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Title A Systematic Review of Approaches for Modelling Current and Future Impacts of Extreme Rainfall Events Using Green Infrastructure

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Abstract

A range of modelling approaches has been developed to assess how green infrastructure could mitigate the effects of extreme rainfall events. This paper seeks to develop this agenda by reviewing how these modelling approaches incorporate, consider, and appraise information of value to land-use planning, policy, and practice to better understand why their implementation is infrequent and to help develop a research agenda. Our findings indicate that the information generated by current GI modelling approaches are not well integrated into the demands of land-use planning, and may more reflect the information availability than useability. We find that modelling outputs do not tend to generate the type of high resolution information covering the appropriate spatial and temporal scales that is needed to best support planning decisions. There are also gaps in the assessment of future climate risks, such as increased rainfall intensity, and how this links to future pressures, such as escalating urban growth and development demands, and the interaction between the two areas. The paper concludes that to increase the implementation of green infrastructure, modelling researchers should work more closely with decision-makers to better link data on the effects of GI to the politics involved in their implementation in planning decisions, particularly how trade-offs occur over different scales and times, and between sectors.

Key words: flooding, low-impact development - LID, stormwater management, land-use planning, urban drainage, climate change

Introduction

Flood damages have increased through time and flood risks continue to rise due to issues such as ongoing urbanisation in flood-prone areas, a lack of integration between land-use planning and flood risk management, and ageing stormwater infrastructure unable to deal with intensified runoff loads (Sohn et al., 2019). Recently, green infrastructure[1] (GI) has

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[1] Green infrastructure refers to a multifunctional and interconnected network of natural areas and open

emerged as a promising flood risk management alternative to grey infrastructure[2], particularly given its potential to deal with extreme rainfall events and associated flood risks (Arnone et al., 2018). It is argued that GI can minimise flood risks because it may reduce demand loads on stormwater infrastructure, especially GI alternatives that can increase rainfall infiltration and retain and store stormwater runoff (Jia et al., 2015).

Nonetheless, widespread GI implementation still faces resistance. As an emerging approach, there is limited empirical evidence of its effectiveness in managing flood risks (Thorne et al., 2018). In particular, the selection of GI alternatives requires significant experimental and modelling investigations to test their efficiency in addressing flood risks, which are context specific and not easily transferable (Baek et al., 2015). There are also unresolved questions related to both implementation and maintenance costs (Jia et al., 2015). Given this context, it is unsurprising there is limited adoption and implementation of GI alternatives into land-use planning (O'Donnell et al., 2017; Pappalardo et al., 2017). The deficit between potential and practice suggests that there is a substantial knowledge gap, not only relating to GI effectiveness, but also in promoting and prioritising GI in long-term growth plans, planning policies, and decision-making processes. This is becoming ever more urgent considering the growing threat from rainfall intensification as a result of climate change (Gill et al., 2007; Hislop et al., 2019), and the new urbanisation demands associated with addressing the housing crisis in many countries (White and Nandedkar, 2019). This also suggests that to better inform land-use plan-making and plan-implementation, information on the effectiveness of GI in flood minimisation needs to provide context specific granularity at both spatial and temporal scales, along with more practical issues, such as relating to their space requirements, to gain support from developers and decision-makers.

The spatial granularity is important because such information needs to be translated into the various land-use overlays and risk assessments routinely used in development control and land-use planning (LeGates et al., 2009; Zevenbergen et al., 2008), as well as to clarify potential trade-offs between policy arenas (e.g. housing, nature conservation, transport) (Busscher et al.,

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spaces managed by humans that aims to preserve principles and functions of natural ecosystems and related ecosystem services (Benedict, M.A., McMahon, E.T., Mark, A.t.C.F., Bergen, L., 2006. Green infrastructure : Linking landscapes and communities. Washington: Island Press, Washington, Salata, K., Yiannakou, A., 2016. Green infrastructure and climate change adaptation. Tema 9(1), 10-27.).

[2] Grey infrastructure relates to human-made infrastructure and includes measures relating to build structure such as dams and levees (Soz, S.A., Kryspin-Watson, J., Stanton-Geddes, Z., 2016. The role of green infrastructure solutions in urban flood risk management. Urban Floods Comunity of Practice.).

2019). The temporal granularity is required because this information needs to be future-oriented in order to balance costs between current and future ratepayers, and consider the range of climate change futures to help development avoid, reduce or better manage flood risks (Campbell, 2006; Quay, 2010; Woodward et al., 2014). While it seems obvious that strategic land-use planning[3] considers future impacts and risks, traditionally, decisions have been made based on past events (Duinker and Greig, 2007; Kelly et al., 2004; O' Brien and O' Keefe, 2013). For example, there is a tendency to see a 'Tyranny of the Present' (White and Haughton, 2017) as many localities use historical flood events to establish set rules and regulations for development control, and struggle to incorporate uncertain future risks into long-term growth plans (Schuch et al., 2017). Lastly, when applied to urban form and decision-making, the analysis of GI should also assess their cost-effectiveness (Lemes de Oliveira, 2019). This information is particularly useful to assess not only how GI implementation can be more economically efficient in comparison to other measures, but also whether the adoption of GI alternatives is a realistic and politically acceptable use of that particular space (Block and Strzepek, 2010).

As GI became an emerging field of study, a plethora of modelling approaches has been developed to assess its effectiveness, including to minimise flood risks (Alves et al., 2019). A consistent analytical framework for assessing the effectiveness of GI in planning, however, is still missing, perhaps due to the variety of functions GI can serve and the different user groups (Salata and Yiannakou, 2016). This paper seeks to address this gap in knowledge by providing a systematic literature review incorporating (i) how different approaches for modelling current and future impacts of rainfall events incorporate GI, (ii) how models addressed differing spatial and temporal scales in their analyses, and (iii) what aspects related to GI design and assessment were considered by differing models. In doing so, we also sketch out a potential research agenda; one which we hope holds potential to help close the gap between both modelling and planning disciplines, and between science and implementation more generally.

