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Practitioner Perspectives of Flood Source Area (FSA) Analysis for System-Based Flood Risk Management

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ABSTRACT

Urban Flood Risk Management (FRM) is a critical aspect of developing resilient environments for future generations to inhabit. It is now interconnected with the requirement to be more environmentally conscious through blue-green infrastructure and the delivery of wider co-benefits. The complexity of balancing urban growth with environmental drivers and increasing resilience is a key challenge for strategic urban decision-making. Through computational modelling developments, new approaches to assess the spatial contribution of area to flood hazard are improving our understanding of the catchment response and our ability to develop multifunctional, multi-beneficial projects. Yet at present, these approaches remain largely theoretical or are a 'best intention'. This study uses an adapted 'Unit Flood Response' approach to generate Flood Source Area (FSA) maps for an urban catchment in the UK. A user-focused engagement approach is applied using FSA outputs to generate key insight into its applicability from a practitioner perspective. The FSA modelling identified several hazard sources, from widespread contributions upstream to discrete contributions downstream. Stakeholders concluded that the FSA can support FRM at the pre-planning stage by providing a clearer strategic vision across the catchment to support traditional 'receptor-led' decision-making. Improved identification and negotiation of project partners and the potential to support/identify wider scale options that integrate with existing and planned infrastructure in other sectors, for example, housing and transport, were additional benefits of this approach. While the computational aspects of FSA analyses could be improved for model robustness (e.g., calibration, validation), they must do so with a full understanding of the practicalities of applying these techniques on the ground, demonstrating the importance of co-development of research with practitioners and decision-makers.

1 | Introduction

Over 50% of the world's population lives in urban areas, and by 2050 expert projections suggest this figure could reach almost 70% (United Nations 2018). Urban environments are complex habitats that are formed of multiple systems supporting societies with interconnected infrastructure and the presence of more natural systems (green and blue space) in varying spatial patterns (Donati et al. 2022). The management of water is fundamental to these interdependent systems, as water influences urban climate, biodiversity, and amenity (Dawson et al. 2020). Excess water in urban spaces causes additional problems of flooding and associated economic, social, and environmental costs (Jenkins et al. 2018), leading to the generation of Flood Risk Management (FRM) practice as a key component of civil services. Urban FRM has shifted from a dominant 'hold the line'

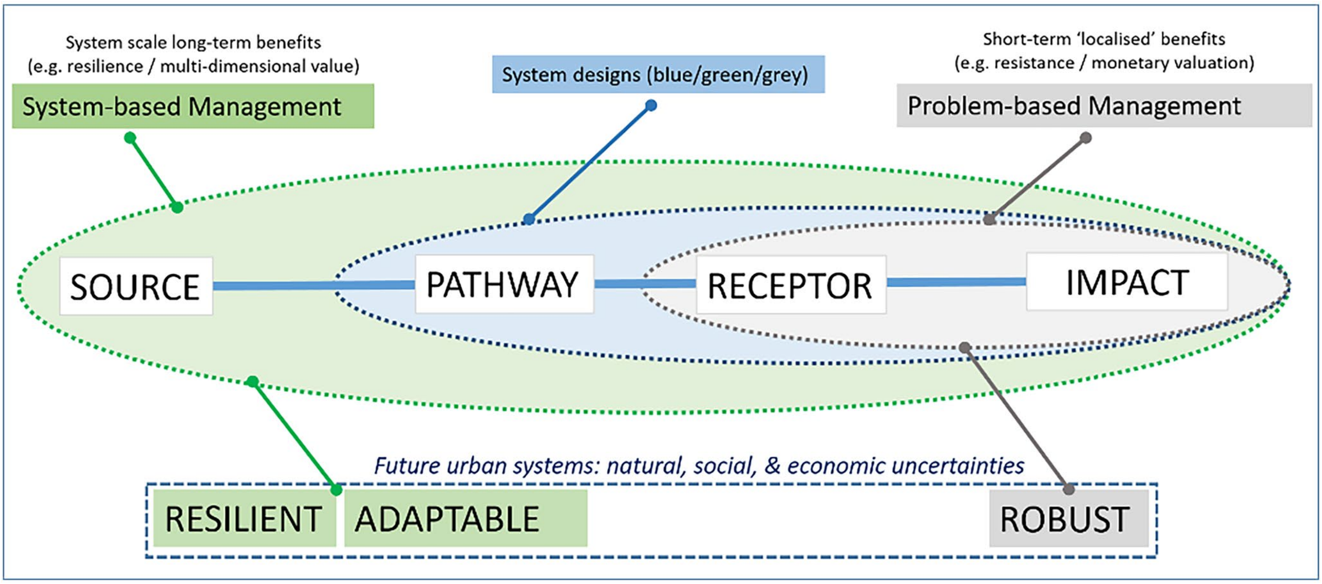

FIGURE 1 | Conceptual 'system' for urban Flood Risk Management (FRM) illustrating the need to consider the 'source' of flooding for system-based flood risk management. Based on the source-pathway-receptor-consequence (SPRC) model.

