# Blue-Green Systems

# From site-focused intervention towards landscape-scale surface water management using Synthetic Stream Networks and Rapid Scenario Screening

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## ABSTRACT

This research addresses the need to transform success in technical understanding and practical implementation of surface water management (SWM) interventions at a site-scale towards integrated landscape-scale management. We achieve this through targeting the informative preliminary stages of strategic design, where broad, early and effective exploration of opportunities can enhance and direct a regional SWM perspective. We present a new method, 'Synthetic Stream Networks' (SSN), capable of meeting these requirements by taking advantage of easily accessible data, likely to be available during regional screening. We find that results from the SSN are validated by existing, 'downstream' focused data (90% of the river network is within 30 m of an associated SSN flow path), with the added advantage of extending understanding of surface water exceedance flow paths and watersheds into the upper catchment, thus establishing a foundational and physically based sub-catchment management unit exploring surface water connectivity at a catchment and landscape scale. We also demonstrate collaborative advantages of twinning the new SSN method with 'Rapid Scenario Screening' (RSS) to develop a novel approach for identifying, exploring and evaluating SWM interventions. Overall, we find that this approach addresses challenges of integrating understanding from sub-catchment, catchment and landscape perspectives within surface water management.

Key words: exceedance flow, GIS, regional hydrology, scenario screening, surface water management

## HIGHLIGHTS

- Despite many advances in surface water management (SWM), landscape-scale management remains unrealised.
- We develop a Synthetic Stream Network approach to evaluate exceedance flows and sub-catchments across landscapes.
- This supports transition from site-scale intervention to regional SWM.
- SSN is validated by existing downstream data while enhancing upstream detail.
- SSN can be coupled with complementary approaches to screen SUDS needs.

## INTRODUCTION

In this paper, we respond to a key challenge in surface water management (SWM), the current paradigm of site focused intervention planning; and in doing so, we look to advance towards the benefits and opportunities of integrated SWM at a catchment and landscape scale.

In November 2018, James Bevan, CEO of the UK Environment Agency, described surface water flooding as the 'biggest flood risk of all' (Bevan 2018). About 3.2 million properties in England are currently at risk from surface water flooding (DEFRA 2018). For comparison, this is higher than the total number of properties at risk from fluvial or coastal flooding counterparts, which combined reaches 2.7 million (Bevan 2018). Current surface water flood damages are estimated to be between £250 and £500 million annually (DEFRA 2012; Committee on Climate Change 2017); and some studies estimate that annual damages could rise between £500 million and £1 billion across the next 50 years (Committee on Climate Change 2012). This challenge is not restricted to the UK and is apparent at a global scale (Fletcher et al. 2015).

It has long been understood that surface water hazards are predicted to worsen in response to changing climates, increasing urbanisation and a reliance on legacy drainage infrastructure (Wong & Eadie 2000; Carter

*et al.* 2009; Ana & Bauwens 2010; Djordjević *et al.* 2011; Committee on Climate Change 2017). However, recent advances in research highlight that the magnitude of these hazards has been systematically underestimated (Wing *et al.* 2018). Even in low emission scenarios, cities are likely to face far greater hazards from flooding than previously recognised (Guerreiro *et al.* 2018). Of particular concern are forecasts of increasing intensity and duration of extreme precipitation, which are likely to exceed current drainage systems and generate high magnitude runoff more regularly (Westra *et al.* 2014). Many climate scientists highlight that it is extreme events, and not a gradual change, which pose the most risk to humans (Meehl *et al.* 2000). Therefore, it is crucial that future hazard management accommodates mechanisms to plan for extreme events. In the case of SWM, these extreme events lead to exceedance flow, water which overwhelms drainage system and infiltration capacities and so results in overland runoff across catchments (Balmforth *et al.* 2006).

Practice and research has responded to increasing hazards through developing new intervention strategies, planning frameworks and legislation directed at SWM (Pitt 2008; DCLG 2010; HM Government 2010, 2016; DEFRA 2018). Interventions include a range of measures, such as conventional urban drainage (Butler *et al.* 2018), nature-based solutions (Schanze 2017), sustainable drainage systems (Woods Ballard *et al.* 2015), green infrastructure (Schubert *et al.* 2017), water-sensitive urban design (Wong & Eadie 2000; Wong & Brown 2009), property-level resilience (Environment Agency 2015; White *et al.* 2018) and blue green systems (O'Donnell *et al.* 2020; Oral *et al.* 2020; Zhang *et al.* 2020). This list is not exhaustive and it is important to note that many other measures, under a range of synonymous terminologies, are also available (Fletcher *et al.* 2015). However, despite this wealth of interventions alongside established legislation that has been in force for over a decade (Pitt 2008; DCLG 2010; DEFRA 2010; HM Government 2010), reviews indicate that the current implementation of SWM, and in particular novel interventions, remains opportunistic, localised and insufficient to manage future threats (Committee on Climate Change 2015; Kabisch *et al.* 2016; Kuller *et al.* 2018; Frantzeskaki 2019). This inertia is apparent at a global scale (Brown & Farrelly 2009; O'Donnell *et al.* 2017; Thorne *et al.* 2018). Barriers include failure to accommodate new measures in institutional decision-making frameworks, uncertainty regarding effectiveness of novel interventions in a heavily regulated and risk averse water industry and a lack of evidence and integration of strategies and stakeholders at the catchment and landscape scale (Cettner 2012; Gersonius *et al.* 2012; Ellis 2013; Fenner 2017; O'Donnell *et al.* 2017; Ossa-Moreno *et al.* 2017; DEFRA 2018; Tozer *et al.* 2020; Zhang *et al.* 2020).

In particular, a gap exists regarding limited practical integration of SWM at a landscape scale, with predominant implementation of interventions being focused at individual sites (Kabisch *et al.* 2016; Kuller *et al.* 2018; Giese *et al.* 2019), with limited consideration of novel approaches (Mijic *et al.* 2016; O'Donnell *et al.* 2017, 2020). Effective SWM is best achieved through strategic synergies of centralised and decentralised interventions (Wong & Brown 2009). Therefore, enhancing consideration of all possible interventions and opportunities to connect implementation across spatial scales is a crucial component required to bridge this gap and advance practice towards effective and diverse catchment management approaches (Hoang & Fenner 2015; Oral *et al.* 2020; Zhang *et al.* 2020). This is best achieved through open, collaborative and early consideration of all options (Frantzeskaki 2019; O'Donnell *et al.* 2020).

Our research responds to this through two key pathways: (1) by developing a high-level regional screening approach that makes use of a novel Synthetic Stream Network (SSN) method to enable efficient and effective preliminary spatial evaluation, identification of catchment connectivity and opportunities to target interventions across landscapes; (2) through applying exploratory modelling to strategically inform, evidence and steer integrated catchment partnerships. Targeting these pathways facilitates a high-level screening methodology, suitable for application during the fundamental and instructive preliminary stages of catchment evaluation, to promote an integrated and diverse range of regional interventions as opposed to fragmented and localised site-scale design. The main novelty in this approach is through transferring and developing the tools and principles for integrated landscape-scale management, which have historically been restricted to fluvial hydrology, towards application to develop an integrated multi-catchment perspective in SWM.

