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Review

Sustainable Catchment-Wide Flood Management: A Review of the Terminology and Application of Sustainable Catchment Flood Management Techniques in the UK

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Abstract: Climate change has seen increased pressures put on the existing ageing flood mitigation infrastructure. As a result, over recent decades there has been a shift from traditional hard-engineered approaches to flooding to more sustainable methods that utilise nature-based processes in order to slow flow, store water and increase infiltration. Doing so has resulted in a range of different nomenclature for such techniques, particularly in the rural environment. This paper takes a critical review of such terms to draw parallels in the different approaches, with the aim of developing a more unified, consistent approach to flood management. Furthermore, links have been drawn with the urban environment, where Sustainable Drainage Systems (SuDS) are used as a sustainable approach to urban flooding. The findings from this review have identified a series of issues that result from the current UK approach of differentiating between urban and rural flood risk, with funding often given for Natural Flood Management (NFM) projects separately to SuDS, with little integrated thinking from source to sea. Hence, the review suggests (1) a greater consideration of scale, focusing on the catchment as a whole, is required to ensure a more holistic approach to flood management, under the phrase “sustainable catchment-wide flood management”, to ensure that the focus shifts from NFM (rural) and SuDS (urban), to a more integrated catchment-wide approach; (2) the development of robust policy and regulatory framework, to ensure that such an approach is more widely adopted; (3) a greater consideration of the long-term costs is also required, with future research needed on the long-term maintenance costs of different methods; (4) the development of modelling approaches that can simulate flow at a range of spatial and temporal scales, to support stakeholders, such as local authorities, flood risk engineers and government agencies when considering flow not only in rural areas, but also to understand the impact beyond the immediate area around the scheme.

Keywords: sustainable catchment-wide flood management; Natural Flood Management (NFM); Sustainable Drainage Systems (SuDS)



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1. Introduction

Evolving approaches to sustainable flood management have resulted in a variety of different terms and techniques, producing a series of challenges when attempting to embed such approaches in legislation. With a changing climate and a UK Government plan to build 300,000 new homes per year, increasing the urban footprint, flood events, such as those seen in 2016, 2020 and 2021, are expected to increase in severity and regularity [1,2]. As a result of the summer 2007 storms, the UK Government commissioned an independent review by Sir Michael Pitt to identify lessons that could be learned from the floods, with the

27th recommendation encouraging the need to work with natural processes [3]. However, flooding in 2015/2016 across northern England, Scotland, Northern Ireland and parts of Wales resulted in a further review, the National Flood Resilience Review, focussing on extreme fluvial and coastal flood risk [4]. A subsequent review followed this publication in 2020 of surface-water flood risk [5]. Key outcomes from the reviews were:

- The need to reconsider approaches to assessing flood risk and developing resilience
- A need to better manage rainfall and the interaction with the natural environment
- The requirement for national advice to highlight the importance of developing Sustainable Drainage Systems (SuDS) for all new developments.

This review was further supported by a pledge from the UK Government to spend £5.2 bn over six years developing resilient, sustainable flood infrastructure as part of the 2020 budget and the 25 Year Environment Plan [6,7]. However, the need to develop a joined-up approach to flood management, identifying the importance of and relationships between rural and urban runoff and to mitigate fluvial and pluvial flood risk are often overlooked. Furthermore, while Fletcher et al. [8] addressed the various terms used to address SuDS globally, such an approach has not yet been presented for the multitude of terms used in rural areas to manage river flow. These approaches are most commonly referred to as Natural Flood Management (NFM) in the UK, but also by a range of other terms both in the UK and international community, creating internal divisions regarding best practice for flood management. Consequently, this review paper introduces and investigates the relationship between the different terms and associated techniques used for NFM in the UK, and presents an approach to integrating sustainable catchment scale flood risk and local drainage measures to develop a joined-up approach to sustainable flood management. By reviewing practices for sustainable pluvial and fluvial flood risk, it will be possible to characterise a best practice approach to sustainable flood management in the UK to inform future policy and practice.