approach using hard engineering (e.g., flood walls, barriers, underground pipes, and tunnel networks; Chen et al. 2021) to more flexible, environmentally considerate approaches using blue and green infrastructure (O'Donnell and Thorne 2020), often in combination with grey (Alves et al. 2019). This paradigm shift has led to a wider 'system-based' understanding of the problem, solutions, and benefits of implementation (Zevenbergen et al. 2020), which is reflected in environmental policies across the world (e.g., United Kingdom, Netherlands, United States, Japan, China, Australia). The shift is a practical challenge in urban areas where competition for space is a premium, and flood management is competing with other 'systems' of value such as mobility, living spaces, and economic growth. A key barrier to a more 'systemic' approach to FRM, however, is that current practice is driven by hydrodynamic and hydrological modelling that provides the hazard element 'system', for example, the receptor (or flood impact through which damages can be evaluated), and thus ignores the risk or opportunities of examining the source of the flood hazard and the flow paths across the wider system or area (see Figure 1). Problem-based FRM led by the use of hazard maps that provide the receptor impacts, that is, using hydrodynamic or hydrological models, is suited to generations of FRM schemes that focus on reducing specific risk receptors (e.g., critical buildings and infrastructure) with interventions (green, blue, or grey) that can be assessed. Economic funding models used to evaluate economic receptor risk reduction schemes also support this narrow focus (see Pregnolato and Dawson 2018). In order to promote a paradigm shift in urban FRM with more system-based management or management train techniques (e.g., Nature-based Solutions (NbS), Sustainable Drainage System (SuDS)), urban planners may benefit from understanding the wider water system (from source to impact) linked to single or multiple flood hazards across an area or catchment.

Recent urban adaptation studies (e.g., Vercruysse, Dawson, and Wright 2019; Dawson et al. 2020) have rediscovered and adapted an existing hydrological approach known as Unit Flood Response (UFR). UFR was first introduced by Saghafian and Khosroshahi (2005) and identifies the source of the flooding, or Flood Source Area (FSA), across the watershed (Singh et al. 2021). The study of FSA is beneficial as it can highlight the spatial disconnect between flood source and flood hazard (receptor) and, theoretically, support the identification and strategic prioritisation of flood mitigation measures over broader spatial scales (Vercruysse, Dawson, Glenis, et al. 2019; Qi et al. 2022). This is based on its ability to provide indicator-based GIS representation of existing land use data that inform hazard indicators such as depth and area flooded and buildings, roads, or green space flooded (Vercruysse, Dawson, Glenis, et al. 2019). It is also suggested to have the potential to identify interoperability between infrastructure systems (Vercruysse, Dawson, and Wright 2019) and could highlight roles and responsibilities of different stakeholder groups in both managing flood risk at source and mitigating flood hazards further downstream.

Producing hydrological data that maps water flows from source to hazard supports the widely acknowledged benefits of management trains within sustainable drainage systems; however, they are challenging to put into practice (Ferrans et al. 2023). In a recent review of FSA approaches (Singh et al. 2021), a clear commonality among studies is the recommendation of this approach to policymakers and urban planners; however, there remains limited evidence of how FSA can realistically be integrated into FRM practice. This research paper investigates the FSA methodological approach in collaboration with FRM practitioners to gather expert insights on the utility of the FSA concept in existing UK regional flood scheme development. The findings are also analysed within the context of existing national policy frameworks. Specifically, this study applies the FSA methodological approach to an urban catchment in Leeds, United Kingdom (UK) (section two). The FSA output maps are utilised to evaluate the location of FRM strategies in the area (section three). In Section 4, Practitioner perspectives on the methodology are collected through a series of workshops involving key stakeholders (< 10 representatives; section four). The study results are subsequently discussed and concluded (Section 5). The following section introduces the case study site and background information.

1.1 | Case Background

Wyke Beck Catchment in the city of Leeds, UK, where a flood scheme was completed in 2020, was selected for study (Figure 2a). Wyke Beck is a predominantly urban catchment originating at Waterloo Lake in Roundhay Park in the north of Leeds and has a long history of flooding and drainage issues (Leeds City Council 2021). Flood alleviation has been implemented along its course to the confluence with the River Aire in the southeast of the city, and involved several sites situated in three of the five Local Nature Reserves (LNRs), namely:

1. Arthur's Rein LNR—removing a culvert and re-profiling the channel
2. Killingbeck LNR—naturalised flood storage
3. Halton Moor LNR—naturalised flood management

The catchment-wide programme of work was led by the local authority using a standard problem-based approach, utilising hydrological modelling to identify hazard areas and evaluating the monetary effectiveness of each option using cost benefit analysis (CBA) based on receptor risk reduction (for further details of funding in UK flood schemes see DEFRA, (2020)). A unique aspect of this programme was the collaborative, or partnership, funding (costing a total of £4.75 M), following previous unsuccessful and more 'traditional' attempts to leverage central government funding (Green 2018). The partnership evolved with local housing developers in response to opportunities to take advantage of Section 106 developer contributions, also known as 'planning gain' (HM Government 2022). Developers (in this case, housing) are legally bound to contribute to a Community Infrastructure Levy (CIL) to off-set the additional burden of surface water drainage and mitigate the increased flood risk (HM Government 2022). In this instance, a business case was put to the local authority for the developers' Section 106 contributions to co-fund the green infrastructure scheme, which would also provide additional capacity for surface water drainage. Over several years, the project grew into a multi-benefit strategy involving environmental and green space improvements, as well as managing flood risk. The payments made by developers were equal to or less than costs associated with installing the required attenuation tanks on the development sites. As a result, both partners benefited from the collaboration, and the case met the criteria for UK Government support. The expert practitioners involved suggested Wyke Beck for FSA study due to the developments that had occurred already and the potential to learn more from the approach retrospectively.

