

Evolution, applications, and emerging challenges in probable maximum precipitation estimation: A bibliometric and systematic review

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Abstract

The characterization of extreme events is essential for the design and planning of critical hydraulic structures; however, the procedures used to define upper bounds on precipitation have been increasingly reformulated in response to new data sources, advances in modeling, methodological uncertainties, and climate change. This study examined the global evolution of the literature on Probable Maximum Precipitation (PMP), its main estimation procedures, applications, incorporation of future conditions, evidence of temporal changes, and research gaps. The search was conducted in the Scopus and Web of Science Core Collection databases, covering the entire period available through July 31, 2026, using the exact expression "Probable Maximum Precipitation". Of the 671 records retrieved, 422 remained after duplicate removal, and 354 underwent full-text review; among these, 222 produced new PMP estimates. Scientific output increased markedly in recent decades, with 70.9% of the articles published between 2011 and 2026. Among studies that estimated PMP, 66.22% primarily employed classical statistical procedures or storm maximization-based methods, while physically based numerical, probabilistic, multifractal, atmospheric, and hybrid techniques reflected increasing methodological diversification. Thirty-five studies explicitly incorporated future projections into PMP estimation or updating, with responses varying according to region, duration, scenario, and representation of atmospheric processes. Only nine articles reported statistical or modeling evidence of temporal changes in PMP or in variables directly related to its estimation. The findings indicate that the field is progressing toward more adaptable, physically based, and uncertainty-transparent approaches, without simply replacing traditional methods.

1. INTRODUCTION

Extreme precipitation events represent one of the major challenges in contemporary hydrology, particularly because of their potential to trigger floods, erosion, mass movements, drainage system failures, and damage to critical hydraulic infrastructure. These events are characterized by high spatial and temporal variability, may occur over short time intervals, and can produce disproportionate impacts across urban, rural, and mountainous watersheds (Fowler et al., 2021; Westra et al., 2014). Moreover, the intensification of the hydrological cycle under a warmer climate has increased scientific concern regarding the future magnitude of extreme precipitation, particularly in regions prone to flash floods and structural failures associated with low-probability, high-impact events (Visser et al., 2022).

The estimation of extreme precipitation is essential for the planning, design, and safety assessment of hydraulic structures, including dams, spillways, reservoirs, bridges, drainage systems, and strategic facilities. For high-risk structures, underestimating design precipitation may compromise hydraulic safety and increase population exposure to catastrophic events, whereas excessively conservative estimates may lead to higher costs and economically inefficient designs (Martin et al., 2025; Micovic et al., 2015).

The World Meteorological Organization defines Probable Maximum Precipitation (PMP) as the greatest depth of precipitation that is meteorologically possible for a given duration, area, and geographic location under plausible critical atmospheric conditions (Salas et al., 2020; WMO, 2009). Traditionally, PMP has been used as an input for estimating the Probable Maximum Flood (PMF) and is applied in the design and safety assessment of dams, hydropower facilities, nuclear installations, and other structures whose failure could have severe consequences (Salas et al., 2020).

Historically, the concept of PMP emerged from the need to estimate upper bounds of precipitation for design purposes at a time when hydrometeorological records were limited and statistical extrapolation to rare events involved substantial uncertainty (Hansen, 1987). Early operational procedures were strongly influenced by hydrometeorological approaches based on the maximization of observed storms, spatial transposition, depth-area-duration analysis, and atmospheric moisture maximization (Paulhus and Gilman, 1953). In parallel, statistical methods, such as that proposed by Hershfield, became widely adopted because of their simplicity, applicability in regions with available precipitation records, and ability to estimate PMP from annual precipitation maxima (Hershfield, 1961; Koutsoyiannis, 1999).