2. Natural Flood Management

2.1. Defining Natural Flood Management

Urban creep, coastal squeeze and erosion, land reclamation, agricultural intensification, and widespread deforestation have reduced catchments' natural regulatory functions to manage extreme events. Therefore, policy and practice have sought more catchment scale approaches, such as Working with Natural Processes (WwNP) [9]. As part of the portfolio of WwNP referred to in this paper, NFM is widely recognised as the most prevalent across the rural and agricultural landscape, applied across rivers, floodplains, estuaries and coasts. However, whilst a commonly used term in the UK, due to the wide range of associated techniques and a multitude of international terminology, there is added complexity around the nomenclature for NFM. Furthermore, while NFM is frequently referred to as 'new' and 'novel', neither are the case. Historically, NFM principles (and even some of the methods) have been applied, normally in isolation at the local scale, for centuries [10,11]. Predating the intensification of agricultural land management in the era of land drainage between the 1940s–1970s [12], the practice of holding water in the landscape for multiple functions has been well reported [13]. For example, early Mesopotamia (400BC) is recognised as the first civilisation to develop irrigation systems that allowed fields to flood, replenishing silts and associated nutrients in farmed environments in spate conditions when the Tigris and Euphrates burst their banks [14,15].

More recently, what is considered NFM in the UK has developed multiple terms of reference internationally, as outlined in Table 1. Whilst these definitions vary, the principle aim of reducing flood and erosion risk involves implementing measures that help to protect, restore and emulate the natural functions of catchments, floodplains, and rivers [9,16]. Table 1 demonstrates the complexities of the common phrasing, with different terms being used to cover the spectrum of flood risk management strategies. While NFM is prioritised in the UK, emerging phrases such as "nature-based solutions" (NBS) have become more popular since 2016. NBS has been used globally to discuss approaches that focus on

natural adaptations to societal issues, particularly climate change [17]. As highlighted by Keesstra et al. [18], the Sustainable Development Goals in 2015 and the consequent UN Water report [19] positioned NBS as a primary approach to adapting to the challenges of a changing climate. While putting nature at the heart of engineering provides opportunities for flood risk management, this can overlook structural “non-natural” approaches that are integrated under other terms of references. Similarly, whilst green infrastructure is also commonly used globally, several techniques are considered sustainable approaches to flood management that are not “green”. Again, such terminology can overlook potentially effective methods by favouring approaches such as green roofs, swales and ponds [8]. This is also similar for Engineering with Nature (EWN) and Natural and Nature-Based Features (NBBF), both of which are terms commonly used in North America [20,21], along with Best Management Practices (BMPs) [22]. However, BMPs are more often associated solely with urban stormwater management, with a focus on pollution prevention, as opposed to the fluvial flood management focus on NFM [8].

As such, NFM involves landscape bio-mimicry, encouraging and (when required) modifying the landscape to manage the water sources and pathways which lead to flooding post urbanisation, agricultural intensification and coastal squeeze. NFM has also been implemented in coastal settings, typically through the breaching or lowering of defences through managed realignment (MR). Some sites, such as the Medmerry Managed Realignment Site [23], have been implemented on open coasts to compensate for intertidal habitat loss and for flood defence benefits, the latter achieved in Medmerry via saltmarsh vegetation providing an estimated 60% reduction in wave energy [24]. Despite this, there remains a lack of empirical evidence regarding the level of defence provided by MR sites against waves during storm events, as the majority of schemes have been carried out in fetch and depth limited, estuarine and lower catchment environments. Sites such as those implemented as part of the Sigma Plan in Belgium (e.g., Jacobs et al. [25]) have been developed as flood storage areas to protect areas upstream and elsewhere within the catchment during storm surge events. However, there has been the suggested possibility of an increase in the flood risk due to MR sites drawing more water into estuaries [26], although further investigation of the change in flood risk is required.

These methods typically aim to reduce fluvial flood risk while also ideally enhancing other potentially significant ecosystem services (aquatic, riparian and terrestrial) such as greater biodiversity, improved soil structure, reduced diffuse pollution, carbon sequestration, reduced soil erosion, greater agricultural productivity and improved amenity [27–29]. Lane et al. [30] define NFM in the context of Catchment Based Flood Management (CBFM) as a component of managing the sources and pathways of flooding by intercepting, slowing, storing and, if possible, filtering flood water. This risk-based approach is also commonly applied to the built environment systems by using SuDS, or in a rural setting with Rural SuDS [31] to manage flood flows across a management train approach [32,33]. The terms ‘NFM’ and ‘Rural SuDS’ can be applied interchangeably. However, the NFM literature more commonly refers to Rural SuDS as a component of NFM [34,35], applied on farms (either in fields or farmyards) to treat effluent runoff before slowly discharging treated storm flow into the receiving watercourse. NFM is used herein as the main term of reference for such techniques in a rural catchment setting.

Table 1. National and international terms of reference for NFM.

