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REVIEW ARTICLE

A review of modelling methodologies for flood source area (FSA) identification

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Abstract

Flooding is an important global hazard that causes an average annual loss of over 40 billion USD and affects a population of over 250 million globally. The complex process of flooding depends on spatial and temporal factors such as weather patterns, topography, and geomorphology. In urban environments where the landscape is ever-changing, spatial factors such as ground cover, green spaces, and drainage systems have a significant impact. Understanding source areas that have a major impact on flooding is, therefore, crucial for strategic flood risk management (FRM). Although flood source area (FSA) identification is not a new concept, its application is only recently being applied in flood modelling research. Continuous improvements in the technology and methodology related to flood models have enabled this research to move beyond traditional methods, such that, in recent years, modelling projects have looked beyond affected areas and recognised the need to address flooding at its source, to study its influence on overall flood risk. These modelling approaches are emerging in the field of FRM and propose innovative methodologies for flood risk mitigation and design implementation; however, they are relatively under-examined. In this paper, we present a review of the modelling approaches currently used to identify FSAs, i.e. unit flood response (UFR) and adaptation-driven approaches (ADA). We highlight their potential for use in adaptive decision making and outline the key challenges for the adoption of such approaches in FRM practises.

Keywords Flooding · Flood sources identification · Hydrological modelling · Unit flood response · Adaptation · Variable source areas · Flood source areas

1 Introduction

Flooding is characterised by the overflow of water onto dry land (Parker 2000), while this is part of the natural water cycle; the impacts are significant and influenced by both the frequency and magnitude of flood events (Roxy et al., 2017). The combined increase

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in urbanisation and the effects of climate change project an increase in the frequency of extreme weather events that lead to flooding (Reynard et al. 2001; De Vleeschauwer et al. 2014; Balsells et al. 2015; Miller and Hutchins 2017; Haghighatafshar et al. 2018; Mignot et al. 2019; O'Donnell et al. 2019). Consequentially, this projected increase in flood risk will negatively affect economies, livelihoods, infrastructure, and health. This has underpinned the need to study the physical causes of flooding, its potential impact on society, and how to respond effectively (IPCC 2014).

Studies in the 1940s primarily assumed that the upstream reaches of a catchment were the main contributors of stream flow and runoff to downstream areas and floodplains, referred to as Horton's theory of overland flow (Bernier 1985; Horton 1945). Hortonian flow identifies overland flow as the product of high rates of precipitation surpassing rates of soil infiltration (referred to as infiltration excess overland flow). Building upon Horton's theory, variable source areas (VSA) emerged as a complementary concept but proposed two differences from Horton's Theory (Hewlett and Hibbert 1966; Bernier 1985; Hibbert and Troendle 1988):

1. The contribution of a drainage basin varies on spatial and temporal scale
2. Precipitation received by saturated soil results in runoff; hence, subsurface flow is a major contributor of runoff in a vegetated basin, also known as saturation excess overland flow

VSA characterises runoff as a dynamic process stating that catchment contributing areas (i.e. the sources of excess water) depend on the characteristics of the rainfall event and catchment itself. For example, VSA accounts for the temporal dynamics of seasonality, recognising that runoff expands in the winter and shrinks in the summer (Lim 2016). Similarly, the size of the area that contributes to flooding is a product of the duration of rainfall, as longer precipitation events result in the greater extent of saturated areas and increase the total area that generates runoff (Qiu 2003). The concept of VSA improved the understanding of flood processes by identifying the importance of multiple parameters that affect flooding such as land use, topography, and soil properties (i.e. soil type, depth, and compaction) (Jencso et al. 2009; Mejía and Moglen 2010; Miles and Band 2015). To examine such dynamic processes and variable catchment characteristics fully depends on the ability to compute hydrological flows with enough spatial detail.

Since the 1970s, computationally based hydrological and hydraulic models have been developed to provide a simplified representation of 'real world' processes that lead to flooding. Both hydrological and hydraulic models are now established as crucial tools for managing excess water. Hydrological modelling has been traditionally used to model the generation of flow from a catchment under rainfall drivers, and hydraulic models have been used to simulate the resulting flow through river channels and floodplains (Syme et al. 2004; Krysanova and Bronstert 2009; Jajarmizadeh 2014; Teng et al. 2017). Increasingly, these two categories of models now overlap in their capabilities and many modelling packages enable the representation of both the hydrology and hydraulics of a catchment. In this paper, we will refer to these models generically as flood models and specify the hydrological or hydraulic components as necessary.

Research and professional modelling software can model catchment areas, rivers, and floodplains in one dimension (1D), two dimensions (2D), and three dimensions (3D). The majority of flood models solve variations of the shallow water equations to simulate overland and channel flow during a flood event. Technological advancements such as increased computational power have enabled modellers to include a more detailed representation of flood processes (Teng et al. 2017; Nkwunonwo et al. 2020); representing the dynamic concepts of VSA, Hortonian flow, and saturation excess by incorporating infiltration models such as Green–Ampt and Horton equations in hydraulic models (Mishra et al. 2003; Gülbaz et al. 2020; Zhang et al. 2020).

While the availability of flood models has improved the understanding of runoff processes leading to flooding, it also established a set of traditional methodologies used to answer specific questions for FRM. For example, the identification of water depths and extents at specific locations supported the development and use of hazard mapping and damage assessments (Apel et al. 2009; Koivumäki et al. 2010; Teng et al. 2017). Although hazard identification is critical from a flood protection perspective, a clearer understanding of the whole catchment contribution to flood risk will improve the scope for broader and/or alternative interventions (Saghafian and Khosroshahi 2005; Dawson et al. 2020).

