69

Review paper
Doi 10.61892/STP202601045DJ
ISSN 2566-4484

STEPGRAD
СТЕПГРАД

Nikola Đokić, University of Nis, nikola.djokic@gaf.ni.ac.rs
Borislava Blagojević, University of Nis, borislava.blagojevic@gaf.ni.ac.rs
Vladislava Mihailović, University of Belgrade – Faculty of Forestry, vladislava.mihailovic@sfb.bg.ac.rs
Ilija Ilić, University of Nis, ilija.ilic@gaf.ni.ac.rs

THE ROLE OF BASIN PHYSICAL CHANGES IN FUTURE FLOOD PROJECTIONS

Abstract:

Although both climatic factors and basin physical characteristics influence flood generation, projections of future floods predominantly emphasize climate change, while changes in land use, urbanization, and basin morphology are less systematically addressed. This paper presents a brief literature overview on the assessment of future floods at the basin scale. The analysis examines the relationship between meteorological drivers and catchment properties. The findings are discussed with reference to three comprehensive review studies to highlight key research trends and methodological gaps. Finally, conclusions are made to better integrate climatic and physical drivers in future flood estimation.

Keywords: Floods, Climate Change, Basin Physical Change.

УЛОГА ПРОМЕНЕ ФИЗИЧКИХ КАРАКТЕРИСТИКА СЛИВА У ПРОЈЕКЦИЈАМА БУДУЋИХ ПОПЛАВА

Сажетак:

Иако на формирање великих вода утичу и климатски фактори и физичке карактеристике слива, у пројекцијама будућих поплава нагласак је претежно на климатским променама, док се промене коришћења земљишта, урбанизације и морфологије слива ређе разматрају. Рад даје кратак преглед литературе о процени будућих поплава на нивоу слива. Резултати су размотрени у контексту три релевантна прегледна рада ради идентификације кључних трендова и методолошких ограничења. У закључцима су дате могућности за унапређење интеграције климатских и физичких карактеристика слива у процене будућих поплава.

Кључне ријечи: поплаве, климатске промене, промене физичких карактеристика слива.

1. INTRODUCTION

Flood estimation is not only a scientific challenge but a core engineering task directly linked to structural reliability, serviceability, and long-term resilience of built systems. As climate variability intensifies and exposure increases due to urbanization, the engineering relevance of robust future flood projections becomes even more pronounced [1].

The integration of climate change into water management and hydraulic engineering has evolved over several decades. Early applications relied primarily on stationarity-based flood frequency analysis (FFA), assuming that statistical properties of hydrological extremes remain constant over time [2]. With the development of global climate models (GCMs) and successive emission scenarios like Representative Concentration Pathways-RCPs, attention shifted toward assessing non-stationarity [2] and detecting climate-driven trends in hydrological series [3]. More recently, Shared Socioeconomic Pathways (SSPs) have further expanded scenario frameworks by linking climate forcing with socioeconomic development, reinforcing the need for integrated climate–hydrology–impact modelling chains in engineering practice [4].

Within this evolving framework, the quantities of interest remain essentially hydrological: peak discharges, flood quantiles, water levels, inundation extents, and derived hazard indicators. Traditionally, hydrological-hydraulic design focused on estimating design floods through FFA, producing return-period-based metrics for infrastructure sizing. However, increasing recognition of non-stationarity and socio-economic exposure has driven a paradigm shift from flood quantile estimation toward probabilistic flood risk assessment. Contemporary approaches increasingly combine hydrological modelling, hydraulic inundation modelling, land-use dynamics, and exposure–vulnerability analysis to quantify not only the magnitude of extreme flows but also expected damages and societal risk [5]. This shift reflects a broader transition in civil engineering from hazard-based to risk-informed design and management.

Within the flood risk framework, the relative contribution of climate change versus basin alteration to future flood behaviour is questioned. Whitfield [6] argues that, at the basin scale, projected changes in floods are often more strongly influenced by land-use change, urbanization, drainage modifications, and other anthropogenic alterations than by climate change alone.

To understand approaches to flood estimation at the basin scale in future climate and physical conditions, the framing question in this paper is: Which methodological approaches are employed for estimating future floods at a basin scale, and how do they differ in terms of underlying assumptions, data requirements, and treatment of climate change and basin physical characteristics?

The central research question is addressed through a set of specific questions that structure the analytical framework of the study:

1. How are future meteorological forcings (e.g., precipitation, temperature, snow processes) derived from climate models and downscaling techniques and applied in basin-scale flood estimation approaches?
2. How are changes in physical basin characteristics (e.g., land use/land cover, urbanization, population-driven imperviousness) incorporated into basin-scale flood estimation approaches under future conditions?
3. How do studies attribute changes in future flood magnitude and frequency to meteorological drivers versus physical basin changes?
4. What are the dominant sources of uncertainty in future flood projections arising from meteorological inputs compared to those related to physical basin representation?

The paper is organized as follows. In the Methodology section, the approach to the selection of literature is explained. Section Results is organized to systematize material required for answering specific research questions, while the Discussion part is a comparison of our findings to three reviews on flood assessment in the future climate [5], [6], [7]. The concluding section provides answers to the research questions based on the studied references and points out to potential directions of future research.

2. METHODOLOGY

The literature review was conducted using a structured, multi-stage screening procedure. Relevant studies were identified through a targeted search in Google Scholar, using the query “prediction of flood in future climate conditions”. The initial search results were screened based on titles and abstracts.

In the first iteration, 62 studies were identified as potentially relevant and were examined at the abstract level. During the second iteration, studies focusing primarily on general methodological concepts, model descriptions without application, or flood analysis under present-day climate conditions without the use of climate model projections were excluded. This filtering step reduced the dataset to 27 studies.