Term	Acronym	Definition	Reference
(Urban or Agricultural) Best Management Practices	BMPs <i>North America</i>	"... techniques or methods that aim to manage the quantity and improve the quality of stormwater runoff in a cost-effective manner... BMPs often aim to replicate natural processes and, depending on their design-can offer several social, environmental, and financial benefits to people who live nearby or downstream of the installed BMP."	[22]
Catchment based approaches	CaBA <i>UK</i>	"... management interventions that seek to modify land-use and land management, river channels, floodplains and reservoirs (where present), in order to reduce the frequency and severity of flooding."	[29]
Engineering with Nature	EWN <i>North America</i>	"... the intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental and social benefits through collaborative processes."	[20]
Green Infrastructure	GI <i>World-wide</i>	"... a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services such as water purification, air quality, space for recreation and climate mitigation and adaptation."	[36]
Integrated Catchment Management	ICM <i>UK</i>	"... the co-ordinated and sustainable management of land, water, soil vegetation, fauna and other natural resources on a water catchment basis"	[37]
Natural and nature-based features	NBBF <i>North America</i>	"... the use of landscape features to provide engineering functions relevant to flood risk management while also producing a range of other economic, environmental, and social benefits. NNBF can be incorporated into riverine/fluvial and coastal systems and includes such features as beaches and dunes, islands, forests, wetlands, and reefs, all of which can occur naturally or be constructed as nature based features through human engineering."	[21]
Natural Flood (Risk) Management	NF(R)M <i>UK</i>	"... involves techniques that aim to work with natural hydrological and morphological processes, features and characteristics to manage the sources and pathways of flood waters. These techniques include the restoration, enhancement and alteration of natural features and characteristics, but exclude traditional flood defence engineering that works against or disrupts these natural processes."	[16]
Natural Water Retention Measures	NWRMs <i>EU-wide</i>	"... are multi-functional measures that aim to protect and manage water resources using natural means and processes, therefore building up Green Infrastructure, for example, by restoring ecosystems and changing land use."	[38]
Nature Based Solutions	NBS <i>World-wide</i>	"... actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits."	[39]
Nature-based Flood Risk Management	NbFRM <i>England</i>	"... aim to increase interception and infiltration, slow overland and channel flows, and add catchment storage by introducing changes to land use and surface roughness and networks of "soft" engineered features constructed mainly from natural and immediately sourced materials."	[40]
Rural Sustainable Drainage Systems	Rural SuDS <i>Scotland</i>	"... will reduce agricultural diffuse pollution impacts as they are physical barriers that treat rainfall runoff. They are low cost, aboveground drainage structures that capture soil particles, organic matter, nutrients and pesticides before they enter our water environment. Rural SuDS for steadings prevent blockages in drains and ditches. They contribute to good environmental practice and farm assurance schemes. In fields they can be used for returning fertile soil back to farmland and will help your business become more resilient to the impacts of climate change."	[31]
Rural Sustainable Drainage Systems	R SuDS <i>England and Wales</i>	"... are tools that help maintain and manage the provision of good water quality. They provide an important role by intercepting runoff and trapping soil before it leaves the field."	[41]
Working with Natural Processes	WwNP <i>England</i>	"... aims to protect, restore and emulate the natural functions of catchments, floodplains, rivers and the coast."	[9]

2.2. Techniques and Application of Natural Flood Management

Table 2 details all the reported NFM measures and associated methods based on common catchment applications and functions. These are adapted from multiple guidance documents, principally the Environment Agency evidence directory [9] with the addition of hedgerows and wet woodlands, identified from the Dadson et al. [29] NFM Oxford Martin restatement, the EU NWRM guidance [42], and the North American EWN evidence synthesis [20]. All methods aim to reduce runoff at source and associated flood wave propagation across pathways by slowing, storing (attenuating), disconnecting and, where appropriate, filtering flood flows [13] from the source of catchments in the headwaters to the estuarine and coastal lowlands.

Table 2. Source to sea NFM techniques.

