Invited Review Paper

A review of the effects of climate change on riverine flooding in subtropical and tropical regions

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ABSTRACT

Tropical and subtropical regions can be particularly severely affected by flooding. Climate change is expected to lead to more intense precipitation in many regions of the world, increasing the frequency and magnitude of flood events. This paper presents a review of studies assessing the impacts of climate change on riverine flooding in the world's tropical and subtropical regions. A systematic quantitative approach was used to evaluate the literature. The majority of studies reported increases in flooding under climate change, with the most consistent increases predicted for South Asia, South East Asia, and the western Amazon. Results were more varied for Latin America and Africa where there was a notable paucity of studies. Our review points to the need for further studies in these regions as well as in Australia, in small to mid-sized catchments, and in rapidly urbanising catchments in the developing world. Adoption of non-stationary flood analysis techniques and improved site-specific socio-economic and environmental model scenarios were identified as important future directions for research. Data accessibility and mitigation of model uncertainty were recognised as the principal issues faced by researchers investigating the impacts of climate change on tropical and subtropical rivers.

Key words | climate change, climate projection, extreme weather, flooding, subtropical, tropical

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INTRODUCTION

Floods are one of the most costly and widespread climate-related natural hazards (Jonkman 2005). Between 1980 and 2009, it was estimated that floods led to the death of 539,000 people and adversely affected the lives of 2.8 billion people (Doocy *et al.* 2013), totalling US$654 billion worth of damage (adjusted for inflation) worldwide (Munich Re 2017). Tropical and subtropical regions are often subjected to some of the worst flooding and this may be exacerbated under climate change. The United Nations International Strategy for Disaster Risk Reduction (2009) reports that the 10 countries most prone to flooding are all located in tropical South and South East Asia, with countries in South America and Africa also widely affected. As there are a number of developing countries in the tropics and subtropics, the effects of flooding may be exacerbated due to poor infrastructure and health care. In Bangladesh, for example, water-borne diseases are responsible for a greater number of flood-related deaths than drownings (Jha *et al.* 2012).

The intensity of extreme precipitation events is predicted to increase throughout most parts of the world under climate change (Groisman *et al.* 2005), potentially leading to an increase in the magnitude of extreme flows. Despite a wide consensus of increased precipitation extremes under rising temperatures, several studies have suggested that this has not led to an increase in flooding, except in small catchments where flashy flows dominate (Wasko & Sharma 2017; Sharma *et al.* 2018). However, trend analysis of extreme flooding events exceeding 100-year levels has shown a significant

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increase towards the second half of the twentieth century (Milly *et al.* 2002), while analysis of less extreme events has generally indicated a decreasing trend, particularly for large catchments (Do *et al.* 2017). Modelling on a global scale suggests that the increasing trend of the most extreme floods may continue into the future (Hirabayashi *et al.* 2013). Changes in the magnitude of these extreme flooding events will have major implications for landholders, flood mitigation strategies, and infrastructure design. Quantifying these effects allows engineers and managers to consider changes to urban and infrastructure design standards based on a range of possible future eventualities and scenarios.

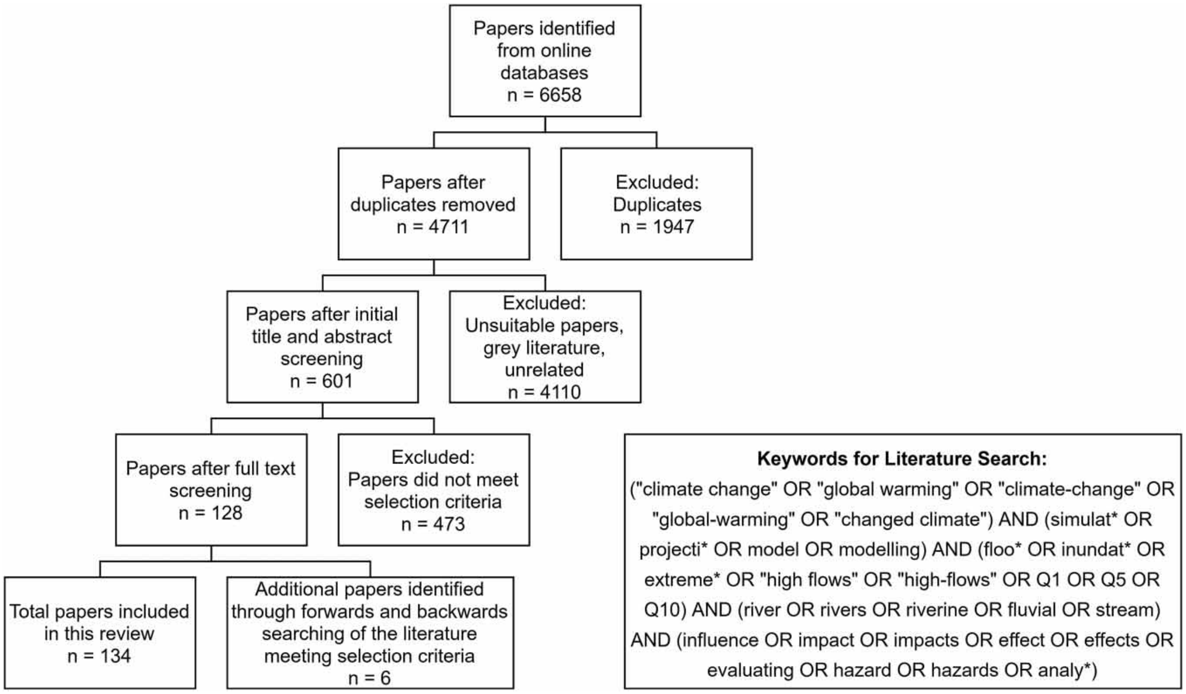
A large number of studies have been conducted using climate change projections to quantify the effects on riverine flooding. These studies typically follow a model chain outlined by Xu *et al.* (2005) consisting of the following, global circulation model outputs, global climate model (GCM) downscaling and bias correction methodologies, and hydrological model applications. Selection of the most appropriate models and techniques for a given catchment can be challenging, as catchment size, topography, location, and climatic conditions must all be taken into account. Changes to sea levels and anthropogenic activities (land-use changes, urbanisation, water demand, and flood mitigation/control structures) may also be considered, adding further complexity to models. Each step in the modelling process involves assumptions, which inevitably cause some degree of error, and is compounded with each successive modelling step (Praskievicz & Chang 2009). The mitigation and quantification of this model uncertainty is a major consideration in impact studies.

Review articles assessing the impacts of climate change on riverine flooding can be found on a global (Hunt & Watkiss 2011; Kundzewicz *et al.* 2014), European (Kundzewicz *et al.* 2010; Madsen *et al.* 2014), and country-wide scale (Miller & Hutchins 2017) but are lacking elsewhere. This paper aims to critically evaluate the current literature in the tropical and subtropical regions of the world and examine the factors that are unique to these climates. For this purpose, a systematic quantitative literature approach has been adopted (Pickering & Byrne 2014), whereby articles have been coded into a customised database to quantitatively assess the literature. This is the first review of its kind conducted in tropical and subtropical regions and the first to adopt a quantitative approach.