The last decade has seen a transformative change in methods utilised for FRM (O'Donnell and Thorne 2020). This change is driven by the recognised need for an integrated understanding of the processes involved in flood risk, and that flood prevention and protection are key to tackling the issue. Hence, approaches such as natural flood management (NFM) and sustainable urban drainage systems (SUDS) have taken a lead in addressing flooding (Vercruysse et al. 2019; Ghofrani et al. 2017; O'Donnell et al. 2017). NFM and SUDS type solutions provide a holistic approach to flood risk and offer multiple benefits alongside flood mitigation (Fletcher et al. 2015; Zevenbergen et al. 2017; Fenner et al. 2019; Vercruysse et al. 2019; O'Donnell and Thorne 2020). Commonly, these solutions are used as 'source control' measures to reduce runoff to flood risk areas identified through impact maps; however, there is a lack of modelling guidance to implement them efficiently (Saghafian and Khosroshahi 2005; Petrucci et al. 2013; Saghafian et al. 2015).

Dealing with floodwater at its source and minimising flood risk in critical locations (e.g. within the built environment) is becoming an increasingly important area of FRM and hence flood modelling (De Vleeschauwer et al. 2014; Fletcher et al. 2015; Dawson et al. 2020). As such, researchers are revisiting the concepts of VSA to help identify the sources of flooding and steer integrated FRM with more systemic approaches and methodologies. Such studies can be reoffered as flood source area (FSA) identification approaches and aim to explicitly identify how best to locate the main sources of flooding across a catchment to help improve preventative management practices.

At present, there are many systematic reviews on traditional flood modelling (Jacobson 2011; Pechlivanidis et al. 2011; Biondi et al. 2012; Ochoa-Rodríguez 2013). State-of-the-art benchmarking reviews are also available for many flood modelling packages (Zoppou 2001; Syme et al. 2004; Hunter et al. 2008; Néelz and Pender 2013). Significant literature is available on flood mitigation and management strategies such as structural flood protection, sustainable urban drainage systems (SUDS), sponge cities, and blue-green infrastructure (BGI) (Van Der Weide 2011; Kryžanowski et al. 2014; Jato-Espino et al. 2016; Ghofrani et al. 2017; Dawson et al. 2020). Approaches and methods related to FSA identification, however, are currently poorly documented and disparately published. This paper, therefore, provides a critical review of modelling methods used for FSA identification that exist in current literature. The objective of this paper is to reintroduce the concept of FSA identification as a tool for FRM and to summarise how flood models are currently used to identify FSAs. The review begins by defining FSA identification and presents a summary of the hydrological models, methods, and frameworks that have been used to investigate FSA, and presents a detailed account of literature that has developed and implemented methods of FSA (Sect. 2). Section Three discusses the advantages and disadvantages of the described approaches regarding the adoption of FSA identification methods in mainstream modelling practises and identifies key research gaps. Last, the paper provides recommendations for further work to address the research gaps within this emerging topic (Sect. 4).

2 Flood source area identification

FSA identification refers to the approaches that identify source areas of flooding within a catchment. This is not to be mistaken with the source–pathway–receptor–consequence model that was implemented in fluvial and coastal flooding (Narayan et al. 2012). FSA identification approaches primarily utilise hydrological models of varying complexity and detail. For this review, it is important to define the term ‘flood models’ as it is one of the key tools used for FSA identification. Flood models/modelling refers to modelling packages that represent hydrological, hydraulic, and hydrodynamic processes, e.g. rainfall-runoff, stream flow, and infiltration within a catchment. There are many hydrological models available to aid researchers and practitioners in modelling floods depending on the needs of the project (Néelz and Pender 2013; Teng et al. 2017).

The availability of multiple models, however, presents significant challenges associated with their classification. A review of flood models conducted by Jajarmizadeh (2014), for example, identified that different users of the models and overlapping characteristics within the model itself create complexity with their classification. For this review, therefore, hydrological models are classified simply as lumped, semi-distributed, or fully distributed (Cunderlik 2003; Jajarmizadeh 2014; Buddika and Coulibaly 2020). Lumped models are relatively simple as they represent catchment characteristics as average ‘lumped’ values. They require few inputs, spatial variability is considered homogeneous, and rely heavily on water balance equations (Ghavidelfar and Reza 2011; Lavenne et al. 2016). Semi-distributed models have some spatial variability and are generally more physically representative and allow for a lumped quantification of sub-catchment responses (Mengistu and Spence 2016). They are computationally more demanding than lumped models but less demanding than fully distributed models that require inputs for all parameters and therefore significant run times (Jajarmizadeh 2014). Fully distributed physically models represent spatial variability at a higher

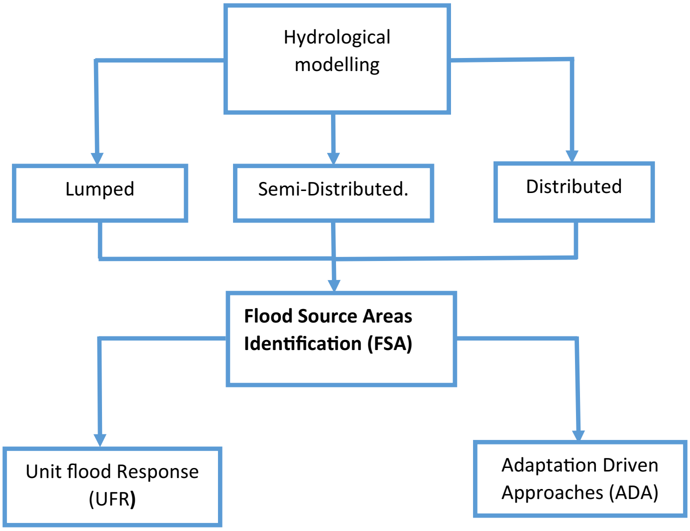

Fig. 1 Classification of hydrological models and flood source area identification approaches

level of detail, i.e. at a grid-scale and require measurable parameters as inputs. Fully distributed models have a two-dimension discretisation (e.g. flood depth and area) of overland surface features (Pina et al. 2016).

While there are other methods capable of FSA identification such as remote sensing, soil moisture analysis, and field observations (Islam and Sado 2000; Foody et al. 2004; Chormanski et al. 2011; Mengistu and Spence 2016), this review concentrates on studies that are reliant on flood models. This is because flood models are a crucial tool within research and industry when investigating flood processes and influencing FRM decisions globally (Mason et al. 2003; Priya 2019; Papacharalampous et al. 2020). FSA identification methods have been categorised based on their modelling intent; first, those that directly apply a framework to identify FSAs, referred to as unit flood response (UFR) driven approaches. Second, those that are used to identify area contributions for source control implementation, referred to as adaptation-driven approaches (ADA). Figure 1 illustrates the main models used for FSA identification and the sub-classification of FSA identification methodologies. For a full summary of the approaches, tools, and case studies reviewed, see Table 1.