We structure this paper through first outlining a method for the identification of regional surface water runoff dynamics using a SSN. We then evaluate the effectiveness and practicalities of this new approach through implementation across a pilot study in South West UK. We apply the advantages from this work to inform and direct subsequent exploration of sub-catchment flood hazards and management opportunities by combining the approach with Rapid Scenario Screening (RSS). We conclude by discussing the advantages and limitations of the approach and present considerations for practical implementation towards landscape-scale SWM.

## METHODOLOGY

### Screening catchment characteristics using SSNs

We develop regional analysis of surface water catchments through generating a series of likely exceedance flow routes and sub-catchments, which form the basis for delimiting a catchment into smaller spatial units. We refer to this as a SSN. The network is comprised of computationally derived flow paths, which map likely overland runoff to delimit the spatial relationships of surface water catchments.

The concept of a SSN is inspired by catchment delineation and automated watershed mapping algorithms applied in fluvial hydrology (Skop & Loaiciga 1998; Lindsay *et al.* 2008; Ding *et al.* 2016). Automated techniques have been available since the 1980s and are now routinely available within geographical information systems (GIS) (Band 1986, 1989); however, this analysis is not routinely applied to analyse surface water catchment characteristics at the regional scale, where analysis tends to be *ad hoc* and opportunistic (Kabisch *et al.* 2016; Kuller *et al.* 2018; Lechner *et al.* 2020; Oral *et al.* 2020). Recent developments in computational processing have made this possible at high resolutions across extensive spatial extents.

Automated mapping of fluvial sub-catchments is made through identifying locations which drain to a shared outlet point, typically based on stream junctions where multiple watercourses meet (Band 1986, 1989; Lindsay *et al.* 2008). Fluvial systems consist of mostly permanent streams, which present clearly defined networks enabling straightforward identification of these points across large regions.

Discretising regional catchments into stream sub-catchments enables spatial evaluation of localised characteristics and connectivity within the broader context of regional landscapes, and as such functions as a useful opportunity to address barriers regarding the integration of spatial scales and systems within regional SWM (Hoang & Fenner 2015). However, surface water flow paths are typically transient and thus only visible during periods of prolonged or intense rainfall generating overland flow. Even areas with significant historical flooding may not have detailed records of runoff routes (Bates *et al.* 2006; Neal *et al.* 2009; Fewtrell *et al.* 2011). Design standard drainage is also heavily influenced by micro-topographical features and surface drainage systems (Fewtrell *et al.* 2011; Dottori *et al.* 2013), which, while adequately managing rainfall during everyday situations, may also disguise potential exceedance flow routes which may be significant during intense rainfall.

### Defining a SSN for surface water runoff using open data

We applied the watershed mapping approach (Lindsay *et al.* 2008) to surface water runoff through developing a SSN, predicting likely overland flow paths across a region. In order to address the challenges of identifying regional opportunities through connecting stakeholders at the instructive initial stages of management, we based this method on open-source data and generally available GIS software, which diverse catchment management stakeholders could apply and replicate across a range of international contexts (Wong & Eadie 2000; Burns *et al.* 2015; Frantzeskaki 2019; Lechner *et al.* 2020). Figure 1 presents the steps taken to define a SSN.

Stage one of the processes is acquiring and processing a regional DEM. Extensive DEM coverage is available to cover the vast majority of England through the Environment Agency data portals (DEFRA 2020). DEM coverage is generally available at a 5 or 2 m resolution, with very high-resolution coverage between 1 and 0.25 m in specific areas of interest. Similar data are generally available, at a range of resolutions, across the globe.

The resolution requirements of data are subject to a trade-off between precision and computational cost of evaluating data; this should be considered on a case-by-case basis with reference to data availability, licensing and eventual application of the catchments (Dottori *et al.* 2013). In this case, we are interested in bridging the barriers
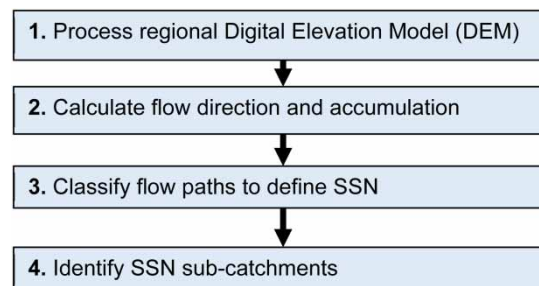


**Figure 1** | Methodology to define a SSN.

to implementing catchment partnerships and novel interventions through addressing the informative early screening stage of strategy development, and so coarser data remain appropriate to identify regional-scale patterns. This type of preliminary analysis is then complemented through additional modelling to support and develop findings (Webber et al. 2018b).

When evaluating a large area, it is likely that a variety of DEM products may be required. This is managed through merging and resampling different sources to ensure a single file representing elevation at the same cell size in one layer; this can be achieved using 'merge', 'mosaic' and 'resample' commands in standard GIS packages. This DEM is further processed to remove artefact depressions and develop a connected hydrological surface representing flow across the region; as with the above, this process can be achieved using standard hydrological analysis functions in common GIS packages, such as 'fill'. This ensures that each cell remains connected to an outlet (stream) (Lindsay et al. 2008). We achieved this using the ArcGIS 10.5 merge, resample and fill functions.

It should be noted that DEM products can include Digital Surface Models (DSMs), which include bridges, buildings, trees and other surface features, or Digital Terrain Models (DTMs), which solely include the elevation of underlying terrain. The application of the two approaches will lead to different outcomes. For a broad-scale mapping study, such as the intention of this method, it is suitable to use a DTM; however, for detailed 2D modelling studies simulating runoff, we would recommend that high-resolution representation of surface features, such as buildings, is included. This is of particular pertinence in urban areas.

Stage two requires calculating the runoff flow direction and accumulation for each cell on the DEM. We applied the ArcGIS flow direction algorithm to determine the inflowing and outflowing connectivity within neighbouring cells based on gradient (Lindsay et al. 2008). We then applied the ArcGIS flow accumulation algorithm to transform flow direction into a flow accumulation per cell. This algorithm assumes each cell has one unit of water and then uses the flow direction to trace where this water will flow based on a 'rolling ball' methodology, aggregating the sum of the water to identify cells which have a higher through-flow (Figure 2). Once we applied the flow, each cell was represented with a value indicating the number of upstream cells flowing into it. Cells with a higher accumulation value are indicative of predominant flow paths across the terrain. We note that this does not take into account the saturation, infiltration or drainage capacities of cells; however, this does enable a sufficient representation of exceedance flow in an extreme flood scenario, responsible for the majority of surface water impacts (Meehl et al. 2000; Environment Agency 2013). Overland flow of this type can be caused by intense or prolonged rainfall, catchment saturation due to antecedent conditions or ineffective and non-functional drainage systems.

During stage three, flow paths are classified through applying a cell accumulation threshold to identify cells with an accumulated area above a certain value. In terms of the threshold value, a smaller threshold will equal a larger number of flow paths and thus a more extensive stream network. However, as the classification is only trimming the size of the previously calculated cell accumulation paths, the SSN will still always converge to the main flow paths. Figure 3 presents the steps to classify flow accumulation into a SSN.