In the third iteration, the selection was further refined to retain only studies that explicitly addressed future flood projections at the basin or sub-basin scale from the year 2015, in line with the central aim of this paper. As a result, 19 studies were included in the core analysis.

Finally, three additional studies/reviews with research objectives closely aligned with this paper were incorporated into the Discussion section to support the final synthesis and comparative interpretation.

In total, 22 studies (papers) addressing future floods projections were ultimately adopted for analysis in this paper.

3. RESULTS

3.1. APPROACHES FOR PROJECTING FUTURE FLOOD EXTREMES AT THE BASIN SCALE

Conducted analysis of 19 relevant studies [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23],[24], [25] shows that the estimation of future flood extremes at the basin and sub-basin scales relies on a limited number of dominant methodological approaches. These approaches differ not only in the type of models employed but more fundamentally in their underlying assumptions, data requirements, and the way climate change signals are incorporated into the analysis, here referred to as translation. In most studies, future flood behaviour is assessed through a modeling chain that combines climate projections with hydrological, hydraulic, statistical, or empirical modeling components. Differences among approaches therefore arise from choices made across the entire modeling framework, including climate scenario selection, downscaling techniques, and bias correction (BC), representation of basin processes, and the definition of flood metrics and extremes.

Based on the dominant methodological framework, the reviewed studies were classified into three groups:

1. Physically based hydrological models (8 studies - [8], [9], [10], [11], [12], [13], [14], [15]),
2. Data-driven and machine learning (ML) based approaches (7 studies - [16], [17], [18], [19], [20], [21], [22]), and
3. Hybrid models combining multiple methodologies (3 studies - [23], [24], [25]).

This classification provides a structured basis for comparing how different approaches conceptualize future flood processes and handle climate change impacts.

3.1.1. Underlying assumptions

Basin-scale projections of future flood extremes rely on simplifying assumptions about how well relationships derived from historical data apply to future climate conditions.

In physically based hydrological models, the assumption is that the main runoff-generation and routing processes are properly represented and maintain their structural validity under changed climatic forcing. Climate change is represented through downscaled and bias-corrected climate model outputs, while catchment characteristics are usually considered stationary unless land-use scenarios are explicitly included [8], [10], [11], [14].

Data-driven and machine learning based approaches assume that the statistical or functional relationships derived from historical data are still valid under future climate conditions. Future flood behavior is estimated based on projected meteorological predictors, while catchment processes are implicitly included in the training data and usually assumed to remain unchanged over time [16], [17], [18], [22].

Hybrid approaches integrate physically based, statistical, and machine learning components based on the assumption that combining complementary methods enhances robustness and representation of extremes. This integration also allows climate signals and uncertainties to be carried through several stages of the modeling chain [23], [24], [25].

Across all approaches, a common assumption is that non-stationarity arises mainly from climate forcing. Dynamic changes in basin physical characteristics are often simplified or ignored, shaping the attribution of future flood changes primarily toward meteorological drivers.

3.1.2. Data requirements

Physically based hydrological models are associated with the highest data requirements, typically requiring long hydro-meteorological time series, detailed basin characteristics, and extensive calibration. Their applicability is therefore often limited by data availability and quality, and uncertainties related to hydrological modeling can be comparable to or exceed those associated with climate projections [8], [14], [15].

Data-driven and ML approaches generally require fewer process-based hydrological data, relying instead on historical flood records, meteorological variables, and, in spatial applications, physiographic datasets such as topography, land use, and soils. This lower data demand makes ML approaches attractive for large-scale analyses and data-scarce regions, although their performance remains sensitive to data representativeness [16], [17], [18].

Hybrid approaches combine data requirements from multiple modeling components, often integrating climate projections, hydrological simulations, and additional datasets related to flood impacts or risk assessment [23], [25].

3.1.3. Treatment of climate change

In physically based modeling studies, climate change is explicitly incorporated by forcing hydrological models with downscaled and BC outputs from global or regional climate models, from which future flood characteristics are derived using simulated discharge time series and extreme-value analysis [9], [12].

In data-driven and ML–based flood studies, climate change is usually included indirectly by using projected rainfall and other meteorological variables as model inputs [16], [19], [20]. Future flood changes are therefore mainly linked to changes in climatic forcing derived from these projections. Although some studies also consider land-use change [21] or apply hydrodynamic river modeling [17], most approaches do not explicitly simulate how watershed characteristics and hydrological behavior may evolve over time. Instead, basin properties are often treated as fixed or only partly updated. Even broader assessments that combine flood risk with population projections [22] rely on projected hazard estimates rather than dynamically modeling long-term watershed changes.

Hybrid and integrated approaches treat climate change as a driving signal propagating through multiple modeling components, often combining climate projections with statistical, probabilistic, or impact-based analyses to better capture extreme behavior and uncertainty interactions in future flood projections [23], [24], [25].

3.2. METEOROLOGICAL FORCINGS

The choice of meteorological forcing is closely linked to the underlying climate model ensembles and emission scenarios employed, which differ substantially across Coupled Model Intercomparison Project (CMIP) phases (Table 1). The CMIP provides standardized climate model simulations to compare and project future climate changes under different greenhouse gas scenarios.

Expectedly, among the selected literature, there are no studies that use CMIP3 scenarios, because these are newer papers (from 2015 onward). CMIP5 was used in several papers [8], [15], [16], [18], [20], [23], and the most recent studies have fully transitioned to the CMIP6 framework [17], [19], [24], [25], [26].