Runoff Management [9,43]	
Soil and land management	Conservation tillage, crop rotation, winter cover crops, reduced stocking density, compaction management, vegetation cover and buffer strips
Headwater drainage	Track drainage and grip/gully blocking
Runoff pathway management	Bunds, ponds, swales and sediment traps
River and Floodplain Management [44]	
River restoration	Re-meandering, stream bed raising, floodplain reconnection, deculverting and two-staged channels
Floodplain/wetland restoration	Embankment removal and restoring wetlands
Leaky barriers	Large leaky woody debris dams, coarse woody debris and beaver dams (lodges)
Offline/Online storage areas	Washlands, wetlands, offline and online pond
Woodland Management [9]	
Catchment woodland	Hilltop woodland, large-scale woodland cover
Cross-slope woodland	Woodland belt and shelterbelt
Hedgerows	Hedges and cross-slope interceptors
Wet woodland	Woodland water retention area and leaky deflectors
Floodplain woodland	Floodplain zone woodland and floodplain roughening
Riparian woodland	Riparian zone woodland and bank crest roughening
Estuarine Management [9]	
Managed realignment	Mudflats, saltmarshes and washlands

3. Sustainable Drainage Systems

Whereas there remains ambiguity surrounding the terminology used for NFM in the UK, SuDS is a reasonably well-established approach to drainage solutions, with defined non-statutory standards [45] and a manual for their design, as developed by the Construction Industry Research and Information Association (CIRIA) [33]. Fletcher et al. [8] presented the variety of alternative terms that are used to cover more sustainable approaches to drainage, for example, best management practices, green infrastructure and low-impact design. Whilst NFM aims to reduce runoff at the wider catchment scale, particularly runoff that flows directly into a river, SuDS focuses on localised, typically urban runoff to limit pluvial flood risk [46,47]. A traditional combined sewer drainage system will characteristically overflow into a watercourse during high rainfall events [48]. SuDS presents an alternative approach to such drainage, prioritising the storage and slow infiltration of runoff through a range of different techniques (Table 3). This management is ideally done through a “management train” approach, whereby water is firstly managed “at source”, or when it reaches the ground and along their pathway to the main water course [33]. Combining SuDS to form a “management train” ensures a cumulative reduction in runoff instead of utilising standalone devices [32]. The flow will ideally be conveyed from source control devices by swales or pipes, where required, to a larger site control device and then onto

a regional control device, if necessary [33]. Like NFM, the goal is not just to reduce the runoff, but also to improve its quality and increase the biodiversity of a site while providing amenity benefits [8]. This multi-benefit approach led CIRIA to develop the “SuDS Sphere”; a theoretical plan that demonstrates the wider benefits that can be achieved by integrating SuDS [33].

Table 3. SuDS techniques and scale.

SuDS Techniques	Source	Site	Regional
Attenuation Pond		X	X
Bioretention Areas	X	X	
Detention Pond		X	X
Filter Drain	X		
Filter Strips	X		
Green Roofs	X		
Infiltration Trench	X	X	
Permeable Paving	X		
Rainwater Harvesting	X		
Soakaway	X		
Swale	X	X	
Wetland		X	

Research has demonstrated the possible reduction in runoff that can be achieved by integrating SuDS, instead of traditional piped drainage, and the improvement in the quality of runoff [32,49–53]. Lashford et al. [32] demonstrated the benefits of integrating a combination of SuDS devices in a Management Train, which echoed the findings of Jefferies et al. [54], who presented the improvements in runoff water quality that such a strategy can provide. However, the terminologies surrounding scale regarding SuDS management differ from those applied for NFM. Table 3 presents the scale at which different SuDS techniques work most effectively. Source control SuDS aim to manage runoff at the point rainfall reaches the surface before entering a drainage system, whereas NFM considers source measures in the context of the wider basin [33,55]. Additionally, the catchment area for managing runoff for larger SuDS, as part of a management train, is typically defined by the size of the urban development, with larger regional devices capturing runoff from across a site before discharge into the receiving watercourse, usually a river [56]. Consequently, SuDS will focus on the immediate urban area and the opportunities to disconnect from traditional piped drainage as opposed to the wider river catchment considered by NFM [57,58].

Regardless of the benefits that can be achieved from integrating SuDS, there remains resistance to their incorporation into wider drainage schemes, usually due to perceived high long-term costs or a lack of understanding regarding design or ownership of maintenance [59–61]. The Non-Statutory Standards for SuDS aimed to ensure they were more widely considered during the development phase of new sites in England [45]. However, the lack of implementation of Schedule 3 of the UK Flood and Water Management Act has proven to be a considerable barrier to their wider integration in England, as highlighted by the review of surface flooding by the Department for Environment, Food and Rural Affairs [5]. This issue is particularly evident in the existing urban landscape, where examples of sustainable flood management opportunities are limited due to restricted available space [28,59,62].

