reasonableness of results, the established suitability of the Modified Rational Method in highly urban areas, and wide range of reasonable runoff coefficients for each land type indicate that the ANaRM modelling structure is appropriate for the study catchment and peak flows are generally valid.

4.2. Re-greening and NBS model results

As shown in the methods, runoff generation is affected by modifying the surfaces between land cover scenarios, through varying the runoff coefficient C_V, while peak flow attenuation is affected by ponds, through application and variation of the FARL index. Peak flow values at the nine checkpoints in the default BASE and GREEN scenarios are detailed in Table 5. This shows the effects on peak flows at the checkpoints identified in Fig. 3 that result from applying LUC/SuDS (Modifying C_V - conversion 1 and 2: Table 3) or installing ponds (Modifying FARL - conversion 3: Table 3). The overall effect of the GREEN scenario compared to baseline conditions (BASE) is to reduce peak flow at the catchment outlet by 26.4%, from 47.9 m^3s^{-1} to 35.3 m^3s^{-1}. The largest reductions in peak flow (>20%) are all located at sites (28039,1, 2) downstream of a large pond on the Rea – with the reduction much greater at location 2 (30.6%) due to the proximity of the lake and its downstream effect on peak flow. The large relative effect of ponds compared to any upstream LUC or SuDS (Conversions 1 and 2) is evident in the low percentage reduction in peak flow attributable to C_V effect at either the outlet or checkpoints 1 and 2 (1.82%, 2.35%, and 2.63% respectively).

Table 4
Model results for the BASE scenario, from ANaRM and available FEH methods (ReFH2, WINFAP5 – ungauged and enhanced single site (EnhSS) – across Rea network checkpoints. Values in parentheses denote % difference from ANaRM values. Values marked with a * are not true EnhSS, as they make the assumption that the ratio of gauged to ungauged peak flow estimate at Calthorpe Park can be transferred approximately 1.5 km upstream to give quasi-gauge-enhanced estimates for the two largest subcatchments. NA values denote sites located too far upstream to allow quasi-gauge-enhanced estimates).

Location	ANaRM (m^3s^{-1})	ReFH 2 (m^3s^{-1})	WINFAP 5 (ungauged) (m^3s^{-1})	WINFAP 5 (EnhSS) (m^3s^{-1})
Rea Outlet (28039)	47.94	30.44 (-36.5%)	27.90 (-41.8%)	52.45 (+9.4%)
Rea lower (1)	29.24	17.49 (-40.2%)	19.27 (-34.1%)	36.22* (+23.9%)
Rea mid (2)	19.35	12.94 (–33.1%)	15.99 (-17.4%)	NA
Rea upper (3)	7.55	5.77 (–23.6%)	7.73 (+2.3%)	NA
Bourn lower (4)	17.90	14.35 (-19.8%)	12.47 (-30.3%)	23.44* (+31.0%)
Bourn tributary (5)	0.741	0.677 (-8.6%)	0.935 (+26.2%)	NA
Bourn upper (6)	3.53	3.48 (-1.4%)	4.39 (+24.3%)	NA
Bourn reservoir (7)	0.164	0.617 (+276.8%)	0.096 (-41.4%)	NA
Merrits lower (8)	7.31	4.82 (-34.1%)	5.22 (-28.6%)	NA

The only other site where the reduction exceeds 10% is checkpoint 5. Here, Conversion 2 is applied to 90% (0.7 km^2) of this small urban drainage area (0.78 km^2: Table 5), resulting in a 14.5% reduction in flow attributed entirely to a reduction of C_V. One further site (3) has peak flow reduced by>5%, and like site 5 this is fully a result of C_V reduction, here from a combined effect of both LUC and SuDS. The remaining two sites with any peak flow reduction (4, 8) exhibit small reductions resulting from any LUC or SuDS conversion area effects being effectively diluted due to the overall relatively large upstream catchment areas of 28.5 km^2 and 11.1 km^2 for (4) and (8) respectively. The two sites with no upstream NBS conversion areas (6, 7) exhibit no change – both being located directly downstream of some form of NBS already: a nature reserve (6) and a reservoir (7).