Table 1. Key differences between CMIP3, CMIP5, and CMIP6 climate model ensembles relevant to flood projections

CMIP Phase	Spatial resolution	Emission / Socio-economic Scenarios	Key Modeling Advances Relevant to Flood Projections
CMIP 3	~200–300 km	SRES (A1, A2, B1, B2)	Coarse spatial resolution and simplified representation of physical processes, with limited ability to reproduce extreme precipitation events and land–atmosphere interactions relevant for flood generation.
CMIP 5	~100–150 km	RCPs (2.6, 4.5, 6.0, 8.5)	Improved physical parameterizations and higher spatial resolution compared to CMIP3, including better representation of precipitation processes and land–atmosphere coupling, leading to more realistic simulations of hydrological extremes.
CMIP 6	50–100 km	SSPs (SSP1-2.6, SSP2-4.5, SSP5-8.5)	Further advances in model physics and spatial resolution, incorporation of interactive aerosol processes and enhanced land–surface schemes, resulting in stronger and more frequent simulated precipitation extremes, but also increased inter-model variability.

3.2.1. Climate model translation into hydrometeorological inputs

The reviewed studies can be classified into three groups according to the range and combination of meteorological variables used to translate climate model outputs into hydrometeorological inputs.

The first group of studies translates climate projections into precipitation-only inputs, particularly when flood susceptibility or frequency is derived using statistical or ML frameworks that do not explicitly simulate snow processes. For example, CMIP5/CMIP6 precipitation outputs are used to estimate changes in flood occurrence or susceptibility in [8], [16], [18], [19], [23], [24]. In these studies, precipitation extremes (often annual maxima or event-based rainfall) represent the primary driver of flood hazard. Similarly, basin-informed deep learning approaches [20] and some probabilistic flood risk frameworks [25] rely primarily on projected precipitation changes to infer shifts in flood frequency or inundation probability. In such cases, temperature is either implicitly embedded in the climate simulations or considered secondary to rainfall-driven runoff generation.

The second and more common configuration employs precipitation and temperature jointly**,** enabling simulation of evapotranspiration, soil moisture dynamics, and seasonal runoff processes. This approach is characteristic of physically based or conceptual hydrological modeling studies, such as [10], [11], [12], [13], [14], [15], [26]. In these cases, temperature is critical for estimating potential evapotranspiration and modifying antecedent moisture conditions, which in turn affect flood magnitude. Studies assessing combined land-use and climate impacts [9], [21] also rely on precipitation–temperature inputs to capture interactions between climatic forcing and catchment processes. Rathnayake et al. [17] similarly use projected hydro-meteorological variables to estimate future water levels through hydrodynamic simulation.

The third group explicitly incorporates precipitation, temperature, and snow-related processes, particularly in cold or mixed rainfall–snowmelt regimes. In northern or high-latitude basins, temperature projections are directly translated into snow accumulation and melt dynamics within HBV type or similar hydrological models [11], [14]. This allows assessment of shifts from snowmelt-dominated floods toward rainfall-driven regimes under warming scenarios. Although snow processes are not always the primary focus, their inclusion substantially alters projected seasonality and magnitude of high flows, especially in regions historically influenced by winter snow storage.

3.2.2. Downscaling techniques and bias correction methods

Across the reviewed studies, both dynamical and statistical downscaling (DD and SD) approaches are employed to bridge the scale gap between coarse-resolution GCM outputs and basin-scale hydrological models. DD using RCMs is reported in studies such as [11], enabling a physically consistent representation of mesoscale processes (orographic precipitation enhancement, convective storm development, frontal dynamics etc.). However, many investigations rely on SD due to its computational efficiency. For example, [8], [10], [15], [26] apply BC and spatially disaggregated climate projections, while [11] explicitly compare multiple SD and BC methods to demonstrate that methodological choices significantly affect projected flood extremes.

Regarding BC, quantile mapping and distribution-based scaling techniques are frequently applied to adjust precipitation and temperature series before hydrological modeling [13], [14], [15]. These methods aim to align modeled and observed statistical properties, particularly extremes. Ensemble approaches are often used to propagate climate model spread [10], [11], [12]. Some studies employ hybrid frameworks combining statistical corrections with ML [19] or probabilistic modeling [23], [25].

Beyond conventional downscaling, several papers adopt alternative translation strategies. ML-based susceptibility mapping [16], [18] integrates projected climatic variables directly with terrain and land-use predictors, bypassing explicit hydrological simulation. Lazin et al. [20] employ deep learning to derive basin-informed flood frequency projections without traditional rainfall–runoff modeling.

3.3. CHANGES IN BASIN PHYSICAL CHARACTERISTICS

The selected basin-level flood projection studies indicate that most investigations primarily assess the impacts of climate change, while the physical characteristics of the basin are often treated as unchanged in future projections. In a large number of studies, precipitation and temperature projections derived from CMIP frameworks are propagated through hydrological, statistical, or ML-based flood models without explicitly modeling future changes in land-surface properties [8], [10], [11], [13], [14], [15], [17], [19], [20], [23], [24], [26].

A smaller subset of studies explicitly incorporates changes in land use/land cover (LULC) or urban expansion into flood assessments. For example, Hung et al. [9] integrate projected LULC scenarios into hydrological simulations, modifying vegetation-related evapotranspiration and runoff generation processes. Pal et al. [21] evaluate the combined influence of climate change and future land-use patterns on flood susceptibility.

Demographic dynamics are even less frequently represented. Shu et al. [22] integrate flood hazard projections with spatially explicit future population distributions, thereby accounting for changes in exposure associated with urban growth.

In susceptibility mapping studies [16], [18], topography, soil properties, and land cover are included as conditioning variables, but they are treated as static inputs under future scenarios. In such cases, climatic variables represent the primary source of variation in projections, while the physical structure of the basin remains unchanged over time.