It should be noted that this only represents the direction of overland flow assuming no redirection of flows by infiltration or subterranean drainage networks. Therefore, the classification does not represent inherent flood risk and should be used in conjunction with flood mapping to identify where a hazard is located.

In stage four, we identify SSN sub-catchments. The flow paths developed in stage three are split into stream branches and sub-catchment watersheds are calculated by identifying the cells which flow to each stream junction. We achieve this through evaluating the flow direction on the DEM and performing a topographical analysis to delimit all cells which flow to a specific outlet point, as defined by flow path junctions (Figure 3). This concept
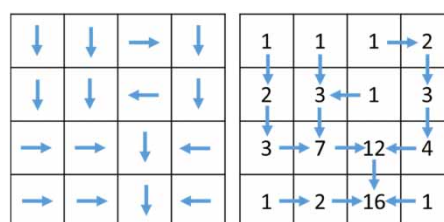


**Figure 2** | Flow direction and accumulation to identify flow patterns: (a) cell flow direction and (b) cell flow accumulation.
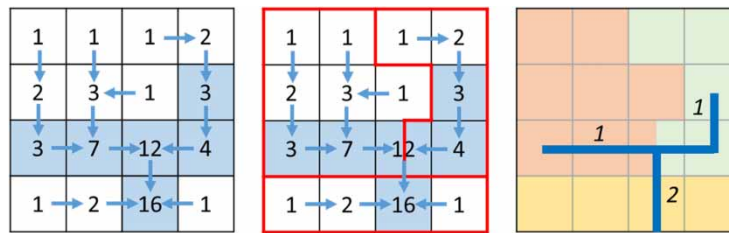
**Figure 3** | Catchment identification based on the threshold value and Strahler classification of stream and catchment order: (a) predominant flow routes highlighted through a threshold value, (b) catchments identified through delimitation of contributing area and (c) classification of resulting SSN.

is also applied in fluvial hydrology to define sub-catchments, with some studies referring to it as a 'support area' (Blöschl & Sivapalan 1995).

A stream order is attributed to branches through applying a Strahler classification to the SSN (Strahler 1957). Strahler classification develops a hierarchy of stream branches and sub-catchments, with first-order catchments located at the furthest upstream branches and then the order increasing as each branch connects to downstream channels. This approach details the spatial connectivity of a catchment. Sub-catchments are classified in line with their associated stream branch.

Stages one to four can be undertaken using commonplace GIS software, examples include, but are not limited to: 'ArcGIS', 'QGIS' and 'Mapinfo'. The processing applied in this study has been undertaken using 'ArcGIS 10.5'.

## Integrating landscape-scale SSN with catchment-scale RSS to evaluate SWM needs and opportunities

While the SSN is a useful method for understanding and screening exceedance flow paths, it does not indicate the likelihood or magnitude of runoff or flooding, factors which require significantly more detail and understanding of physical processes across catchments and sub-catchments. Therefore, we have combined this method with another high-level screening methodology, 'RSS'. RSS enables preliminary analysis of catchments based on easily accessible data, and as such complements SSN through supporting initial analysis which can go on to inform requirements for further, more resource intensive, decision support regarding SWM.

Our intention in this combination of approaches is to illustrate the benefits of initial analysis at a regional scale using the sorts of data and efficient analytical resource which is likely to be available to stakeholders when evaluating SWM needs and opportunities, thus providing an opportunity to advance current practice towards more regionally integrated strategies, which accumulate benefits of site-scale implementation.

The RSS framework applies CADDIES-2D, a spatially explicit 2D routing model based on a cellular automata system architecture, to simulate surface water flow dynamics across the catchments. The main advantage of this cellular automata modelling approach is reduced computational resource cost versus standard hydrodynamic modelling, resulting in fast analysis speeds and subsequent possibility of evaluating many catchment scenarios (Webber *et al.* 2018a). The approach has been validated versus industry standard modelling, to find that RSS provides an accurate model for the purposes of high-level surface water modelling, suitable for intervention optioneering in the initial stages of strategy design and stakeholder engagement (Gibson *et al.* 2016; Webber *et al.* 2018b).

The model requires parameters describing elevation, water input, water output and roughness values for each cell at each timestep. Parameters are specified at a high spatial resolution using parameter-specification raster files representing a DEM (elevation), rainfall (water input), infiltration and drainage (water output) and surface type (roughness). The RSS spatial resolution is determined independently from the SSN and can be set at whatever resolution is available (including high-resolution products such as 0.25 m LIDAR). However, the same elevation data can also be applied for both RSS and SSN. We caution that higher resolution data are not always required or warranted, and data inputs should be determined based on the purpose of modelling, which in this case is intended as an engagement and screening process. Dottori *et al.* (2013) provide a comprehensive review of considerations when evaluating resolution, uncertainty and purpose in modelling.

The extent and data requirements for these are informed through the analysis of connected sub-catchments using the SSN. Full details of the CADDIES-2D model, RSS framework and comparisons versus other 2D modelling packages are available across literature (Ghimire *et al.* 2013; Guidolin *et al.* 2016; Webber *et al.* 2018b).

## DEVELOPING, VALIDATING AND EVALUATING A SSN ACROSS A SOUTH WEST ENGLAND PILOT STUDY

### South West England study area

The concept of SSN and catchment ordering has been applied to South West England as an opportunity to implement, develop and test the approach working with a range of regional stakeholders.

South West England is the largest of nine official regions of England, covering over 20,000 km$^2$. The region has a population of approximately five million residents and consists of the counties Avon, Cornwall, Devon, Dorset, Gloucestershire, Somerset and Wiltshire (ONS 2013). The region is a mix of rural catchments, including two UK National Parks, and urban centres, making it a useful case study to examine integrating regional SWM using a range of strategies.

### Developing an open access SSN to support regional partnerships

A key feature of regional analysis is the need for a range of stakeholders to integrate their decision support to work collaboratively across connected catchments (DEFRA 2018). Therefore, data applied for defining a stream network should be open access, so understanding is transferred with ease across multiple organisations and partners.

The main data requirement is a DEM of sufficient resolution. The DEM in this case study has been produced using source data from the Environment Agency LIDAR Composite DEM (Environment Agency 2017). This DEM is a 2 m resolution raster describing surface elevation across the region. The 2 m DEM is a composite of best available data and updated annually to provide the best available data. The extent currently covers approximately 75% of England; however, some gaps remain in isolated locations where previous mapping studies have not been undertaken. To resolve this, we patched a small number of gaps in 2 m DEM coverage using the ubiquitous Ordnance Survey 50 m elevation model (Ordnance Survey 2020).

Matching our objective for an open-source analysis, applicable to a range of stakeholders, these elevation models are open access under a UK Open Government License (UK Government 2020), which grants the ability to adapt, distribute and transmit the information both commercially and uncommercially. This provides an effective resource for our pilot study and could be expanded across the rest of England. It is likely that similar resources are also available in other countries to differing standards of resolution and coverage.