The spatial (gridded) reductions in peak flow between the BASE and GREEN scenarios (Q_P (GREEN) / Q_P (BASE) – 1) for the full Rea catchment are illustrated in Fig. 5 and expressed as percentage changes. It is clear from Fig. 5 that reductions in peak flow vary considerably across the conversion types listed in Table 3, and across the conversion areas and checkpoints 1–8 identified in Fig. 3. For most of the catchment area the reduction remains zero as no local or upstream change in land cover has occurred. The highly localised effect of LUC and SuDS (Conversions 1 & 2) is shown in Fig. 5a, where local reductions within and surrounding the changes in conversion areas 1 and 2 are significant (>25%) but are rapidly diluted downstream as the overall contributing area of unconverted land accumulates. This leads to reductions in channel peak flow below 5% further downstream of either LUC or SuDS. Channels downstream of attenuation ponds see substantial reductions (>25%) to peak flows that propagate along the network for notable distances within areas highlighted at risk of flooding (Fig. 5b-c). The reduction in channel peak flow downstream of both ponds here is attributed primarily to the presence of the ponds and the effect of FARL in eq. (2) rather than the reduction in C_V from upstream LUC/SuDS, which remains modest (less than3%).

Taken together, the results in Table 5 and Fig. 5 suggest that ponds are the most effective means for reducing flood peaks in main river channels downstream of any NBS location and, relative to size, produce the greatest impact over the longest distance. Considering the mapping of the GREEN effects on peak flows in Fig. 5, it is also clear that these effects are transmitted through a number of flood zones identified by the Environment Agency. This highlights the significant potential of attenuation ponds for reducing fluvial flooding in downstream riparian areas.

While SuDS and LUC measures might not have a significant effect on downstream flows, they are clearly shown in Fig. 5 to have strong local effects. Areas with SuDS (Conversion 2) exhibit the greatest reductions, often resulting in large areas where reductions exceed 15% and occasionally 40–56%. Areas with LUC (Conversion 1) have a less noticeable effect within the converted areas, but it should be noted the overall relative area being converted (from built to greenspace) is much lower than in Conversion 2. The effect is clearly greatest on the areas that have been converted but the effect on surrounding local areas is also

Table 5

Modelled peak flow for BASE and GREEN scenarios, showing results using the default parameters, and for sensitivity analysis to C_V and *FARL* parameters. The pair of bracketed numbers below the flows for both the default and sensitivity analysis GREEN scenarios indicate the percentage reduction in flow compared to the respective BASE scenario (left), and the percentage reduction in flow attributable only to the reduction in C_V (right).

Catchment name	Area km^2	Default parameters Flow (BASE) m^{3}s^{-1}	Flow (GREEN) m^{3}s^{-1}	Sensitivity – Low Flow (BASE) m^{3}s^{-1}	Flow (GREEN) m^{3}s^{-1}	Sensitivity – High Flow (BASE) m^{3}s^{-1}	Flow (GREEN) m^{3}s^{-1}
Rea Outlet (28039)	73.5	47.9	35.3 (26.4%, 1.82%)	23.1	16.4 (29.1%, 5.35%)	50.2	39.6 (21.2%, 1.82%)
Rea lower (1)	42.0	29.2	22.9 (21.7%, 2.35%)	14.1	10.5 (25.2%, 6.73%)	30.1	24.9 (17.5%, 2.35%)
Rea mid (2)	27.4	19.3	13.4 (30.6%, 2.63%)	9.64	6.63 (34.0%, 7.42%)	20.0	15.0 (24.8%, 2.63%)
Rea upper (3)	9.9	7.55	7.17 (5.11%, 5.11%)	3.65	3.13 (14.1%, 14.1%)	7.66	7.27 (5.11%, 5.11%)
Bourn lower (4)	28.5	17.9	17.7 (1.13%, 1.13%)	8.69	8.37 (3.70%, 3.70%)	18.9	18.7 (1.13%, 1.13%)
Bourn Tributary (5)	0.780	0.741	0.633 (14.5%, 14.5%)	0.452	0.260 (42.3%, 42.3%)	0.741	0.633 (14.5%, 14.5%)
Bourn Upper (6)	4.58	3.53	3.53 (0%, 0%)	1.60	1.60 (0%, 0%)	3.53	3.53 (0%, 0%)
Bourn Reservoir (7)	1.91	0.164	0.164 (0%, 0%)	0.0970	0.0970 (0%, 0%)	0.281	0.281 (0%, 0%)
Merrits lower (8)	11.1	7.31	7.14 (2.28%, 2.28%)	3.33	3.12 (6.54%, 6.54%)	7.58	7.41 (2.28%, 2.28%)