2 | Methodological Approach

2.1 | Flood Source Area Analysis

The FSA methodology (Vercruysse, Dawson, and Wright 2019) was applied to the Wyke Beck catchment, firstly by creating a $1 \times 1\,\text{km}^2$ (of equal size) grid over the area (1–37—Figure 2A). The FSA approach, in brief, sequentially removes the modelled rainfall in each grid (re-running the rainfall model described below) to identify the grid contribution to flooding across the remaining grids. The hazard mapping of both pluvial and fluvial risk is based on a rain on grid two-dimensional LISFLOOD model with modifications to the domain to account for channel conveyance. Outputs consist of flood area (m^2) and flood depth (mm), and can be combined to present a representation of maximum flood hazard (area $\times$ depth). Rainfall was determined from Flood Estimation Handbook (FEH) catchment characteristics, and the flood profile (event) is based on a 1-in-100 years summer storm with a 10-h duration (1% probability). Drainage and flood loss assumptions calculated by the FEH process are also applied, leaving a net rain amount that is used in the model as the input rainfall. The model is calibrated using the Revitalised Flood Handbook 2 (ReFH2) estimation of flow at the catchment outlet, and FEH catchment characteristics. The model and its outputs (see Figure 2B, Figure 3) clearly illustrate the FSA methodology and indicate potential future flows. The pluvial component was visually compared with the Environment Agency Surface Water Maps (EASWM); overlap was observed between the two sources. As this paper aims to gain insight into the practitioner's response to the FSA method, the pluvial flood risk used as visual outputs during the expert workshops comprised all surface water exceeding 1 mm across the catchment. This contrasts with the UK's Environment Agency approach that presents surface water risk above 50 mm. The assumption is that with comparison of both the ReFH2 and the EASWM maps, it is adequate for the purpose of the study.

2.2 | Understanding FSA Useability Through Expert Elicitation

Following the generation of FSA maps and associated data (presented in Section 3), the outputs were utilised to evaluate the efficacy of the FSA methodology with flood risk managers in the local authority (also including Government FRM policy officers). The study involved two workshops (< 5 people), and presentations at pre-scheduled meetings organised by the research team or stakeholder participants. A third workshop (16 people), held at the West Yorkshire Flood Innovation Programme (WYFLIP) Annual General Meeting, explored expected versus modelled flood hazards through participatory GIS, consulting flood risk experts across public, private and third sector organisations on the potential for an FSA methodology. At all workshops, discussions and notes were recorded and returned to the representatives for additional reflections and written feedback. Structured discussions were centred on the following key areas: evaluation of the FSA outputs, assessment of the advantages and disadvantages relative to existing hazard mapping and scheme generation, and specific reflections on how the FSA methodology could have supported previous schemes with broader systemic benefits or facilitated the identification of new schemes. Similar to other studies (Fothergill et al. 2021), this study adopted an interpretivist constructionist position, and inductive thematic analysis was used to analyse the workshop notes to first synthesise practitioner-focused feedback on FSA in FRM and, second, to generate general principles for the use of FSA in FRM. Finally, the stakeholder feedback and general principles developed were cross-referenced with national flood risk policy and guidance to

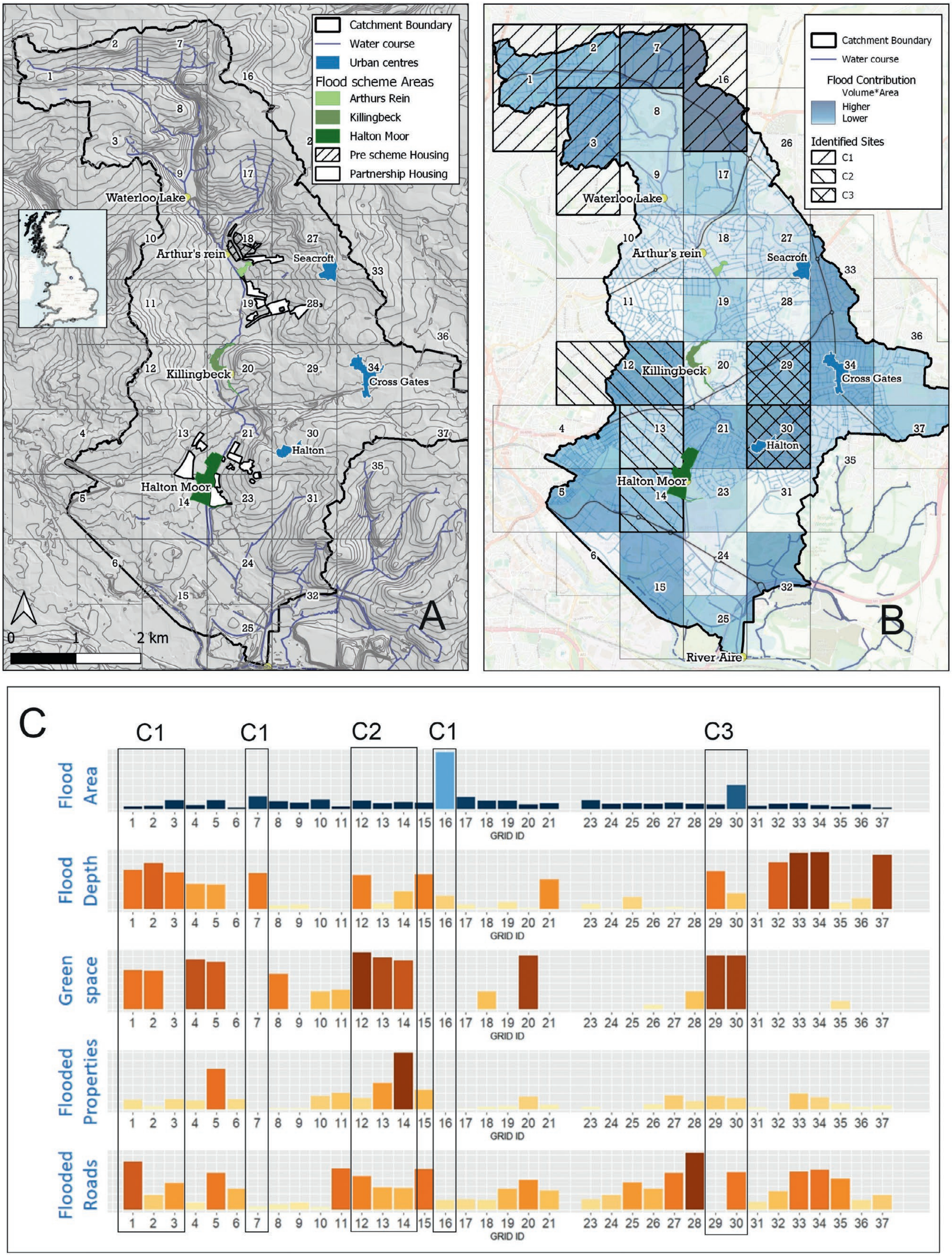

FIGURE 2 | Legend on next page.