From this perspective, the frequency factor proposed by Hershfield was initially treated as constant, but subsequent studies demonstrated that its magnitude may vary according to duration, the mean intensity of precipitation maxima, and regional climatic characteristics (Hershfield, 1965). This finding paved the way for critical reassessments, regionalization procedures, and adaptations of the method, including discussions on envelope curves, probabilistic bounds, and the validity of the assumption that precipitation has an absolute physical upper bound (Chavan and Srinivas, 2017; Koutsoyiannis, 1999).

Because PMP has traditionally been treated as a deterministic quantity, it has often been presented as a single estimate, even though its calculation involves several methodological choices and sources of subjectivity, including storm selection, transposition, moisture maximization, definition of the critical duration, and spatial representation of precipitation (Ben Alaya et al., 2018). More recent studies have adopted probabilistic approaches, sensitivity analyses, and uncertainty quantification methods to assess the robustness of PMP estimates and their implications for hydraulic design (Rouhani and Leconte, 2019).

Over the past decades, the literature has also incorporated new scientific questions related to the regionalization of estimates, comparison among approaches, parameter sensitivity, methodological uncertainty, physical representation of storms, and the influence of climate change (Tarouilly et al., 2023; Wright et al., 2020). Consequently, PMP research has moved beyond focusing exclusively on determining “how much it can rain at most” and has increasingly investigated how different assumptions, datasets, models, and climatic contexts influence the estimation of this extreme (Wright et al., 2020).

Another major area of development concerns the incorporation of climate change. The classical definition of PMP considers meteorologically possible conditions for a given period and location but historically did not explicitly account for long-term climate trends (Kunkel et al., 2013; Stratz and Hossain, 2014). However, recent evidence indicates that changes in air temperature, atmospheric moisture, and circulation patterns may alter the magnitude of extreme events and, consequently, the operational PMP values used in the design of critical infrastructure (Xiong et al., 2024).

In this context, recent literature has questioned the adequacy of static PMP estimates under a nonstationary climate. Studies conducted in Australia, China, Hong Kong, and other regional settings indicate that PMP values may change in response to increasing atmospheric moisture, intensification of precipitation extremes, and projected changes in future climatic conditions (Chan et al., 2024; Visser et al., 2022; Xiong et al., 2024). In addition, approaches based on climate models, atmospheric reanalyses, and high-resolution simulations have provided new opportunities to assess extreme storms under current and future conditions, broadening the scope of PMP estimation beyond traditional methods (Hiraga et al., 2025).

Thus, whereas classical hydrometeorological methods rely primarily on the maximization of observed storms, atmospheric models make it possible to investigate the physical mechanisms associated with convective organization, water vapor transport, moisture convergence, orographic effects, and interactions between atmospheric dynamics and thermodynamics (Chen and Hossain, 2018; Hiraga et al., 2025). Recent studies have shown that the relationship between extreme precipitation and atmospheric moisture is not always linear, particularly for convective storms, mesoscale systems, and regions with complex topography, challenging the traditional assumption that greater moisture availability necessarily results in greater precipitation (Yang and Smith, 2018).

In parallel, recent advances in the field have also been associated with the diversification of data sources. Estimates based exclusively on rain gauges have increasingly been complemented by satellite products, weather radar, atmospheric reanalyses, high-resolution climate datasets, and machine-learning algorithms (Ekpeteri et al., 2024; Rahimi et al., 2025). This transition is particularly relevant in regions with sparse rain-gauge networks, where products such as IMERG, CHIRPS, reanalysis datasets, and high-resolution gridded precipitation products can improve the spatial coverage of estimates and enable new strategies for PMP regionalization and updating (Kalura et al., 2024; Pandey et al., 2026).

Despite these advances, existing reviews tend to address specific aspects of PMP, such as statistical methods, hydrometeorological procedures, climate change, or applications related to dam safety (Cyphers et al., 2022). There remains a need for a comprehensive synthesis that interprets the evolution of PMP research as an integrated scientific process,

highlighting how emerging research questions have contributed to the development and diversification of methodological approaches over time (Lee and Singh, 2020).