Method

Given the range of studies and methodologies aiming to model the current and future impacts of rainfall events using GI alternatives, we undertook a systematic review of literature to

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[3] Strategic land-use planning is a systematic process that aims to prepare cities for future social and environmental change and ensure current and future development and growth management is planned accordingly (Khalil, H.A.E.E., 2012. Enhancing quality of life through strategic urban planning. Sustainable cities and society 5, 77-86.).

assess the parameters used by different modelling approaches (Paré et al., 2015). A systematic literature review is an established method for finding, analysing and evaluating information on a specific topic (Bilotta et al., 2014). While it was first applied to the medical sciences, the method has gained popularity in studies related to the environment (Mallett et al., 2012). In particular, it is now accepted as an effective method to summarise information related to a specific field because it provides textual evidence, helps remove researcher's bias, and adheres to scientific rigour, especially reproducibility, transparency and reliability principles (Bilotta et al., 2014; Mallett et al., 2012). This paper followed the steps proposed by Bilotta et al. (2014): pre-identification, identification of potential studies, screening and eligibility, and inclusion.

Pre-identification

A search of literature first investigated studies that incorporated GI in flood modelling to assess differing approaches for modelling current and future impacts of extreme rainfall events. These were identified through a systematic search of peer-reviewed literature (Web of Science and Scopus databases) following the protocol of Preferred Reporting Items for Systematic Literature Reviews and Meta-Analyses (PRISMA) (Moher et al., 2009). The initial search terms used were: (i) “green infrastructure” + “modelling”, and (ii) “LID” + “modelling”. Depending on the central goal of the study, a wide range of approaches to flood modelling were found: from vast and sophisticated mathematical and statistical models, through to multi-methods models combining numerical and non-numerical evaluations. This first screening resulted in more than 5,000 returns. It was, therefore, necessary to narrow that down to those which considered modelling impacts of extreme rainfall events using GI options. A second search was therefore undertaken to identify key definitions of terms and concepts relating to modelling impacts of extreme rainfall events using GI techniques. A series of steps then followed to refine the initial search results and select studies for further content investigation (see Figure 1).

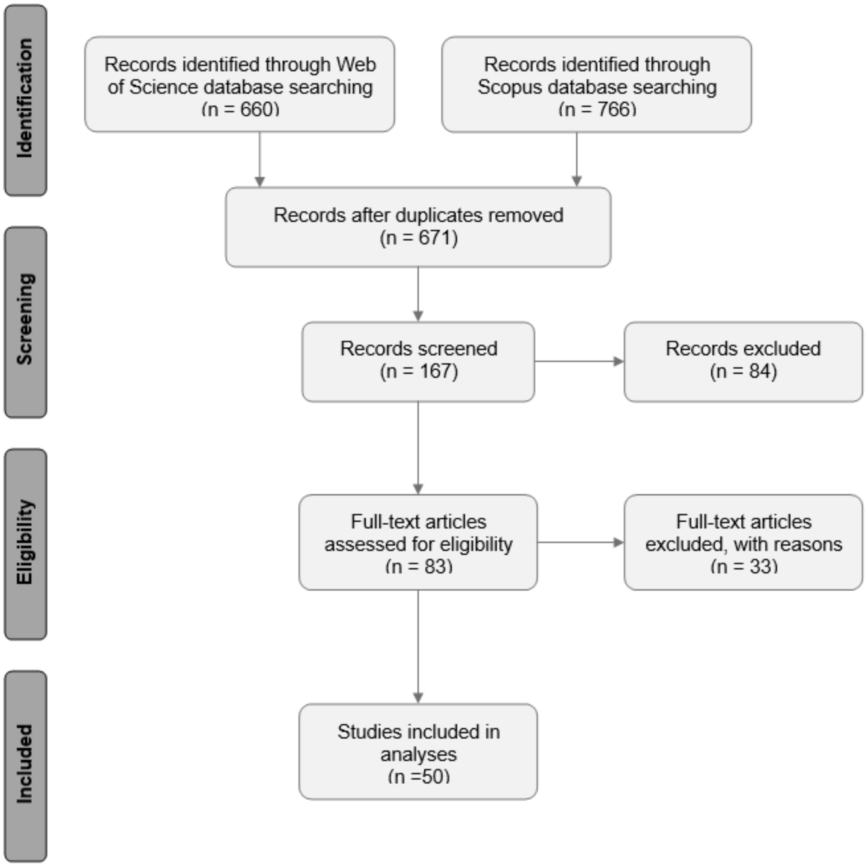

Figure 1 - Flow diagram showing the different steps of the systematic literature review refinement process

Identification of potential studies

The pre-identification step informed the selection of key terms used to refine the search and narrow down initial results to a manageable size. Terms were now defined based on three questions:

(i) How do different approaches for modelling current and future impacts of rainfall events incorporate GI?
(ii) How do models address differing spatial and temporal scales?
(iii) What aspects related to GI design and assessment are being considered?

The suite of terms used included a combination of relevant terms, namely: “modelling” + “Green Infrastructure” + “storm” or “modelling” + “LID” + “storm” or “modelling” + “WUSM” + “storm” or “modelling” + “source control” + “storm” or “impacts” + rainfall” + “Green Infrastructure” or “impacts” + “rainfall” + “LID” or “impacts” + “rainfall” + “WUSD” or “impacts” +

“rainfall” + “source control” or “Green Infrastructure” + “flood risk” + “management” or “LID” + “flood risk” + “management” or “WUSD” + “flood risk” + “management” or “source control” + “flood risk” + “management”. The terms relating to GI aspects followed the most used terminologies reported in the study by Fletcher et al. (2015), including: Low Impact Development (LID), Green Infrastructure, Source Control, and Water Sensitive Urban Design (WSUD). Best Management Practices (BMPs) were excluded because their primary focus is on pollution prevention (Fletcher et al., 2015) and not flood risks or effects from extreme rainfall events. The collocation of keywords followed a sequence guided by key terms related to the key concepts underpinning this paper: flood modelling, climate change impacts, and GI terminologies. The clear identification of such terms ensures the method is reproducible and the outcomes transparent. This yielded 660 results in the Web of Science and 766 in Scopus published between 2013 and 2019. A summary of the search results based on different combinations of search terms is shown in Table 1.

Table 1 - List of databases, keywords, and number of results used in the preliminary search.