To maintain a comparable standard of literature, 'grey' literature, including reports, conference papers, unpublished articles, theses, and book sections have been excluded from this review, rather only English language peer-reviewed journal articles have been considered. Scopus and Web of Science were searched using a defined set of search terms. The inclusion criteria specified that articles must consider climate change scenarios, the use of hydrological modelling, and analysis of extreme river flows in either tropical or subtropical regions. A total of 134 peer-reviewed journal articles were included in this review from an initial evaluation of 4,711 (Figure 1). The multitude of papers included in this review allows for a more comprehensive analysis of the literature than that found in other similar reviews. A critical evaluation of the following aspects of the literature has been included, (i) the geographic distribution of studies, (ii) the chosen methodologies in terms of downscaling, bias correction, hydrological model choice, and analysis, (iii) the key findings of the literature and, (iv) the implications of these findings and future directions for research.

DISTRIBUTION OF THE LITERATURE

An updated version of the Köppen Climate Classification (Peel *et al.* 2007) was used as the basis to delineate subtropical and tropical catchments (Figure 2). When river basins covered numerous climate zones, only when the majority of the catchment was within tropical or subtropical climates was it considered in this review. As such, studies on the lower Mississippi River were excluded, while those on the lower Yangtze were included. The literature was approximately evenly split between tropical and subtropical catchments, covering 5 continents and 37 countries. Most of the research (59%) was published on Asian river basins, with the remainder published in Africa (13%), the Americas (12%), and on a global scale (16%). Figure 3 presents the number of studies included in this review on a per-country basis, excluding those studies conducted on a global scale. Table S1 in the supplementary materials presents a detailed summary of the studies conducted in East Asia, Table S2 in the supplementary materials for those in South East Asia, Table S3 in the supplementary materials for South Asia, Table S4 in the supplementary materials for Africa, Table S5 in the supplementary materials for the Americas, and Table S6 in the supplementary materials for those studies



Keywords for Literature Search:

("climate change" OR "global warming" OR "climate-change" OR "global-warming" OR "changed climate") AND (simulat* OR projecti* OR model OR modelling) AND (floo* OR inundat* OR extreme* OR "high flows" OR "high-flows" OR Q1 OR Q5 OR Q10) AND (river OR rivers OR riverine OR fluvial OR stream) AND (influence OR impact OR impacts OR effect OR effects OR evaluating OR hazard OR hazards OR analy*)

Figure 1 | PRISMA diagram (Moher *et al.* 2009) showing the number of papers included and excluded at each stage of the review process and the keywords used to find the relevant literature from the online databases.

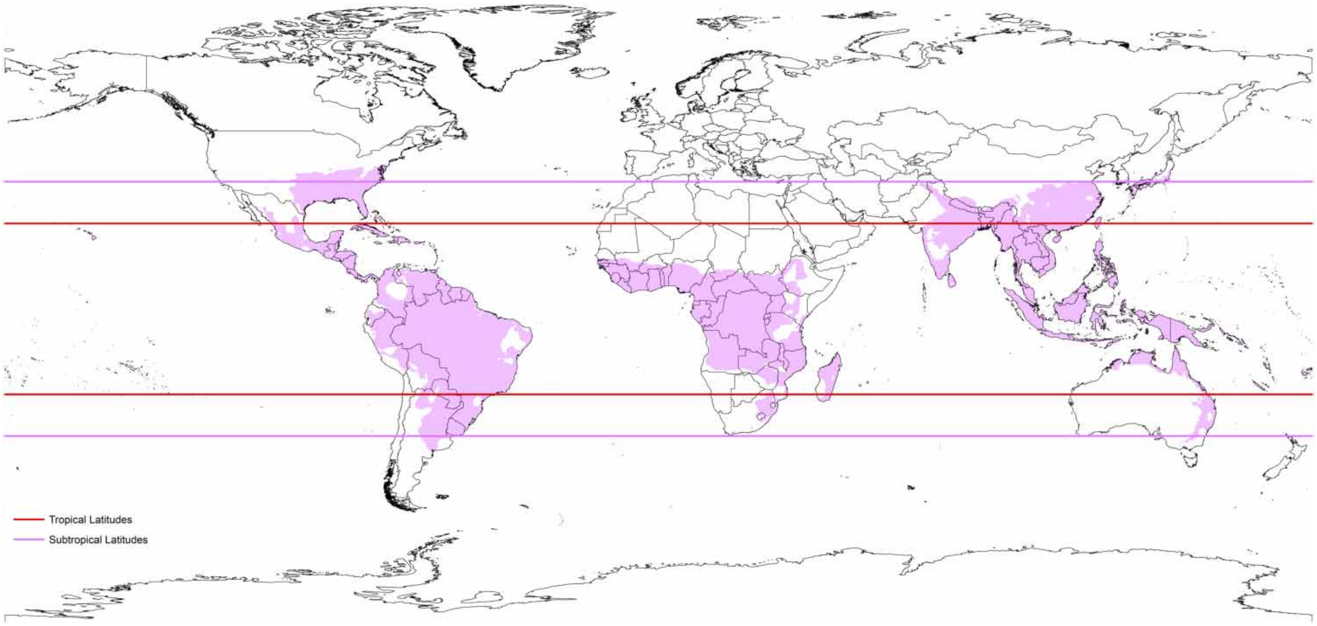


Figure 2 | Regions in this study considered as tropical or subtropical (highlighted) based on the Köppen Climate Classification devised by Peel *et al.* (2007).

conducted on a global scale. A full list of acronyms used in these tables can also be found in the supplementary materials.