Against this background, this study presents a systematic review supported by bibliometric analysis to examine the scientific evolution of research on Probable Maximum Precipitation. Specifically, it seeks to characterize its temporal and geographical expansion, systematize the predominant methods and applications, and assess the incorporation of climate change and nonstationarity into PMP estimates. Finally, the main research gaps and recommendations identified in the literature are synthesized, providing an integrative perspective on the advances and challenges shaping the future development of the field.

2. METHODOLOGY

The review was structured to characterize the evolution of the scientific literature on Probable Maximum Precipitation (PMP), the procedures used for its estimation, its applications, the incorporation of future climate conditions, the assessment of nonstationarity, and the main research gaps identified in the studies. To systematically guide data extraction, classification, and synthesis, seven research questions were established:

RQ1 – Temporal evolution, geographical distribution, and research themes

How has scientific production on PMP evolved over the period analyzed, how are the studies geographically distributed, and which research themes predominate in the literature?

RQ2 – PMP estimation methods and methodological evolution

Which methods and methodological approaches have been used to produce PMP estimates, what is their frequency within the corpus of estimation studies, and how are these approaches distributed across the literature?

RQ3 – Research purposes and engineering applications

What are the main purposes of studies that estimate PMP, and how have these estimates been applied to engineering problems?

RQ4 – Climate change in PMP estimation

To what extent and in what ways have future climate projections been incorporated into the estimation, updating, or comparison of PMP values, considering climate scenarios, models, and projection horizons?

RQ5 – Nonstationarity and implications for PMP estimation

In what proportion of studies has nonstationarity in PMP, extreme precipitation, or variables directly related to its estimation been formally assessed, which procedures have been employed, and what evidence has been reported by the authors?

RQ6 – Scientific gaps and future directions

Which limitations, scientific gaps, and recommendations for future research are explicitly reported by the authors of PMP studies, and which recurring themes emerge from these records?

RQ7 – Limitations of the review

Which limitations arising from the search strategy, full-text availability, classification procedures, metadata treatment, and temporal coverage should be considered when interpreting the findings of this review?

The first six research questions guided the extraction and synthesis of information from the included studies, whereas RQ7 was designed to critically assess the limitations inherent in the review protocol and the methodological decisions adopted in this study.

2.1. Search strategy and eligibility criteria

The bibliographic search was conducted in Elsevier's Scopus and Clarivate's Web of Science Core Collection databases, covering the entire period available through July 31, 2026. The exact expression "Probable Maximum Precipitation" was searched across all available fields. Scopus was selected because of its broad multidisciplinary coverage, whereas Web of Science was included because of its selective coverage and the availability of established indexing and citation analysis tools (Mongeon and Paul-Hus, 2015). Access to both databases was obtained through the CAFE-CAPES portal, institutionally linked to the Federal University of Espírito Santo (UFES).

Only documents classified as scientific journal articles were included. Records classified as conference paper, book chapter, review, conference review, book, and data paper were excluded.

The search strategy retrieved 380 records from Scopus and 291 from Web of Science, totaling 671 documents. Bibliographic metadata were exported in BibTeX format and integrated into the RStudio environment using the *bibliometrix* package. Duplicate records were identified based on DOI, title, authorship, and other available bibliographic information. After duplicate removal, 422 unique records remained.

The full text of each record was searched individually. Studies whose complete content could not be located or accessed were excluded from the full-text review stage. Of the 422 unique records, 68 had no full text available, resulting in a final corpus of 354 articles subjected to analysis.

2.2. Data extraction and organization

The 354 articles with full texts available underwent full-text review and standardized extraction of the information required to address the research questions. When necessary, the texts were translated to enable assessment of the different sections of the articles.

For each study, bibliographic, geographical, and methodological information directly reported by the authors was recorded, including title, authorship, publication year, journal, DOI, country or region in which the study was conducted, data type and source, spatial and temporal scales, and procedures used in PMP analysis or estimation.