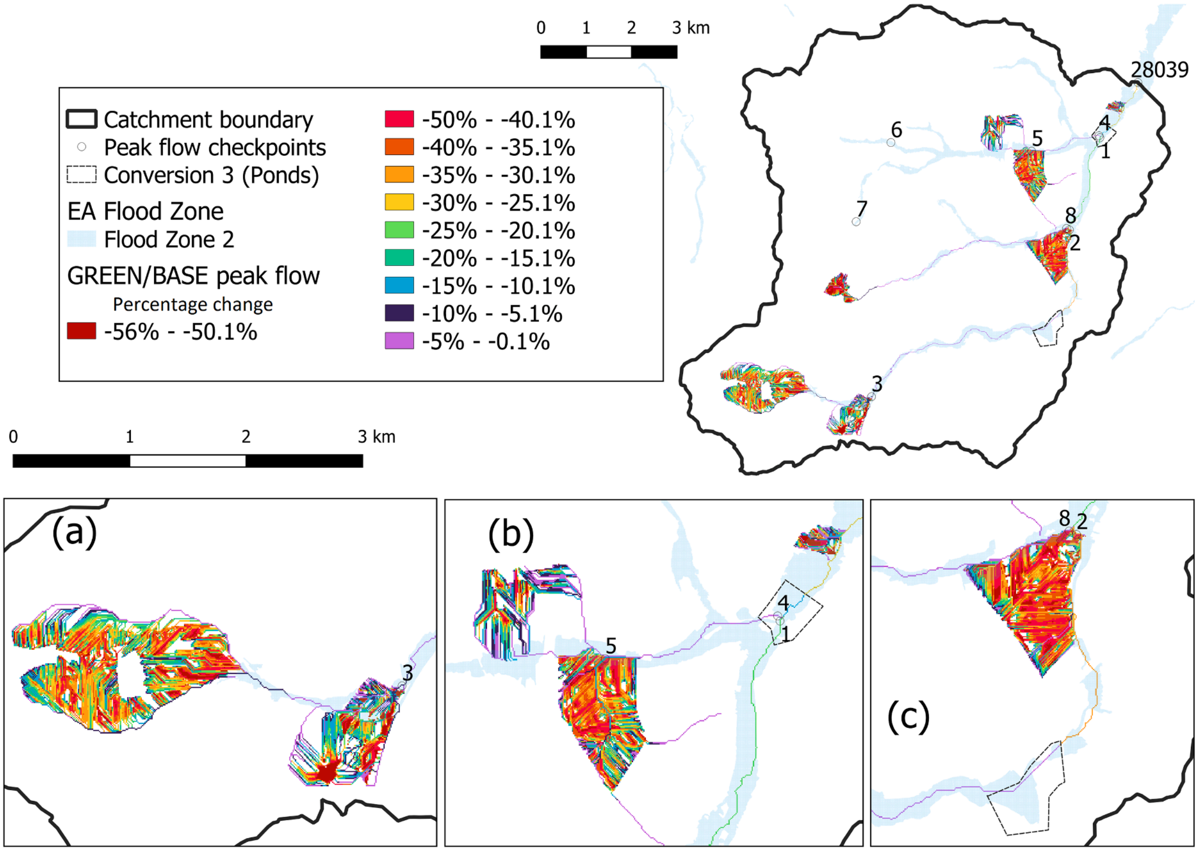

Fig. 5. Gridded percentage changes between GREEN and BASE peak flows across the network, with insets a-c highlighting changes across certain reaches, confluences, ponds and checkpoints. EA Flood Zone 2 (EA, 2022) is also displayed to give an approximate indication of the area that could benefit from reduced flood risk. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