4. Creating a Sustainable Approach to Flood Management: The Intersect between SuDS & NFM

4.1. Policy

While recent Governmental reviews have highlighted the need for a shift in current flood management policy to increase the focus on sustainable approaches, there is a continued reliance on the Flood and Water Management Act [5,63]. At present, there is little focus

on developing a regulatory framework in the UK that focuses on flooding at the catchment scale, and which acknowledges different inter-connected urban, rural and coastal sources. While there are significant policy drivers in the UK, including Defra's 25 Year Environment Plan [7], Defra's Flood and Coastal Erosion Risk Management 2020 Policy Statement [64] and the Environmental Land Management Scheme [65] for the management of agricultural runoff as part of the Sustainable Farming Incentive, this does not translate into policies. The devolved Governments in the UK have developed their legislation and standards for SuDS separately, with the Statutory Standards for SuDS in Wales [66] and Non-Statutory Standards for SuDS in England [45]. The need for SuDS to be implemented in Scotland is highlighted in the Flood Risk Management Act [67], while in Northern Ireland it is the Water & Sewerage Act [68]. Whilst standards are in place in England and Wales (either statutory in the case of Wales or non-statutory in England), there remains limited requirements to specifically implement the suggested measures as part of Schedule 3 of the Flood and Water Management Act. However, there is even less legal clarity for NFM adoption, ownership and maintenance responsibilities, with devolved guidance currently being developed across the UK, discussed further in Section 4.2. Both the Environment Act [69] and Agriculture Act [70] reference measures that fall under the wider banner of NFM, including the new Environmental Land Management Scheme (ELMS) that is replacing the Countryside Stewardship scheme that was part of the European Union's Common Agricultural Policy (CAP) in the UK. However, to date, the ELMS scheme does not recommend any mechanism, funding or specific sustainable water management techniques to be used under the scheme. Defra initiated pilots will be set up to review the mechanisms whereby farmers can be paid for 'services for public good', such as environmental or animal welfare improvements; this will be published in February 2024 [71].

Nonetheless, the Environment Agency's National Flood and Coastal Erosion Risk Management (FCERM) Strategy for England [64] heavily advocates the implementation of NFM measures, as does the corresponding FCERM Strategy for Wales [72]. Like SuDS, however, the approach to NFM differs between the devolved Governments. While there is a commonality between the approach by the Environment Agency and Natural Resource Wales, the Flood Risk Management (Scotland) Act [67] focuses on natural approaches to flood management, specifically detailing the Scottish Environment Protection Agency's (SEPA's) role "to assess possible contribution of alteration etc. of natural features and characteristics". In contrast, schemes implemented in estuarine and lower catchment settings are typically driven by the need to protect habitats as recognised in the European Habitats Directive (92/43/EEC) [73] with the additional benefit of flood defence.

Although SuDS and NFM aim to manage runoff at different scales and from different sources, they ultimately aim to achieve a similar goal of reducing runoff. As catchments are rarely solely urban or rural, there is a need to integrate a combined NFM and SuDS approach to managing combined rural and urban runoff. More commonly, there is a gradation from urban to rural, requiring a better appreciation of both combined challenges. Consequently, a comprehensive policy is required to achieve a more sustainable catchment-wide approach that incorporates rural and urban flood management [29,55,74,75]. While existing policy and guidance documentation focuses on similar approaches for NFM and SuDS, they typically remain disconnected when implemented. Nonetheless, while the development of the SuDS policy remains limited, it is further developed across the devolved UK governments than similar policy for NFM. However, there remains an issue of ongoing maintenance costs of SuDS techniques, with their effectiveness at managing the original design volume of water deteriorating over time due to several factors such as clogging and siltation [59,76].

The adoption and long-term maintenance responsibility for NFM is even less considered than for SuDS [58,77–79]. Most NFM schemes are primarily funded by "capital pilot grants", investing in the installation of measures, with an expectation that these measures would require "little to no-maintenance" [78]. Exceptions to this arrangement include those methods currently maintained under Pillar II of the European Union's Common

Agricultural Policy (CAP) for “environmental betterment”. This exception includes the capital payment and maintenance funding for the “installation and preservation of natural measures that can provide multiple benefits”, administered under the Countryside Stewardship Scheme (CSS). At the time of writing, plans are in place for the Environment Act [80] and Agriculture Act [69] to improve Pillar II payment mechanisms for NBS via the Environmental Land Management Scheme (ELMS). Further details are to be confirmed on reflection of initial pilot schemes prior to the full rollout in late 2024. Therefore, current ownership and maintenance responsibilities for most NFM measures fall to the good will of farmers or landowners unless alternative arrangements were agreed with the funding authority [78]. Creating a combined policy that covers both approaches under a unified title will help enforce the role of rural methods and further advance the challenges with techniques that could potentially integrate with the traditional sewer network.