FIGURE 2 | A–C: (A) Wyke Beck catchment grid ID for unit flood analysis. The existing flood scheme improvements & partnership locations (housing) are also highlighted. (B) Flood source analysis illustrating maximum hazard (volume × area) contributions in the catchment (darker shade = more contribution to flood hazard) C1-3 indicate selected sites for interventions (See Figure 3) (C) Data analysis per catchment ID: Units are based on area (m^2) covered by hazard flows (e.g., green space flooded, & roads flooded), flood depth represents grid contribution to flood area above 200 mm, flooded properties is based on number of buildings covered by modelled flows.

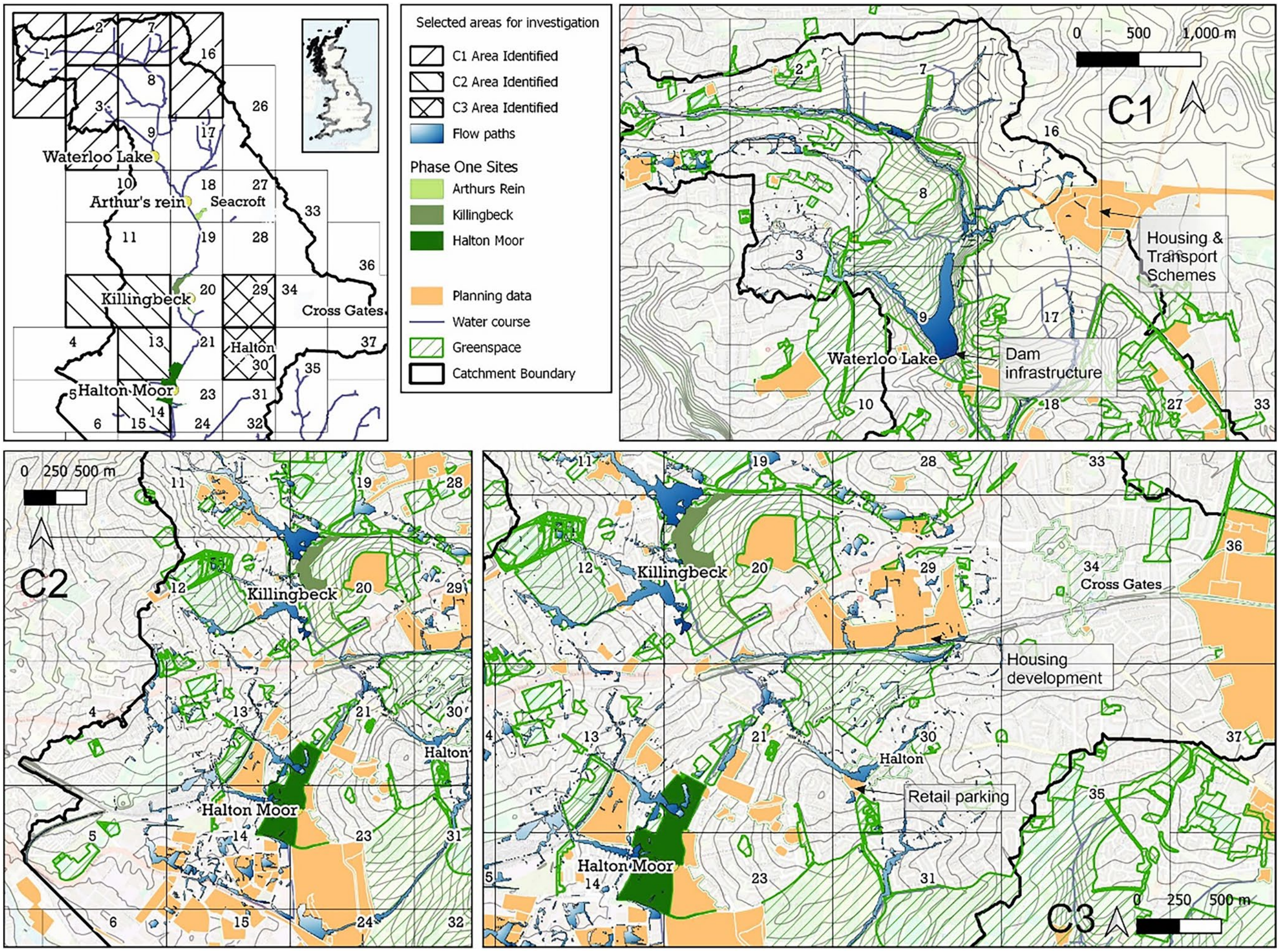

FIGURE 3 | Future FRM sites, selected flow paths, green space and planning data: Upper catchment (C1). Future proofing Roundhay/Waterloo Lake Dam Infrastructure. Flood contribution flows show contributions from grids 1–3, 7 and 16. Mid catchment (C2) East End Park, additional storage using green space. Flow contributions from grids 11 to 14. Lower catchment (C3). Halton Town Centre (grid 30 and 29) has the highest contribution to flooding (depth & area). See Section 3.2 for further descriptions.

provide national context for the approach. The outcomes of this process are presented in Section 4.