Figure 4 presents the development of the regional SSN for South West England. For clarity, we present this as a zoomed-in area from the regional case study (Figure 6), with panels (a)–(d) corresponding to the four stages outlined in the SSN methodology. Panel A shows a processed DEM (stage one), with sinks and basins removed. This is then used as the basis for calculating flow direction and accumulation (stage two) in Panel B. Panel C shows the flow path classification and SSN delineation (stage three). Panel D shows the resultant sub-catchments identified and ordered on the intersection of stream junctions (stage four).

For this case study, we applied a classification threshold of 25,000 cells. As each cell has an area of 4 m$^2$, this equates to a runoff flow path identification threshold of a cell being included as a primary runoff route when 100,000 m$^2$ contributes to flow in that cell. This equates to a total contributing area of at least $315 \times 315$ m, which is a pragmatic balance between the size and number of sub-catchments when considering an applicable scale of analysis and intervention for strategic regional planning. When considering this threshold, it is important to note that adjusting this value only trims (if threshold increased) or extends (if threshold decreased) the upstream flow paths and does not change the spatial relationship of overland flow catchments or downstream flow paths as these are delineated by the underlying topography. A higher number of upstream catchments could be achieved by decreasing the classification threshold; however, this would need to be considered versus the trade-off in applicability of sub-catchments. An ideal size for sub-catchments could be considered on a community scale where effective design, management, ownership and engagement of interventions could be practically achieved. This is of particular note for interventions such as blue green systems, where community engagement can be a positive driving force in success (Brown & Farrelly 2009; Lopez-Marrero & Tschakert 2011; Kabisch *et al.* 2016; Frantzeskaki 2019; Tozer *et al.* 2020).

### Validating the SSN

In this section, we describe the approach used to validate the SSN flow paths through spatial correlation versus comparable existing catchment data. A driving factor underpinning our development of SWM sub-catchments is that suitable alternative exceedance flow sub-catchments are not available, except for *ad hoc* analysis not
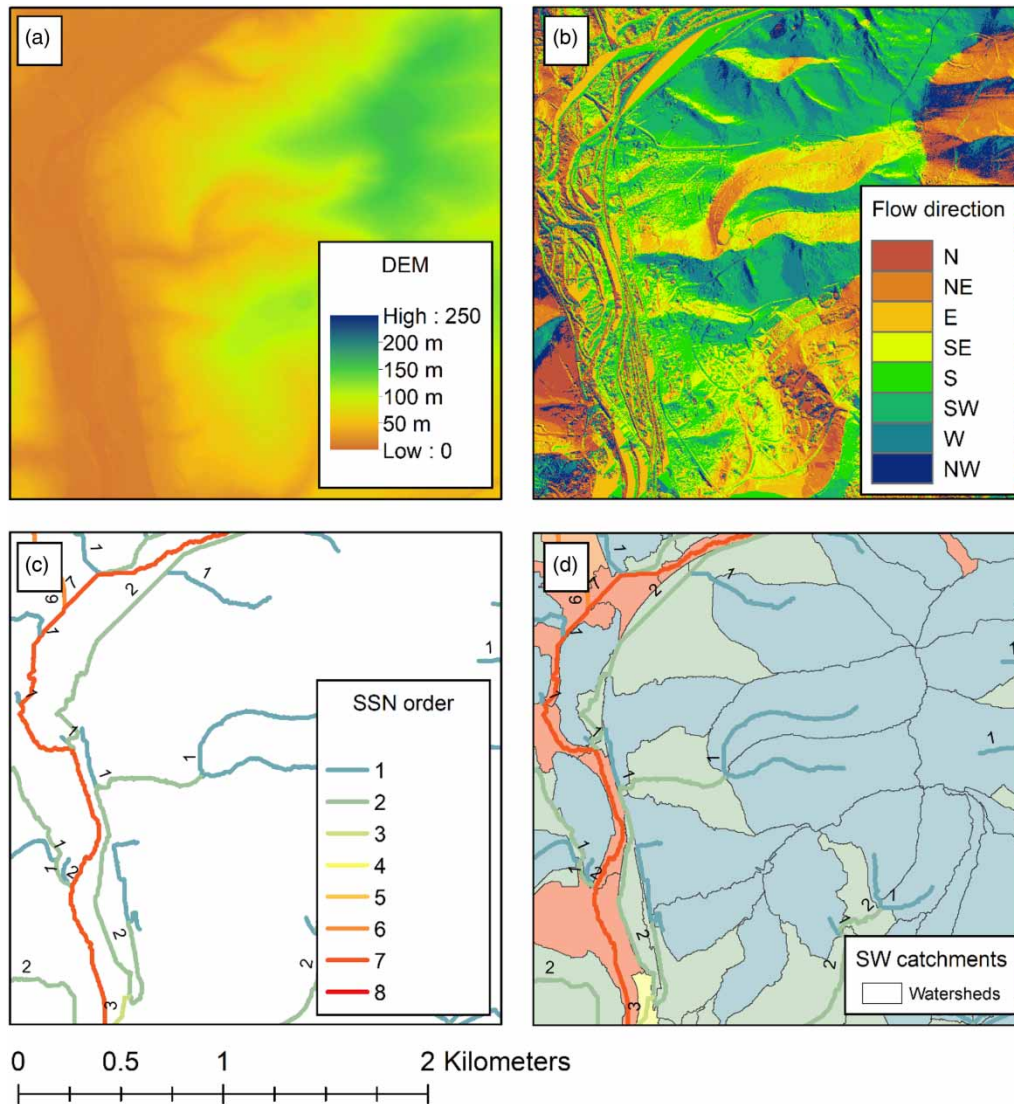
**Figure 4** | Example SSN classification in South West England using a 2 m resolution DEM: (a) process regional DEM, (b) calculate flow direction and accumulation, (c) classify flow paths to define SSN and (d) identify SSN sub-catchments.

integrated or uniform across the regional scale we wish to promote within SWM. Instead, current SWM units in South West England typically cover large proportions of entire fluvial catchments, which provide a poor comparison with our objectives. An example of this is shown in Figure 5, where 'Water Framework Directive Surface Water Operational Catchments' are clearly far too large to be a useful integration resource between regional and local analytical contexts. Discretising to a SWM sub-catchment basis has not been previously modelled, and empirical evidence describing exceedance catchments is unavailable due to the rare, time-dependent and transient nature of overland flows (Dottori *et al.* 2013). Therefore, validation of our regional-scale SSN was challenging due to limited suitable comparisons with this novel data.