3.4. ATTRIBUTION OF FUTURE FLOOD CHANGES

3.4.1. Meteorological Drivers

Changes in the magnitude and frequency of future floods are predominantly attributed to meteorological forcing in the reviewed literature. In physically based hydrological modeling studies, system non-stationarity is introduced through ensembles of GCM/RCM models and various RCP/SSP scenarios [8], [10], [15]. Increases in flood susceptibility or intensity are therefore primarily linked to projected changes in precipitation extremes and temperature regimes.

A similar pattern is observed in data-driven and ML-based approaches. Mahdizadeh Gharakhanlou & Perez [16] explicitly state that all predictors other than precipitation—including LULC, lithology, and geomorphology—are assumed to remain constant in future projections. Consequently, any projected increase in flood susceptibility is attributed exclusively to climatic changes.

The dominance of meteorological attribution does not necessarily reflect the limited importance of physical basin changes. Rather, it is a consequence of modeling frameworks that do not dynamically represent catchment evolution. In the absence of explicit modeling of basin transformation, climate becomes the only evolving variable, and changes in flood behavior are therefore implicitly attributed to atmospheric forcing.

3.4.2. Physical Basin Changes

A smaller subset of studies explicitly incorporates changes in physical catchment characteristics, primarily focusing on urbanization and imperviousness. These studies demonstrate that modifications in the basin surface can significantly amplify or even dominate the climate signal at local scales [9], [25]. However, the attribution of changes to physical drivers remains methodologically less consistent.

An observation from the analyzed studies is that even when physical changes are considered, they are often represented through simplified, discrete scenarios of land-use change. In contrast, other potentially vital physical drivers, such as long-term geomorphological shifts, changes in soil hydraulic properties due to climate feedback, or the impact of flood defense infrastructure, are rarely integrated into future projections. This leads to a situation where the physical catchment is treated as a static container that merely reacts to dynamic atmospheric forcing, rather than a co-evolving system.

3.5. UNCERTAINTY IN FUTURE FLOOD PROJECTIONS

Projections of future floods are affected by multiple, interacting sources of uncertainty that arise at different stages of the modeling chain, as seen in the reviewed references.

Figure 1 summarizes the dominant methodological approaches for projecting future floods at the basin scale through physically based, data-driven, and hybrid modeling chains. The framework emphasizes the propagation of uncertainty across climate models, downscaling procedures, model structures, and basin representation, ultimately affecting projected flood magnitude, frequency, and flood risk.

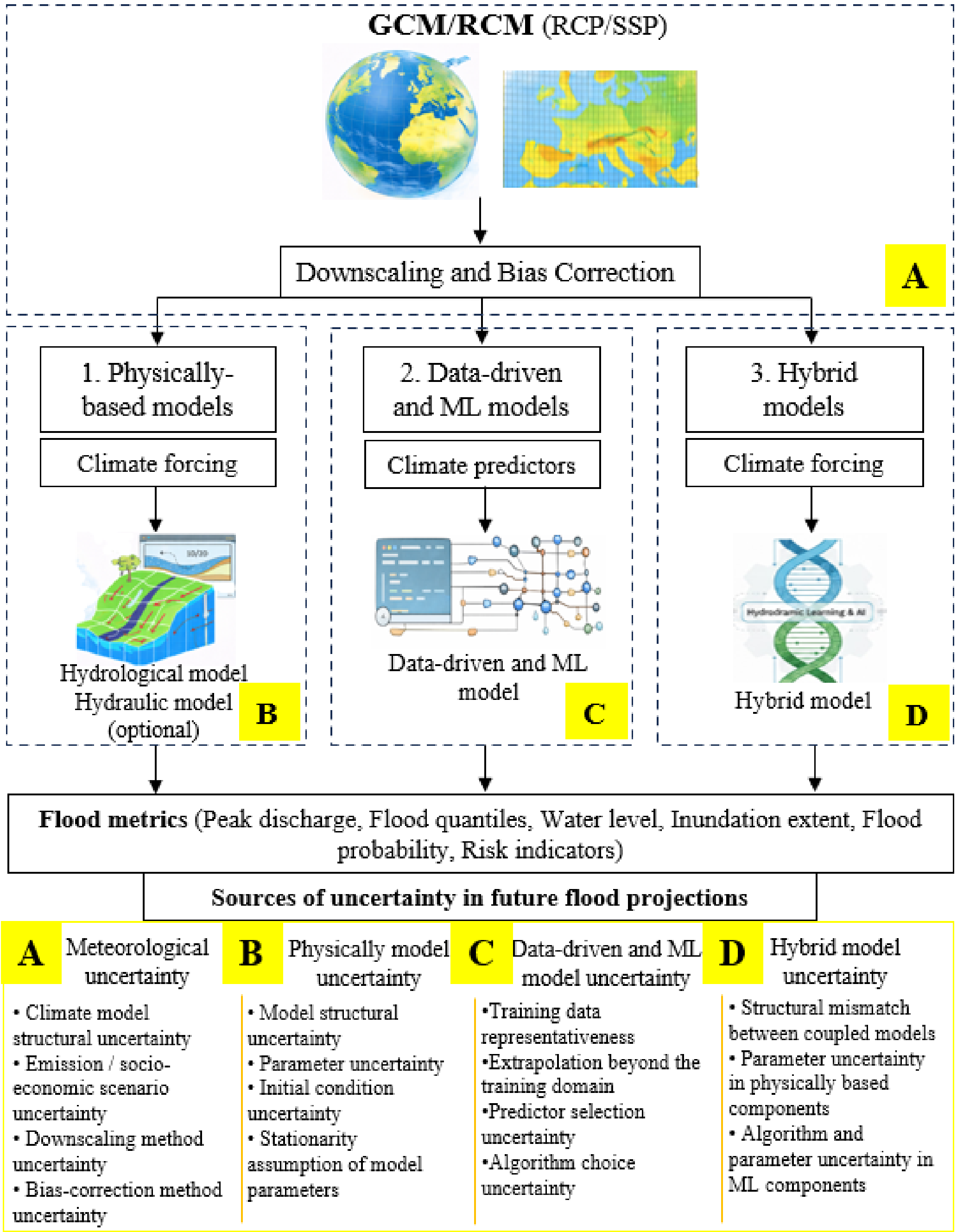

Figure 1. Modeling chains and uncertainty sources in future flood projections (diagram by author).