Data extraction was guided by the research questions. For RQ1, publication year, geographical location of the studies, and terms included in the *Keywords* field were recorded. For RQ2, the procedures employed to produce new PMP estimates were documented. For RQ3, the purposes explicitly associated by the authors with the PMP estimate produced were identified. For RQ4, information related to the use of future climate projections was extracted. For RQ5, the formal procedures used to investigate temporal changes and the corresponding results reported by the authors were recorded. For RQ6, limitations, research gaps, and recommendations explicitly presented in the articles were extracted.

When a study included multiple methods, applications, scenarios, models, or results, all relevant information was recorded during extraction and subsequently organized according to the criteria established for each research question.

2.3. Temporal evolution, geographical distribution, and research themes – RQ1

The temporal evolution of scientific production was determined from the year of publication by counting the number of articles published each year. Because the search was completed on July 31, 2026, publications from that year were treated as representing an incomplete period.

The geographical distribution was defined according to the country or region in which each study was conducted rather than the institutional affiliation of the authors. Studies conducted entirely within a single country were assigned to that country, whereas studies encompassing two or more countries or jointly analyzing different national territories were classified as multinational. The distribution was also summarized by continent.

Research themes were examined using terms recorded exclusively in the *Keywords* field. The 50 most frequent terms were counted after removing missing values and records without valid content. Terms were retained as reported in the original metadata, without standardization of synonyms or terminological variants. Their frequencies were represented using a word cloud, in which the visual size of each term was proportional to the number of occurrences.

2.4. PMP estimation methods and methodological evolution – RQ2

To address RQ2, the articles were initially assessed to determine whether they produced at least one new quantitative estimate of Probable Maximum Precipitation. Estimation studies were defined as those that calculated, recalculated, updated, reassessed, or produced PMP values for a station, location, watershed, region, or spatial domain using observed or simulated data.

Articles were not classified as estimation studies when they merely mentioned or conceptually discussed PMP, reproduced previously published values, or used estimates obtained from maps, standards, reports, or other external sources without performing a new calculation. Likewise, the isolated calculation of auxiliary components, such as precipitable water or depth–area–duration curves, was not considered sufficient when these components were not integrated into a procedure resulting in new PMP values.

Estimation of the Probable Maximum Flood (PMF), flood modeling, spillway design, and dam safety assessment were also not considered, in isolation, evidence of PMP estimation. In such cases, the source of the precipitation input was examined, and only articles that produced their own PMP estimates and subsequently used them in hydrological, hydraulic, or safety analyses were included in the estimation subset.

For studies classified as estimation studies, the procedures used were recorded as described by the authors and harmonized, for quantitative synthesis, into the following categories: Hershfield statistical method, hydrometeorological method, physically based numerical method, other statistical methods, atmospheric modeling, multifractal method, probabilistic method, hybrid method, empirical method, and comparative or multi-method approach.

When only one procedure was used, classification directly followed the method described. When different procedures were employed, the method explicitly identified by the authors as the primary approach was adopted. When multiple methods were independently applied to produce and compare PMP estimates without identification of a primary approach, the study was classified as comparative or multi-method. Each article was therefore counted only once in the distribution of methodological approaches.

2.5. Research purposes and engineering applications – RQ3

To address RQ3, the purpose directly associated by the authors with the production or use of the PMP estimate was recorded. Coding was based on objectives explicitly stated in the abstract, introduction, or objectives section of each article, thereby avoiding the attribution of purposes not declared by the studies themselves.

The identified purposes were harmonized into the following categories: direct PMP estimation; updating of PMP values; regionalization and mapping; Probable Maximum Flood estimation; dam safety; spillway design; flood modeling; hydrological risk assessment; climate change assessment; and methodological comparison or development.