We overcame this challenge through focusing comparison of downstream flow paths, which, if upstream accumulation is correct, should closely align with the existing fluvial network. Therefore, we analysed correlation of the OS Open Rivers dataset with downstream flow paths indicated by the SSN through measuring the distance of river links to corresponding SSN branches. We analysed the proximity of polylines representing the centre of SSN flow paths and OS watercourses, and applied this analysis across the counties of Devon and Cornwall where we had full spatial coverage from both the SSN and Open Rivers datasets. The advantage of comparing versus the OS Open Rivers is that benchmark data are empirical and identify the exact locations of the fluvial network, therefore providing a real-life, as opposed to a model–model, comparison; however, future research can improve on this comparison if empirical data describing monitored overland flow routes in the upper catchments become available.
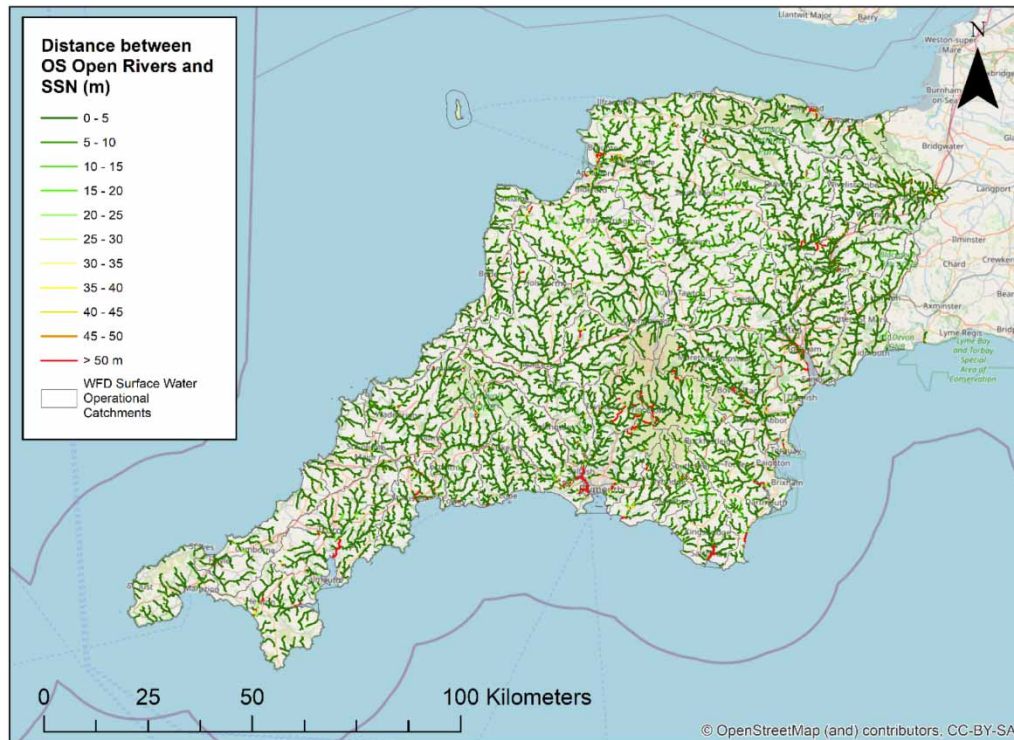
**Figure 5** | Comparison of OS Open Rivers data with the associated channels included in the SSN (contains OS data © Crown copyright and database right 2021).

Table 2 shows that 90% of river channels are within 30 m of the corresponding SSN branch, indicating a high degree of spatial correlation between datasets, with 95% of channels within 45 m of an associated SSN branch. This strong correlation supports the application of the SSN data towards utility of a high-level screening dataset, adding a representation of upstream exceedance routes, not currently present within accessible datasets, while ensuring that these flow contributions map across to existing datasets representing the fluvial network.

Furthermore, our analysis also shows that more than 80% of channels are within 20 m, and approximately 70% of channels are within 10 m, of the associated SSN exceedance flow path. This shows that a large proportion of the SSN demonstrates high accuracy relative to existing datasets and supports the application of SSN for analysis at a local level which bridges to the context of a regional scale. This is of particular note given that we analysed proximity based on a polyline at the centre of the water course and flow route, rather than using the outline of the full watercourse. We did this to ensure a fair comparison of like for like data types, but acknowledge that correlation would likely appear stronger again if we would apply the full spatial extent of watercourses.

**Table 1** | Distribution of sub-catchment order in South West England

| Distance to SSN (m) | Proportion of OS Open Rivers (%) |
| --- | --- |
| <50 | 95 |
| <45 | 95 |
| <40 | 93 |
| <35 | 92 |
| <30 | 90 |
| <25 | 87 |
| <20 | 82 |
| <15 | 77 |
| < 10 | 69 |
| < 5 | 59 |

**Table 2** | Distribution of sub-catchment order in South West England

| Catchment order | Count | Count (%) | Area (ha) | Area (%) |
|---|---|---|---|---|
| Unclassified | 26,370 | 25.4 | 1,074.8 | 0.1 |
| 1 | 39,893 | 38.5 | 893,077.3 | 60.9 |
| 2 | 18,408 | 17.8 | 283,693.2 | 19.4 |
| 3 | 9,657 | 9.3 | 161,043.5 | 11.0 |
| 4 | 5,457 | 5.3 | 83,032.0 | 5.7 |
| 5 | 2,766 | 2.7 | 31,164.9 | 2.1 |
| 6 | 769 | 0.7 | 8,564.6 | 0.6 |
| 7 | 361 | 0.3 | 4,348.0 | 0.3 |
| 8 | 6 | 0.0 | 55.5 | 0.0 |
| *All* | *103,687* | *100.0* | *1,466,053.9* | *100.0* |

Where differences are apparent, these are typically attributed to three main criteria.

Firstly, the most significant degree of difference is attributed to the classification of watercourses extending out into estuaries. The SSN is restricted to terrestrial runoff and as such these estuaries are not modelled within analysis, resulting in a substantial spatial variation. Figure 5 presents the distribution of channels from our analysis. This shows higher spatial correlation in shades of green to amber, with red indicating a deviation of more than 50 m between an Open Rivers polyline and the SSN. This shows that areas of poor correlation are frequently associated with estuaries or the coastline.

Secondly, the SSN methodology focuses on overland exceedance flow, assuming that drainage systems are overwhelmed. Therefore, subterranean alterations to watercourses, for example culverted streams, are not represented in the SSN dataset, so deviation is apparent between culverted watercourses and associated overland flow routes. A similar difference is also caused where watercourses are subject to other manmade alterations, such as pumping, aqueducts or regulated and managed above-ground channels. This requires caution when evaluating specific overland flow routes at a local scale, but also provides a useful resource to indicate the presence of potential overland flow routes when existing drainage features exceed capacity. Because of this discrepancy, we highly recommend the application of this regional-scale dataset is applied with caution and full consideration of local contexts and upstream flow paths when applied at a local scale.

Thirdly, the SSN is developed using a 2 m resolution elevation model. Many micro-topographical features are therefore not represented at this scale. While these features may not be significant at a landscape scale, research highlights that small features may be highly influential to exceedance flow routes at a site scale (Fewtrell *et al.* 2011; Chen *et al.* 2012; Schubert & Sanders 2012; Dottori *et al.* 2013); therefore, as with our previous point, we reiterate the need to apply this methodology with caution when considering this regional-scale resource at local contexts. The degree of correlation presented in Table 2 does highlight that the SSN remains likely to be a useful resource at this scale; however, consideration of the local context is crucial for effective merging of regional and local decision support.

Overall, we find that the SSN represents surface water hydrology effectively for regional-level screening, and can serve as a useful tool to integrate knowledge to a local scale, provided appropriate analysis of local context is applied. However, it is important to note that the application of the approach should be considered at a site-by-site basis, and analysis of consistency versus supporting data, such as that presented in Figure 5, should be used to inform suitability and identify areas where local features create deviation. The next section of our paper evaluates utility of this approach.