4.2. Practice & Challenges

A lack of robust, interconnected policy is, however, only part of the challenge, as there are practical barriers currently inhibiting the wider integration of a sustainable, coherent catchment-wide approach to flood management in the UK. While software such as SCIMAP has developed a method to map sources of pollution across a catchment [81] with ongoing development to apply the method to understand areas of flood risk through SCIMAP-FLOOD [82], the practical implementation of managing rural and urban runoff typically remains separated. Urban flooding is often managed at source, with a few successful examples of a joined-up SuDS Management Train approach, whereby SuDS are connected at a site to provide aggregated benefits for reducing runoff and pollutant loads [32]. Those schemes that have been developed, such as Lamb Drove, Cambridgeshire and Hamilton, Leicestershire, will typically use a large retention pond or wetland area to retain water that will be slowly released to a nearby watercourse [33]. Furthermore, the Non-Statutory Standards for SuDS state that water should be discharged from a SuDS system to a nearby watercourse at rates equivalent to greenfield runoff [45]. While this attempts to manage the total outflow of water into neighbouring watercourses, it is imperative that flow across the whole catchment is considered to ensure that peak flows are not synchronised, exacerbating flood risk [18,73]. Nonetheless, the SuDS Management Train approach demonstrates the benefits and opportunities for flood management provided by small, site scale measures that, if applied appropriately across a catchment, can assist with wider catchment flood management [32].

Developing an approach that models the likely outflow across a catchment from rural and urban flood management techniques is extremely complex. NFM methods are typically modelled in the UK using catchment scale models, such as Flood Modeller, INFOWORKS-ICM or TUFLOW, with a key consideration being to ensure that peak runoff is not synchronised through the installation of flood management methods across a catchment [83,84]. Such models require high processing powers and therefore have a limited resolution, tending to focus on measures that slow down runoff from rural areas into a watercourse.

A hydraulic model, such as MicroDrainage©, is more often used for understanding urban flow, requiring high-resolution data to model pipe and overland flow, and consequently requires high processing powers [32]. XP Solutions, for example, have developed MicroDrainage© with the primary purpose of understanding drainage design, integrating equations that solve flow in a SuDS system, particularly source control devices such as permeable paving and green roofs. Creating a coupled model that simulates outflow from urban areas, integrating SuDS into a wider catchment model that accounts for river flow and NFM measures is necessary to improve the understanding of the linkages between both networks to develop an all-encompassing “sustainable catchment-wide flood management plan”. However, applying such equations concurrently at both the fine resolution in an urban environment and wider catchment scale will increase model run-time and, therefore, the usability of an integrated model. It is therefore suggested that multiscale model guide-

lines be developed that simultaneously simulates the fine spatial requirements of urban environments and considers often larger scale rural environments. Such amendments to modelling methodologies would enable cross rural and urban fringe communication of flood impacts and catchment flood management performance at the entirety of the catchment scale. Furthermore, due to the time pressure and resources of staff, particularly those in local authorities that manage local flood risk, developing such an approach for all catchments is unlikely [85]. There also remains a need for high-resolution Digital Elevation Model (DEM) data to ensure that models can run as accurately as possible across a whole catchment [86]. Since early 2022, England and Wales currently have Light Detection and Ranging (LiDAR) coverage at 1 m resolution, with incomplete coverage at <1 m resolution in some catchments [87]. Nonetheless, a finer resolution DEM would further aid the development of accurate catchment scale models, ensuring that they were able to identify flow pathways. This resolution is particularly important in urban environments to identify highly localised pathways, often undertaken using either ground-based LiDAR or a UAV (Uncrewed Aerial Vehicle) with a camera attachment and photogrammetric processing [88,89].

As highlighted in Section 4.1, the ongoing cost and maintenance of such flood management schemes are relatively poorly understood, with cost often cited as the primary barrier to catchment scale flood projects being constructed [78]. Developing a model that is capable of identifying the cost-benefit of different catchment scale projects, but also identifying opportunities and priority locations for flood management, would further engage stakeholders, such as local authorities, flood risk engineers and government agencies, with such methods. SCIMAP-Flood, for example, is able to recommend sites to target in the rural environment; however, it requires more information on urban flow pathways to incorporate urban flood mitigation methods [82].