It is evident from Figure 4 that there has been considerably more research published on Chinese, South Asian, and South East Asian rivers compared with other regions in the tropics/subtropics. The literature is also skewed towards studies of major river basins. Six major rivers including the Amazon, Niger, Ganges, Brahmaputra, Mekong, and Pearl River, are

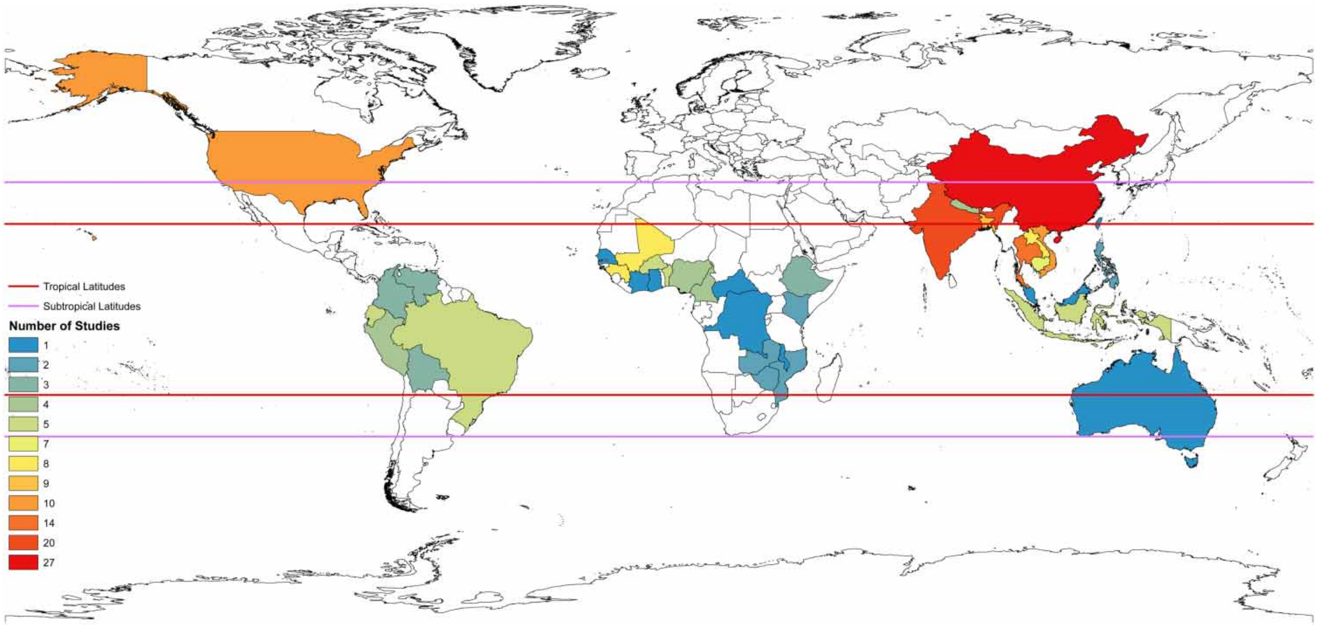


Figure 3 | Number of studies conducted by country in tropical and subtropical by regions. For rivers that were transboundary, only those countries that made up part of the study area and were in tropical or subtropical climates were considered.

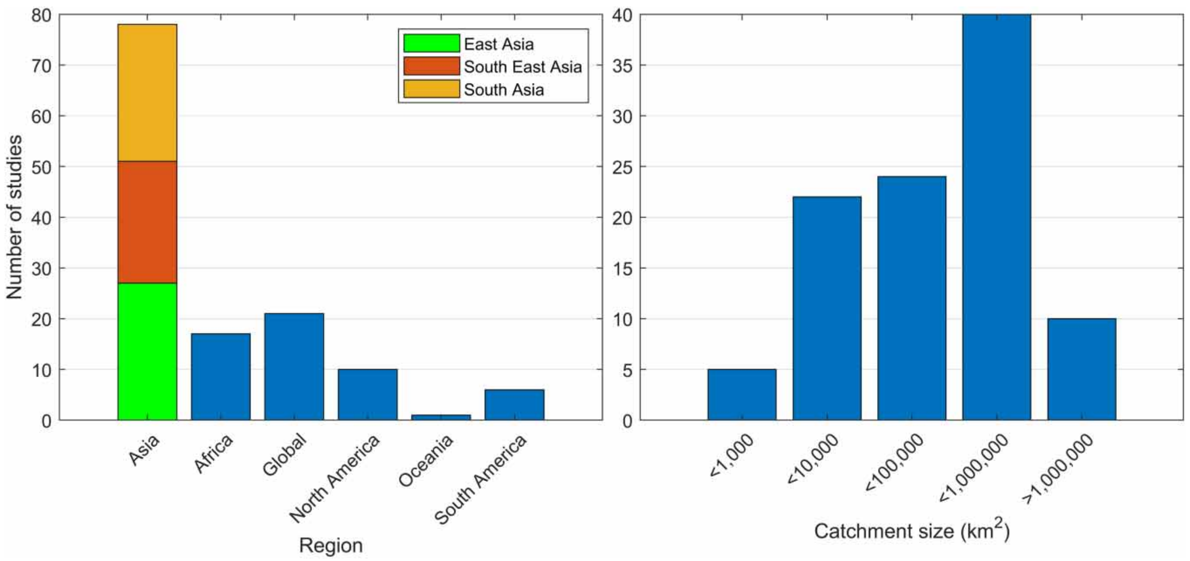


Figure 4 | Number of studies conducted by continent and region (left) and number of studies conducted by catchment size (right). For the catchment size plot, <10,000 is the range between 1,000 and 10,000 km^2, <100,000 is the range between 10,000 and 100,000 km^2, and <1,000,000 is the range between 100,000 and 1,000,000 km^2.

the focus of approximately 26% of all studies reviewed, each having an area greater than 450,000 km^2. Most of the literature has been conducted on similarly large river basins, while just under 4% of the literature was published on river basins less than 1,000 km^2 in area (Figure 4). This suggests that there is a need for further studies on smaller river basins as the flood-producing mechanisms are inherently different. Furthermore, studies are also required on heavily urbanising catchments in developing regions of the tropics and subtropics as they may be disproportionately affected by future flooding.

There is a marked shortage of literature focussing on parts of the Americas, Africa, and Australia. While the exclusion of non-English language journals in this review likely omitted a number of studies from Latin America and Africa, there is already low research output in these regions due to the difficulty of funding research. No studies were retrieved from Central America or the Caribbean, despite several studies being conducted in South America. This may relate to the small size of river basins in Central America and the Caribbean, as small river basins have been shown to receive considerably less research attention than larger basins (Figure 4). This assertion would seem to be supported in South America, as five of the six studies included in this review focussed on the Amazon River or its tributaries, while just one study was conducted elsewhere on the continent. In Africa, there has been a similar disproportionate focus towards the Niger River, though the literature is overall much more evenly distributed across the continent. A paucity of studies originating from central Africa including the Congo River can also be noted. The scarcity of literature originating from tropical/subtropical northern Australia is perhaps most surprising, as a large portion of the country and population reside in tropical and subtropical zones. Here, research has focussed on the temperate southwest (Evans & Schreider 2002) and southeast (Schreider *et al.* 1996, 2000), with only one study obtained for the tropical and subtropical northern regions. There is a clear need for further tropical and subtropical river basin research to be conducted throughout Australia, Latin America, and Africa.