For quantitative synthesis, each article was counted in a single category. When the authors explicitly identified a primary purpose, this designation was used directly. When multiple objectives were presented without an explicit hierarchy, the purpose directly associated with the central analysis in which PMP was estimated or evaluated was adopted. This

classification was used exclusively to organize the quantitative synthesis and does not imply that a study was restricted to a single application.

In addition to the quantitative classification, engineering applications were examined according to how PMP values were used in subsequent analyses, including PMF estimation, dam safety assessment, spillway design or verification, flood modeling, and hydrological risk assessment.

2.6. Climate change in PMP estimation – RQ4

To address RQ4, studies that incorporated information on future climate conditions directly into the estimation, updating, or comparison of PMP values were identified. Inclusion in this subset required two simultaneous conditions: explicit use of future climate projections and integration of this information into the procedure used to estimate or reassess PMP.

Future climate information included emission scenarios or socioeconomic pathways, global or regional climate models, atmospheric models forced by future conditions, or projected changes in variables directly used in PMP estimation, such as temperature, humidity, dew point, precipitable water, or extreme precipitation. Climate perturbation approaches, such as *Pseudo Global Warming* and WRF-PGW, were also included when used to produce future PMP estimates.

The mere mention of climate change, global warming, or potential future impacts was not considered sufficient for inclusion. Similarly, studies based exclusively on historical observations were excluded from this subset when future projections were not incorporated into the estimation procedure.

For each included article, the climate scenario, climate or atmospheric model, reference period, future period, and reported PMP change relative to reference conditions were recorded whenever available. Scenario nomenclature was retained as reported in the original studies, including the SRES, RCP, and SSP families. When an article used more than one scenario, model, or future period, all information was recorded, although the study was counted only once in the total climate-related subset.

2.7. Nonstationarity and implications for PMP estimation – RQ5

To address RQ5, the articles were assessed to determine whether formal procedures had been applied to investigate temporal changes in PMP, extreme precipitation, or variables directly used in or explicitly related to its estimation. Nonstationarity was analyzed separately from climate change because the use of future projections or simple comparisons between climatic periods does not, by itself, constitute a formal assessment of nonstationarity.

Studies were considered to have formally assessed nonstationarity when they applied statistical trend tests, change-point or regime-shift detection methods, statistical comparisons between periods, temporal regressions, or models with parameters varying as functions of time or climatic covariates. Analyses of changes in the location, scale, or shape parameters of extreme-value distributions were also considered when such variation was explicitly modeled or tested.

For each study, the variable analyzed, procedure employed, period assessed, and result reported by the authors were recorded. Evidence of nonstationarity was recorded when the study itself reported statistical or modeling results indicating a trend, change, structural break, temporal or climatic dependence, or superior performance of a nonstationary formulation compared with a stationary formulation, according to the criteria used by the authors.

Temporal plots without formal testing, exclusively descriptive percentage differences, isolated comparisons between historical and future periods, and general discussions of climate change were not considered formal evidence of nonstationarity. When the analysis involved an auxiliary variable, such as dew-point temperature, precipitable water, or a maximization factor, it was considered relevant only when the article explicitly established its relationship with extreme precipitation or the PMP estimation procedure.

The synthesis was performed at two levels. First, it was recorded whether nonstationarity had been formally assessed. Subsequently, the result reported by the study was recorded, distinguishing cases in which evidence of nonstationarity was

identified from those in which the procedures employed did not indicate statistically significant changes.

2.8. Scientific gaps and future directions – RQ6

To address RQ6, limitations, scientific gaps, and recommendations for future research explicitly reported by the authors of the studies included in the review were identified. Extraction was based on verifiable textual passages found primarily in the discussion, limitations, and conclusions sections.

Limitations or gaps were recorded when the authors themselves recognized constraints related to data, methods, models, assumptions, scales of analysis, conditions of application, or available knowledge. Recommendations for future research were recorded only when explicitly formulated in the articles.