4.3. Sustainable Catchment-Wide Flood Management

As is presented in Sections 4.1 and 4.2, there remains a series of challenges regarding the successful integration of SuDS and NFM at the wider catchment scale. This considerable level of divergence is evident in the performance literature of the two when examining their ability to reduce flood damages as well as other multiple benefits. For example, Burgess-Gamble et al. [9] provides a comprehensive review of NFM measures performance in the WwNP evidence directory, as does the SuDS Manual [33] using SuDS case-studies. While performance is well discussed in both, the possible aggregation of gains at the catchment scale of combining the two across rural and urban land uses, similar to the management train approach, is not [32]. Furthermore, developing policy and practice that appreciates the differences between urban and rural runoff requires a common dialogue to link both approaches. This approach will help remove the “siloeing” that typically occurs through NFM or SuDS. Guidance has traditionally referred to each approach as entirely separate elements of flood management, with funding in England typically offered for rural projects (with a focus on NFM) or urban projects (focusing on SuDS) separately [90,91]. The use of the word “nature” or “natural” in several terminologies referring to NFM can cause further confusion, as anthropogenic alterations to a basin can rarely be considered “natural”. This confusion has coincided with the more recent movement to “Nature Based Solutions” or “Blue-Green Infrastructure”, which provides a link between both NFM and SuDS [76,92,93]. However, such terms can neglect key NFM and SuDS techniques that traditionally fall into each category; for example, permeable paving or filter drains in terms of SuDS and leaky barriers for NFM. For this reason, a return to the previously used terminology of “sustainable catchment-wide flood management” is recommended that allows strategies to be considered that encompass both rural and urban extents of a catchment from source to sea. The literature has demonstrated the effectiveness of NFM and SuDS to separately deal with runoff [29,51,94]. However, given the challenges surrounding climate change and an urbanising landscape, not just in the UK but internationally, consideration of resilience with regards to flood management is imperative [95,96]. As identified by Fenner et al. [97],

such approaches can ensure flood resilience, by providing environmental, societal and economic benefits.

Consideration is nonetheless required as to what “sustainable catchment-wide flood management” would look like if it were successfully implemented. Figure 1 is a matrix that combines NFM and SuDS measures in relation to the scale for which they intercept and manage runoff (source to regional) and spatial application (diffuse to concentrated), to provide the basis for which techniques can be implemented as part of “sustainable catchment-wide flood management”. The classification of measures in relation to their location and extent highlights potential governance issues related to implementation. Diffuse measures may require greater cooperation between landowners and coordinated deployment across a catchment. Furthermore, the modelling and monitoring of such projects across different hydrological scales is required to account for the linkages needed between urban and rural fringe flood management areas.