RESEARCH METHODOLOGIES ADOPTED IN THE LITERATURE

Climate models

The selection of GCMs, Regional Climate Models (RCMs), emission scenarios, downscaling techniques, bias correction techniques, and hydrological models all influence the outcome of climate impact studies. Various combinations and ensembles of these components have been applied throughout the reviewed literature. In total, 99 different iterations of GCMs and numerous additional RCMs were used across all papers. This is somewhat unsurprising, given that the literature extends back approximately 17 years over which climate models have been continually updated and revised. There has been a steep upward trend in the number of studies conducted since 2010 with 90% of all reviewed literature published since this year and over half published since 2016 (Figure 5). This trend is most likely to continue as governments and researchers prioritise climate change impacts to assess past and future engineering design and planning.

Approximately 71% of the studies adopted an ensemble approach in which two or more climate models were employed to provide multiple projections as has been widely recommended (Dankers & Feyen 2009; Prudhomme & Davies 2009; Teutschbein & Seibert 2010). The remaining 29% of the reviewed literature applied just a single climate model for assessing the impacts of climate change. This is considered a major limitation as results from these studies represent just a single plausible climate outcome that may not be representative of the likely effects of climate change.

Several of the reviewed papers have reported that the largest source of uncertainty in the modelling process is from the GCM structure (Aich *et al.* 2014, 2016; Li *et al.* 2016a). Similar results have been found globally (Prudhomme *et al.* 2003; Kay *et al.* 2009), highlighting the importance of considering a range of climate models. Liu *et al.* (2013) reported that the relative uncertainty in

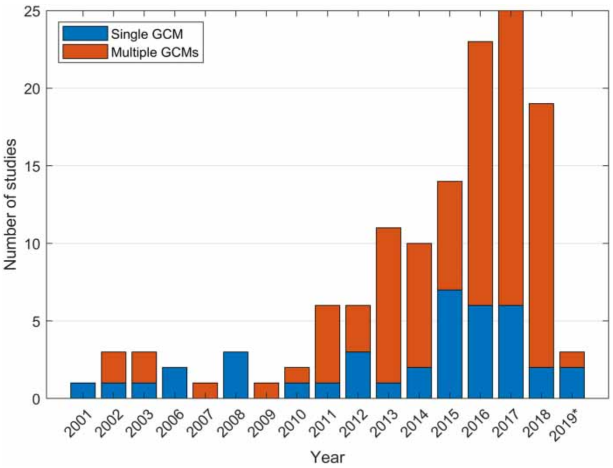


Figure 5 | Number of studies published and number of studies reporting use of a single or multiple GCM(s) by year, where 2019 only included part of the year.

predictions arising from the GCM structure was greater for projections in the mid- to late century while statistical downscaling and emission scenario selections are greater sources for predictions in the 2020s. Similar results were reported by Shen *et al.* (2018), suggesting that as climate projections advance further from the baseline, the divergence between model projections increases. Li *et al.* (2016a) found the uncertainty from GCM predictions to be spatially variable, with greater relative uncertainty in the subtropical regions to the south and east of China, compared with the more arid north and west where the uncertainty from hydrological modelling was more pronounced. Similarly, Pechlivanidis *et al.* (2017) reported greater relative uncertainty from GCMs in the tropical and subtropical Niger and Ganges Basins compared with the Lena and Rhine Basins. Precipitation projections from GCMs in the deep tropics, particularly over Africa and South America, have been shown to be the more uncertain than elsewhere in the world (Rowell 2012). Vetter *et al.* (2015) concluded that the high uncertainty introduced from climate models in the upper Niger Basin was due to the local monsoonal climate in which river runoff responds principally to high precipitation driven by the GCMs.

Emission scenarios

Over 43% of the studies employed emission scenarios from the International Panel on Climate Change Special Report on Emissions Scenarios (SRES; Nakicenovic *et al.* 2000), while just under 50% used the more recent Representative Concentration Pathways (RCP; Meinshausen *et al.* 2011). The remaining (usually older studies) made use of alternative emission scenarios. Approximately 40% of the reviewed literature applied one emission scenario, 32% applied two, 13% applied three, and 12% applied four emission scenarios (Figure 6). Compared with climate models, emission scenarios introduce only minor uncertainty, especially for projections in the mid- to late twenty-first century (Liu *et al.* 2013; Tian *et al.* 2016; Wang *et al.* 2017; Yuan *et al.* 2017).

Downscaling

GCMs run on a coarse resolution (typically 100–300 km) which make them unable to adequately represent local climatic features (Fowler *et al.* 2007), and as such, downscaling is often required. Both dynamic and statistical downscaling techniques have been widely applied throughout the literature. Approximately 35% of the studies reviewed adopted dynamic downscaling using RCMs while the remaining studies applied either statistical techniques or no downscaling at all. Bias correction is applied to correct systematic biases present in climate models including an overestimation in the number of wet days, underestimation in rainfall intensity, and inadequate year-to-year variability (Ines & Hansen 2006). The most common bias

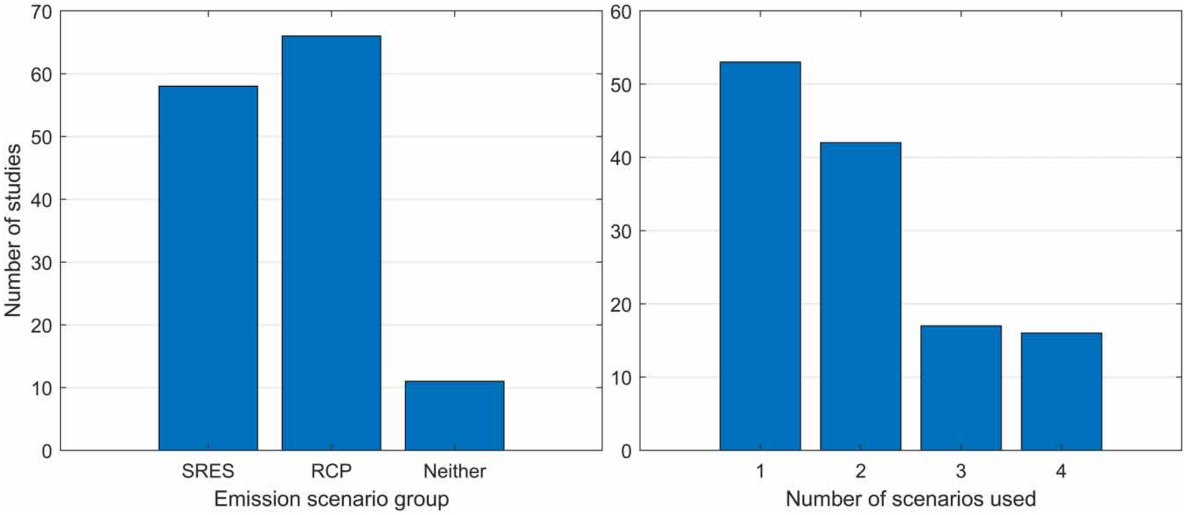


Figure 6 | Number of studies conducted by emission scenario group and number of emission scenarios used.

correction approaches adopted in the literature include the delta change, quantile mapping, scaling, and a trend preserving technique proposed by Hempel *et al.* (2013), applied in 24, 22, 13, and 14% of studies, respectively. Numerous variations of these techniques were utilised in addition to a number of alternative approaches.