After extraction, the records were manually grouped according to thematic similarity to support qualitative synthesis. This grouping served exclusively an organizational purpose and did not alter the content originally reported by the studies. When a single article presented more than one limitation, gap, or recommendation, all were recorded during extraction.

For presentation of the results, the records were organized into recurring thematic axes. The assignment of a study to a particular axis was used solely to organize the synthesis and does not imply that the article was exclusively related to that category. The main synthesis presents recurring themes and representative studies, whereas the complete list of articles included in this stage, together with their limitations, gaps, recommendations, and corresponding textual evidence, is provided in the supplementary material.

2.9. Limitations of the review – RQ7

RQ7 was devoted to the critical assessment of limitations associated with the design of the review itself. Aspects related to the search strategy, bibliographic databases used, full-text availability, study classification procedures, treatment of bibliographic terms, and temporal coverage of the search were considered.

Potential effects arising from the use of a specific search expression, exclusion of records without full-text access, the need to synthesize methodologically heterogeneous studies into common categories, and the adoption of mutually exclusive categories for selected quantitative analyses were also considered.

The limitations were examined in terms of their potential effects on literature coverage, representation of the observed frequencies, and scope of the inferences derived from the review. This stage was critical and interpretative in nature and was used to delimit the scope of the findings without modifying the inclusion, extraction, or classification criteria applied to the preceding research questions.

3. RESULTS AND DISCUSSION

3.1. Temporal evolution, geographical distribution, and research themes

Scientific production on Probable Maximum Precipitation covered the period from 1953 to 2026, with only articles available through July 31 considered for the final year. As shown in Fig. 1, the first article in the corpus was published in 1953, followed by a prolonged period of limited scientific activity. By 1979, only six publications had been identified, with several years in which no articles on the topic were published.

Between 1980 and 2010, the literature showed gradual growth, although it remained characterized by fluctuations and a low annual number of publications. During this period, 97 articles were published, generally fewer than ten studies per year.

The highest annual number of publications before 2011 occurred in 1995, with eight articles. The trajectory shown in Fig. 1 therefore indicates that PMP remained a relatively restricted research field during much of the period analyzed.

The increase in scientific production became more pronounced from 2011 onward. Between 2011 and 2026, 251 articles were published, accounting for 70.9% of the 354 studies included in the review. In addition, 178 publications, corresponding to 50.3% of the corpus, were concentrated between 2017 and 2025. The highest annual number was recorded in 2025, with 32 publications, followed by 2022 with 28, 2019 with 23, and 2018 with 22 articles. In 2026, 15 publications were identified up to the search cutoff date; however, because this was an incomplete year, this value should not be interpreted as an actual decline in scientific production.

The concentration of 70.9% of publications between 2011 and 2026 demonstrates that research on Probable Maximum Precipitation expanded primarily in recent decades, following a prolonged period of limited and discontinuous production. This growth coincided with increasing attention to uncertainty, updating of estimates, climate change, and the safety of hydraulic structures. Martin et al. (2025) highlight that current methods still have limitations associated with variables that are not directly observed, successive approximations, and difficulties in uncertainty quantification. Complementarily, Wasko et al. (2024) identify a persistent gap between advances in climate science and their incorporation into operational guidelines used for design flood estimation.

The 354 articles analyzed showed broad geographical coverage, encompassing different continents and climatic contexts. However, the studies were concentrated in a relatively limited number of countries, as shown in Fig. 2.

The leading contribution of the United States, accounting for 86 articles and 24.3% of the corpus, is consistent with the country's historical role in the development and institutionalization of PMP estimation methods. Early hydrometeorological approaches were consolidated in this context, together with the Hershfield statistical method and storm maximization and transposition procedures that were subsequently disseminated internationally (Lee and Singh, 2020). However, the recent expansion of the literature has not remained restricted to countries historically associated with the development of the concept.