3 | Results & Findings

3.1 | FSA Analysis and Scheme Identification

Figure 2B presents a typical FSA map, where flood source, in this case maximum hazard, is calculated using area × volume examined. Areas that have a high contribution to flood hazard can be seen in the upper catchment (grids 16, 7, 3, 2, 1), where green space is more prominent, and in the lower catchment (e.g., grid 30), where urban areas are present. Figure 2C provides data outputs for each grid, indicating the relative contribution of each grid to catchment flooding. This is subdivided to present the two hazard indicators: flood area and flood depth, and the receptor indicators: Green space, Properties, and Roads. For users of this data, it allows observations such as grid 33 causes the deepest flooding, impacting little/no green space, and contributes to smaller amounts of flooding of roads and buildings. Units for each metric were not included in the figure presented during workshops, as the relative contribution of the grids (and identification of scheme areas) was the focus of discussion.

In respect to the three Wyke Beck LNR scheme sites (see Figure 2A), the analysis highlights the Halton Moor LNR (Grids 14, 21) as being located within an area of catchment that contributes to deep flooding (but not the highest). Proximal grids north of the site (grids 12, 13, Figure 2C) show a further contribution to the flooding of green space, and the flooding of the road network and properties (grid 14). The Killingbeck site (north of Halton Moor, grid 20) is ranked similarly high for contribution to the flooding of green space, and the analysis suggests some contribution to the flooding of roads and buildings. From a strategic level analysis, this provides some justifications for the sites that were chosen for green infrastructure development as they are in a location to retain a larger quantity of flood hazard water than other locations. They do not provide a clear correlation, however. More detailed stakeholder reflections on the interventions at Halton Moor and Killingbeck LNRs are presented in section four.

3.2 | Evaluating Sites for Future FRM Intervention

Figure 2B,C were used at the workshops to explore how practitioners could use FSA for future scheme identification and identify potential additional partnership opportunities (similar to those funded previously). FSA maps were reviewed along with complementary data on planned infrastructure developments in the city. From this, three opportunities were identified during the workshops (Figure 2, sites C1–3). More detailed mapping (including visual flow paths) is presented in Figure 3. The additional schemes identified comprised of:

- C1: Climate proofing lake/dam infrastructure in the upper catchment (Roundhay) (Figure 3) and investigating partnerships with the planned transport and housing developments taking place within proximity of the area (Grid 16, 26).
- C2: Surface water retention schemes in East End Park (Figure 3) to maximise the flooding of green space in the catchment and reduce flooding of transport networks (Grids 12–14). Numerous development/planning sites (e.g., in Grid 14) exist that could be investigated to determine how they could receive benefits from FRM interventions or support partnerships in managing surface water in this area (through, for example, increasing storage).
- C3: Halton Town Centre Surface Water Scheme (Figure 3). According to the FSA analysis, this densely urbanised area contributes significantly to flooding in the catchment (Grid 30) and presents an opportunity to adapt the built environment to reduce surface water input into the drainage system. For example, planning is in place for a retail and car park extension (Grid 29), thus making the car park permeable or increasing the storage of the car park would be an optional improvement (see Figure 3). Similarly, in residential areas with high FSA contributions, increasing public participation in home water storage activities (e.g., water butts) could reduce stress on the drainage network. Any potential changes in public behaviour would need to be accompanied by engagement and knowledge exchange activities to promote uptake.

3.3 | Stakeholder Perceptions

3.3.1 | Strategic and Operational Use of FSA Analysis

Following the workshops, feedback was collected and reviewed via thematic analysis, which identified themes and both positive and negative comments on the FSA methodology. Two key themes emerged: (1) FSA methodology use in strategic optioneering (option identification and pre-planning discussions), and (2) potential operational use to support actual scheme assessment (e.g., evidence generation). Reflections from the stakeholder workshops are provided in Table 1. The most prominent comment (from all stakeholders) was related to theme one; using FSA was from a strategic FRM perspective. This indicated that practitioners agreed the FSA methodology could support 'high-level' investigation of pre-study schemes and help with earlier identification of potential strategic options for partnerships on collaborative funding. This was first outlined when considering how FSA could have helped the recently completed Wyke Beck scheme (e.g., Figure 2A), as it could have helped negotiate drainage access with housing developers near the site. This was described as a result of 'chance' rather than as a result of the intended analytical approach. The workshops also identified that an additional housing scheme was in the 'build phase' when Arthur's Rein LNR site was under planning (see Figure 2A pre-scheme housing, Grid 18). An opportunity was therefore missed for additional collaborative funding to support the potential success of the scheme. From existing funding contributions, this could have ranged from £17,000 to £430,000 (Green 2018). Considering the second theme, operational use of FSA maps for evidence (or impact) generation, it is possible to indicate, relatively, which areas would create the most benefit to reduced receptor risk (e.g., buildings and transport), but the analysis is not at a level which could be used directly in a scheme assessment (without additional analysis and investigation). Finally, it was not possible to quantify the retrospective benefits of using the FSA maps in the initial Wyke Beck scheme, although 'time saved' in the identification of areas of interest seeking partnership funding and the provision of evidence to support the negotiation of planning obligations with housing developers (e.g., HM Government 2021) were frequently cited as clear benefits. Further specific points noted during the workshop discussions were that the practitioners felt the FSA approach supports:

- Earlier identification of opportunities for collaborative working (partnership approaches, infrastructure interactions etc.) at the catchment scale;
- Collection of 'strategic' evidence and narratives for partnership approaches;
- Identification of complimentary interventions when scheme locations are already decided, and;
- The identification of further areas that might influence flooding around the existing flood schemes, again, to help support evidence for wider benefits, and a more strategic approach at a catchment scale.