Yuan *et al.* (2017) conducted a thorough assessment of the relative contributions to uncertainty from the emission scenario, climate model, statistical downscaling/bias correction technique, hydrological model, and flood frequency distribution. They reported that statistical downscaling and bias correction were the predominant source of uncertainty for projections involving high flows and flooding events. Chen *et al.* (2013) concluded that uncertainty due to downscaling and bias correction was more significant for projections of extremes than mean flows. Dobler *et al.* (2012) found similar results for Europe and suggested applying a range of bias correction techniques to account for this uncertainty when conducting impact studies related to extreme events. These findings highlight the importance of bias correction, especially for the modelling of flooding. In smaller to mid-sized catchments (where intense, short-duration precipitation can be a major source of flooding), bias correction is especially important. Of the bias correction techniques adopted within the literature, the quantile mapping approach appears the most suitable for flood impacts studies as it is best able to reduce systematic errors at high quantiles (Dobler *et al.* 2012; Chen *et al.* 2013).

Hydrological models

Fifty-one different hydrological, rainfall-runoff, and hydrodynamic models were applied across all studies. The most commonly used were the 'Variable Infiltration Capacity' (Liang 1994), 'Hydrologiska Byråns Vattenbalansavdelning' (Bergstrom 1976), and 'Soil and Water Assessment Tool' (Arnold *et al.* 1998) hydrological models, adopted in 16, 15, and 9% of the studies, respectively. A small subset of the research utilised hydrodynamic modelling for more accurate assessments of river flow, applying models such as SOBEK (e.g., Budiyono *et al.* 2016; Wei *et al.* 2016), MIKE 11 (e.g., Mirza 2002; Mirza *et al.* 2003; Kure & Tebakari 2012; Supharatid *et al.* 2016; Vo *et al.* 2016), HEC-RAS (Arunyanart *et al.* 2017; Shrestha & Lohpaisankrit 2017), and FLO-2D (e.g., Mishra *et al.* 2017). Distributed grid-based models were adopted in 37% of literature and were most widely used for global and large-scale studies. Model resolution ranged from 0.5° (approximately 55 km; e.g., Gain *et al.* 2013; Dankers *et al.* 2014; Arnell & Gosling 2016) to 200 m (e.g., Zhao *et al.* 2016). The remaining literature utilised semi-distributed models, and in some cases, lumped models.

The potential uncertainty derived from hydrological modelling is often overlooked in the literature. While some studies have suggested that this uncertainty is significant and cannot simply be ignored (Tian *et al.* 2013, 2016), others have concluded that the relative uncertainty contributed from hydrological modelling is minor, especially when compared with GCM structure (Menzel *et al.* 2006; Kay *et al.* 2009; Teng *et al.* 2012). Asadieh & Krakauer (2017) reported in their global study that the global hydrological models contributed more to uncertainty in streamflow changes than the GCMs. They therefore recommended that future studies adopt an ensemble of hydrological models in addition to an ensemble of GCMs.

Consideration of dams

Many studies in this review were carried out on sizeable river basins regulated by many large dams and reservoirs. The Mekong Basin has seen major dam developments over recent years for hydropower and irrigation purposes, with many more in the planning phase. When all planned dams are complete, the active storage capacity is expected to increase to 100 km^3 from the 5 km^3 initially available in 2010 (Johnston & Kummu 2012). Given this significant increase, several studies have considered the combined effects of climate change with future damming in the Mekong (Lauri *et al.* 2012; Wang *et al.* 2017; Whitehead *et al.* 2019). Lauri *et al.* (2012) found an increase in the annual peak discharge downstream under climate change, but a decrease when considering additional effects of future dams. Whereas Wang *et al.* (2017) reported that while regulation would have a significant impact on upstream flooding, it would have only minor effects on flood peaks and frequency downstream. Other studies have chosen to ignore current and future dams altogether, instead focussing on the impacts of climate change as if the system were in its natural state (Kiem *et al.* 2008; Västilä *et al.* 2010; Phi Hoang *et al.* 2016).

Likewise, studies in South Asia have generally considered rivers as if they were unregulated, despite numerous large dams and irrigation schemes throughout the region. A shortage of available data throughout the region, as noted by Hopson & Webster (2010), may explain why dams are often overlooked. Nonetheless, Mohammed *et al.* (2018) argued that the effects of regulation were minimal during the flooding season for the Ganges River as most structures are intended for use primarily during the dry season and not as flood mitigation measures. Similarly, due to the large number of dams and a lack of knowledge of the operating procedures, studies along the Yangtze River have also neglected the impacts of the numerous large dams constructed over the last 50 years (Gu *et al.* 2014, 2018; Yu *et al.* 2018). However, again it has been argued that due to the high precipitation totals in the wet season, these dams have little effect on the main channel discharge (Birkinshaw *et al.* 2017; Gu *et al.* 2018). By contrast, many studies in the Niger Basin have often considered the effects of major dams but not the effects of future planned dams (Aich *et al.* 2014, 2016; Thompson *et al.* 2016, 2017). However, this typically only involves the consideration of a few key structures which are sufficient to capture the effects of regulation, compared with the many hundreds or thousands of dams that would need to be considered throughout the Yangtze or Ganges Basins.

Data accessibility

A subset of the literature discussed difficulties in obtaining high-quality observational data for model setup, calibration, and validation. Obtaining suitable resolution in datasets for digital elevation models, land use, and bathymetry can be challenging in these regions, particularly for the analysis of small river systems. In parts of Africa, Asia, and the Americas, there is often a lack of climate observations at a sufficiently high spatial and temporal resolution to be effectively used for hydrological modelling and bias correction (Andersson *et al.* 2011). This was most evident for studies conducted in Africa where spatial coverage of meteorological and streamflow gauges was especially coarse. An array of reanalysed climate datasets, such as APHRODITE (Yatagai *et al.* 2012) and WATCH (Weedon *et al.* 2011), have thus been used within the literature to supplement the limited observational data. There are, however, often large discrepancies in precipitation values between the various reanalysed datasets, especially in regions with poor gauge density such as much of Africa (Fekete *et al.* 2004).

The application of erroneous datasets for model calibration and bias correction may result in a biased hydrological model affecting flood estimates. Stream gauge networks are also limited throughout much of the tropics and subtropics, with historical records having neither the longevity nor consistency of similar gauges in Europe and North America. Model calibration and validation is thus more complicated and historical flood frequency analysis is less accurate with limited historical streamflow records. A lack of cross-border cooperation in transboundary catchments and delays between data collection and data availability in some countries further limit data accessibility (Artan *et al.* 2007). There is evidently a need to improve data accessibility and for continual improvements to be made to reanalysed datasets. The development of remote sensing technology may help to improve access to quality meteorological data in remote and poorly gauged regions, which would be beneficial to modellers.