Search Terms	Web of Science	Scopus
modelling AND green infrastructure AND storm	85	130
modelling AND LID AND storm	167	172
modelling AND WSUD AND storm	7	11
modelling AND source control AND storm	26	39
impacts AND rainfall AND green infrastructure	79	66
impacts AND rainfall AND LID	170	205
impacts AND rainfall AND WSUD	12	10
impacts AND rainfall AND source control	18	21
green infrastructure AND flood risk AND management	78	85
LID AND flood risk AND management	13	22
WSUD AND flood risk AND management	3	5
source control AND flood risk AND management	2	3
Total	**660**	**766**

Screening and eligibility

When combined, and after removal of duplicates, the dataset included 671 publications from different fields. These included environmental management, hydrology, urban ecology, industrial ecology, ecological engineering, flood risk management, environmental modelling, and ecological modelling. Titles and abstracts of the 671 publications were assessed to determine whether they were suitable for inclusion in the core review. This enabled the identification of studies investigating the use of single and/or combined GI alternatives as a way of minimising flood impacts. This step resulted in 167 publications which were then screened in full. Those with no primary focus on flooding (e.g. water quality, material performance, numerical modelling, groundwater, runoff coefficients, health, rain gage data, soil, evapotranspiration, erosion, or thermal characteristics) were excluded, resulting in the selection of 50 studies to be included in the final review (see Supplementary Material A for a full list).

Content analysis

The next stage was a content analysis. This approach is designed to understand the essence of written or visual sources by systematically assigning their content to pre-defined, comprehensive categories, and then both quantifying and interpreting the outcomes (Byrne, 2017; Neuendorf, 2017; Payne and Payne, 2004). Using NVivo 12 Pro, the content of selected articles (n=50) was first analysed and grouped based on the aim of the studies (see Table 2), as the objective of the study can be a determinant on the modelling approach applied.

Table 2 - Key aims identified across publications selected

Aim of study	Calculation and simulation of the hydrological performance of GI
	Application of varying types and combinations of GI
	Estimating flood risk/damage
	Governance perspective of the implementation of GI
	Application of GI for Urban Water Management (UWM)

The content analysis then followed a coding frame (Byrne, 2017) based on the set of exploratory questions. The exploratory questions intended to investigate the extent to which the modelling approaches generated outputs that could inform land-use planning decisions. To this end, the questions provided an analytical framework to investigate how publications dealt with aspects related to spatial and temporal scales, as well as GI design and assessment in their modelling approaches (see Table 3). This was designed to facilitate the link to land-use planning processes and practices, and to identify similarities and differences between articles. They also enabled the assessment of types of data sets used by publications to gain a more advanced understanding of how each model dealt with current and future impacts of rainfall events, and how this was applied to different GI types and combinations. The coding frame was regularly reviewed by the authors based on the actual content of the publications to improve its reliability and content coverage so as to ensure all evidence was collated and summarised (see Supplementary Material B for further information regarding the coding process).

Table 3 - Themes and exploratory questions used to analyse publications content

Theme	Exploratory questions
Spatial Scale	What is the spatial scale covered by the study (e.g. whole catchment, single waterway)?
	What kind of urbanisation pattern does the study focus on (e.g. urban infill, peri-urban, or greenfield development)?
	What types of land-use are included in the study (e.g. residential, commercial, industrial)?
Temporal Scale	What range of historical rainfall data is used by the study?
	What range of future rainfall data projection is used by the study (e.g. climate change projections)?
	How does the study deal with past and future land-use/land cover change?
GI Design and Assessment	How does the study design and assess GI alternatives (e.g. single option, multiple options not combined, or combined multiple options)?
	How does the study deal with data paucity and quality?
	What GI implementation aspects are discussed (e.g. cost analysis, an optimal combination of GI, runoff management, suitable locations)?

Results

The global reach of the selected publications shows the fundamental challenge rainfall extremes present for urban areas, with a predominance of studies carried out in China (19) and the U.S.A. (13). Few publications (three out of 45) focused on more than one case study location, including across multiple countries. As may be expected in an emergent field, most of the studies were published between 2017 and 2019 (36 out of 50), with 2019 accounting for seven, 2018 eighteen, and 2017 eleven. Detailed information about all 50 studies, including key findings related to the application of the exploratory questions to selected publications and overall results from the content analysis can be found in the Supplementary Material C, D, E and F.

Choice of modelling approach based on study aims

While GI has a broad remit, two out of the five aims identified in Table 2 were predominant amongst the publications. These focused on providing data relating to the calculation and simulation of the hydrological performance of GI, and the application of varying types and combinations of GI. The objective of the study was found to be a crucial component in the choice of the approach used to model extreme rainfall events. In particular, two main families of approaches were identified for modelling impacts of rainfall events: hydrological models and social-technical perspectives.

Types of hydrological models and social-technical perspectives

While varied in the way GI was incorporated, hydrological models dominated the strategies used to evaluate the effects of rainfall events in comparison to social-technical perspectives (45 out of the 50 studies used hydrological models as their key modelling approach). All of the publications using hydrological models focused on two aims, namely: calculation and simulation of the hydrological performance of GI, and application of varying types and combinations of GI. For example, Cipolla et al. (2016) used a hydrological model to analyse the performance of green roofs as an opportunity to manage stormwater runoff after urbanisation, simulating a long-term hydrologic response (over one year), and comparing the results to an adjacent impervious roof of the same scale. Goncalves et al. (2018) assessed to what extent different GI alternatives were able to reduce flood risk by developing feasible scenarios where GI units were placed throughout the study area and comparing the results against a baseline scenario. The approach given by the publications using hydrological models connect the use of GI options to the hydrology and engineering fields, rather than to land-use planning or as an instrument to minimise the effects of climate change.

Hydrological models are effective in describing water processes at the catchment or waterway level (e.g. precipitation, flood, runoff) and in determining the requirements for the conservation and management of water resources (Parra et al., 2018; Rusli et al., 2015). They are usually designed for multiple spatial and temporal scales and allow a variety of GI design and assessment options. Potentially, this is highly relevant to inform land-use planning decisions as they can provide various scenarios to evaluate different scales and GI assessments. However, they tend to oversimplify the real world (Dietrich et al., 2016) and modelled processes (Parra et al., 2018), as well as ignore the exchange of groundwater (Pellicer-Martínez et al., 2015). They also tend to emerge from technical disciplines that may not typically capture and consider the political trade-offs that characterise discussions over differing land-use futures.