At the continental scale, Asia accounted for the largest number of publications, with 138 articles, representing 39.0% of the corpus. North America comprised 105 studies (29.7%), whereas Europe accounted for 51 (14.4%). South America, Africa, and Oceania showed smaller contributions, with 11 (3.1%), 10 (2.8%), and seven publications (2.0%), respectively.

The high contribution from Asia was particularly associated with scientific production from India and China. Research development in these countries was characterized by a transition from local applications to national and spatially distributed assessments and, in some cases, to analyses integrated with climate projections. In India, Sarkar and Maity (2020) produced maps of daily PMP for different periods between 1901 and 2100 by combining observational data, regional climate models, and emission scenarios. In China, Xiong et al. (2024) employed daily data at 1-km resolution generated with the aid of machine-learning algorithms to represent the national distribution of PMP. These examples demonstrate that the quantitative expansion of scientific production was accompanied by increases in both the spatial scale and methodological complexity of the studies.

Country participation also varied over the period analyzed. Figure 3 presents the temporal evolution of scientific production for the 20 countries with the highest number of publications in the analyzed corpus. The early decades were characterized by discontinuous publication activity, concentrated primarily in the United States, with only isolated contributions from a few other countries.

From the 1990s onward, India became increasingly represented, while publications from other regions progressively emerged. This process intensified after 2010, when both the number of articles and the diversity of participating countries increased. In recent years, expansion was particularly evident among Asian countries, including China, Iran, Malaysia, South Korea, Indonesia, Japan, Sri Lanka, and Vietnam. North America maintained a consistent contribution, particularly through the United States and Canada, whereas European countries showed more dispersed contributions over time.

Studies conducted in more than one country were classified as multinational and totaled 32 publications, corresponding to 9.0% of the analyzed dataset. Ben Alaya et al. (2019), for example, evaluated changes in six-hour PMP across North America using Canadian regional climate models. Such internationalization is particularly relevant for atmospheric phenomena and watersheds that are not constrained by political or administrative boundaries.

Considering the three countries with the highest scientific production, the United States, India, and China together accounted for 146 articles, equivalent to 41.2% of the corpus. When the multinational category is added, these four classes comprise 178 studies, or 50.3% of all publications. These values demonstrate that, despite the diversification observed in recent decades, scientific production on PMP remains significantly geographically concentrated.

This inequality is also evident among continents. South America, Africa, and Oceania jointly accounted for only 7.9% of the articles, whereas Asia and North America accounted for 68.6%. Lower bibliometric representation does not necessarily indicate lower relevance of PMP in these regions but may reflect limitations related to monitoring, data availability, and institutional capacity to produce and update estimates.

These limitations are particularly relevant in regions characterized by sparse observational networks or complex climatic and topographic conditions. In a poorly monitored Andean watershed in Chile, Lagos-Zúñiga and Vargas (2014) demonstrated that the low density of monitoring stations and strong orographic influence increase uncertainty in the spatial distribution of precipitation, requiring the integration of observations, regional models, and topographic criteria. In South Africa, Johnson and Smithers (2020) found that national estimates used in professional practice had been developed approximately five decades earlier and that incorporating longer data series and updated methods generally resulted in higher values. In Algeria, Zeroual et al. (2022) highlighted that short record lengths and the scarcity of high-flow measurements hinder the assessment of extreme floods in arid and semi-arid regions. These cases demonstrate that geographical diversification of research should be accompanied by strengthening observational networks and adapting methods to regional climatic characteristics.

The combined analysis of Figs. 2 and 3 therefore indicates that the recent growth of the literature was not driven solely by increased activity in countries historically most prominent in PMP research. It was also associated with the emergence of new countries, greater continuity of publications across different regions, and increased participation of multinational studies. Thus, the evolution of PMP research was characterized by two simultaneous processes: a substantial increase in the annual number of studies and greater geographical diversification of scientific production, although significant regional inequalities persist.