3.5.1. Uncertainty arising from meteorological inputs

Across all methodological frameworks, uncertainty in future flood projections is strongly influenced by the meteorological inputs used to drive models. Differences among climate models, emission scenarios, and downscaling or BC methods introduce variability in projected precipitation, temperature, and extreme events, which directly affect flood magnitude, frequency, and extent. In physically based hydrological models [8], [9], [10], [11], [12], [13], [14], [15] rainfall and temperature projections serve as primary forcing variables, making outputs highly sensitive to model choice and scenario selection.

In data-driven and ML-based approaches [16], [17], [18], [19], [20], [21], [22], meteorological inputs define the predictors for flood susceptibility or frequency, with uncertainties propagating through algorithm training and prediction. Hybrid models [23], [24], [25], inherit uncertainties from both climate forcings and statistical or ML components. Overall, across all approaches, variability in meteorological inputs represents the dominant source of uncertainty, particularly for projections of extreme floods and large-scale flood risk.

3.5.2. Uncertainty related to physical basin representation

Uncertainty also arises from how basin characteristics are represented in flood models. In physically based models, simplifications or assumptions regarding topography, river network geometry, soil properties, and land-cover dynamics can affect simulated flows and flood extents [8], [10], [12]. Many studies assume stationary basin characteristics, neglecting potential changes due to urbanization, vegetation shifts, or soil evolution, which can lead to local over, or underestimation of flood risk [9], [11]. In data-driven and ML approaches, basin properties are often indirectly represented through predictor variables, meaning that physical changes in the basin are usually not explicitly modeled, though they may influence model training and generalization [16, 21]. Hybrid models partially integrate physical and data-driven components, but uncertainties related to basin representation remain significant at the local scale [23], [24]. While critical for accurate flood mapping and depth prediction, uncertainties associated with basin representation are generally secondary to those arising from meteorological inputs, especially for regional-scale or long-term projections.

4. DISCUSSION

A review of contemporary flood and climate impact literature reveals a strong emphasis on climate-driven hydrological change, but comparatively limited integration of dynamically evolving basin physical characteristics in future flood assessments.

In their comprehensive synthesis of flood modelling approaches, Kumar et al. [5], catalogue advances in hydrologic, hydraulic, GIS-based, and ML techniques, emphasizing improvements in computational capacity, data availability, and model integration. While the authors acknowledge the importance of incorporating climate change projections into flood simulations, particularly through modified precipitation inputs, basin characteristics such as land use, soil properties, and topography are primarily treated as static model inputs derived from existing datasets. The review does not provide a systematic discussion of how projected changes in urban extent, river morphology, drainage infrastructure, or basin condition might be dynamically represented within future flood modelling frameworks. As such, climate change is conceptualized largely as an external forcing applied to relatively fixed basin structures.

A similar pattern is evident in Whitfield's review [6] of floods under future climatic conditions. The analysis concentrates on how projected changes in temperature and precipitation regimes may alter flood frequency and magnitude, with particular attention to rainfall-driven versus snowmelt-dominated systems. Although the study explicitly recognizes that land-use change, urbanization, and drainage alterations can significantly influence flood response and may confound climate signals, these factors are primarily discussed as interacting influences rather than as systematically modelled future scenarios. The review underscores the complexity of attributing observed or projected flood changes to climate alone, but also provides a list of questions for the identification of dynamic basin transformation within predictive modelling studies.

Olsson et al. [7] extend this discussion by examining the methodological chain linking global and regional climate models to hydrological impact assessments across spatial scales. Their focus is on uncertainty propagation through climate projections, downscaling procedures, BC methods, and hydrological model structures. While the authors highlight important scale-dependent challenges in simulating hydrological responses, basin physical characteristics are generally assumed to remain constant within the reviewed modelling frameworks. Future changes in channel morphology, soil degradation, urban expansion, drainage system evolution, or the implementation of nature-based solutions are not comprehensively treated as interior components of impact modelling. Instead, uncertainty is framed predominantly in terms of climate model variability and hydrological parameterization.

Collectively, these studies indicate that future flood assessments are typically driven by alterations in climatic forcing, while basin structure is held constant or adjusted only through simplified land-use inputs. Dynamic transformations in basin physical characteristics (such as urban growth trajectories, geomorphic evolution, infrastructure adaptation, or ecosystem-based interventions) remain underrepresented in mainstream flood modelling practice [5], [6], [7].

This suggests a methodological gap at the intersection of climate impact modelling and socio-hydrological change, where integrated approaches capable of representing co-evolving climate and basin systems remain comparatively limited.

Table 2 shows the different discussion angles of three reviews.