Three studies adopted social-technical perspectives with specific aims (e.g. estimating flood risk/damage, governance perspective of the implementation of GI, and application of GI for

Urban Water Management). Liu and Jensen (2018) used a multi-level perspective to investigate the role of GI in urban water management practices of five cities famous for their progressive approach: Singapore, Berlin, Melbourne, Philadelphia, and Sino-Singapore Tianjin Eco-city in China. The authors adopted an analytical framework based on transition theory to analyse the main challenges for GI implementation. Schifman et al. (2017) suggested a Framework for Adaptive Socio-Hydrology in which GI planning and implementation advanced from a purely hydrological viewpoint to an integrated social-hydrological approach. In contrast to other research, their study sought to provide an integrated, multifaceted decision-making process rather than focusing on highly centralised stormwater management aspects that are often disconnected from other elements of urban landscapes. O'Sullivan et al. (2015) used Life Cycle Assessment (LCA) to quantify the environmental impacts associated with materials, construction, transport and maintenance of GI alternatives. The authors evaluated the LCA of GI alternatives to provide a guiding tool for practitioners such as planners, engineers and decision-makers. The analysis of these three publications indicated that the adoption of social-technical perspectives can cover several aspects, but they did not include issues connected to why GI has had little practical influence as a means to mitigate extreme rainfall events.

There is potential in this area though. Social-technical perspectives are efficient in analysing elements dependent on the behaviour of those who use it (Lamond and Everett, 2019). Therefore, these approaches can provide a deeper understanding of how GI design alternatives, co-creation and incorporation into dynamic socio-ecological-technical processes can be improved (Ward et al., 2019) and how GI alternatives impact (or are impacted by) land-use planning. Such strategies can enhance the awareness of practitioners, individuals and communities, which is important in recognising a diversification of assessments (Ward et al., 2019). In particular, they are useful in estimating flood risk/damage, evaluating governance arrangements for implementing GI, and the application of GI for urban water management. Some weaknesses to note include not accounting for co-benefits produced (O'Sullivan et al., 2015), missing wider perspectives or data that could have linked GI design with existing resources (Schifman et al., 2017), and challenges in incorporating future rainfall data and cross-scale dynamics.

Two studies used a combination of approaches (hydrological modelling and social-technical perspectives). Song and Chung (2017) developed a multi-criteria decision analysis framework in order to prioritise sites and types of GI alternatives, coupling it with a hydrological model called Storm Water Management Model (SWMM). While Yang and Chui (2018) first ran a hydrological simulation using SWMM and then adopted a relative performance evaluation method (RPE) to assess hydro-environmental impacts of GI techniques in a case study in Brooklyn, New York. While rare, studies aimed at calculating and simulating the hydrological performance of GI, or applying various types and combinations of GI, can bring benefits from the use of both families of approaches (Goncalves et al., 2018; Schubert et al., 2017; Wang et al., 2019).

A range of models was used by hydrological and social-technical approaches to assess current and future impacts of rainfall events, but there was a clear dominance in the use of SWMM. Some studies used single models (e.g. Ahiablame and Shakya (2016) and Eckart et al. (2018) focused only on SWMM, and Jia et al. (2015) utilised SUSTAIN), while others utilised a set of models. For example, Zhu and Chen (2017) used SWMM and a particle swarm optimization algorithm. Song and Chung (2017) used a combination of models, including SWMM, TOPSIS, Delphi method, and multi-criteria decision analysis (MCDA). By using a combination of models or utilising different complementary models it is possible to minimise the gaps present in each of the models, and linking them to land-use planning demands and parameters, resulting in a more realistic simulation.

Application of hydrological models

Spatial scale

The majority of studies using hydrological models (35 out of 45) assessed waterways at different spatial scales, typically single waterways (26) or whole catchments (9). For example, Yau et al. (2017) based their research on Waterway Ridges, a four-hectare pilot urban development project in Singapore with a single waterway (Punggol Creek). Their study investigated different types of GI alternatives which were innovatively integrated into the design at the precinct level. With respect to whole catchments, Ahiablame and Shakya (2016) carried out a study in the City of Normal-Sugar Creek Watershed, McLean County in Central Illinois, due to its high urbanisation rate and good data availability. Their study assessed to what extent large scale adoption of GI alternatives in an urban watershed could increase flood reduction capabilities.

There was variation in the way the different models used by the publications dealt with the spatial scale, but the majority of the studies used SWMM (25 out of 37). Damodaram and Zechman (2013) used a combination of links and nodes representing the stormwater infrastructure, composed of a box and circular storm sewers, open channels, and a single natural waterway in order to design a GI scenario for managing peak flow alterations. Two publications used the L-THIA-LID model to study the entire catchment. For example, Eaton (2018) used various combinations of GI strategies to evaluate stormwater reduction for the whole Alley Creek watershed in New York City.

Concerning urbanisation, 16 out of 45 publications studied waterways within urban infill developments. For example, Baek et al. (2015) studied a commercial area in Gwangju, Korea, characterised by high imperviousness (approximately 85%) to define an optimal combination of GI alternatives to reduce flood and improve water quality. Nine out of 45 publications investigated entire catchments located in peri-urban areas. Kong et al. (2017) used a case study located west of downtown Bazhong which was predominantly rural, covered by farmland (49.2%), forest (42%), with housing, roads, and water bodies only representing 3% of the total area (838 ha). Their research focused on several sub-catchments (80 sub-catchments in the pre-development state and 118 sub-catchments in the urban development scheme) to model the potential effects of large-scale implementation of GI alternatives. Few studies assessed waterways in greenfield developments (four out of 45 studies). None used a single waterway as their spatial scale. For example, Bai et al.'s (2018) study area was Sucheng District, located in the north of Jiangsu Province, China, which was divided into 83 sub-catchments and the river channel (treated in the study as a pipeline) to evaluate the impact of GI strategies on the reduction of surface runoff and flood volume.

Urbanisation patterns appear not to be a key determinant employed by the studies in the selection of models used to assess GI strategies; rather their selection relied on models' capability and richness of functions with SWMM being the predominant choice. Some of the main capabilities included the integration with GIS, the number of GI alternatives available, and the ability to input rainfall data. However, none of the studies included urbanisation patterns. Interestingly, while models do not present specific capabilities or functions concerning urbanisation patterns, these were used as external information to determine the size of the study area and the selection of GI alternatives. For example, Liao et al. (2013) used SWMM to study a highly urbanised area in Shanghai, China, to simulate runoff reduction, peak flow rate reduction and waterlogging volume reduction using five GI alternatives. Kong et al. (2017) used SWMM to study a peri-urban area with predominantly rural cover in the west of downtown Bazhong to assess the hydrological responses of stormwater runoff related to four different land-use conversion scenarios using GI alternatives. Burszta-Adamiak and Mrowiec (2013) applied SWMM to an experimental greenfield development site in Poland to investigate the hydrological performance of green roofs in reducing surface runoff and flood risks due to snowmelt and heavy rainfall.