significant – until the main channels are reached. The reductions are significant as there is not a large relative area of un-converted catchment to dilute the effects. Thus, while a pond might have a higher overall effect on channel flow, there is no benefit for surrounding land. These results show SuDS and LUC have a much greater effect at reducing runoff and flooding over a wider localised area, compared to only the downstream channel and bankside areas benefitting from Ponds.

4.3. Model parameter sensitivity

Under the ‘Low’ run the use of lower C_V values while retaining the high *FARL* power results in reduced river flows in both BASE and GREEN scenarios (columns 5 & 6 of Table 5). The reduction in runoff is greatest for permeable surfaces, but more modest for impermeable surfaces which always produce a high runoff fraction (Table 2), feeding through to BASE scenario flows that are reduced by 40% to 55% depending on the proportions of permeable and impermeable surfaces. The relatively larger reduction in runoff for permeable surfaces also results in a considerable increase in the modelled effectiveness of green measures. For all catchments the percentage reduction in modelled peak flows attributed to reduced runoff in GREEN scenarios is increased by a factor of approximately 3 (range 2.8 – 3.3) when the ‘Low’ parameters are used (compare right bracketed numbers between columns 4 and 6 of Table 5). For example, at site 5, the reduction in runoff due to green interventions results in modelled peak flow that are 42.3% lower in the GREEN scenario compared to BASE when ‘Low’ parameters are used (compared with 14.5% when default parameters are used).

The use of a lower power for *FARL* under the ‘High’ run (columns 7 & 8 of Table 5) results in lower attenuation from water bodies and thus an increase in the modelled river flows. For most catchments the sensitivity of the BASE scenario flow to the power of *FARL* is modest (typically a less than 5% increase in flows for ‘High’ runs), due to the typically modest influence of *FARL*. However, in catchments where the flow is strongly influenced by water bodies, the changes can be considerable. For example, modelled peak flow in the Bourn Reservoir (7) catchment increase by 72% when lower power for *FARL* is used. The modelled effectiveness of NBS ponds (conversion 3) added in the GREEN scenario is also reduced. The reduction in peak flows is only 21.2%, 17.5% and 24.8% for the GREEN scenario at Rea Outlet (28039), Rea lower (1), and Rea mid (2) respectively when the low *FARL* power is used, compared 26.4%, 21.7%, and 30.6% when the default power is used. Note that *FARL* and C_V are independent factors in the flow (eq. (2) and thus the power used for *FARL* does not affect the reduction of flow attributed to C_V under the ‘High’ runs.

5. Discussion

Spatial modelling of surface runoff or flood regulation is an emerging area within Ecosystem Service toolkit development and application that is important when tools are to be applied over a city area and capture meaningful ecosystem service pathways. Users are reliant on either a limited number of complex hydrological models that require considerable time and data to implement and validate, or toolkits that are spatially limited and/or fail to include any quantitative validation or sensitivity analysis of outputs (Vigerstol & Aukema, 2011; Ochoa & Urbina-Cardona, 2017; Lüke & Hack, 2017). This paper focused on bridging that gap, to provide a simple model that could meet a need, set out by Hutchins et al. (2021), for ES evaluation tools capable of quantifying scale-dependence and the relationship between NBS intervention and proximal benefit – here peak flow reduction both locally and along a river network.

The close match (±10%) to the FEH statistical enhanced single-site estimate of peak flow at the catchment outlet provides validation for design storm applications and suggests that the model provides hydrologically sensible estimates of peak flow across an urban catchment hydrological network. A limited number of hydrology-orientated ES toolkits include validation (e.g. Wang et al. 2008: UFORE-Hydro, Kadaverugu et al. 2021: InVEST) but in general, studies do not incorporate such steps (e.g. Song et al. 2020: i-Tree) or indirectly allude to them (e.g. Bautista & Peña-Guzmán, 2019: i-Tree). Studies employing hydrological models are more likley to include validation, however, even urban stormwater models such as SWMM typically do not have model accuracy>90% (Xu et al., 2019) and tend to be calibrated to common observed events. This suggests that, while uncertain and subject to further evaluation, ANaRM’s performance in this study (within ± 10% of an industry standard approach) represents reasonably robust performance for a relatively simple approach.