The negative comments on the FSA approach focused on theme two primarily, and the operational use of FSA in option appraisals and scheme evaluation (CBAs). The operational members of the workshop (e.g., FRM principal engineers) were interested in the technical validity of the inputs (hydrological model) of the hazard source (Figure 2B) and flow maps (e.g., Figures 3), and if any validation and calibration could be presented. FSA is a post-processing technique that utilises standard hazard modelling and existing flood models; therefore, it inherits all the model uncertainty of standard approaches. In addition, those

TABLE 1 | Summary of practitioner reflections during development workshops.

Workshop question	Selected practitioner responses
What are your impressions of the FSA outputs	'It is extremely useful to have a graphical representation of the sources of flooding in a map based system it would give us more confidence where the interventions should be' 'The statistical summary is really useful, can be used to bespoke evidence to metrics of specific funding criteria ... steering us towards where collaborative funding could be harnessed'
How does FSA compare with traditional approaches?	'but FSA looks at it in a slightly different way, especially when including other forms of funding – partnerships from S106 and council capital funds' 'storage is often thought of but could be used more in the future, and this helps identify potential areas to investigate'
What could have been done differently in Wyke Beck using FSA?	'We could have identified all developments that could have contributed to our scheme... [providing more] justification for section 106 negotiation cost with the developer – or costs they could avoid if they donot have to design SU–s – so they can design more houses.' 'This approach could have reduced the need for serendipity and saved time in negotiations'
How do you think FSA will help FRM in Leeds?	'[The approach] allows us to move beyond receptor risk and prioritise the catchment grid by grid and then seek contributions to funding' '[FSA] can be used as a catchment prioritization tool, allowing for pre-business case optioneering before requesting specific sites for full study' 'Providing a system perspective for city-wide strategic flood risk planning/policy, in the upcoming Strategic Flood Risk Assessments'

associated with theoretically switching of rainfall in individual grids, therefore assuming uniform rainfall across the grid. Feedback from the workshops implied that some level of trust must be gained in the data before any use of the analysis could be utilised. There is a need, therefore, to quantify and communicate the level of confidence (e.g., calibration and validation of flood source outputs) decision-makers can have in the information provided by the FSA.

Confidence the FSA method is especially relevant as the third workshop, in which participatory GIS was used to map user-identified flood hazard areas, compared with FSA-modelled and expert-expected hazard areas (Figure 3; compare to Figure 2B). Fluvial pathways and hazard areas were readily identified by stakeholders (Figure 4) and matched well to the modelled FSA (Figure 2B). In comparison, surface water pathways and hazard areas were less well identified. This likely reflects the highly heterogeneous nature of surface water, which is recognised as a challenge to predict and often occurs during smaller, more frequent events (not modelled in this study). Flood risk managers who attended the workshop noted that surface water flooding often occurs from overflowing or blocked drains, and therefore the source of the flooding is highly variable and/or unknown. The key function of the FSA approach is the modelled flow pathways, associating flood source and hazard areas; therefore, future research should investigate confidence in these flow pathways for surface water sources compared to fluvial source areas.

Interestingly, from an operational perspective, stakeholders did not clearly or explicitly identify how FSA could be used to support the evaluation of options or to add more evidence to enhance the justification of implementing past schemes. Although the quantification of scheme benefits could have been better explored in workshops with the understanding of the connection between the site and road and buildings flooded (e.g., Figure 2C). The operational use of the approach (in actual scheme development/bid generation) therefore remains unclear without additional complexity and resources to improve the output resolution (i.e., to a site scale). Finally, searching for additional collaborative funding using existing city planning data highlighted a more systemic issue in the local authority. Planning allocation data are not sufficiently collected and disseminated in a way to support early identification of partnership funding. For example, it is difficult to extract the stage of development (e.g., design, accepted, completed) without further analysis. This is something that hinders the FSA approach and goals at present and presents a challenge for wider FRM on multiple scales.

3.4 | Regional and National Policy Context

The final aspect of this study was to analyse the findings within the context of existing national policy frameworks. From the thematic analysis of workshop observations, three key principles for FRM emerged (see Table 2). First, Principle 1 refers to *embedding water risk in urban regeneration*. FSA analysis can be used to connect FRM with existing development plans, such as transport and housing, to ensure that water risk is considered more broadly across the catchment. This may include prioritising interventions, for example, by highlighting opportunities to manage water from source to receptor (as in C1–C3). The second principle, *sustainable and resilient growth through project co-development*, is supported by the potential to use FSA to identify