Table 1 Summary of studies that apply flood source area (FSA) identification approaches listed by modelling method. Studies highlighted in blue belong to the unit flood response (UFR) approach and those in green belong to the adaptation-driven approach (ADA)

Model		Location	Size (km^2)	No. of sub-catchments/ cells	Contribution	Source
Lumped	**HEC-HMS**	Damavand, Iran	758	7	The first introduction of the UFR approach	(Saghafian and Khosroshahi 2005)
		Golestan, Iran	4,802	11	Application of UFR to quantify the contribution of FSA from land-use changes.	(Saghafian et al. 2008b)
		1. Tangrah, Iran 2. Walnut Experimental watershed	1,970 93.4	6 5	Comparative study of UFR & "Self-Organising Feature Mapping Fuzzy c-means" to identify hydrologically homogenous regions.	(Dehghanian et al. 2019)
		Golestan Province, Iran	n/a	9	Demonstration of the differences in prioritising source areas based on UFR and discharge at the outlet	(Basin et al. 2015)
		Konar Reservoir, India	998	124	Impact of varying land use on flood peaks; data-scarce environment	(Sanyal et al. 2014)
		Kelentan River Basin, Malaysia	6281	4	Assessing the impact of land use/land cover on FSA includes a new index for sub-catchment ranking.	(Abdulkareem et al. 2018)
	Runoff curve number estimation	Niger	141	12	Applied a simplified hydrological method (e.g. elementary territorial units) to analyse sub-catchment contributions during a flood event: flood risk evaluation method (FREM).	(Fiorillo and Tarchiani 2017)
Semi- distributed and Distributed	**HEC-RAS & Mod Clark**	Roodzard, Iran	900	278 'cell units'	UFR carried out at a pixel scale. Development of the iso-flood mapping method for FSA and output visualisation.	(Saghafian et al. 2010)
		Khanmirza catchment, Iran	391	7 sub-units, unit cells unstated	Compared distribution patterns of unit cell approach to sub-catchment approach	(Rezaei et al. 2017)
		1.Tangrah, Iran 2. Walnut Experimental watershed	1,970 93.4		Compared the use of artificial neural networks (**ANN-GA)** and ModClark for FSA identification.	(Dehghanian et al. 2020)
	SWAT	Talar River Basin, Iran	1727	21	Applied the UFR approach to quantify the contribution of source areas due to climate change.	(Maghsood et al. 2019)
	RAFTS	Pole Manjahnigh sub-catchment, Iran	284.6	7 Isochronal areas	Applied a Tc model for sub-grouping & prioritisation based on land use for FSA.	(Roughani et al. 2007)
	N/A	Hoder catchment, UK	N/A	2634 tiles	Identified and mapped the effect of changes in land use parameters to discharge at the outlet, using algorithmic differentiation and mosaic impact maps.	(Ewen et al. 2013)
	CityCAT	Newcastle-upon-Tyne, UK	9.15	37	Introduction of source-to-impact analysis as a criterion for intervention prioritisation	(Vercruysse et al. 2019)
	SWMM	Espoo, Finland	0.105	-	Introduction of FSA as a function of slope, contributing area and water depth to improve the application of SUDs	(Jato-Espino et al. 2016)
	MOUSE	Novi Sad, Belgrade	-	-	Promoted site-specific implementation of SUDs, areas that score high on the suitability value were best suited for source control measures	(Makropoulos et al. 2001)

2.1 Unit flood response

The unit flood response (UFR) approach is a framework that is applied using flood models to identify source areas that contribute significantly to flood risk. This procedural framework was first introduced by Saghafian and Khosroshahi (2005). The UFR method is similar to the unit response matrix approach applied in petroleum engineering and groundwater modelling (Gorelick 1983). Initially, the use of the response matrix was to optimise oil production and identify the drawdown curve of each well. In groundwater modelling the unit, response matrix is used to quantify the effect of sink/source rates at pre-selected well locations on various design variables (Lee and Aronofsky 1958; Aronofsky and Williams 1962; Gorelick 1983). The UFR method comprises four key steps (Fig. 2), which enables the ranking of sub-catchments in order of priority based on their flood index. A flood index is generated by using either Eq. 1 or 2.

$$FI_n = \frac{Q_{bs} - Q_s}{Q_{bs}} \times 100 \tag{1}$$

$$fi_n = \frac{Q_{bs} - Q_i}{A_i}, \tag{2}$$

where FI_n is the gross flood index of the sub-catchment in percentage (%); Q_{bs} is the baseline peak discharge generated at the outlet (in m^3/s) with all the sub-catchments present in the simulation. Q_s is the peak discharge at the outlet when s sub-catchment (in m^3/s) is omitted from the simulation. In Eq. 2, fi_n is the flood index of the n sub-catchment based on the sub-catchment area (in $m^3/s/km^2$), Ai is the area (in km^2) of the sub-catchment. The UFR approach also draws heavily on the flood estimation handbook (FEH) approach to flood unit hydrographs known as disparate sub-catchments (Kjeldsen, n.d.) and the ModClark distributed model explained (see Fig. 3).

Since the introduction of this approach, UFR has been used to investigate land use and spatial variability for numerous locations (see Table 1). For instance, in Iran, Bahram Saghafian et al. (2008) studied how land use change alters the location of source areas of flood risk. Additionally, Maghsood et al. (2019) utilised the Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Models (GCM) to investigate the impact of climate change on FSAs. The modelling simulations revealed that climate change projections increased flood sources located closest to the catchment outlet. Furthermore, the application of UFR by Basin et al. (2015) has demonstrated that sub-catchments that have high discharge rates are not always the key contributors to flood risk. This was due to the routing of waterways and the location of the sub-catchments, which altered their contribution to the overall flood impact. Although UFR is mostly applied to case studies in Iran, an effort has been made to understand its applicability to catchments in other countries.