To assess the effects of key urban NBS on peak flows we selected three different types of NBS, represented across three conversion types: 1) LUC (impermeable to greenspace), 2) source control SuDS (green roof and permeable paving), and 3) Ponds. These were combined in a single scenario of land cover (GREEN). Both LUC and SuDS were shown to offer significant reductions in local runoff and have a considerable localised effect on reducing peak flows within targeted areas. However, the downstream contribution for flood mitigation along the main channel network is relatively low, in line with other studies that assess various LUC/SuDS spatial hydrological effects (e.g. Palla & Gnecco, 2015). Ponds, conversely, were found to offer much larger effects per unit surface area and with effects that are diluted more slowly downstream. The findings reinforce other studies that tend to suggest that configuration, SuDS type and location all play a role in the cumulative impacts of localizes GI on downstream hydrology (Golden & Hoghooghi, 2017). They are in line with studies showing source control SuDS such as green roof and permeable paving are most effective at reducing runoff entering stormwater systems and mitigating pluvial flooding, while ponds are more effective at reducing flow peaks in channels and associated fluvial flooding of at risk areas (Villarreal et al., 2004; Hu et al., 2017).

The relative impacts of SuDS, LUC and ponds also needs to be considered in relation to the availability of suitable sites. LUC and SuDS clearly offer the potential to reduce the impacts of pluvial surface water flooding across wide and targeted areas when storms exceed drainage design capacity (e.g. Scholz & Grabowiecki, 2007; Lashford et al., 2019). SuDS such as green roofs and permeable paving further offer the opportunity for retrofitting without any net land take. Ponds, in comparison, only reduce flows in the receiving watercourse and require exclusive use of land. It is therefore under such ‘real-world’ constraints that the importance of combining NBS that act at local and downstream scales becomes apparent for optimally reducing both pluvial and fluvial flood risk. This reduces both the source generation of runoff, alongside the retention of potential flood water, without needing large dedicated or homogenous areas of a single type of NBS, and which can be combined to fit the catchment conditions and land use restrictions optimally.

The effectiveness of engineered NBS at reducing flood peaks during a given storm can depend critically on their construction, level of maintenance, the antecedent conditions, and the intensity of that storm (Woods Ballard et al., 2015). This was tested by varying the two main sets of parameters controlling modelled peak flow under a Low and High parameter sensitivity test. The use of low C_V values to reduce runoff (Sensitivity – Low scenario) gave considerable reductions in peak flow for the BASE scenario, and a proportionally greater reduction in peak flows for the GREEN scenario due to the assumed greater reductions in possible runoff proportions generated by conversion of LUC to greenspace or urbanised surfaces to SuDS. The zero C_V value for both NBS is clearly at the lower end of a plausible range but does demonstrate how sensitive the ANaRM model is to NBS functionality and performance. Conversely, the use of a lower power (θ) for *FARL* to increase runoff downstream of waterbodies through reduced attenuation effects (Sensitivity – High scenario) resulted in only slightly higher peak flows for BASE conditions and a decrease in the effectiveness of new waterbodies added to reduce peak flows under the GREEN scenario. Taken together, the results suggest that such a model is very sensitive to the runoff coefficients chosen but only slightly sensitive to attenuation effects provided by *FARL*. This points to the importance of sensitivity testing, generally lacking across ES models, for providing what Redhead et al. (2016) highlight as valuable insights into ES model performance. Storm intensity was not explicitly altered as increasing the storm intensity will increase the amount of runoff generated across all land cover types, as per equation (2), but will not change the ratio of peak flows between any BASE or GREEN scenario for any specific land cover type unless C_V lookup values (Table 2) are adjusted. Any end-user would mimic less intense storms by reducing rainfall intensity (or vice-versa), and altering C_V lookup values, so they can study the effects of rainfall intensity and percentage runoff separately. Appropriate C_V values should reflect the storm of interest and antecedent soil/surface conditions, as higher rainfall totals are generally expected to cause greater saturation excess runoff and ultimately a reduced effectiveness of NBS, while infiltration of excess runoff may dominate during short intense storms.