## Evaluating flow paths and catchments

Figure 6 presents the SSN developed for South West England. The main figure presents the full extent of the study area and shows broad regional trends of catchment order and flow paths. As outlined in the analysis presented in Figure 5, the distribution of flow paths and catchments, particularly those of a higher order, closely aligns with the fluvial system, with large rivers such as the Exe and Tamar clearly visible.
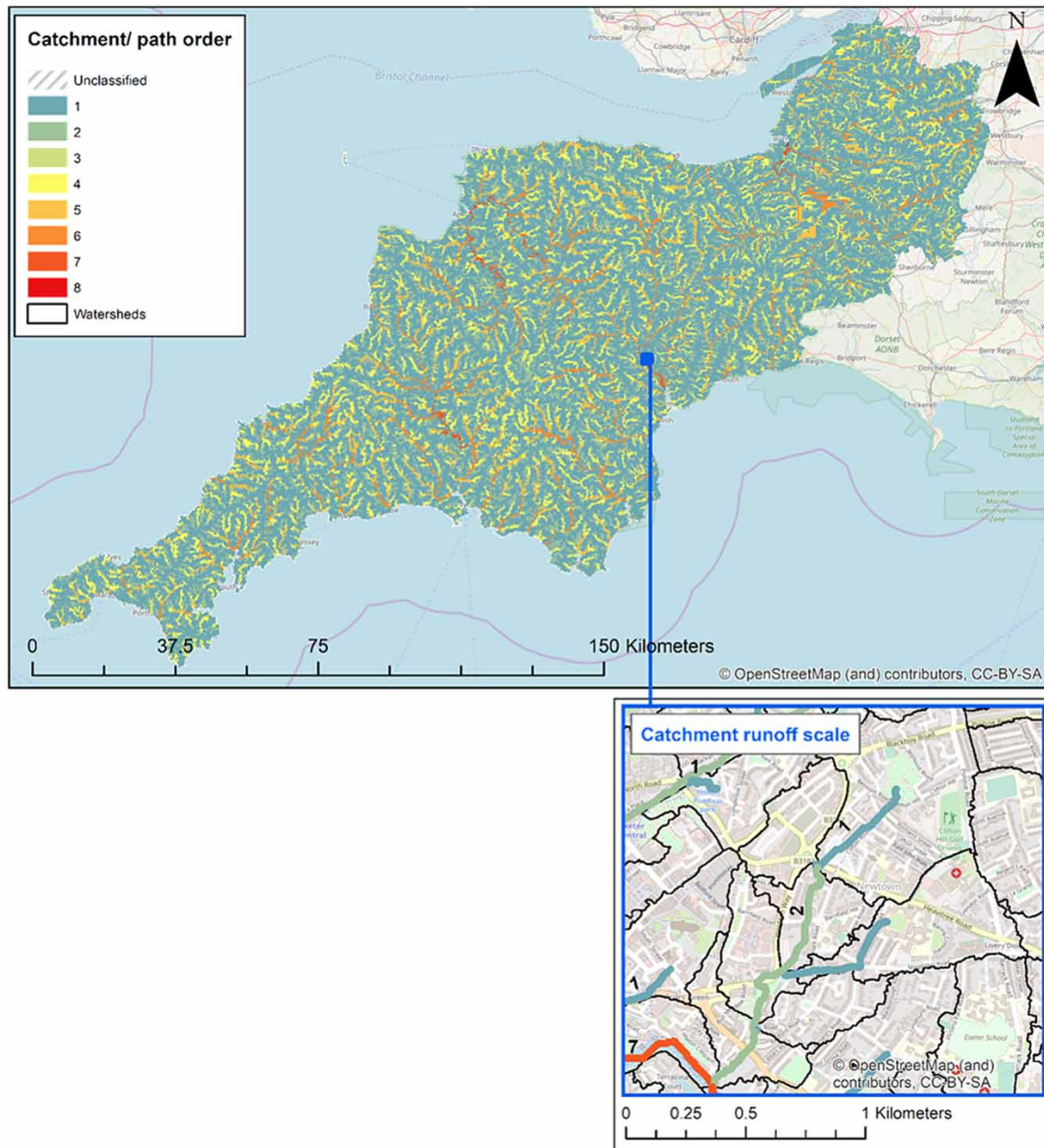
**Figure 6** | South West England SSN analysis with the zoomed area to highlight catchment runoff detail.

The inset in the figure illustrates the level of possible detail when zoomed in to a local level, demonstrating the utility of fine spatial disaggregation of sub-catchments and flow paths across an urban area. This level of detail provides a useful resource to indicate requirements for management, such as the scope, extent, stakeholders, likely overland flow routes and key data requirements for sub-catchment decision support. Comparing this level of detail with impacts from predicted or recorded flood and pollution events will also effectively aggregate regions across a catchment which contributes to future management.

### Analysis of catchment order

Figure 6 shows that sub-catchments are predominantly first and second order across the region. Table 2 presents a detailed breakdown of catchment orders, indicating the number of catchments within each category and the spatial extent of those catchments. Analysis of catchment count indicates that the majority of catchments are first (38.5%) and second order (17.8%), with totals decreasing as channels join downstream.

The first step of the DEM removes local depressions which could cause ponding; however, certain areas remain unconnected to the DEM and as such are 'unclassified' within our methodology. There are a large number of catchments where this is the case (25.4%); however, these only represent a small proportion of the land area (0.1%). The predominant area where this occurs is the coast, where water runs towards the coastline and so runoff does not connect to the stream network. In some instances, unclassified catchments can also be generated in narrow strips between regions in very flat areas (such as the Somerset levels) where numerous but very small pockets of runoff are unconnected between two catchments. These features are typically very narrow strips; hence, the very small proportion of catchment area it accounts for (0.1%).

Targeting SWM interventions is informed through understanding catchment order. For example, hazards occurring in upstream (low-order) catchments will have limited or no connected catchments in which to manage runoff and so interventions should focus on site-scale capture of surface water within the catchment itself. Capture can be achieved using nature-based solutions (such as blue green infrastructure), property-based solutions (such as rainwater harvesting) or conventional drainage systems (Melville-Shreeve *et al.* 2016; Butler *et al.* 2018; O'Donnell *et al.* 2020). On the other hand, downstream (higher-order) catchments will have significant contributing areas upstream, and so hazards can be managed through distributed runoff management and source control across connected catchments. This regional analysis alone is insufficient for a full assessment of SWM options. However, when the strategic spatial perspective it offers is combined with site-scale understanding, it can inform and direct subsequent stages of management; acting as a bridge to integrate strategic planning and stakeholder engagement at a site, sub-catchment, catchment and landscape scale.

## APPLYING THE SSN TO TARGET INTERVENTION EXPLORATION USING RSS

The purpose of this section is to demonstrate the process of applying understanding derived using the SSN as a basis for exploratory modelling connecting landscape analysis with local-scale implementation of strategies.

We applied the SSN in combination with existing flood hazard data (Environment Agency 2013) as a resource to scope surface water flood hazards and intervention opportunities around the region. One area of interest was the Dartington Estate, a rural area located in the south of the study area.