Table 2. Comparison of reviews for projecting future floods

Discussion angle	Kumar et al. [5]	Whitfield [6]	Olsson et al. [7]
Review aim	To synthesize the body of information available on several flood model types and identify the benefits, drawbacks, and challenges of each.	To compare and contrast different types of floods; to review assumptions and uncertainties related to the analysis and modelling of floods; the issues on modelling future floods and future climates.	An overview of recent progress with respect to small- and large-scale hydrological climate change impact assessment.
Typical methodological framework	The choice of model, which may include hydrodynamic models, statistical models, and physically based models, is a crucial component in flood modeling.	A summary of the complexities of the study of floods at present and future climates.	A synthesis of recent (~5 years) CC impact research in Sweden for small and large scales (basin), with development and application of all the components, i.e., climate models, bias-adjustment and downscaling, and hydrological or hydraulic modelling.
Introduction of future climate (translation)	No.	The issues listed are related to GCMs.	Simulations with hydrological models are commonly preceded by the tailoring of the GCM or RCM output. This tailoring may include bias-adjustment and/or downscaling.
Main contribution/focus	A distinct contribution by comprehensively addressing various methods used in flood models, including hydrologic, hydraulic, numerical, rainfall–runoff, remote sensing, and GIS-based, artificial intelligence and machine learning-based, multiple-criteria decision analysis-	Foundational conceptual review with limited methodological mapping. Provision of potential questions for assessing floods in future climates.	Focus on scale, uncertainty, and future assessment frameworks throughs structured chain: climate modeling, tailoring & hydrological modeling, impact assessment.

Discussion angle	Kumar et al. [5]	Whitfield [6]	Olsson et al. [7]
	based models, as well as heuristic and metaheuristic approaches		
Basin physical characteristics	Addressed implicitly: a) Data management and processing—improving flood modeling will require the efficient administration and processing of huge and varied data sources; b) Adaptation to climate change—as the climate changes, it will be crucial for flood models to take these effects into account and to help decision-making in terms of adaptation and resilience.	At the basin scale, land-use effects are more important than changes in the meteorological inputs of future climates. Basins are dynamic systems with many processes and interactions in the situation where land use and climate change interactions and feedbacks may be altered; hydrology remains a data-limited discipline, and the degree of limitation is often related to the development stage of the country.	In the context of stormwater quality: Future societal changes, such as population increase and urbanization, may have a stronger impact on future small-scale hydrological processes than climate change.

Finally, a crucial topic for this paper, the treatment of basin physical characteristics in future flood contexts varies in explicitness and analytical depth across the three reviews. Whitfield [6] adopts a strongly process-oriented perspective, emphasizing that at the basin scale, land-use change may exert a greater influence on floods than altered meteorological forcing, and framing basins as dynamic systems with feedbacks between land cover, climate variability, and hydrological response, while also highlighting data limitations as a structural constraint. Olsson et al. [7], in the context of stormwater and small-scale hydrology, similarly recognize that future societal drivers such as urbanization and population growth can outweigh climate change effects on local processes, thereby foregrounding anthropogenic alteration of basin characteristics. In contrast, Kumar et al. [5] address basin characteristics more implicitly, primarily through discussions on data management demands and the need for models to support climate adaptation and resilience, without explicitly conceptualizing basins as dynamically evolving physical systems.

Within the reviewed studies, Pal et al. [21] stand out for explicitly incorporating projected LULC changes into future flood susceptibility modelling (Figure 2). In addition, Pendić et al. [27] present a comprehensive and methodologically detailed framework for modelling future LULC dynamics in a mid-sized basin in Serbia. Although developed as a stand-alone analysis, their approach provides a transferable methodological basis for researchers intending to integrate LULC projections into future flood modelling.

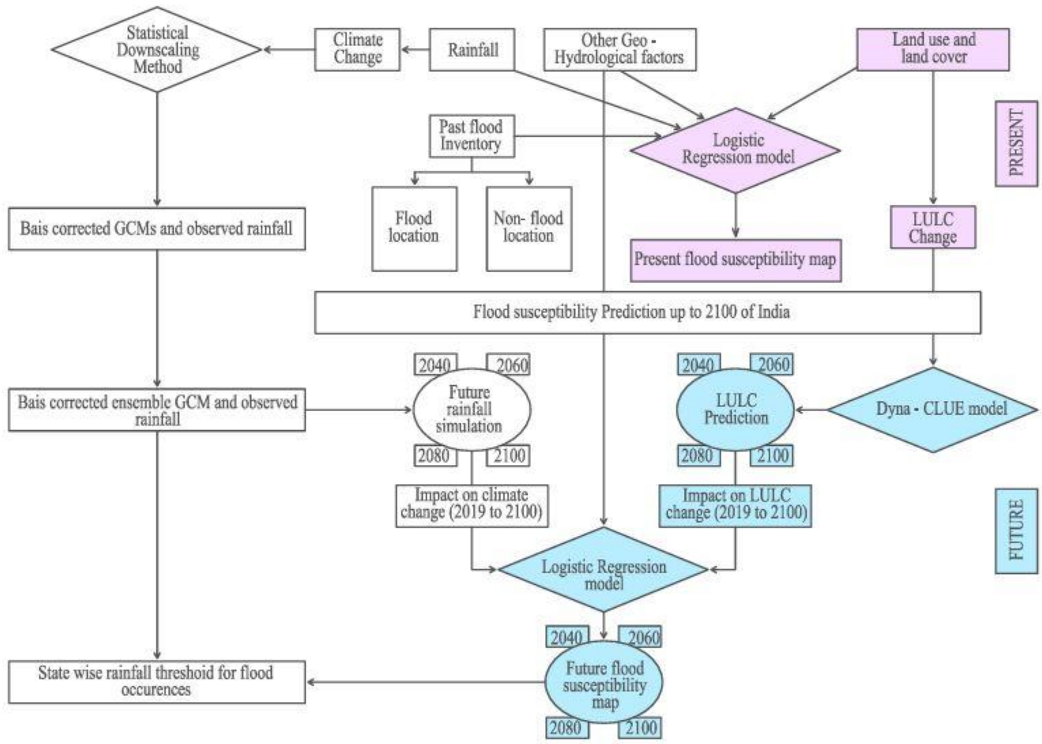

Figure 2. An example of methodological steps related to land use/land cover change within flood susceptibility modelling (modified from Pal et al. [21]).