Sanyal et al. (2014), for instance, use the natural reserve conservation service curve number (NRCS-CN) approach for runoff estimation in the data-sparse Konar Reservoir in India. The study aimed to investigate the impact of land use change on FSAs. Two land use maps were generated using satellite images from the year 1976 and 2004. Following the generation of a baseline hydrograph for both the scenarios, the UFR approach was applied to establish the contribution of each sub-catchment. A positive correlation between land use change at a sub-catchment scale and its impact on the flood peak at the outlet was established. However, the results also indicated that other factors such as the timing of

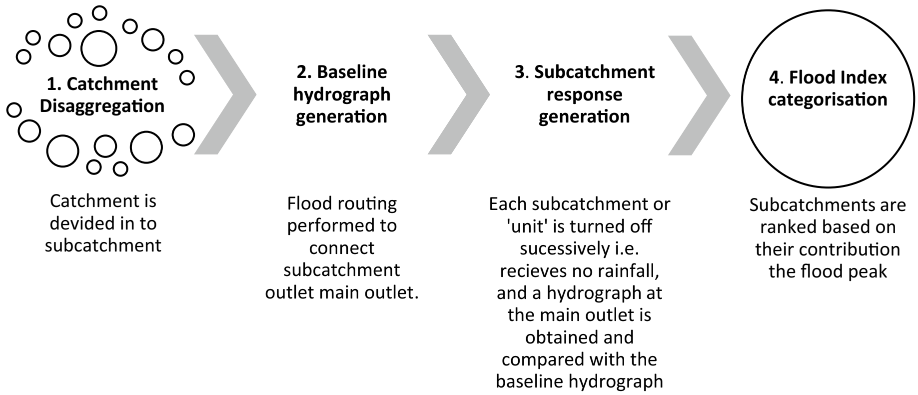

Fig. 2 The methodological steps of the unit flood response approach

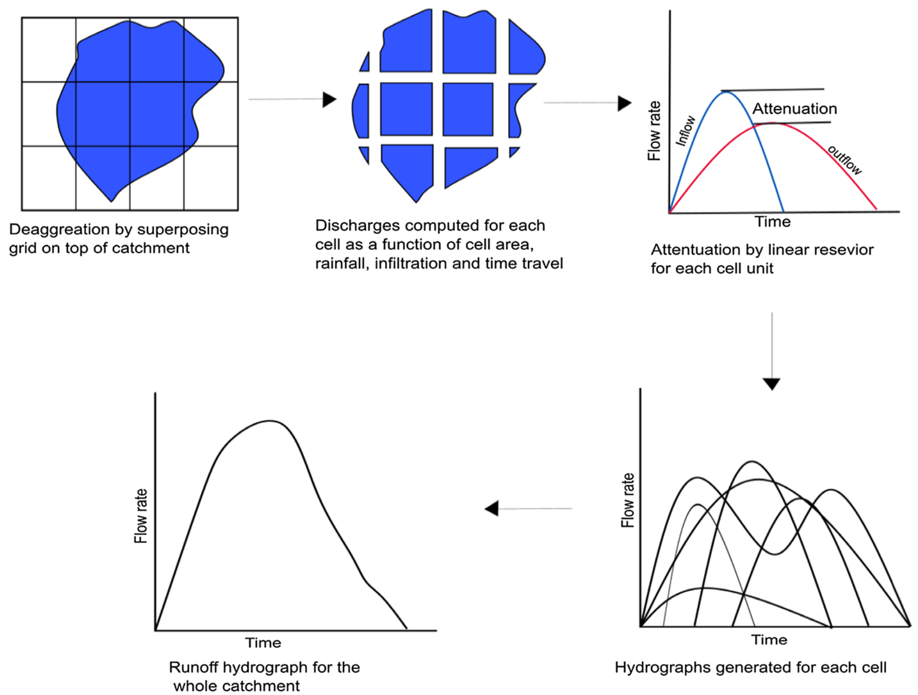

Fig. 3 ModClark distributed model adapted from Kull and Feldman (1999), where the study area is divided into uniform cells, runoff for each cell is determined and lagged based on the travel time to the outlet. Runoff is also directed through a reservoir function to account for storage. Last, results from each cell are then combined to generate a hydrograph for the whole catchment, i.e. the baseline hydrograph

storm event, slope, sub-catchment size, and shape also have a significant impact on the results, which alter the hydrological response of a sub-catchment. The study also identifies a limitation for the UFR method to FSA identification, stating that UFR method is ideal if a singular land use condition is investigated. Land use and land cover changes, however, are dynamic in space and time resulting is complex hydrological responses. Hence, source areas identified through UFR change based on hydrological factors such as season, duration, and soil types. Abdulkareem et al. (2018) also investigated land use and its impacts on peak discharge at the catchment outlet. Flood hydrographs for the year 1984, 2002, and 2013 were simulated to observe changes in peak discharge and runoff volume for varying land use and land cover for the Kelantan Basin, Malaysia. The methodology adapted the UFR approach, however, to consider the initial peak flow per unit area and the change peak flow per unit area.

The UFR framework has additionally been used to show the importance of spatial variability in rainfall when investigating FSAs. The impact of spatial rainfall on the flood index of sub-catchments was further examined through Monte Carlo analysis (Saghafian et al. 2013). The simulation and analyses concluded that the use of spatially varied rainfall has a significant impact on the prioritisation of FSAs. The results indicate that prioritised flood source areas are sensitive to the spatial distribution of more frequent rainfall events, rather than rainfall events that have high return periods. Dehghanian et al. (2019) compared the UFR approach with self-organising feature maps and fuzzy c-means (SOMFCM) algorithms as a method for applying FSA identification; however, it is difficult to make a direct comparison between the two approaches, since SOMFCM cannot provide absolute values for FSA and hence cannot be represented on a map.