Land-use types were categorised and investigated by the majority of the studies (28 out of 45). These predominantly included residential (19), commercial (10), industrial (8) and open space (10). Most of the studies (25 out of 28) used mixed land-use types. Li et al. (2019) focused on residential areas with condominiums and parking lots, residential areas with condominiums but no parking lots, residential areas with single-family houses, industrial areas, and commercial areas for testing GI options to assess the impacts of land-use on runoff. Residential land-use was evaluated by three studies as a single land-use type. For example, Zhu and Chen (2017) used a typical highly-developed residential area in Guangzhou, China, to evaluate the effects of GI techniques on urban flooding under different rainfall intensities.

Temporal scale

Most of the studies using hydrological models assessed rainfall at different temporal scales (36 out of 45) - that is, historical (28), historical and future (five) or future rainfall data (two). The majority of the studies considering historical rainfall data in their models used up to one decade as their temporal analyses (19 out of 28), followed by three decades or more (seven), and two decades (two). Using historical data, Palla and Gnecco (2015) calibrated and validated their model based on seven rainfall events collected between February and May 2005 to analyse how GI techniques performed as source control for peak flow reduction, volume reduction, and hydrograph delay. Utilising historical and future data, Zhang et al. (2019) applied a downscaling method to assess the reliability of GI techniques in pollution reduction, flow frequency mitigation, and potential to provide an alternative water supply comparing various future climate conditions (2040-2049) against the base-line period (1995-2004). Using future projections, Zhang et al. (2018) assessed hydrological effects and performance of GI options in four urban catchments based on differing scenarios for the period between 2040 and 2059.

Some studies (10 out of 45) used predefined rainfall models in their simulation without considering any temporal scale. For example, Bai et al. (2018) adopted the Chicago Rainfall Model, a widely used uneven rainfall model based on the intensity-duration-frequency relationship, to simulate the effect of four different types of GI scenarios on urban flooding.

Climate change projections were specifically assessed by few studies (only seven out of 36). Five considered historical and future rainfall data, and two focused only on future rainfall projections. Concerning future rainfall, studies focused on ranges of three or more decades (seven). Chen et al. (2017) considered climate change conditions for the 2021-2040 and 2061-2080 scenarios to identify optimal GI layout and enable decision-making to minimising flood risk. Some studies (three out of seven) used both historical and future data. Wang et al. (2019) used selected climate change scenarios for 2020-2050 and compared them with scenarios from 1997-2000 to assess the performance of porous pavement and bioretention cells for stormwater management.

Few studies (12 out of 45) assessed the temporal scale in association with potential land use or land cover change. Mao et al. (2017) reclassified land use data to match time-series input (2008) in order to assess the ecological benefits of aggregated GI techniques for stormwater runoff control. Li et al. (2019) tested two land-use scenarios simulations (2011 and 2050) to assess the effects on surface runoff of GI techniques under different land uses.

GI design and assessment

There was variation in the number of GI options considered by the publications, with most studies incorporating three or more GI techniques into their models (25 out of 45). The alternatives most investigated were bioretention (30), permeable pavement (29), green roofs (24), and vegetated swales (15). Wang et al. (2016) simulated future scenarios to assess cost-effectiveness of bioretention on stormwater as a response to urbanisation and climate change. Although using a generic methodology, the authors acknowledged that the performance of bioretention in an urban catchment is more efficient for dealing with urbanisation changes than for climate change effects. Wang et al. (2019) assessed the performance of bioretention cells and permeable pavements for stormwater management as a response to climate change in Guangzhou, China. The authors found that both permeable pavement and bioretention cells could reduce runoff volume and peak discharge in response to rainfall events in short periods, but not for heavy storms with a longer return period. Bai et al. (2018) tested four different types of GI scenarios to control runoff in urban areas: (i) no GI technique; (ii) GI technique based on infiltration; (iii) GI technique based on water storage; and, (iv) GI technique based on a combination of infiltration and water storage. The combined model (infiltration + storage) presented the best performance in runoff reduction. The research also acknowledged that GI alternatives could reduce the risk of urban flood impacts caused by extreme rainfall events - if planned correctly.

The difference between the number of GI alternatives used by the hydrological models and the socio-technical perspective seems to rely more on authors' choice than on some features of the models. Although there are some pre-defined GI options available for hydrological models, none of the publications have used all the possible alternatives in the same study. In practice, differing GI features do, however, take up very different space within a city, and so there are considerable political and resource implications of these modelling selections.

The majority of studies assessed combined GI options (31 out of 45). Li et al. (2018) selected GI alternatives based on differing characteristics of the study area, including buildings with flat green roofs, buildings with sloping roofs and rain barrels; parking lots and impervious roads with porous pavement; and existing green gardens along roadways converted to bioretention cells. Zhu and Chen (2017) investigated the effects of rain gardens and bioretention cells on flood control under different rainfall scenarios. These included different return periods (one year, five years and ten years), rainfall durations (1h, 1.5h and 2h) and rainfall peak coefficients (0.375, 0.5 and 0.8) to evaluate the changes before and after GI. The outcomes demonstrated that with the increase in rainfall peak coefficient, intensity and duration, the control effects of both GI options tend to be reduced.

Fewer studies acknowledged single options of GI (eight out of 45) or multiple but not combined GI alternatives (three out of 45). Ercolani et al. (2018) analysed the implementation of green roofs as source control solution for mitigating the impacts of urbanisation. The authors assessed the effect of four spatially homogeneous installations of green roofs (25%, 50%, 75%, and 100% of roofs area covered) and a spatially heterogeneous targeted conversion (concentrating green roofs where conduits were more prone to filling) using six storm events differing in both duration and return period. The heterogeneous scenarios presented better results in terms of reduction rates of peak flow and volume at the network outlet. Li et al. (2019) explored the cost-efficiency scenario for runoff water quantity reduction of green roofs, rain cisterns, rain barrels, porous pavement, bioretention cells, grassed swales, wet ponds, and dry ponds. The authors tested the efficiencies of combined individual GI types and found that the combination of grassed swales, rain barrels, dry ponds, and porous pavement were the most cost-efficient scenario for reducing the amount of water runoff.