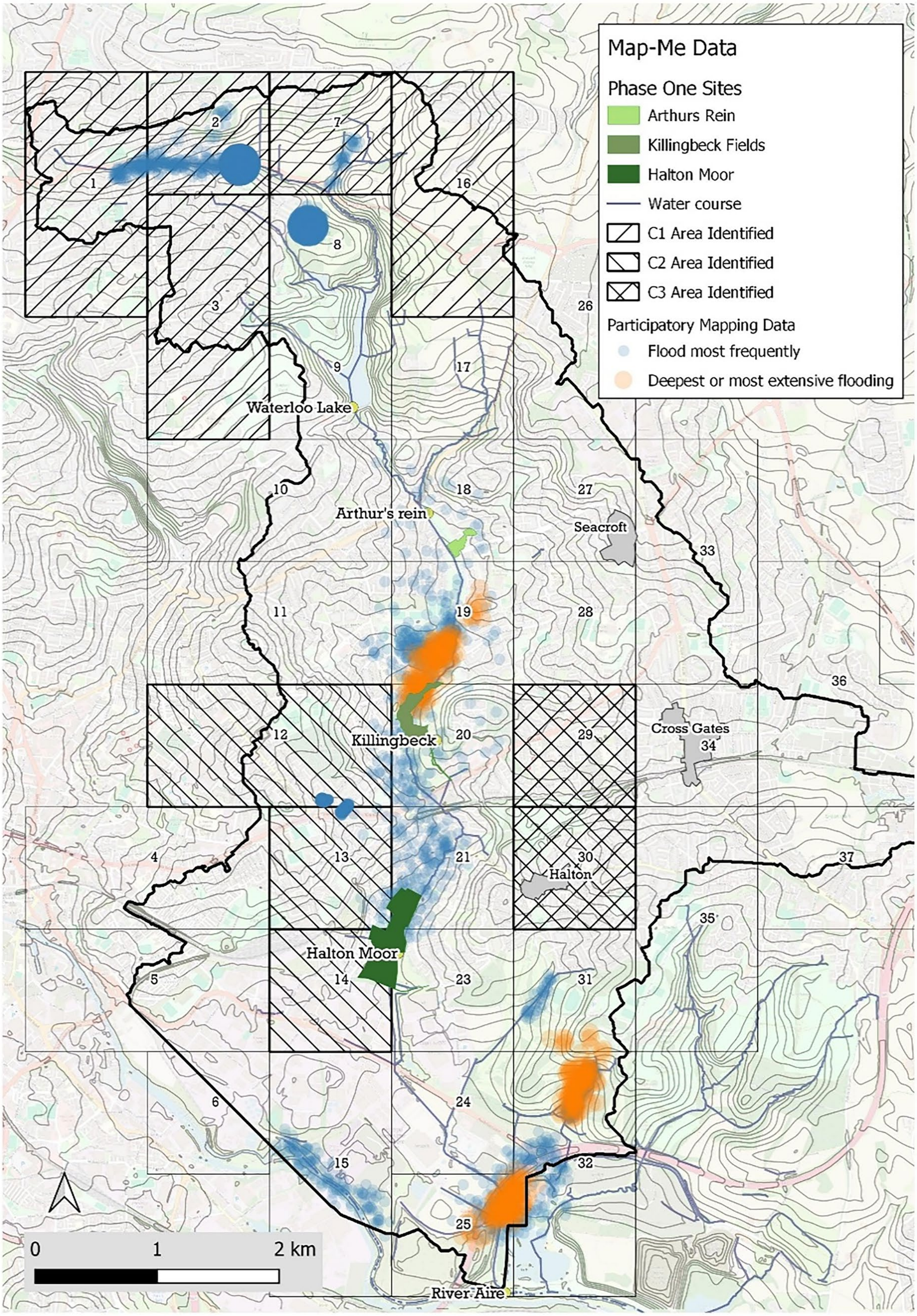

FIGURE 4 | Wyke Beck participatory GIS (spray can tool) output map from the WYFLIP AGM 2024. Workshop participants were asked to identify, based on their expert opinion, the locations that flood most frequently and the locations, which see the deepest/most extensive flooding.

TABLE 2 | Three key Flood Risk Management (FRM) principles supported by the Flood Source Area (FSA) approach and links with the UK's Environment Agency guidance on flood scheme funding published in 2020.

FRM principle	FSA support	Environment agency guidance (2020)
Embedding water risk in urban regeneration	Reviewing FSA maps with spatial development data to prioritise intervention and catchment scale strategic plans	**General guidance:** • Assisting the development of stakeholder engagement plans: For example, defining scope and business case opportunities • Providing a stronger narrative for the appraisal need, for example in the 'strategic report' or Strategic Outline Case of the Five Business Case Model (HM Treasury 2018: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/749086/Project_Business_Case_2018.pdf) **Improving management through:** • Clearer descriptions of the source of the opportunity for FRM schemes • The timeliness of the opportunity (through the connection of existing planning timelines and potential sources of co-funding)
Sustainable and resilient growth through project co-development	Earlier identification and engagement with partners/funding, and the development of shared objectives (outcome measures)	
Building city-wide strategic resilience portfolios	Evidence for improving strategic business cases from multiple sources of funding: identification of programmes and portfolios of schemes connected using FSA outputs as evidence	

partnerships earlier in the planning process, and the ability to identify shared objectives (in terms of costs and benefits). Finally, the third key principle refers to *building citywide strategic resilience portfolios*. Although this study only represented one case study area, several additional scheme options were identified that could be used to build a 'portfolio' of projects that, when combined, have a greater value/benefit than a single scheme. The novelty of the FSA evidence is that it can provide some of the background narrative for connecting a series of projects together to enhance the delivery of FRM and wider benefits in future business cases.

These principles were cross-referred with the latest UK guidance on flood scheme funding (Funding for Flood and Coastal Erosion Risk Management (FCERM), Defra 2023) to examine the connection of the FSA methodology to existing national policy. The FSA methodology can align with national policy and general FRM guidance on stakeholder engagement planning (identification and scope of partners) and providing a narrative via the connection of different systems (Principle 1). The narrative of the timeliness of the intervention opportunity can also be improved (e.g., partnership development timelines), so that opportunities to gain collaborative funding are not missed (as noted in this case study) (Principle 2). By extension, the FSA method could promote wider policy alignment, for example, by increasing regeneration that enhances biodiversity, that is, using green infrastructure (Principles 1 and 2); developing integrated infrastructure systems (Principles 1 and 3), and community enhancements (Principles 2 and 3). Finally, practitioners involved in this study recommended that the FSA be used practically when the local authority undertakes updates to the city-wide Strategic Flood Risk Assessments (SFRA). These are government-recommended plans and strategies required to make policies and decisions about the type and location of developments (HM Government 2022).