Roughani et al. (2007) applied *isochrones* for spatial analysis and sub-catchment grouping. Isochrones or isochronal areas were generated by using a distributed model of time concentration developed in ArcView. *Isochrones* are used for sub-catchment grouping based on their spatial heterogeneity. The principal aim of the study was to introduce an alternative method for prioritisation of FSAs; however, after generating the *isochrones* the method utilises the UFR approach. The *isochrones* are obtained for a group of seven sub-catchments within Khanmirza in the south-east of Iran. The study found that areas that are within isochronal area 1 and 2, located closest to the outlet, have the least impact on the flood peak, whereas sub-catchments that are in isochronal area 5, have the greatest effect on the flood peak, even though it was the smallest in size.

Saghafian et al. (2010) introduced iso-flood severity mapping as a fresh approach for FSA identification representation. The method introduced the unit cell approach (UCA), which superimposes a grid to disaggregate catchments, instead of irregular hydrological sub-catchments. The ModClark method explained in Fig. 3 was used to account for spatially distributed rainfall, losses, and storage within a catchment. The underlying assumption of the ModClark model is that the velocity of the flow is uniform over the entire area and the duration of runoff to the outlet is directly proportional to the distance from the outlet (Kull and Feldman 1999; Bhattacharya et al. 2012).

The study compared the subs-catchment approach and the unit cell approach to identify which method is best suited for FSA identification. The study area was subdivided into 278 cell units of 2km^2, where each cell unit represented a sub-catchment. Following this, the URF approach was applied to obtain a hydrograph that quantifies the effect of each cell unit at the main outlet. The results indicated that the sub-catchment approach to disaggregation and hydrograph generation would suffice if FRM was to occur at a sub-catchment scale, and the requirement for a distributed model at a fine-scale is not essential. Similar to Saghafian and Khosroshahi (2005), Saghafian et al. (2010) found that the largest, or the closest, catchments do not contribute the most or rank as high-priority areas.

Rezaei et al. (2017) also utilised the ModClark model to investigate spatial variability in flood source areas. Using the URF approach, the study concluded the unit cells that contained soil class D (clay-rich soils) contributed the most to overall flood risk and recommended that forest-cliff, dry land, and rangeland surfaces should be prioritised for flood management within the study area. Furthermore, FSAs increased from downstream to upstream in sub-catchments; however, this distribution pattern is not observed when compared to cell units.

The most recent advancement of the UFR approach is the utilisation of the artificial neural networks (ANN) optimised using genetic algorithms (GA) to predict contribution at a cell scale. The study conducted by Dehghanian et al. (2020) compared the flood index outputs generated by the UFR approach using HEC-HMS and ModClark with the outputs generated by ANN-GA. The study identified hydrological homogenous regions (HHRs) using SOMFCM (explained previously). Following the identification of HHRs, the ANN-GA is used to predict flood indexes in the HHRs at a cell scale. The results indicated that the spatial pattern of flood index generated by the UFR approach using the ModClark model and the ANN model were similar. The study concluded that for semi-arid catchments, ANN-GA is effective in identifying flood source areas and generating a flood index. To summarise, the UFR approach has been developed and applied using a range of innovative tools and discretises a study area into 'units' which can either be represented as a uniform grid or multiple sub-catchments. In reviewing the UFR literature, the following key conclusions have been made:

- The spatial distribution pattern of source areas (i.e. location of FSAs) differs when using the unit cell approach vs sub-catchment approach.
- There is a nonlinear relationship between the input variables (e.g. rainfall, land use) and the flood index generated using the UFR approach. Therefore, the hydrological factors of the sub-catchment should be heavily considered when generating a flood index.
- Units reach a 'steady' state of response when subjected to higher return periods, meaning that all units contribute somewhat equally at higher return periods. However, it is unclear if the shape or size of the units impacts the steady-state response.
- Spatial variability in rainfall and climate change factors influence the contribution and placement of flood source units.

2.2 Adaption driven approach (ADA)

Adaption driven approaches refer to approaches that go beyond just FSA identification. The fundamental difference between UFR and ADA is that the unit flood response has a defined procedural method to identify a unit as a major source of flood risk in the area, whereas ADA methodologies used to identify FSAs are variable. For instance, coupled geographical information systems (GIS) with flood modelling are used to identify areas best suited for sustainable urban drainage systems (SUDs) intervention within an urban catchment in Espoo, Finland (Jato-Espino et al. 2016). This method identifies locations that would benefit from SUDs; in order to identify as a location that would benefit from SUDs, the location is required to have:

(1) contributing area of <1.2 ha.
(2) $<5\%$ slope.
(3) a water table depth of >0.6 m.
(4) low infiltration rates.

Two major aspects that were considered as identifying flood-sensitive areas were flooded sewer nodes in the model, and peak flows within the sub-catchment. SUDs were implemented within these areas in the flood model, and their hydrological response was investigated. The study found that SUDS reduced discharge within the catchment by 50% (Jato-Espino et al. 2016). The results from this study highlight the importance of site-specific SUDs application for optimising SUDs performance, and, although not the main aim of the study, it provides an approach to FSA identification.

Vercruysse et al. (2019) followed the UFR method for FSA identification; however, they emphasise the interactions between flood dynamics and existing urban infrastructure systems to prioritise intervention locations (called source-to-impact). The analysis was applied to the urbanised city centre of Newcastle-upon-Tyne (~9km^2 in area) using a fully distributed hydrological model. Spatial maps were generated and used to identify locations for adaptation and FRM intervention, based on flood dynamics (e.g. depth and extent of exceedance) and land use areas (e.g. green space and existing infrastructure). The novelty of the study is the application of the UFR method to an urbanised catchment in an object-driven manner. The study highlights that identifying FSAs can be beneficial to developing preventative adaption plans within the catchment, especially in an urban catchment, and how different criteria can target and change source areas. The study identified four key criteria:

(1) Flood extent generated by each cell.
(2) Maximum flood depth generated by each cell.
(3) Land use type flooded by each cell.
(4) Flood exposure to buildings and roads cause by each cell.