Data input and calibration is a complex step in GI design and assessment, and several studies used different levels of simplification to calibrate and run their models (23 out of 45). Hu et al. (2019) tested a range of storm events with differing intensity-duration-frequency curves for rainfall to evaluate the hydrological performance of GI techniques using an empirical formula of rainfall and Chicago hyetograph method for rainstorm design. No effort was made to calibrate the model due to the lack of observed data. Furthermore, model parameter values were obtained from the published literature. Fu et al. (2018) used remote sensing to analyse land-use and land cover change types and runoff variations in response to urbanisation at different spatial scales using scenarios with and without GI alternatives, including basin, watershed, and city scales. Their results demonstrated that at the basin scale, land-cover changes interpreted from satellite images were very helpful for identifying watersheds with urbanisation hotspots that might have larger runoff outputs. However, at the watershed scale, the resolution of the land cover data was too low and needed to be replaced with observed land-use data using sophisticated hydrological modelling to evaluate runoff for scenarios with and without GI alternatives at different spatial scales.

The most recurrent GI implementation aspects investigated by the studies were: (i) cost analysis (14 out of 45); (ii) optimal combination of GI alternatives (10 out of 45); (iii) runoff management efficiency (43 out of 45); and, (iv) suitable locations for implementing GI alternatives (four out of 45). Eckart et al. (2018) used three storm events (with different return periods) to test five different GI implementation scenarios, including rain barrels, porous pavement, bioretention options (both engineered bioretention and simple rain gardens), and infiltration trenches. After evaluating the performance of GI for all three design storms for each of the five GI implementation scenarios, the authors concluded that infiltration trenches would be the most cost-effective GI alternative for reducing peak flow. Baek et al. (2015) proposed the optimal size for each GI alternative (bioretention, green roof, infiltration trench, porous pavement, rain barrel, and vegetative swale) by conducting intensive stormwater monitoring and numerical modelling in a commercial area in Korea for minimising flood effects.

With respect to runoff management efficiency, Sun et al. (2014) showed that GI techniques were effective in controlling stormwater flow for small rainfall events but not for larger rainfall events. Qin et al. (2013) analysed the effects of three GI alternatives (permeable pavements, green roofs and swales) to control urban flooding and compared the results with conventional drainage system design. Their results indicated that the tested GI scenarios were more effective in flood reduction during heavier and shorter storm events, and that permeable pavements performed best during a storm event with a middle flow peak, green roofs performed best with a late peak, and swales performed best with an early peak. Suitable locations for GI alternatives were briefly assessed (four out of 45). Eaton (2018) identified that the search for the optimally effective GI combination should start with the most effective techniques for each land-use type. Results were responsive to the relative location of various land-use types and showed that bioretention and rain gardens provided the most significant reduction on a residential watershed. A key observation is that the low prevalence of location and combination aspects within these models, despite being a core consideration for land-use planning, may help explain why these elements have struggled to be implemented in practice.

Application of the social-technical perspective

Spatial scale

Spatial scale was assessed by one out of five studies applying social-technical perspectives. Song and Chung (2017) used a case study at a university campus in Seoul, with a single waterway to test a multi-criteria decision analysis (MCDA) framework in order to prioritise sites and types of GI alternatives.

Regarding urbanisation patterns, two out of five publications focused on urban infill. Schifman et al. (2017) proposed a decision-making framework to allow a more interactive process for the installation of GI rather than a ‘one-size-fits-all’ approach by comparing Cleveland and Atlanta, USA. The study showed that a multi-stakeholder, integrated, decentralised network with co-decision project plan resulted in enhanced multifunctionality, enabling resilience in urban systems at multiple scales. Song and Chung (2017), using a case study in South Korea, tested a system capable of simulating and ranking multiple GI scenarios based on hydrological aspects along with social factors, using scenario performance values.

Land-use type is not well represented in social-technical studies. This was only mentioned by Song and Chung (2017), who briefly stated 92.7% of the study area was covered by building, roads, and green spaces, without linking this discussion to long term plans, development pressures, or political priorities. Again, this may help explain why modelling results are struggling to influence land-use planning decisions.

Temporal scale

Fewer studies using social-technical perspectives assessed rainfall at different temporal scales (two out of five), that is, up to one decade of rainfall data (one out of five) and three or more decades (one out of five). None of the publications assessed climate change projections relating to future rainfall data. Yang and Chui (2018) used the hourly precipitation record from 1969 to 2013 at JFK International Airport in New York City) to simulate a long-term hydrological performance of various GI techniques before applying a relative performance evaluation method to assess the hydro-environmental impacts of GI techniques in small urban catchments. Song and Chung (2017) utilised a daily rainfall event between 17 August 2014 and 26 August 2014 to run the hydrological model before applying multi-criteria decision analysis to prioritise site and type of GI selection. None of the studies acknowledged land-use cover change, neither past nor future.

GI design and assessment

Most of the publications applying social-technical perspectives (four out of five) defined GI options, including combined multiple possibilities (two out of five) or a single GI alternative (two out of five). Song and Chung (2017) tested a framework to prioritise types and sites of GI, running scenarios combining bioretention cells, rain gardens, green roofs, infiltration trench, porous pavements, and rain barrels. Yang and Chui (2018) assessed the hydro-environmental impact of bioretention cells and green roofs in different urban areas of New York.

Most of the publications applying a social-technical perspective (three out of five) had to simplify their assessments to deal with data scarcity and quality. Song and Chung (2017) obtained all of the design parameters of porous pavement from previous research results. Liu and Jensen (2018) collected their data from open sources (such as official websites, published plans, documents, and articles) and validated the data using an online questionnaire. O'Sullivan et al. (2015) excluded vegetation data in their model due to the lack of data for rain gardens.

All the studies using social-technical perspectives assessed runoff management efficiency as one of their implementation aspects. Liu and Jensen (2018) verified the GI potential for flood control and climate adaptation to reduce water footprints in Berlin and Singapore, to protect the ecosystem in Philadelphia, and to support potable water saving in Melbourne and Sino-Singapore Tianjin Eco-city. Song and Chung (2017) compared runoff reduction between infiltration trenches and porous pavements. Their results demonstrated that a single GI type can perform differently when applied to different locations and that different GI options can be more effective for different hydrological components. Cost analysis was assessed by O'Sullivan et al. (2015), who found that the incorporation of GI techniques in stormwater treatment reduced the costs of running and building urban stormwater treatment systems.

Discussion

To provide more evidence about how modelling approaches can produce more effective outputs to better advise land-use planning decisions, this systematic review sought to investigate: (i) how different approaches for modelling current and future impacts of rainfall events incorporated GI, (ii) how models addressed differing spatial and temporal scales in their analyses, and (iii) what aspects related to GI design and assessment were considered by differing models. Overall, findings from this study indicate that the information generated by current GI modelling approaches are useful and informative, but not sufficient to stretch beyond their discipline and aid land-use planning in its policy response to climate change risks, including floods (see Table 4 and Supplementary Material G). This gap, both between scientific disciplines and between science and decision-makers helps explain why, despite GI's potential, its implementation is not widespread in land-use planning.