Flood analysis techniques

Several techniques were adopted in the literature for the analysis of riverine flooding, of which, flood frequency analysis was the most commonly applied, being used in 53% of the studies. This involved comparisons between historical and future projected flood magnitudes for specified return periods. Of the studies using flood frequency analysis, 90% used the Annual Maxima (AM) series, whereby yearly flow maxima's were used for flood estimation. The remaining literature utilised the Peak-Over-Threshold (POT) in which all statistically independent discharge values exceeding a selected threshold were analysed. This series is advantageous compared with the AM series as it allows for more data points to be analysed and ignores superfluous data that might have otherwise been included, a crucial advantage in highly variable climates. While the AM series dominates the literature, the POT series is potentially more appropriate for flood estimation, given the short timeframes considered (typically 20 or 30 years) for analysis of historical and future climates.

Traditional flood frequency analysis assumes stationarity, whereby the distribution of the flood frequency curves is assumed to be invariant for a given period (Prudhomme *et al.* 2003). However, due to continually changing climatic and hydraulic conditions (e.g., from land use, river infrastructure, and urbanisation changes), the assumption of stationarity may not always be reasonable, especially in cases where large man-made changes occur within a catchment during the time frame in question (Strupczewski *et al.* 2001). However, few studies have utilised non-stationary flood frequency techniques for flood impact assessments and this requires additional research attention.

Other studies have made comparisons between historic and future mean annual floods, high flows, and flood events derived from specific return period precipitation or storm events. Changes in high flows were assumed to be indicative of changes to flooding and were utilised in 26% of the reviewed papers. This method can be advantageous compared with flood frequency analysis as projections of high flows are more accurate than those of large flooding events (Aich *et al.* 2016). However, the rate of change predicted for high flows may not be the same as the rate of change for extreme flows, and as such, this method should only be used to provide an indication of flood changes.

Summary

There is evidently a wide array of possible approaches for assessing the impacts of climate change on extreme discharge. The choice of GCM/RCM, downscaling technique, bias correction, hydrological model, and analysis technique collectively affect the results. These choices can depend on a number of factors including computational power, budget, research domain, RCM availability, data accessibility, model familiarity, and topographic and climate variability within the spatial domain. It is largely up to the discretion of the researcher to choose adequate methods and techniques that suit their individual needs and to justify their choice appropriately.

KEY FINDINGS

Asia

Both increases and decreases in extreme flows were predicted across the literature. There was a general consensus throughout Asia towards increased flooding under climate change. In South Asia, increased flooding was projected for southern Nepal (Devkota & Gyawali 2015; Mishra & Herath 2015; Perera *et al.* 2015), Bangladesh (Mirza 2002; Mirza *et al.* 2003; Masood & Takeuchi 2016; Mohammed *et al.* 2018), various catchments in India (Jana *et al.* 2015; Mathison *et al.* 2015; Whitehead *et al.* 2018), the Mahanadi (Gosain *et al.* 2006; Asokan & Dutta 2008; Jin *et al.* 2018b), the Ganges (Whitehead *et al.* 2015; Tsarouchi & Buytaert 2018), and for the Brahmaputra River (Gain *et al.* 2011, 2013; Dutta & Ghosh 2012; Mohammed *et al.* 2017a, 2017b; Philip *et al.* 2019). Contrasting some of these findings, Gosain *et al.* (2011) predicted minor decreases in high flows for the Ganges, Brahmaputra, Krishna, and Cauvery Rivers but increases for the remainder of the country. Pichuka *et al.* (2017) predicted a decrease in the number of small flood events, but an increase in the magnitude of larger floods for the Bhadra River, while Bothale & Katpatal (2017) reported uncertain changes for the upper Wardha River. Decreased flooding was predicted for the Wainganga River (Das & Umamahesh 2017, 2018) and for two small catchments in south India (Mudbhatkal *et al.* 2017).

In South East Asia, increases in flooding were projected for the Mekong (Kiem *et al.* 2008; Västilä *et al.* 2010; Lauri *et al.* 2012; Phi Hoang *et al.* 2016; Edangodage Duminda Pradeep *et al.* 2017; Wang *et al.* 2017; Whitehead *et al.* 2019), the Yang (Shrestha & Lohpaisankrit 2017), the Trian (Dong *et al.* 2018), and for the Red River (Giuliani *et al.* 2016). Increases were also projected for catchments in Malaysia (Amin *et al.* 2017), the Philippines (Tolentino *et al.* 2016), and for the Ciliwung River in Indonesia (Emam *et al.* 2016; Mishra *et al.* 2017). Conversely, Budiyono *et al.* (2016) projected decreased flood risk for the Ciliwung River when considering only the effects of climate change; however, when combined with the effects of sea-level rise and land-use changes, flood risk was predicted to increase considerably. Muis *et al.* (2015) reported an increase in the severity of floods over large parts of Indonesia with decreases projected for Java. For the Va Gia-Thu Bon catchment in Vietnam, Vo *et al.* (2016) predicted an increase in flooding, while Dang *et al.* (2017) reported uncertain changes. Similarly, for the Chao River in Thailand, both increased flooding (Wichakul *et al.* 2015; Supharatid *et al.* 2016) and uncertain changes were reported (Hunukumbura & Tachikawa 2012; Kure & Tebakari 2012). Decreases to annual maximum flows have been predicted for the Lampao River in Thailand (Arunyanart *et al.* 2017).

Li *et al.* (2016a) projected flood magnitudes to increase throughout subtropical South China by 2100 despite a predicted decrease in annual precipitation, which was the result of a projected intensification of extreme precipitation. Increased extreme river flows were projected for Taiwan (Wei *et al.* 2016), the lower and middle Yangtze River (Gu *et al.* 2014, 2018; Ju *et al.* 2014; Yu *et al.* 2018), five river basins of Poyang Lake (Li *et al.* 2016b), and numerous smaller basins throughout China (Xu *et al.* 2011; Lu *et al.* 2013; Qin & Lu 2014; Kai *et al.* 2016; Gao *et al.* 2018; Shen *et al.* 2018; Yin *et al.* 2018). In the Beijiang River, both increased flooding (Wu *et al.* 2014, 2015) and uncertain changes were reported (Liu *et al.* 2017). Inconclusive results were also reported for the Lanjiang (Zhang *et al.* 2014) and the Jinhua Rivers (Tian *et al.* 2013), though more recent studies found flood magnitudes were likely to increase for the Lanjiang River (Zhang *et al.* 2015) and decrease for the Jinhua River (Tian *et al.* 2016). Increased flooding was also widely predicted for the Pearl River in south China (Liu *et al.* 2012, 2013; Yuan *et al.* 2016). Liu *et al.* (2018) projected an increase in the occurrence of small flooding events in the catchment and a decrease in larger events. While Yuan *et al.* (2017) and Zhu *et al.* (2017) both reported uncertain changes for the Xijiang River, a major tributary of the Pearl River.