For instance, if criteria three were used to guide spatial prioritisation for flood interventions, floods that commonly affect green spaces will be less critical. These criteria's can also be compared and combined to identify the most suitable intervention locations. However, it is worth noting the storm-water management model (SWMM) used in Finland and CityCAT applied in Newcastle are both fully distributed models, and therefore, would not be considered a viable tool for investigations of FSA in locations where input data is scarce, resources are limited. For instance, utilising CityCAT to apply the UFR method would require significant run times and data inputs. Furthermore, the study conducted by Jato-Espino et al. (2016) makes use of sewer network data, which is in most cases is not openly or easily available.

Identifying areas best suited for SUDs implementation has also been investigated in Novi Sad, Belgrade. Although the study doesn't directly address FSAs, the method can be used for FSA identification. Makropoulos et al. (2001) utilised IDRISI, a GIS tool, to identify application areas for source control measures in Novi Sad (Serbia). Novi Sad has a mixture of peri-urban and extreme urban areas and is home to one of the oldest drainage systems within the Balkan countries. IDRISI was used with the MOUSE drainage model, which represents the artificial drainage system and the catchment as two distinct components in the model. The catchment model was divided up into a series of small sub-catchments connected to a node within the drainage network. The hydrological parameters for each sub-catchment were applied to simulate runoff. The initial output from the study was to generate a suitability map, identifying areas best suited for SUDs intervention, achieved by processing field data into IDRIS and analysing it using multi-criteria analysis module. The module utilises an order weighted area technique on multiple field data such as topsoil, type, and slope, generating an output suitability map. The suitability layer was used in combination with the sub-catchment layer to ‘extract’ a mean suitability value for each sub-catchment. Areas that score high on the suitability value were best suited for source control measures, therefore it could be assumed that these areas are the main FSAs. After applying source control methods, the study found a decrease in water and discharge levels, especially for rainfall events that have a short return period. For instance, for 10-year and 2-year storm events, a 7 and 12.5% reduction in volume was observed, respectively. Similar to the findings of Jato-Espino et al. (2016) and Vercruysse et al. (2019), Makropoulos et al. (2001) study highlights the importance of using FSA identification as a framework for implementing flood source control measures and driving adaptation of urban areas systematically, without neglecting critical city infrastructures such as roads, buildings, and urban drainage.

ADA research efforts, so far, have been applied using complex distributed hydrological models for FSA identification; however, the availability of complex models is limited in developing countries. Fiorillo and Tarchiani (2017) developed a flood risk evaluation method (FREM) to identify areas that contribute to flood risk for a catchment located southwest of Niger. The underlying principle of the method is based on curve number runoff estimation equations, rather than distributed modelling. The motivation for this research was the optimisation of retention measures that help reduce runoff. Areas are grouped into an Elementary Territorial Unit (ETU), which is a collection of areas that have a similar slope, soil type, and land cover within the catchment. The assumption is that each ETU has a homogenous hydrological response (HHR) to rainfall, also known more widely as a Hydrological Response Unit (HRU). FREM uses open-source data from remote sensing and uses GIS for analysis and, therefore, the method is computationally efficient and inexpensive. ETUs are then used to establish the current state of flood risk within the catchment, and two maps are derived using GIS. Namely, runoff maps that present areas with the highest runoff coefficients and priority maps that present sub-catchment units with high runoff coefficients (source areas). Water retention measures are implemented using runoff reduction coefficients in the sub-catchment units that rank high on the priority maps. The approach utilised within this study is one of the simplest approaches presented within this review. The approach simplifies the SWAT (soil and water assessment tool) model principles and is considerate of limited funding, skills, and technology available in developing countries that often cause challenges for the use of FRM practises. The FREM approach based on simple curve number estimation is empirically based and considers important parameters such as runoff depth and land surface conditions. The approach is unique in ADA, as it makes use of free open-source data such as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model (DEM), and the Soil and Terrain Digital Database (SOTER). It is the only approach so far that is inclusive of the receptors/consequences of flood risk, i.e. local community. For the validation of ETU, Fiorillo and Tarchiani (2017) conducted field investigations and participatory mapping with village locals. This enables GIS analysis to be merged with local perspectives, facilitating a truly integrated approach to FRM and FSA identification.

Last, ADA’s can be used to concentrate primarily on land use within the catchment, and its relationship with FSA. For example, Ewen et al. (2013) investigated the causal link between land management and flood risk using reverse algorithmic differentiation. The method involved utilising mosaic tiles to signify the spatial variations in land use management and soil type. Modelling was used to generate impact mosaic maps for source and impact investigation. The model comprises 2,634 mosaic tiles, superimposed within 500 m regular cells. The impact mosaic maps demonstrated the contribution each tile makes at the outlet of the catchment if land management were to change in the study area. A total of 100 parameter sets representing land use were utilised for modelling the catchment before and after land management changes. The various versions of the model are then used to identify the peak flow rate at the outlet of the catchment. This is done for each mosaic tile within the modelling domain, generating a map that shows the sources of impact.

Research grouped as ADAs has highlighted the importance of linking FSAs to adaptation and mitigation. The following key points have been summarised from the studies discussed in this section:

- Novel approaches are used for FSA identification, which allows the modeller to implement a method that is tailored to the data, technology, and resources available to them.
- Processes to identify FSAs when drainage data is available have been identified and implemented.
- Techniques for post-processing and communication of outputs generated by the UFR modelling framework have been developed and provided.
- FSA identification is a key pre-requisite for implementing source control measures.

3 Discussion

When reviewing research conducted for FSA identification (Table 1), the UFR approach introduced by Saghafian and Khosroshahi (2005) has been applied to several case studies, because the UFR approach presents itself as a simple procedural framework by which FSAs can be identified. This makes the application of the framework adaptable regardless of the tools used; hence, it has been applied using lumped, semi-distributed, and fully distributed modelling packages. A common occurrence when investigating literature for this review was the lack of realisation that contributing source areas have been identified or a method to so do has been developed. This is because either identifying FSAs is not the aim of the study or that identification of FSAs has remained under the radar as a fundamental procedure to FRM. This review highlights the importance and benefits of identifying FSAs as a primary method for FRM, regardless of the method used. Nonetheless, it is important to note the tools use, i.e. flood modes, may have a significant impact on the outcome and FSAs identified.