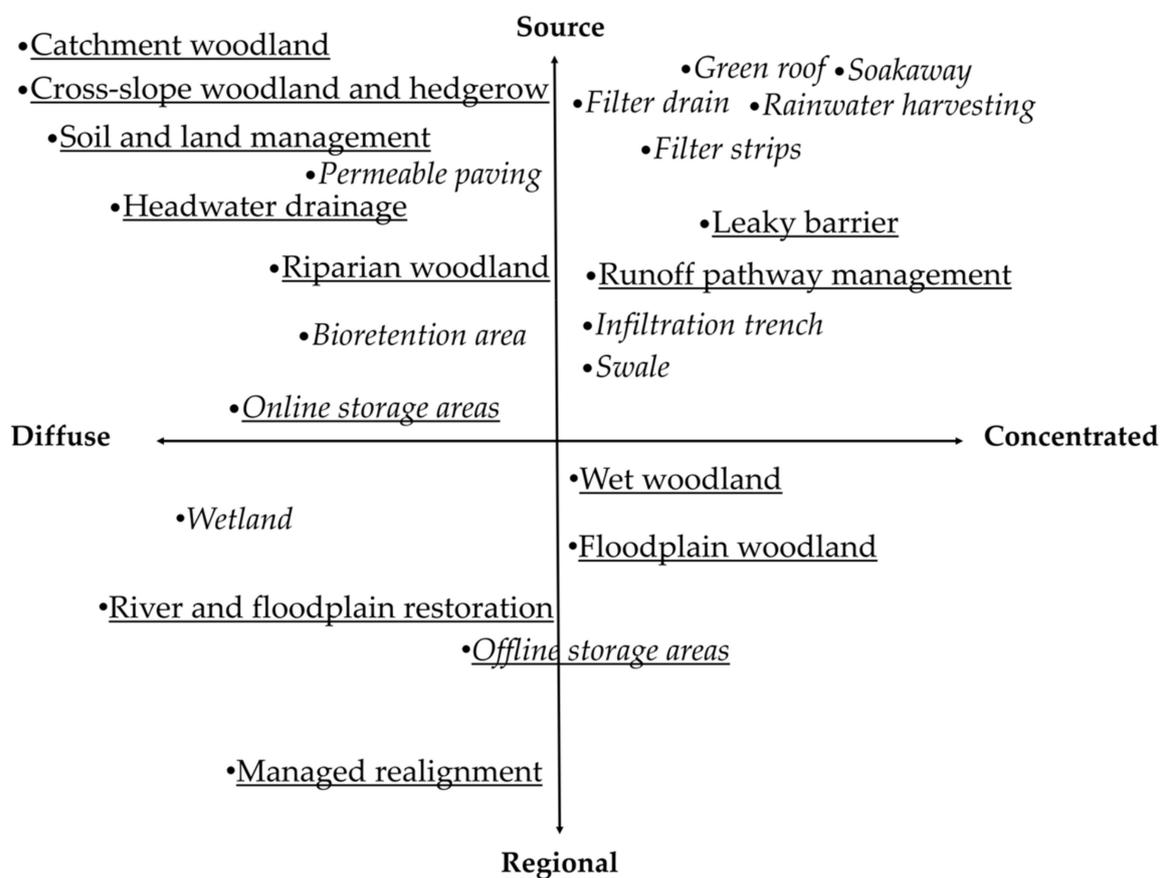


Figure 1. Outline of NFM and SuDS techniques from source to regional scale, which typically manage flood flows at a diffuse or concentrated scale. The dot denotes the position on the scale. Underlined techniques are considered NFM. Italicised techniques are considered SuDS. Techniques that are underlined and italicised are considered as both NFM and SuDS.

5. Summary and Key Recommendations

As is demonstrated in Section 2.1, there is a range of different terminologies used both in the UK and internationally regarding catchment flood management techniques, the majority of which are focused on rural management and alleviating river flows. This review has provided clarity on the range of definitions and aligned the approaches with urban drainage runoff management, specifically SuDS. With a changing climate that will likely result in an increased number of UK flood events and an increasing urban landscape, coordinated thinking is needed to ensure that future catchments are more flood

resilient, accounting for rural and urban challenges in a combined approach. Consequently, the review suggests a series of recommendations to ensure a more holistic approach to flood management:

1. More emphasis on flood management at different scales, unified using the phrase “sustainable catchment-wide flood management”. This phrase removes the focus solely being on NFM (rural) or SuDS (urban), but more importantly, how they can work together across hydrological scales to manage flows by aggregating the benefits regarding flood management and encouraging more integrated catchment wide approaches. Figure 1 outlines the techniques that should be used as part of such a strategy, acknowledging both rural and urban environments and ensuring peaks are not synchronised (further explored in recommendation 4).
2. Development of a robust policy and regulatory framework that defines and considers the sustainable management of water resources and ameliorating flows across the whole catchment. Embedding the term “sustainable catchment-wide flood management” will support the creation of robust policy and ensure wider adoption, removing the existing vagaries and lack of focus that currently exists in UK flood policy. It is suggested that policy shifts focus from existing management of risk via administrative boundaries and types of flooding, and instead developing a management plan at the catchment scale. This will provide additional support and guidance to stakeholders involved in flood management, such as local authorities, utility companies land owners, developers and flood risk engineers.
3. Developing an understanding of the medium- to long-term maintenance costs of different methods and ensuring that all techniques are adopted by the appropriate individuals or institutions.
4. The development of modelling software capabilities and guidelines that integrates both the urban and rural settings in the required detail, allowing for the possibility of multiscale models, which represents the broader scale in rural areas and finer resolution in urban environments. Such models would also need to support flood management approaches at different scales, as highlighted in Figure 1. To support these models, catchment-wide monitoring and higher resolution elevation data products are necessary to provide the data needed to identify opportunities and measure success. This includes recognising the need for models to represent upland environments that are often data poor first order stream networks, at the source of catchment scale flood flow propagation. The ability of computational models to simulate the effects of features performance to variable antecedent conditions (e.g., variable levels of saturation, changing condition of NFM features) and storm events (e.g., double-peaked storms) driven by long-term observed data networks could also reduce uncertainty and improve model confidence. The nature of such models would be computationally demanding, however the visualisation and summary of result outputs is critical to ensure the wide usage of such a model. This would also support stakeholders when considering the impact of techniques beyond the immediate area of the scheme, and includes the wider catchment.

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