5. CONCLUSION

Across the reviewed 19 studies, future flood projections are dominated by approaches that explicitly model climate change while generally assuming stationary physical basin characteristics. Physically based hydrological models are theoretically capable of representing evolving basin processes, yet in practice, they are most often applied with fixed land-surface and channel parameters calibrated under historical conditions. Data-driven and machine-learning approaches further reinforce this tendency by treating physiographic variables as static predictors. As a result, current modelling approaches primarily assess the sensitivity of floods to changing meteorological forcing rather than to concurrent changes in basin physical characteristics.

Based on the analysis of 19 studies, the following can be concluded, as answers to the questions set out in the introduction:

- Meteorological forcing is the primary driver of projected flood changes in most studies, with increases in flood magnitude and frequency largely attributed to intensified precipitation extremes. It is particularly evident in studies relying on precipitation-only forcing, where temperature-driven processes such as evapotranspiration or snow dynamics are either simplified or omitted. From the perspective of physical basin change, this implies that climate signals are propagated through a static system, potentially overstating or misrepresenting future flood responses where land surface or channel conditions are expected to evolve.
- Explicit representation of changes in basin physical characteristics is limited. Only a small subset of studies incorporates land-use or urbanization scenarios, consistently showing that increased imperviousness can substantially amplify flood peaks and frequencies, and/or increase flood risk. Other potentially important physical changes (soil degradation, channel modification, reservoir operation, or geomorphological adjustment) are rarely included. In susceptibility mapping and ML-based studies, physical characteristics are commonly used as conditioning factors but are assumed invariant in future projections, highlighting a persistent gap in coupled climate–basin modelling.
-
- While physical basin changes (such as urbanization) are widely recognized as influential, they remain underrepresented in the attribution of future flood change compared to

meteorological drivers. This imbalance does not reflect their lesser importance, but rather the greater availability of standardized climate model outputs (CMIP5/6), the widespread assumption of stationarity in physical parameters across modeling approaches, and the methodological difficulty of separating overlapping climatic and anthropogenic signals.

- Uncertainty assessments in future flood projections predominantly focus on climate model spread, emission scenarios, and downscaling methods, while uncertainty related to physical basin representation (e.g., parameter non-stationarity, model structural limitations, and unknown trajectories of land-use change) is less consistently quantified. This suggests that current uncertainty ranges are likely incomplete, as they do not fully capture the combined effects of climate model diversity and the potential evolution of basin properties over time.

Overall, explicit representation of dynamic basin physical changes remains limited compared to the extensive treatment of climatic drivers, revealing a persistent research gap in coupled climate–land surface flood projection frameworks.

Acknowledgement
This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, under the Agreement on Financing the Scientific Research Work of Teaching Staff at the Faculty of Civil Engineering and Architecture, University of Niš – Reg. no. 451-03-137/2025-03/200095 and the Faculty of Forestry, University of Belgrade - Reg. no. 451-03-137/2025-03/200169, dated 04/02/2025.

LITERATURE

[1] B. Merz et al., “Floods and climate: emerging perspectives for flood risk assessment and management,” *Natural Hazards and Earth System Sciences*, vol. 14, no. 7, pp. 1921–1942, Jul. 2014, doi: https://doi.org/10.5194/nhess-14-1921-2014

[2] P. C. D. Milly et al., “Stationarity Is Dead: Whither Water Management?,” *Science*, vol. 319, no. 5863, pp. 573–574, Feb. 2008, doi: https://doi.org/10.1126/science.1151915

[3] IPCC, “AR5 Climate Change 2013: The Physical Science Basis — IPCC,” *Ipcc.ch*, 2013. [Online]. Available: https://www.ipcc.ch/report/ar5/wg1/

[4] IPCC, “Climate Change 2023: Synthesis Report a Report of the Intergovernmental Panel on Climate Change,” 2023. [Online]. Available: https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

[5] V. Kumar, K. V. Sharma, T. Caloiero, D. J. Mehta, and K. P. Singh, “Comprehensive Overview of Flood Modeling Approaches: A Review of Recent Advances,” *Hydrology*, vol. 10, no. 7, pp. 141–141, Jun. 2023, doi: https://doi.org/10.3390/hydrology10070141

[6] H. J. E. Rodda and J. Hawkins, “Testing Greenfield run-off estimation techniques using high-resolution field observations,” *Journal of Flood Risk Management*, vol. 5, no. 4, pp. 366–375, Sep. 2012, doi: https://doi.org/10.1111/j.1753-318x.2012.01156.x

[7] J. Olsson et al., “Hydrological Climate Change Impact Assessment at Small and Large Scales: Key Messages from Recent Progress in Sweden,” *Climate*, vol. 4, no. 3, Art. no. 39, Sep. 2016, doi: https://doi.org/10.3390/cli4030039

[8] C. H. Wu, G. R. Huang, and H. J. Yu, “Prediction of extreme floods based on CMIP5 climate models: a case study in the Beijiang River basin, South China,” *Hydrology and Earth System Sciences*, vol. 19, no. 3, pp. 1385–1399, Mar. 2015, doi: https://doi.org/10.5194/hess-19-1385-2015

[9] C.-L. J. Hung, L. A. James, G. J. Carbone, and J. M. Williams, “Impacts of combined land-use and climate change on streamflow in two nested catchments in the Southeastern United States,” *Ecological Engineering*, vol. 143, Art. no. 105665, Jan. 2020, doi: https://doi.org/10.1016/j.ecoleng.2019.105665