Table 4 - Key findings related to the application of exploratory questions to selected publications

Theme	Exploratory questions	How models are currently addressing themes	
		Hydrological	Social-technical perspective
Spatial Scale	What spatial scale is covered by the study (e.g. whole catchment, single waterway)?	Most studies focused on single waterways.	Spatial scale doesn't appear to be a key consideration. Only one out of five studies assessed it, but focused on a single waterway.
	What kind of urbanisation pattern does the study focus on (e.g. urban infill, peri-urban, or greenfield development)?	Although urban infill developments are the most assessed, urbanisation patterns do not seem to be a key determinant in the choice of models used for analysis.	Although it is not a key determinant for social-technical perspectives publications, two out of five studies assessed urban infill developments as the key urbanisation pattern.
	What types of land-use are included in the study (e.g. residential, commercial, industrial)?	The majority of studies used mixed land-use types, residential being the most recurrent.	One out of five studies used land-use data.
Temporal scale	What range of historical rainfall data is used by the study?	Most of the studies used historical data and a one-decade rainfall range.	Fewer studies assessed temporal scales regarding historical rainfall data. Two out of five studies used historical rainfall data.
	What range of future rainfall data projection is used by the study (e.g. climate change projections)?	Few studies incorporated future rainfall data (seven out of 36) and among those three or more decades of rainfall data were the most used.	No climate change projections relating to future rainfall data were used by the publications.

Theme	Exploratory questions	How models are currently addressing themes	
		Hydrological	Social-technical perspective
	How does the study deal with past and future land-use/land cover change?	Fewer publications assessed land-use/land-cover information (12 out of 45).	No study acknowledged land-use cover change (neither past nor future).
GI design and assessment	How does the study design and assess GI alternatives (e.g. single option, multiple options not combined, or combined multiple options)?	Most studies tested three or more GI alternatives, bio-retention cells and permeable pavement being the most frequent.	Two out of five used combined alternatives, while the same number (two out of five) assessed single options).
	How does the study deal with data paucity and quality?	Different levels of simplification were used to calibrate and run the models.	The majority of publications simplified their assessments to deal with data paucity and quality.
	What GI implementation aspects are discussed (e.g. cost analysis, an optimal combination of GI, runoff management, suitable locations)?	The majority of studies assessed runoff management efficiency as a GI implementation aspect.	All studies focused on runoff management efficiency.

Turning to the discussion, from a spatial dimension we can see that the majority of the selected studies investigated GI options applied to single waterways (e.g. Hu et al., 2019; Schubert et al., 2017; Zhu and Chen, 2017). This is an important finding. Waterways are interconnected within a catchment and the wider urban system; therefore, to improve the quality of information for decision-making we recommend that the spatiality of studies needs to better reflect the spatiality of decision-making (Jayawardena and Marjorie, 2017). More tellingly for land-use planning, urbanisation patterns do not seem to be a key determinant utilised by the publications in the selection of models to test GI alternatives; rather their selection focused on models' capabilities and richness of functions instead. A potential solution to address these shortcomings would be the combined use of the hydrological approach with other methods, such as Technique for Order Preference by Similarity to an Ideal Solution - TOPSIS, Land Transformation Model (LTM), GIS, or others. This potentially could result in a more comprehensive assessment of the effects of extreme rainfall events at the catchment scale and guide land-use planning decisions to both deal with existing built up areas at risk and inform future developments in such areas.

While the advances in hydrological models does allow a straightforward analysis of the spatial distribution of floods, GI, and their effects, which has potential to inform land-use plans and policies about the spatial distribution of risks, the impacts of the implementation of GI and even the spatial understanding of the effects of rainfall events primarily focus on a single catchment. This is probematic because even site-based land-use planning decisions are influenced by wider social and political dimensions and routinely address broader spatial and temporal scales, including climate change (Herath and Wijesekera, 2019; Lemes de Oliveira, 2019; Ran and Nedovic-Budic, 2016). A possible way to close this gap is the co-production of tools with end-users (practitioners such as planners and flood managers), which can not only better evaluate GI techniques at larger spatial scales, but also consider more aspirational future urbanisation trends and acknowledge key political trade-offs (such as between types of land-use) in order to provide more evidence to support where GI application can minimise impacts from those land-use changes.

From a temporal dimension, a significant amount of publications continued to primarily focus on the historical data for both rainfall and land-use and land cover change (Chen et al., 2017; Zhang et al., 2019). While some studies developed future scenarios based on detected trends (e.g. Li et al., 2019), future changes to land-use and land cover systems were not a predominant trend in the publications analysed. Surprisingly, these aspects were even less considered by publications applying social-technical perspectives, which in theory should enable more qualitative assessments with a future thinking perspective in mind, and co-production of tools with practitioners (Jorgenson et al., 2019).

Future risks and uncertainty as a result of climate change are likely to increase in the future, demanding the implementation of urban adaptation measures through land-use planning (Ran and Nedovic-Budic, 2016). Higher rainfall intensities and peak flows, along with prolonged duration of rainfall events and more periodic flooding, are predicted to affect the efficiency of traditional stormwater infrastructure and have considerable implications for land-use planning as well as city budgets (Huang et al., 2018; Zevenbergen et al., 2008; Zhang et al., 2019). For example, with an increase in extreme rainfall events or a predicted increase in urbanisation, areas that do not pose a flood risk at present may be flooded in future. Notably, all studies showed limited incorporation of climate change projections, despite the potential of GI to make a significant strategic contribution in reconciling future development demands with changes in future rainfall (Carter et al., 2018; European Commission, 2013). This is also surprising as models such as SWMM allows the construction and assessment of a wide range of scenarios for simulation and analysis – a significant feature that can incorporate climate change projections. While this presents a considerable gap in knowledge for the scientific community to address, it appears that the tools needed for this (such as SWMM) are already available, but not yet used to their full potential.