4 | Discussion

This study has applied a novel FSA methodology to an urban catchment and provided an expert 'user' perspective on its efficacy in urban FRM. The investigation has highlighted key benefits of the methodology for supporting a shift to more 'system'-based FRM. With the ability to visually and hydrologically connect physical systems (infrastructure, buildings, land use) and risk ownership (e.g., local authorities, Environment Agency, land owners) and 'risk action owners' where intervention (or protection) is needed, the FSA methodology can help link FRM with the identification of alternative funding streams and partnerships at a catchment scale. Wyke Beck's existing scheme illustrates that funding for FRM schemes can come from a range of contributors (in this case, housing developers) who may not traditionally be regarded as FRM funders but can be shown to benefit from FRM interventions. Further contributors to FRM schemes could be identified by innovations in sustainable, multi-functional FRM and blue-green infrastructure that demonstrate the delivery of co-benefits alongside water management (e.g., carbon storage, improvements to health and wellbeing, biodiversity enhancement, sustainable travel opportunities (Fenner 2017)). An updated UK Government formula for allocating funding to flood and coastal defences across England reinforces the trend of co-benefit FRM, where health and environmental benefits will be taken into account (DEFRA 2020). Furthermore, users can identify land for development (in this case, housing) that contributes less 'systemic' risk, as opposed to contributing more 'systemic' risk by developing in areas that have a high contribution. This is an area of clear socio-economic (and political) interest as most UK local/regional authorities will be required to balance the urban developments needed to address the housing demand crisis with the additional hydrological consequences of urbanisation under future climate changes.

There is no standardised approach to applying FSA; however, both at the technical modelling stage and the post-processing spatial output stage. For example, the resolution of the grid sizes in past studies has ranged from $2 \times 2\,\text{km}^2$ to $0.5 \times 0.5\,\text{km}^2$ (Saghafian and Khosroshahi 2005; Vercruysse, Dawson, and Wright 2019), and from a practical perspective, the model resolution and number of additional runs impact the computational run times (and cost of the analysis). From the use observation in this study, a $1^*1\,\text{km}^2$ grid size provides adequate analysis for predominantly strategic level planning support. Smaller grid sizes could support site-specific analysis within the catchment area and allow models to better represent urban features (including drainage assets) and land use changes. The FSA methodology allows for better alignment between strategic city level planning (top-down approach) and the selection of actual areas of intervention and optioneering (bottom-up approach). With the same method applied for both top-down and bottom-up approaches, it can realistically support system approaches to FRM. Even at the resolution in this study, it is possible to identify water pathways that are useful from a drainage or management train perspective, and for identifying critical infrastructure at risk from flood source flows. Nonetheless, it can only be used effectively if combined with more detailed terrain information (e.g., road heights, slopes, gradients).

Utilising the FSA methodology does not negate the need for standard approaches for assessing flood risk; however, the study highlights that the requirement of the hydrological assessment of optimal mitigation measures (with and without) is still a necessity. Other challenges facing the FSA methodology are from the technical perspective (see Singh et al. (2021) for a discussion of the hydrological challenges). The calibration and validation of the FSA approach are only considered at the model input stage, and this study has highlighted that consideration of this is also needed to support practitioner confidence. This will be particularly important when taking urban drainage infrastructure into consideration. Where modelling confidence can be quantified, the FSA approach may be used to further validate expert-recognised areas of contribution and hazard flow pathways. Similarly, the technical treatment of rainfall uniformity (or simulation), common in all hydrological studies, is still present, as in the need to consider climate change uplift factors and different levels of current and future risk, and also the use of drainage data in the initial modelling (Singh et al. 2021). The focus on developing funding schemes noted in the practitioner reflections suggests connecting FSA to existing decision-making systems (e.g., Cost Benefit Analysis (CBA)) for valuing systemic resilience measures may be a beneficial next step for practitioners (see Iliadis et al. 2024). Similarly, the ability to connect FSA outputs to alternative decision-making tools, such as adaptive pathways (Kapetas and Fenner 2020) and real-option analysis (e.g., Dawson et al. 2018), is possible. Without the continuous input from end-users, the impact of future technical advancements may be for scientific purposes only, rather than advancing the urban FRM paradigm shift in a practical direction to support system-based adaptation to climate change.

5 | Conclusions

System-based approaches to flood risk management are growing in both research and practice. Flood Source Area (FSA) methodology is an approach capable of examining the source of flood risk in relation to the hazard; therefore, it assesses the catchment system to explore wider interventions beyond the traditional 'receptor' focus. As a relatively new technique, limited information on the applicability of the approach from a practitioner perspective has been recorded; hence, this study is the first of its kind. This study has applied the FSA approach using a rain on grid model for an urban catchment in Leeds, UK. The outputs were presented and discussed at a series of small workshops with local flood risk managers, and reflections were gathered, summarised, and connected to existing FRM guidance using a thematic analysis. In summary, all participants were positive that FSA could support FRM; however, it was clear that FSA does not provide holistic support for the entire FRM process (e.g., from site scoping to site evaluation). Clear benefits of the FSA approach included provision of a clearer strategic vision across the catchment, improved identification and negotiation of project partners, and the potential to support/identify wider scale options that integrate with existing and planned infrastructure in other sectors, for example, housing and transport. Future work should investigate both technical and practical considerations relating to FSA applications; for example, accuracy of the inputs/outputs, inclusion of climate change uplift factors and drainage infrastructure, the standardisation of frameworks to integrate modelling and spatial data within the FSA approach, and connecting to existing decision-making frameworks (e.g., CBA, real-option analysis) and adaptive pathway approaches. In doing so, FSA has the potential to become a mainstream process for FRM planning and the delivery of sustainable and resilient cities.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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