[10] W. Qi, C. Zhang, G. Fu, H. Zhou, and J. Liu, “Quantifying Uncertainties in Extreme Flood Predictions under Climate Change for a MediumSized Basin in Northeastern China,” *Journal of Hydrometeorology*, vol. 17, no. 12, pp. 3099–3112, 2016, doi: https://doi.org/10.2307/26152588

[11] M. Castaneda-Gonzalez, A. Poulin, R. Romero-Lopez, R. Turcotte, and D. Chaumont, “Uncertainty sources in flood projections over contrasting hydrometeorological regimes,” *Hydrological Sciences Journal*, vol. 67, no. 15, pp. 2232–2253, Nov. 2022, doi: https://doi.org/10.1080/02626667.2022.2137415

[12] Z. Ul Hassan, A. J. Jefferson, P. M. Avellaneda, and A. S. Bhaskar, "Assessment of hydrological parameter uncertainty versus climate projection spread on urban streamflow and floods," *Journal of Hydrology*, vol. 638, Art. no. 131546, Jul. 2024, doi: https://doi.org/10.1016/j.jhydrol.2024.131546

[13] A. T. Michalek, G. Villarini, and T. Kim, "Understanding the Impact of Precipitation Bias-Correction and Statistical Downscaling Methods on Projected Changes in Flood Extremes," *Earth s Future*, vol. 12, no. 3, Mar. 2024, doi: https://doi.org/10.1029/2023ef004179

[14] H. K. Meresa and R. J. Romanowicz, "The critical role of uncertainty in projections of hydrological extremes," *Hydrology and Earth System Sciences*, vol. 21, no. 8, pp. 4245–4258, Aug. 2017, doi: https://doi.org/10.5194/hess-21-4245-2017

[15] X. Zhu et al., "Uncertainty Impacts of Climate Change and Downscaling Methods on Future Runoff Projections in the Biliu River Basin," *Water*, vol. 11, no. 10, pp. 2130–2130, Oct. 2019, doi: https://doi.org/10.3390/w11102130

[16] N. Mahdizadeh Gharakhanlou and L. Perez, "Spatial Prediction of Current and Future Flood Susceptibility: Examining the Implications of Changing Climates on Flood Susceptibility Using Machine Learning Models," *Entropy*, vol. 24, no. 11, Art. no. 1630, Nov. 2022, doi: https://doi.org/10.3390/e24111630

[17] N. Rathnayake, U. Rathnayake, I. Chathuranika, T. L. Dang, and Y. Hoshino, "Projected Water Levels and Identified Future Floods: A Comparative Analysis for Mahaweli River, Sri Lanka," *IEEE Access*, vol. 11, pp. 8920–8937, 2023, doi: https://doi.org/10.1109/access.2023.3238717

[18] M. Avand, H. R. Moradi, and M. Ramazanzadeh Lasboyee, "Spatial Prediction of Future Flood Risk: An Approach to the Effects of Climate Change," *Geosciences*, vol. 11, no. 1, Art. no. 25, Jan. 2021, doi: https://doi.org/10.3390/geosciences11010025

[19] K. Yahyazadeh Shourabi, M. H. Niksokhan and M. R. Nikoo, "Enhancing Flood Frequency Predictions Under Climate Change and Uncertainty Using Machine Learning Model Fusion and Wavelet Transform," *Earth Systems and Environment*, Oct. 2025, doi: https://doi.org/10.1007/s41748-025-00859-w

[20] R. Lazin, G. Pallotta, and C. Bonfils, "Basin-informed flood frequency analysis using deep learning exhibits consistent projected regional patterns over CONUS," *Scientific Reports*, vol. 15, no. 1, Apr. 2025, doi: https://doi.org/10.1038/s41598-025-97610-2

[21] S. C. Pal et al., "Threats of climate change and land use patterns enhance the susceptibility of future floods in India," *Journal of Environmental Management*, vol. 305, Art. no. 114317, Mar. 2022, doi: https://doi.org/10.1016/j.jenvman.2021.114317

[22] E. G. Shu et al., "Integrating climate change induced flood risk into future population projections," *Nature Communications*, vol. 14, no. 1, Art. no. 7870, Dec. 2023, doi: https://doi.org/10.1038/s41467-023-43493-8.

[23] M. R. Goodarzi, A. Fatehifar, and A. Moradi, "Predicting Future Flood Frequency Under Climate Change Using Copula Function," *Water and Environment Journal*, May 2020, doi: https://doi.org/10.1111/wej.12572

[24] Ghazi Al-Rawas, M. R. Nikoo, S. Farid, M. R. Hassani, and R. Nazari, "Near future flash flood prediction in an arid region under climate change," *Scientific Reports*, vol. 14, no. 1, Oct. 2024, doi: https://doi.org/10.1038/s41598-024-76232-0

[25] W. Liu, Q. Feng, B. A. Engel, T. Yu, X. Zhang, and Y. Qian, "A probabilistic assessment of urban flood risk and impacts of future climate change," *Journal of Hydrology*, vol. 618, Art. no. 129267, Mar. 2023, doi: https://doi.org/10.1016/j.jhydrol.2023.129267.

[26] S. Malla and K. Ohgushi, "Evaluation of Climate Change Impact on Future Flood in the Bagmati River Basin, Nepal Using CMIP6 Climate Projections and HEC-RAS Modeling," *Water Cycle*, Aug. 2025, doi: https://doi.org/10.1016/j.watcyc.2025.08.004

[27] J. Pendić, M. Milićević, N. Đokić, B. Blagojević, and V. Mihailović, "Uporedni prikaz metoda za predviđanje promene namene zemljišta i zemljišnog pokrivača na primeru sliva reke Toplice do 2100. godine," *Vodoprivreda,* vol. 56, 2024, https://doi.org/10.46793/Vodoprivreda56.3-4.121P