Africa

Aich *et al.* (2014) predicted increases in extreme flows for the upper Blue Nile in Ethiopia, uncertain changes for the Niger River, and no changes for the Oubangui River in central Africa. Other studies have predicted increased flooding for the Niger River (Aich *et al.* 2016; Andersson *et al.* 2017) and decreased or uncertain changes were predicted for the upper Niger Basin (Vetter *et al.* 2015; Thompson *et al.* 2016, 2017; Huang *et al.* 2018). Elsewhere in West Africa, increased flooding was predicted for the Black Volta (Jin *et al.* 2018a) and the Ouémé River (Essou & Brissette 2013). Bodian *et al.* (2018) predicted decreased high flows for the Gambia and uncertain changes for the Senegal River. In East Africa, Taye *et al.* (2011) reported an increase in the magnitude of 10-year flood events for the Nyando Basin in Kenya and uncertain changes for Lake Tana Basin. Likewise, Nawaz *et al.* (2010) projected uncertain changes for the upper Blue Nile. Increased flooding was predicted for the Nzoia River in Kenya (Githui *et al.* 2009) and the Kafue River in Zambia (Ngongondo *et al.* 2013), whereas decreases were projected for the Pungwe River in Mozambique and Zimbabwe (Andersson *et al.* 2011). For the Zambezi Basin, Fant *et al.* (2015) reported an increase in 50-year flood events for sections in Mozambique and Zambia and insignificant changes for sections in Malawi and Zimbabwe.

Americas

In the upper Amazon River basin, increased flooding was widely predicted (Guimberteau *et al.* 2013; Langerwisch *et al.* 2013; Mora *et al.* 2014; Sorribas *et al.* 2016; Zulkafli *et al.* 2016), while decreases or uncertain changes were forecasted for the lower Amazon basin (Guimberteau *et al.* 2013; Langerwisch *et al.* 2013; Sorribas *et al.* 2016). Increases were also predicted for the Upper Grande River in Brazil (Viola *et al.* 2015), the Apalachicola (Chen *et al.* 2014), San Jacinto (Muttiah & Wurbs 2002), Yadkin-Pee Dee (Suttles *et al.* 2018), and Wolf Bay Basins (Wang *et al.* 2014) in the United States. Country-wide studies for the United States reported a likely increase in 100-year floods and high flows throughout the subtropical south east of the country (Naz *et al.* 2016, 2018; Wobus *et al.* 2017). Conversely, Risley *et al.* (2011) reported a likely decrease in high flows for the Flint River, while Zhao *et al.* (2016) and Chen *et al.* (2013) noted significant uncertainty in projections for the San Antonio and Chickasawhay River, respectively.

Global studies

In addition to the studies completed on catchment, regional, and national scales, several global studies have been conducted. Arora & Boer (2001) reported that reductions in flood events throughout most of the tropical and subtropical world are likely with the exception of parts of the Indian subcontinent and Brazil. Voss *et al.* (2002) predicted increased 10-year flood magnitudes for all tropical and subtropical rivers assessed except for the Amazon River. Similar results were reported by Hirabayashi *et al.* (2008)

who predicted increased 100-year flood magnitudes over much of the world, with the most consistent increases in Central Africa and South Asia. Okazaki *et al.* (2012) and Wiel *et al.* (2019) also reported likely increases in flooding throughout most of the tropics. Falloon & Betts (2006) found 8 of the 10 rivers most affected by climate change to be in tropical or subtropical regions, while Alfieri *et al.* (2017) identified that 15 of the 20 most-affected countries were in tropical or subtropical regions. However, most of these studies based their results on the outputs of a single GCM, applying no additional downscaling or bias correction and as such, their findings may not be representative of the likely effects of climate change.

Dankers *et al.* (2014) applied an ensemble of GCMs predicting flood peaks to increase throughout much of the tropics, with the most consistent increases for South and South East Asia. Other multi-model ensemble studies have also consistently predicted increases for South and South East Asia (Arnell 2003; Hirabayashi *et al.* 2013; van Vliet *et al.* 2013; Koirala *et al.* 2014; Arnell & Gosling 2016; Winsemius *et al.* 2016; Döll *et al.* 2018). While the most consistent decreases are projected for parts of South and Central America (van Vliet *et al.* 2013; Koirala *et al.* 2014; Winsemius *et al.* 2016; Asadieh & Krakauer 2017). Hirabayashi *et al.* (2013) predicted large flooding events to increase, especially in South and South East Asia, Eastern Africa, and the northern portion of the Andes Mountains. Krysanova *et al.* (2017) predicted mixed results and moderate uncertainty for future high-flow occurrences over many large tropical and subtropical rivers, with high flows predicted to increase only in the Ganges River, but with moderate certainty. Paltan *et al.* (2018) projected the largest increase in 100-year floods to occur over north India, east China, and the southern Amazon.

Summary

The majority of studies have predicted increases in extreme flows under climate change in both the tropics and subtropics. The percentage of studies predicting increases on a per-country basis is presented in Figure 7. The most consistent changes were observed in South Asia, South East Asia, and the western Amazon, with over 70% of the reviewed literature projecting increased flooding in the future. Results from subtropical China and the United States were also highly consistent, with 67 and 70% of the literature predicting a future increase in riverine flooding, respectively. Mixed findings have been reported for most of Africa and most of South America, likely due to the small subset of literature reviewed from these regions and no consistent, meaningful conclusions can be drawn.