The evaluation of the effectiveness of individual GI techniques in mitigating extreme rainfall events among the selected studies was limited, including the assessment of their potential to be implemented in multiple combinations (e.g. Bai et al., 2018; Xu and Liu, 2018; Zhu and Chen, 2017). Few publications have discussed GI effectiveness (e.g. Baek et al., 2015; Chen et al., 2017) and, when doing so, did not incorporate the spatial and temporal scales that are most useful for land-use planning. Several studies have investigated the efficacy of GI (Ahiablame and Shakya, 2016; Eaton, 2018; Mao et al., 2017), but the impact of climate change on GI effectiveness remains uncertain as impacts will likely differ significantly regarding both their spatial and temporal consequences (Sohn et al., 2019; Zhang et al., 2019). This is another area that research could usefully focus on to link to land-use planning. While it may be easier to model individual GI, in reality they would be used in combination, as their spatial demands need to reflect the differing value of land-uses across the urban area. For example, certain GI options are most appropriate where space is at a premium (e.g planter box, permeable pavement) (Lin et al., 2018), but upstream larger options (e.g. urban forestry) may be a viable solution to reduce the demands elsewhere in the catchment (Webber et al., 2019). A systemic view of space (knowing disadvantages, potentialities and inter-connections), options (understanding costs, benefits and drawbacks), and performance (combining alternatives or using single options) is needed.

Finally, a more interdisciplinary approach to GI modelling (discussing uncertainties in various aspects of the land-use planning process and how these uncertainties affect decisions) is needed to support decision-making (Marot et al., 2015; Pauleit et al., 2017). Different models and approaches have sought to recognise problems in decision-making, but there is still lack of integration (Chen et al., 2017), particularly as decision-making regimes vary significantly (Scott, 2019). Water plays a key role in cities and provides multiple links to other urban management areas, including land-use planning (Jayawardena, 2018). In particular, to effectively make our cities more resilient to flooding, land-use planning strategies need be based on the catchment scale, and different urban management sectors (e.g. land-use planning, stormwater management, urban infrastructure) should work more collaboratively (Hughes and Sharman, 2015). For example, the use of catchment as the land-use planning scale has advantages such as self-regulation capabilities, flood control strategies and ecosystem management which can enhance flood resilience (Jayawardena, 2018). Such collaborative, holistic approaches does require improved spatial and temporal analysis of GI effectiveness, as well as information regarding GI implementation, design, and cost. Should we invest now, or wait? Discrepancy in outcomes around GI implementation and uncertainty regarding climate change impacts (Gill et al., 2007) indicate that there is a key knowledge gap in the identification of GI functions and the timing and prioritisation of GI in policies, strategies and decision-making processes. There is still a degree of siloization between academic fields as well as between science and practice, which makes it difficult to widely incorporate GI (Mell and Lemes de Oliveira, 2019; O'Donnell et al., 2017). In reality, land-use planning decisions require high-resolution information at both temporal and spatial scales (Johan et al., 2004; Zhang et al., 2019). They also require thorough understanding of cross-scale processes and interactions at larger spatial scales (such as catchment scales) and across temporal scales (such as the ones related to climate change projections) (Chen et al., 2017; Lafortezza et al., 2013; Yiannakou and Salata, 2017). This type of information is vital for guiding plan-making and plan-implementation, as it is more easily converted into overlays and risk assessments used to inform current and future development control and land-use planning.

In summary, there is no doubt the current suite of models is useful in understanding how the incorporation of GI can affect the risk of flooding. By considering these models in the context of land-use planning, this article is designed to help progress this agenda further and help sketch out a possible interdisciplinary research agenda. Decision-making concerning the use of land, particularly the need to retrofit resilience into existing urban landscapes, is a political process (Busscher et al., 2019). Evidence and risks are carefully weighted, both over different timescales and spatial scales, and over alternative land uses that can also achieve environmental, social or economic goals. Intensification may occur in one place, while greenspaces are implemented elsewhere. By better linking the two, however, we can help hit multiple goals - from climate change adaptation to amenity values for local communities. The evidence here suggests that this will involve designing research differently to better integrate decision-makers with projects, using multiple complementary models, and considering from the onset how to more deeply connect the scope of studies with the realities and trade-offs regarding current and future land-use.

Conclusion

There has been much discussion in the social science GI literature regarding implementation aspects, including its performance and maintenance (Benedict et al., 2006), reconciling the space it occupies with increasing development demands (Young, 2011), quantifying the amenity (McDonald et al., 2005), health or biodiversity values (Kambites and

Owen, 2006), or moving towards strategic multifunctional land-uses (Hansen and Pauleit, 2014). This study extends this discussion by linking the types of modelling approaches used and the approaches they take, with their potential to inform land-use planning, particularly in the context of precipitation extremes.

Adopting a systematic literature review of 50 publications, the paper assessed different approaches to modelling current and future impacts of extreme rainfall events on the urban environment, including under climatic change conditions. It found that there were two main families of modelling approaches: hydrological and social-technical perspectives, and the aim of the study and choice of modelling approaches led to very different ways to evaluate current and future impacts of extreme rainfall events. After reviewing the application of these two families of modelling approaches with respect to how they spatially and temporally incorporated GI, this study identified two key findings that can provide the basis of a future research agenda and potentially overcome barriers to GI implementation. First, the information generated by current GI modelling approaches are not well integrated into the demands of land-use planning, and may more reflect the information availability than useability. Second, there are particular gaps with regard to understanding future risks and pressures, most notably increased rainfall intensity, escalating development demands, and the interaction between the two. It was surprising to note that climate change projections and land-use futures were only rarely included in the models, despite their potentially high value for decision-makers struggling to reconcile competing demands influencing urban development.

Notably, the observed limitation in the inclusion of temporal and spatial scales in the analyses presents a key challenge for both flood risk management and land-use planning, especially considering increased climate change impacts. If current information does not assess the efficiency of GI in minimising future flood risks as a result of extreme rainfall events this may also limit the uptake of GI alternatives by both land-use planning and flood management sectors. In order to be better inform land-use planning decisions, hydrological models assessing GI efficiency need to incorporate a number of features. These include the incorporation of a range of temporal scales, from historical data to current and future, and the spatial scales that are most useful for planners, which are not typically single waterways but focus on changes in land-use patterns, land cover, and future development options. Decision-makers need to know, for example, which GI alternatives (or combination of alternatives) fit better in which part of the city, what are their performance under current rainfall events and climate change forecasts, how land-use interferes in hydrological parameters and what are the best allocation of GI alternatives. Socio-technical approaches could also incoporate stronger social dimensions to their analysis, particularly relating to land-use constraints and climate change projections, especially because low socioeconomic areas tend to be hit the hardest by flood events. The more holistic the assessment of GI information is, the more useful and robust decisions about their widespread implementation will be.

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