The SSN identified key stakeholders, data extents and catchment management measures for further analysis using RSS. We set up our exploratory model using the same DEM used to generate the SSN. We derived rainfall data using the summer rainfall curves in the Flood Estimation Handbook values, representing standard industry practice (Centre for Ecology and Hydrology 2013). Infiltration and roughness rates were specified based on land cover mapping from OS Mastermap vector data. Building and road locations were included using the same resource.

Figure 7 presents surface water flood assessment for these catchments. Panel a displays the surface water catchments and flow paths identified by the SSN (Figure 6). This indicates that the sub-catchments of interest are first-
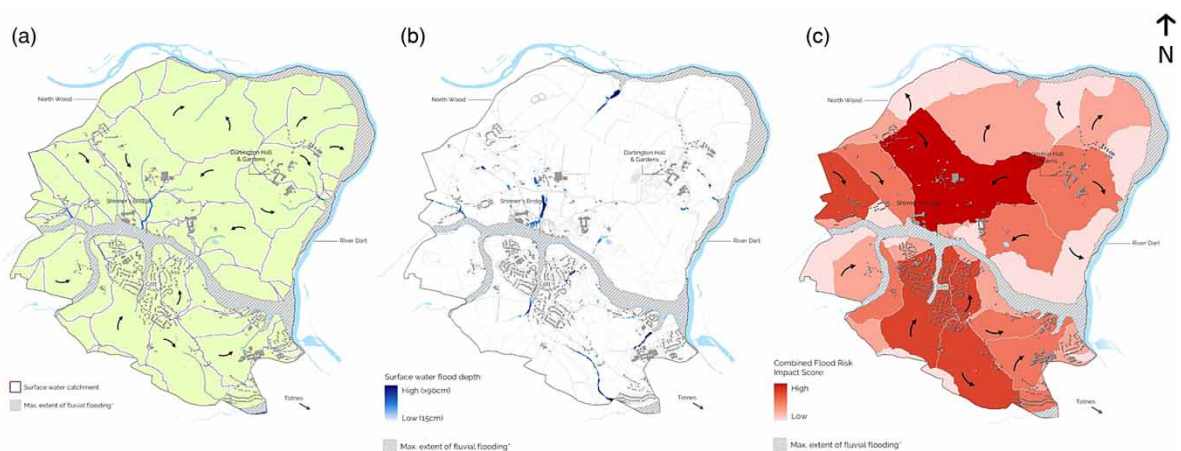


**Figure 7** | Surface water flood assessment at the Dartington Estate: (a) surface water catchments from the regional SSN, (b) surface water flood mapping using CADDIES-2D representing 1 h duration, 100-year return period rainfall and (c) flood risk index.

order catchments with runoff flow routes that drain to the River Dart and its tributaries; as such SWM to manage hazards in these areas should be targeted in the catchments themselves.

Panel b presents flood hazard modelling applied to evaluate areas of flood hazard across the estate. We evaluated flooding across a range of storm durations (1, 3 and 6 h) and return periods (10, 30, 100 and 1,000 year events) and observed maximum flood depth in the 1 h event in all cases. We have, therefore, used this duration to represent the 'critical storm' for analysis of flood hazards. This corroborates Environment Agency recommendations that short duration events are likely to represent critical storms in small catchments (Environment Agency 2013).

Panel c displays a flood risk index for each catchment. This has been summarised at a sub-catchment scale using SSN as foundational units. The flood index aggregates and summarises risk through capturing the number of buildings, length of roads and area of agricultural land flooded to deeper than 30 cm. Each factor was scored from 0 to 5, with 0 representing no risk and 5 representing the highest risk. Specific scoring based on the equal interval classes for each factor and aggregated to create an indicative flood risk index per catchment.

This preliminary analysis demonstrates effective identification of appropriate sub-catchment units, stakeholders and data, enabling exploration indicating locations and likely sub-catchment response to a range of rainfall events and scenarios. This approach identifies the key sub-catchment delimitation and prioritisation which can be targeted to manage flood risk in the downstream locations. As first-order catchments, these regions are likely suitable for distributed interventions across the specified sub-catchment areas. Analysis also highlights that a range of sub-catchments drain directly to the River Dart, and so intervention within these areas would be ineffective to manage hazards across Dartington Estate. Risks to properties attributed to fluvial flooding can also be managed through managing runoff across upstream areas identified by the SSN. Representing results and enabling catchment analysis in this fashion provides an accessible initial resource to shape stakeholders understanding and identify the spatial extent of decision support requirements.

## DISCUSSION

### Regional perspective for SWM

Applying regional analysis as the fundamental basis for SWM connects decision support with a whole catchment perspective on hazard and intervention assessment, supporting consideration and development of novel distributed interventions alongside more typical grey approaches. This is of pertinence in respect to developing a framework to realise the potential for green infrastructure distributed across catchments, particularly where stakeholders can identify upstream locations, which can be managed to create downstream benefits.

The principal advantage of the SSN approach is identifying surface water runoff (overland flow) catchments at a regional scale using open-source mapping. Open-source, regional-scale mapping enhances insight through enabling planners to identify broad spatial relationships at a preliminary stage of catchment management, opening up opportunities for offsetting flooding which may not be apparent when measures are considered at the site level (Mijic *et al.* 2016). This open-source data form a communication tool which supports the development of SWM techniques through visualising high-level spatial relationships, connections and extents between overland flow catchments.

Furthermore, the application of SSN to understand sub-catchment hierarchy and spatial relationships provided an effective basis for collaborating with stakeholders through an iterative process of catchment identification and intervention design. This was particularly useful for spatial visualisation of catchment characteristics, steering stakeholders towards investigating the suitability of a diverse range of interventions. Coupled with the use of RSS, this approach provided an effective screening methodology to efficiently evaluate interventions across contributing areas during an early stage of option screening and decision support.

### Relationship between stream-ordered sub-catchments and widening stakeholder consideration of novel SWM interventions

Many interventions are available with which to manage surface water hazards across catchments, including novel interventions which have widely cited benefits (Zhang *et al.* 2020). However, current SWM implementation, particularly regarding emerging interventions such as blue green systems, remains insufficient and is subject to an 'implementation gap' between opportunities to act and action taken, with most implementation seen as opportunistic rather than co-ordinated and strategic (Kuller *et al.* 2018). Identifying and delimiting stream-ordered sub-

catchments enable regional SWM to address this gap through identifying opportunities for implementing blue green systems across landscapes and stakeholder groups.