When reviewing the UFR methods and ADAs, a clear commonality between the two approaches is the disaggregation of the catchments, i.e. dividing the catchment into smaller units to understand their wider impact. From our review, we have identified six key gaps in the current body of FSA identification research, and these represent future research direction for exploration.

(1) The significance of grid/unit independence on FSA identification.
(2) The effect of modelling tools on the outcome.
(3) The impact of drainage systems on FSA identification.
(4) Connecting source to consequence.
(5) Climate change and future adaptation as per the UFR approach in practise.
(6) Adopting UFR in mainstream practice.

3.1 Grid independence

The unit cell approach can be criticised for being unclear on the impact of grid size on FSAs, for example, iso-flood severity mapping or the *isochrones* approaches offer no guidance on the size of cell units that should be used for disaggregation of a sub-catchment, so far, the unit cell approach has used sizes of 2*2km^2 and 0.5*0.5km^2 (Saghafian et al., 2010; Vercruysse et al., 2019). There is no obvious logic why these dimensions were chosen to apply the UFR approach. It would be interesting to identify whether the unit cell approach follows the ideas of grid independence whereby the distribution of source areas is independent of the grid sizes. The findings of Syme et al. (2004) report that cell sizes play an important role in representing urban features and therefore may play a significant role in identifying FSAs. The issue of cell unit size has the potential to be addressed by applying the UFR to a single case study using varying cell unit sizes. The benefit of this exercise will help identify if cell unit sizes impact FSA, and how their distribution differs from when disaggregating the study area into sub-catchment.

3.2 Multi-model application

Both UFR and ADA are single model applications, i.e. they have been applied to a single case study using a specific type of model. Although this has shown that FSA identification approaches can be applied using a range of models, it sheds little light on the impact the underlying code and numerical solutions have on the identification of FSAs. Questions such as does the application of models that use different numerical solutions generate identical outcomes?, i.e. do all models identify the same 'unit' in a catchment as the source area? Or do model performances and differences have a significant impact on the identification of source areas? Benchmarking reviews on model solutions, performance, and merits have clarified that different solutions and model codes affect the outputs generated in varying magnitudes. It is likely that FSA identification inherits the same uncertainties (Hunter et al. 2008; Neelz et al. 2010; Néelz and Pender 2013); hence, the impact of the uncertainties due to model codes and solutions should be scrutinised and investigated to improve the robustness and credibility of methods such as UFR.

3.3 Artificial drainage system representation

The lack of subsurface drainage representation is an issue not just within approaches of FSA identification, but also for the wider topic of flood modelling. However, the representation of piped drainage system becomes important when studying FSAs, as these are a critical piece of infrastructure for managing water within urban areas (Dawson et al. 2008, 2020; Möderl et al. 2009; Lim 2016; Bertsch et al. 2017; Vercruysse et al. 2019). Underground drainage systems are used to drain water away and reduce runoff within urban areas through the use of storm-water inlets (Bazin et al. 2014; Jang et al. 2018). Although drainage systems aim to augment natural drainage pathways that occur within the environment, they introduce a range of environmental and engineering challenges by modifying the hydrological response of an area (Jacobson 2011; Miller et al. 2014; Fletcher et al. 2015). Artificial drainage systems can change the fundamental connectivity of natural overland drainage paths, thereby altering flow paths from source areas to flood impact areas. Thus, the inexplicit representation of drainage systems in the models that applied the UFR method suggests that the conclusions of the UFR modelling can be considered erroneous, especially in an urban area. For example, pluvial flooding (ponded flooding caused by rainfall intensities higher than that which can normally be drained away) has the potential to alter locations of flooding due to drainage incapacity and surcharge. Furthermore, overland flow from drainage system surcharge can increase the velocity and volume of flow increasing flooding extent and water depth (Butler et al. 2018). Subsequently, the increase in runoff volume may result in high river flow magnitude, increasing the threat of river flooding.

Generally, there is a lack of drainage data available to represent these systems in flood models, and modellers are forced to assume a generic capacity of the drainage system. For example, the rainfall reduction approach is commonly used in these cases. This is when a single depth of rainfall is used to reflect the piped system capacity and this is removed from the rainfall input before modelling overland flow (Hénonin et al. 2015; Wang et al. 2018). When assuming the drainage system operates at a set capacity, the underlying assumption is also that the system operates at full potential. In urban pluvial flooding, this is problematic, as the system is often the source of the hazard itself, e.g. blockage in gullies and inlets, or surcharging manhole (Dawson et al. 2008; Ten Veldhuis 2010; Walsh et al. 2012). It is also impossible to explore intervention scenarios for the drainage system itself, as it is not explicitly represented in the models. The results from studies that apply the UFR approach in urban areas are therefore limited in their effectiveness in identifying FSA and hazards because of the unrealistic representation of key flow paths in urban infrastructure. This neglects completely, the impact of operational faults such as blockages, pumping station regimes, surcharges, and pipe capacity exceedance where pipes are designed for a smaller event. Since drainage systems change the flow paths through an area, they directly affect FSA identification and prioritisation thus, for a full understanding, the drainage system needs to be present in models.

3.4 Identifying connectivity of source to consequence

Similar to the challenge of representing urban infrastructure systems (i.e. the drainage network, impervious surfaces), connecting water pathways from the source to consequences is another key challenge for FSA identification. In urban areas, the connection from source areas to impact zones is catalysed by surface water processes. Surface water connectivity is regarded as a crucial element of flood processes. Therefore, it is crucial to integrate connectivity from FSAs through its flow pathways and to its receptors or impact zones. Although some ADA studies have followed the source–flow pathway–impact zone as singular elements to fully show the benefits of identifying FSA it is essential to establish the relationship of the FSA to overall flood risk. Especially, to comprehend and quantify how this disruption in connectivity affects the entire catchment (Trigg et al. 2013). Particularly in urbanised catchments, connectivity and hydraulic conveyance are of significant interest within FRM. Placement of impervious surface areas, open spaces, and storm-water management structures have a significant impact on the downstream response of a catchment. While this has been addressed in the wider topic of flood risk, it has received no attention while investigating FSAs (Jencso et al. 2009; Mejía and Moglen 2010; Ogden et al. 2011; Miles and Band 2015; Lim 2016). For instance, Lim (2016) identified that in urban areas the response of open space is comparable to that of impervious cover. Developed pervious areas such as urban parks closely represent Hortonian flow due to components that increase hydraulic connectivity such as drainage infrastructure, roads, and paths within green space. The results also highlight that identifying FSA in urban catchments is largely challenged by issues such as compaction of soil, leakages from subsurface drainage systems, and lawn watering of urban open spaces, which may increase saturation and cause saturation excess flow even during small rainfall events.