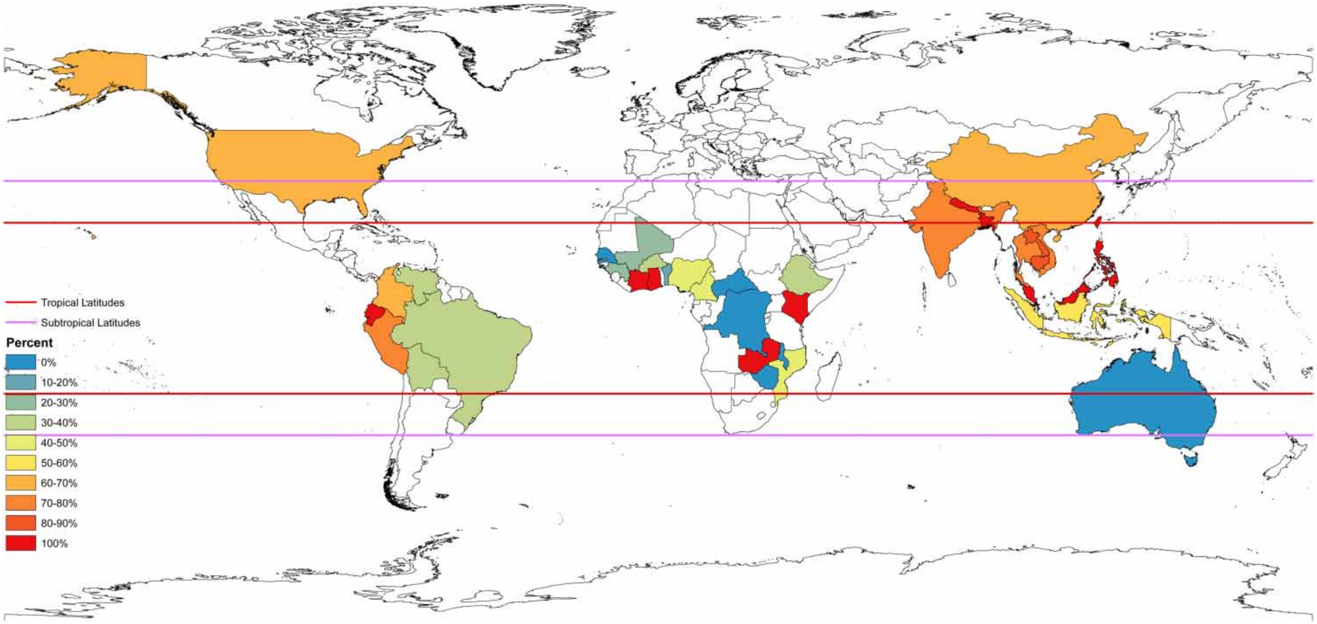


Figure 7 | Percentage of studies (excluding studies conducted on a global scale) predicting increased river flooding on a per-country basis in tropical and subtropical regions.

IMPLICATIONS AND FUTURE DIRECTIONS

Implications

In order for research undertaken by the scientific community to be relevant to engineers and decision makers, it is essential that uncertainty is estimated and mitigated (Andersson *et al.* 2011; Aich *et al.* 2014). Dankers *et al.* (2014) suggest approaching the issue of uncertainty from a risk management perspective, whereby even the most unlikely outcome that carries a high risk is considered. In doing so, the full range of plausible eventualities can be planned for and mitigated appropriately. Even so, the research processes adopted in the scientific literature are not always compatible with the legal and economic constraints placed on decision makers (Madsen *et al.* 2014). Any revisions made to design flood levels are likely to have a wide range of economic ramifications. Changes to the design and operation of hydraulic structures and key infrastructure can be very costly and changes to the delineation of flood hazard mapping will have consequences for insurance premiums affecting property owners. Increased pressure could be placed on water suppliers, as dams may have to operate under lower maximum storage to accommodate the increases in discharge associated with large flooding events.

Greater and more frequent floods would likely also exacerbate erosion processes, as sediment transport occurs disproportionately during extreme events (Romero *et al.* 2012; Gonzalez-Hidalgo *et al.* 2013; Boardman 2015). This could cause greater pollutant and sediment loads in rivers, affecting downstream ecosystems. Accelerated erosion processes may result in channel sedimentation, instability, and river routing changes, which can work to undermine the stability of bridges, levees, and other flood control infrastructure. The entrainment and deposition of coarse sediments in river channels may work to reduce bankfull capacity, thereby raising flood levels under future events (e.g., Lane *et al.* 2007).

The additional effects of sea-level rise and anthropogenic activities (e.g., hydraulic structures construction, land-use changes, and urbanisation) further complicate the issue. In some instances, these effects may be more pronounced than those of climate change (e.g., Budiyono *et al.* 2016; Zhao *et al.* 2016). The combination of these changes may be especially devastating in some developing nations of the tropics and subtropics. Bangladesh, for instance, may be jointly affected by more intense cyclones (storm surges), increased extreme river flows, and sea-level rises, all of which may exacerbate flooding. Adaptation strategies and emergency action plans are required to mitigate economic damage and fatalities from such events. These plans must be flexible and robust to account for the range of plausible scenarios and allow future adjustments to be made with advances in modelling (Mathison *et al.* 2013). Such plans may be more difficult to implement in the developing nations of the tropics/subtropics, as governments understandably may not prioritise them over more immediate issues.

Future directions

Continual improvements must be made to climate models, particularly in the modelling of land-surface processes if projections are to become more reliable (Okazaki *et al.* 2012). Increasing the availability of sub-daily climate model outputs would be advantageous especially for studies conducted on smaller catchments with flashier flows (Kiem *et al.* 2008). As it is widely agreed the largest source of uncertainty is from the GCM structure (Kay *et al.* 2009; Prudhomme & Davies 2009), future research should usefully extend the number of climate models in an ensemble modelling process. Results based on a limited number of scenarios may give a false indication of the direction of change under climate change conditions. Future studies are recommended to avoid overly simplistic bias correction techniques for precipitation, such as the delta change approach as these methods are not well suited to the modelling of extremes. Rather, a quantile mapping technique is recommended as it has been demonstrated to be more reliable in improving the projections of extreme events compared with other bias correction techniques (Dobler *et al.* 2012; Teutschbein & Seibert 2012). Many studies have acknowledged the need to utilise multiple climate models; however, most studies utilise a single hydrological model and downscaling/bias correction technique. Ideally, an ensemble of hydrological models, downscaling, and bias correction techniques could be employed to better account for uncertainty but this is a time-consuming process and may not always be feasible.

The majority of the reviewed literature has assumed the physical characteristics of the catchment remain the same throughout the study. However, land use, vegetation, and hydraulic structure changes all have significant impacts on the streamflow characteristics. Future studies could consider these changes through the development of site-specific socio-economic and environmental scenarios. In many of these instances, the adoption of non-stationary flood frequency analysis techniques may be preferred over traditional stationary approaches, as they allow changes in the catchment characteristics to be considered.

The research considered in this review has been geographically limited, with minimal to no research found for large portions of Africa, Latin America, and Australia. There is a need for further studies in these regions and throughout the tropics/subtropics generally. The majority of the literature has assessed the effects of climate change on large river systems and as such, additional studies on smaller to mid-sized catchments throughout the tropics are required, as the flood-producing mechanisms in these catchments are inherently different. Studies investigating flooding changes in heavily urbanising catchments in developing regions are also required. There is a need to improve the accessibility and quantity of observational data across much of the tropics. Limited historical records in stream gauge networks in the tropics/subtropics can lead to inaccurate flood frequency estimations, as they do not capture the full range of events. Enhancements in monitoring regimes are needed to improve modelling and our understanding of the extent of natural variability (Kundzewicz *et al.* 2008). Generally, there are limited available dynamically downscaled climate change projections for these regions compared with those in Europe (Andersson *et al.* 2011; Phi Hoang *et al.* 2016) and as such, more RCM outputs should be made available throughout the tropics and subtropics.

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