A clear visual identification of the relationship between runoff flow paths at a landscape scale supports consideration of how locations can be strategically aligned for action through connecting the local and regional scales at which interventions impact can be co-ordinated (O'Donnell *et al.* 2020); for example through highlighting opportunities for a series of SWM interventions, sometimes referred to as a ' management train' or 'cascade', to achieve a compounding benefit across a catchment surface. Understanding of how sub-catchments are connected also enables a catchment and regional perspective, which is oriented towards a holistic view of the surface water system. Advancing a holistic view of catchments at the initial stages of strategic decision support can support a transformative deployment of blue green systems, where a range of suitable interventions can be explored relative to different land-use types, catchment locations and interoperability with other systems (Oral *et al.* 2020). Practically, use of the SSN will help identify opportunities for decentralised measures in upstream locations, potentially using catchment management approaches in rural settings (South West Water 2020) or synergistic decentralised interventions, such as rainwater capture, urban greening and rain gardens, in urban locations (Woods Ballard *et al.* 2015; Mijic *et al.* 2016; Fenner 2017; Löwe *et al.* 2017). Similarly, the approach can be used to identify areas for larger blue green systems or infrastructure in downstream areas where the runoff from many catchments congregates, enhancing strategic perspectives for how centralised and decentralised measures relate (Wong & Brown 2009).

Clear communication of hydrological connectivity across a catchment using mapping at an early stage of design supports knowledge transfer across a range of stakeholder's influential in the strategic design process. Providing clear and timely tools, such as preliminary mapping, can be particularly advantageous in multi-disciplinary collaboration, such as that required when designing blue green systems (Kabisch *et al.* 2016; Frantzeskaki 2019); as early understanding of catchment connectivity and runoff flow paths can support non-drainage specialists to consider drainage opportunities to influence and achieve their own remits, supporting multi-functional infrastructure (Jose *et al.* 2015; O'Donnell *et al.* 2017; Zhang *et al.* 2020). Clear understanding of spatial connections also supports blue green systems to be applied in a more equitable and effective manner, with simplified mechanisms providing additional opportunities to bring communities into the design process, particularly when management units are at a similar scale to the communities managing them (Lechner *et al.* 2020; Tozer *et al.* 2020).

## Limitations of our approaches

The methodology is subject to several limitations highlighting it as a preliminary screening tool indicative of spatial dynamics of surface water catchments at a regional scale. This is an important distinction, and we stress that this style of high-level analysis should be used to complement and direct, rather than replace, high-resolution site-scale investigations.

The principal consideration of the SSN approach is that it only accounts for overland flow and does not include interactions with the sub-surface sewer network, which may capture and rout runoff between catchments. This is of importance in urban areas, particularly during design standard rainfall for which the surface water drainage network is designed to operate (Butler *et al.* 2018). Similarly, the SSN does not take into account land-use surface characteristics beyond elevation. For example, the runoff paths are not influenced by the infiltration capacity or roughness of different land cover types and inclusion of these could provide additional insights into surface runoff characteristics during certain rainfall events, such as low-intensity events, where significant proportion of runoff can be infiltrated into soils or captured by drainage systems (Weng 2001; Butler *et al.* 2018). However, as the principle cause of surface water flooding is extreme rainfall leading to exceedance flows (Meehl *et al.* 2000; Kaźmierczak & Cavan 2011; Environment Agency 2013; Westra *et al.* 2014; Hoang & Fenner 2015; DEFRA 2018), it is important to evaluate runoff flow when drainage system and land infiltration capacity are exceeded (Ana & Bauwens 2010; Dottori *et al.* 2013). This supports government advice requiring 'plausible worst case scenarios' to be evaluated in SWM (DEFRA 2018) and echoes the flood resilience agenda, which highlights that it is extreme events, beyond design standards, which create hazards (Meehl *et al.* 2000; Mugume *et al.* 2015; Butler *et al.* 2017).

It is also important to note that the method is developed using regional-scale elevation mapping, and as such does not represent the localised effects of urban microtopography (Fewtrell *et al.* 2011; Schubert & Sanders 2012; Dottori *et al.* 2013). Similarly, the methodology does not account for spatial heterogeneity of surface types or rainfall. However, through coupling SSN, to provide the initial screening of landscape-scale opportunities, with RSS,

which enables higher resolution and spatially heterogeneous analysis of land use, rainfall and opportunities for blue green infrastructure; this method can support and coordinate multi-agency exploration and integration of novel intervention opportunities within regional design.

### Recommendations for practical application

With respect to these limitations, we recommend that the methodology is used as a preliminary screening tool to identify and delimit surface water runoff catchments. As with all models, this provides a tool for a specific purpose and its uncertainties and limitations should be evaluated on a case-by-case basis (Blöschl 2006; Dottori *et al.* 2013). The SSN approach develops a regional-scale product intended to be applied as indicative representations of likely catchments for the purposes of initial catchment screening and planning potential SWM strategies. The RSS then provides an incremental step to bridge the regional exceedance flow dynamics presented in the SSN, towards a more local context, taking into account the effect of high-resolution features with an exploration of management options on runoff propagation.

The key utility of our approach is an accessible initial tool to engage and connect stakeholders across catchments, responding to government calls for effective catchment partnerships (DEFRA 2018) and academic calls to facilitate these using effective communication tools (Blöschl 2006). It is envisioned that this high-level analysis is applied to direct site focused fine resolution modelling and expertise, providing a basis to integrate these towards a wider catchment perspective (Viavattene & Ellis 2013; Fenner 2017; O'Donnell *et al.* 2017; Ossa-Moreno *et al.* 2017) to enhance, rather than replace, current capabilities and direct and inform requirements for future flood management actions.

We see the most effective application of this methodology to be as an initial and exploratory step, enabling a regional perspective to be iterated and refined towards site-scale understanding, and vice versa: to understand the importance of site-scale management in the context of a connected regional SWM strategy.

Practically and specifically, we recommend that this takes place through a chain of decision support tools, iteratively refined to develop engagement, data and decision detail:

1. Identifying regions of interest using stakeholder engagement and national-scale risk reporting, such as the Environment Agency 'Risk of Surface Water Flood Mapping' in the UK.
2. Developing the SSN to identify the scope of regional flow dynamics, stakeholders and data.
3. Exploring intervention opportunities and scenarios using RSS supported by easily accessible data identified through the SSN.
4. Applying outputs from RSS to further refine modelling, data and stakeholders using detailed 1D–2D hydraulic–hydrological modelling. Directing a resource efficient analysis, focused on pertinent and specific scenarios and management opportunities.
5. Deploying existing site focused detailed modelling and design tools to implement specific interventions.

## CONCLUSIONS

This paper addresses the current disconnect between extensive expertise for SWM at the local (site) scale and the need to advance towards more integrated management using the wide range of available interventions synergised across sub-catchment, catchment and landscape perspectives. We have advanced this through developing, testing and demonstrating a novel methodology for regional-scale evaluation of surface water runoff dynamics using SSNs. We find that this method effectively represents downstream channels, correlating 90% of the river network within 30 m of an associated SSN channel, while providing upstream details describing how exceedance paths and sub-catchments coalesce across landscapes. As such, we find this a viable approach to explore and integrate regional surface water hydrology, albeit with limitations which must be considered on a case-by-case basis.

As demonstrated in the real-life case study, the main advantage of the new approach is as a strategic resource deployed to steer and evidence the early stages of SWM, enhancing open consideration of all possible interventions in a way accessible to all stakeholders at the outset of strategic design and supporting the development of SWM from a current paradigm of site-scale design towards integrated landscape management.

Future research should advance findings through streamlining the approach into an easily applicable tool and aligning additional open geospatial criteria to support further analysis of SWM intervention options alongside the SSN approach.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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