To consider whether the tool could be useable and compatible with existing ES toolkits, we consider what authors in the climate model debate, such as Lemos et al. (2012), define as the 'usability gap' between what scientists think is useful and what users recognise as 'useful, useable, and used'. It is unclear if such a debate is taking place around ES toolkits, as it is a relatively new area of research (Hamel et al. 2021) and few review studies have considered such aspects of ES toolkits (e.g. Lüke & Hack, 2017; Ochoa & Urbina-Cardona, 2017; Van Oijstaeijen et al., 2020).

ANaRM certainly meets the criteria for being considered useful. The outputs are intuitive to understand and useful in an urban planning context as they relate to real-world peak flows and how such values change spatially as a result of implementing NBS. ANaRM offers the ability to easily apply design storm data that is readily available for many countries, further making results compatible with considerations of urban hydrulic design for flood management. There are limited ES toolkit studies utilising design storms, often based on hydrological models such as SWMM, but in general such applications tend to focus on flood volumes (e.g. Qin et al., 2013; Randall et al., 2019) or exclude flow routing (e.g. Kadaverugu et al. 2021: InVEST). The gridded representation of routed peak flow through the network represents the major difference and advantage of ANaRM over such existing models.

Useability is subjective, but every effort has been made to produce a simple and computationally streamlined framework, deployed within open access code with minimal user interface or input files. ANaRM requires minimal geospatial data: a DEM to determine the flow pathways, and, a raster dataset of land cover to link with literature values of C_V. This indicates that location and data access are not barriers – with the extra processing applied here to the open access WorldCover dataset being entirely optional and only for the benefit of providing a more detailed dataset for more rigorous model validation. Further, ANaRM needs only mean storm intensity to drive the model hydrology, this being easily derived from regional/national design storm methods that exist in many countries (Svensson & Jones, 2010). It also offers a simple means of sensitivity analysis and testing of various scenarios.

ANaRM was explicitly designed to handle scenarios developed and delivered as spatial data. This would integrate well with any ES toolkit that employs a graphical user interface to draw areas for NBS, with all the processing steps handled by the underlying code, facilitating ease of use for scenario development and testing. Likewise, incorporation of ANaRM into any number of ES toolkits should be facilitated by its implementation as a fairly short piece of code in the popular R programming language, which is freely available to download and modify, and requires little computational resource to run. We suggest that ANaRM could integrate with existing or planned ES toolkits and that it could be useful for routine urban landscape assessments involving flooding, such as environmental impact assessments – particularly when quantifying specific intervention effects is sought. Examples of existing ES toolkit that could integrate ANaRM include GISP (Meerow, 2019), which could easily determine peak flows if an underlying DEM-based flow direction raster were combined with appropriate C_V values, and the InVEST Urban Flood Risk Mitigation model, which does not route runoff at present, whose current documentation notes (https://naturalcapitalproject.stanford.edu/software/invest) that a routing method is considered for future work.

5.1. Limitations and further work

ANaRM is a simple model in comparison to other hydrological models such as SWMM and has received only limited testing at relatively small catchment scales. It is difficult to comment more on how it would perform across the smaller scales without gauged flow data at the study catchment's internal checkpoints. Likewise, performance at larger scales remains uncertain, as the Rational Method itself was not designed to be used over large areas or even in a grid-based approach for estimating variation of peak flows along a river network. The possibility of scaling up beyond 74 km^2 and investigation of the constant time-of-concentration assumption requires further testing. Likewise, while we derived a more detailed land cover dataset, we have not tested how the model would perform in a more data-poor region. Given that it is based mainly on the open access WorldCover data, this should not be a major issue, but it should be investigated.