3.5 Climate change and future adaptation

Besides increasing urbanisation, climate change is one of the key drivers of increasing flood risk (IPCC 2014; Watts et al. 2015; Lowe et al. 2018). For instance, in developing countries such as India the cost of flooding from 1980 to 2017 was $58.7 billion as per the United Nations International disasters database created by CRED (Center of Research for the Epidemiology of Disasters). Future climate change projection for India shows an increase in extreme rainfall events which is likely to increase economic damages (Ali and Mishra 2018; Dubash et al. 2018; Avashia and Garg 2020). In Can Tho, Vietnam climate change-related changes such as sea-level rise and increased river flow have projected to increase flood risk within the city (Huong and Pathirana 2013). In Jakarta, mean future flood risk is projected to increase by 300–400% (Januriyadi et al. 2018). However, climate change and its impacts have received little attention within research focused on FSA identification. Nonetheless, studies conducted by Maghsood et al (2019) have indicated that climate change influences the distribution of FSAs.

In the UK, the effects of flooding have led to increased investment in flood defences, whereby 1,500 flood defences will benefit from £2.3 billion funding by 2021 (HM Government 2016). However, these funding priorities protecting areas that have been recently impacted rather than identifying the sources of flooding. Applying funding to current high-risk areas may prove economically efficient today, but with climate change projections and future urban growth likely to alter hydrological and geomorphic processes, i.e. the source and receptors of flooding (Stevens et al. 2016), preventative measures of source control will be more beneficial in the long term. Using FSA identification approaches alongside climate change projections thus presents itself as a practical and strategic exercise for visualising the change in source areas and flow pathways under various climate scenarios. This would advance flood risk mitigation and management to dynamically address current and future flood risk.

3.6 Adoption of UFR approaches in practice

A key question that remains unanswered is why the UFR approach or ADA has not been adopted by practitioners and decision-makers in FRM. For an approach to be adopted, ideally it would be easy to use, computational efficient/inexpensive, and incorporate enough detail for credible outputs. It is also important to consider the modelling skills required to implement the approach as a normal pre-requisite for FRM. For instance, although the UFR is a straightforward method for FSA identification, it requires multiple iterative runs (e.g. one for every cell at each time step, see Table 1). The resource and time challenge of running distributed and semi-distributed models is already a key limitation for hydrological modelling in FRM (Petrucci and Tassin 2015; Teng et al. 2017). UFR inspired approaches are, therefore, likely to be viewed as computationally expensive and inefficient, depending on the detail and type of model used (Apel et al. 2009; Komolafe et al. 2015; Teng et al. 2017; Nkwunonwo et al. 2020). In developing countries, flood risk managers may not have access to a simple hydrological model for UFR or enough data for ADA. Even if a model was made available, the complexity and additional resource required may prove enough to discourage practitioners from adopting the approach over more traditional flood modelling techniques (Petrucci and Tassin 2015).

Although conceptual models can minimise the computational power needed and establish practical UFR type approaches, the simplicity and coarse representation of catchment parameters potentially raise questions regarding the accuracy of the results and the scale of applicability for interventions. They therefore face further debate regarding the required resolution of modelling for efficient FRM (Apel et al. 2009; Jajarmizadeh 2014). In recent years, the use of computer graphic processing unit (GPU) parallelisation offers faster simulation times (García-Feal et al. 2018; Kalyanapu et al. 2011; Prakash et al., 2020) and hence have the potential to optimise simulations that use fully distributed models, or UFR approaches. Finally, both ADA and UFR require significant post-processing to communicate the modelling outputs effectively and meaningfully, and this further raises the issue of resources and skills available for such a task to be undertaken.

4 Conclusions and next steps

This paper presents a systemic review of methods of flood source area (FSA) identification. FSA identification approaches can be categorised under unit flood response (UFR) method and adaptation-driven approaches (ADA). The UFR approach identifies FSA by assessing the contribution of the sub-catchment or cell units to the flow and volume at the catchment outlet through iterative simulations. The UFR approach presents a methodological framework for FSA identification that is flexible and can be applied using varied hydrological models. However, the approach is not fully developed, as there is little or no guidance on the size of units and the impact of various parameters within those units.

ADA studies are object driven, such that FSAs are identified to implement flood risk intervention, i.e. source control measures. However, these studies are limited in number and therefore this approach requires more attention in the future. The past decade has seen advancements in methodologies designed to identify FSAs, indicating that there is a recognised need to look beyond just the affected areas of flooding. The review of the approaches in this paper represents our current knowledge of FSA identification. Despite the advancement of the approaches used to identify FSAs presented in this paper, the application of the approaches remains a challenge. To this end, the future of FSA identification is most likely a balance between cost, computation efficiency, and inclusions of missing processes. Continuous improvement in technology, however, shows the potential of reducing computational demand as a major barrier in flood risk studies. We have identified six significant avenues that remain unexplored and that have the potential to improve the current approaches of flood source area identification:

(1) Investigating the impact of unit cell sizes on the identification and distribution of FSAs.
(2) Understanding the implications of using different flood models for identifying FSAs.
(3) Identifying the impact of subsurface drainage on FSA.
(4) Addressing the issue of connectivity and hydraulic conveyance when introducing source control measures using FSA Identification.
(5) Climate change and future adaptation as per the UFR approach in practise.
(6) Adopting UFR in mainstream practice.

Consideration of the above-stated points will improve our understanding of the approaches reviewed in this paper significantly, providing a greater understanding of flood processes.

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