A key hydrological limitation of the ANaRM model results from the necessary simplification of hydrology for the ES toolkit application focus. ANaRM is event-based and directed solely on storm events and peak flows for flood mitigation purposes. This neglects a wide range of other continuous hydrological processes and ecosystem services, such as annual water balances or pollutant retention, covered in other available continuous simulation hydrological models and/or ES toolkits such as i-Tree and InVEST. Further, in its current form, the proportion of runoff generated remains constant across any range of storm sizes unless C_V values are adjusted manually alongside rainfall changes to mimic variable rainfall intensity runoff rates. This focus on peak flow also means that no information on the volume and timing of runoff is produced, thus aspects of attenuation in the timing shifts of peak flows across a network, which would be provided by true routing (e.g. in SWMM), are missed. This could lead to the model neglecting potentially important interactions between local interventions (Dadson et al., 2017) that may occur when the attenuation of water in one sub-catchment results in coincident flood peaks with other sub-catchments and therefore increased flooding downstream where flows from different subcatchments meet. It should also be acknowledged that the *FARL* formulation describing the attenuation of river flows due to waterbodies was not developed specifically for this type of urban modelling. Further work should focus on testing the ANaRM model across a range of scales and considering how to integrate methods to automatically adjust runoff with respect to storm size, land cover and antecedent conditions. *FARL* effects should also be validated using suitable case studies with before-after effects of waterbodies on peak flows.

The final limitation is that, while a major motivation for developing ANaRM was to support ES toolkits, we have not been able to demonstrate integration with an existing toolkit within this project's timeframe. Progress with an as-yet unpublished ES toolkit that spatially models the effect of multiple ecosystem services for city planning is positive and further work will focus on providing a user-focused tool for identifying optimal NBS scenarios.

6. Conclusion

This paper has presented a hydrological modelling framework suitable for integration with spatially orientated ecosystem service toolkits and utilised this model to explore the effects of urban NBS on reducing peak flows across a catchment during storm events. The model is called the Adapted Nature-based-solutions Rational Method – ANaRM in short. It provides gridded estimates of peak flows using only minimal data and building on the established Rational Method hydrological model and integration with an index of flood attenuation from rivers and lakes (*FARL*) used in the FEH. The ANaRM model has been validated against estimates of peak flow using design storm rainfall. and can simulate the hydrological effects of NBS such as reduced runoff from greening land use change and source-control SuDS, and the attenuating effects of ponds on river flows. It is further able to isolate different NBS intervention effects at both local and downstream scales.

Taken together model results suggest that the combined effects of land cover change, SuDS and pond installation on peak flows can be much greater than the relative areas of catchment converted. Further they demonstrate that local source-control SuDS and LUC are the more effective option if the intention is to reduce local surface water flooding and reduce inputs into storm drainage systems to reduce pluvial flooding, while ponds are a much more effective option if the intention is to reduce flooding in downstream areas and mitigate fluvial flooding. This highlights the importance of considering the spatial effects of different types of urban NBS on hydrology, something that is not possible when using models or ES toolkits that do not incorporate catchment hydrological pathways. The ease of use of ANaRM recommends it as a potential part of any ES toolkit aiming to consider the spatial effects of NBS on urban catchment hydrology and flooding.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

Authors acknowledge funding from: the UK Natural Environment Research Council (NERC) to UKCEH under the Urban Nature Based Solutions - National Capability Science: Strategic Research & Innovation Short Projects award. The REGREEN Nature-based Solutions project (https://www.regreen-project.eu/) has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821016. The DeSCIPHER project under the Sustainable and Liveable Cities and Urban Areas programme jointly coordinated by the Joint Programme Initiative (JPI) Urban Europe and National Natural Science Foundation of China (NSFC); projects funded under both the Sustainable and Liveable Cities and Urban Areas and all the other JPI Urban Europe programmes (e.g. ENSUF) have received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 857160, with the DeSCIPHER project also receiving UK Economic and Social Science Research Council (ESRC) funding under grant ES/T000244/1.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2023.104737.

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