In addition to the temporal and geographical dimensions, the frequency of terms in the Keywords field provides a complementary perspective on the main themes associated with the PMP literature. The word cloud containing the 50 most frequent keywords is presented in Fig. 4. The term “probable maximum precipitation” was the most frequent, with 53 occurrences, followed by “floods” with 19 and “probable maximum flood” with 14. Terms related to precipitation, statistical methods, estimation, hydrology, extreme events, and probability were also prominent.

The presence of terms such as “dams”, “design flood”, “risk assessment”, “dam safety”, “runoff”, and “reservoirs” highlights the strong association of PMP with extreme flood assessment, hydrological risk, and the safety of hydraulic structures. Terms related to climate change and atmospheric conditions were also identified, although less frequently, indicating the incorporation of these topics into more recent literature. Because synonyms were not standardized, variants such as “probable maximum precipitation”, “probable maximum precipitation (PMP)”, and “PMP” were counted separately, which should be considered when interpreting the reported frequencies.

3.2. PMP estimation methods and methodological evolution

Of the 354 articles subjected to full-text review, 222 produced new PMP estimates, whereas 132 did not meet the established criteria for classification as estimation studies. From this point onward, analyses of the methods employed and the main purposes of the studies were conducted using the subset of 222 estimation studies, as shown in Fig. 5.

The Hershfield statistical method was the most frequently used approach, adopted as the primary method in 80 articles, corresponding to 36.04% of the analyzed subset. Hydrometeorological methods ranked second, being identified in 67 studies (30.18%). Together, these two approaches accounted for 147 articles, equivalent to 66.22% of the estimation studies, demonstrating that PMP estimation remains strongly grounded in established statistical and hydrometeorological procedures.

The continued use of the Hershfield method may be partly related to its relative simplicity, lower data requirements, and ease of application in regions where precipitation time series constitute the main source of available information (Hershfield, 1965). Its widespread use, however, does not imply an absence of conceptual and methodological criticism. Koutsoyiannis (1999) questioned the interpretation of Hershfield's result as an absolute physical upper bound. By reexamining the data used in the development of the method, the author argued that they did not support the existence of a deterministic upper limit to precipitation. Reformulation of the procedure using the Generalized Extreme Value distribution produced results close to those of the original envelope for a return period of approximately 60,000 years. This interpretation brings PMP closer to an extreme estimate associated with probabilistic assumptions rather than an absolutely verifiable natural limit.

Hydrometeorological methods, in turn, remain relevant because they explicitly represent processes associated with storm generation and maximization. However, decisions involved in event selection, transposition, and maximization can introduce considerable variability into the estimates. Micovic et al. (2015) found, for the La Joie Dam basin in Canada, that the upper value associated with plausible combinations of meteorological variables exceeded the single operational estimate by more than 40%. Based on this variation, the authors advocated presenting PMP as a range of values accompanied by uncertainty information rather than exclusively as an isolated deterministic estimate.

A recurrent source of uncertainty in these procedures is the use of surface dew-point temperature to represent precipitable water throughout the entire atmospheric column. Kim et al. (2020), when comparing JRA-55 reanalysis data with values calculated using this approximation at 30 locations in Japan, identified event precipitable water as one of the main sources of error in the maximization process. Deviations were particularly large when surface dew-point temperature was below approximately 18°C, a condition under which the state of the atmospheric column was less adequately represented by surface information. This finding demonstrates that simplifications used to represent moisture availability can directly affect maximization factors and, consequently, final PMP estimates.

Uncertainties also persist in defining the upper bounds of moisture maximization factors. Rouhani and Leconte (2016) observed that traditionally adopted upper limits do not always have a robust physical or statistical basis. As an alternative, they used outputs from a regional climate model to construct annual maximum precipitable water series conditioned on atmospheric characteristics similar to those of the original storm. Application to three basins in Quebec produced factors lower than conventional limits and reduced PMP estimates by approximately 11%, demonstrating that accounting for atmospheric compatibility can substantially alter the resulting estimates.

Alongside the continued use of traditional methods, the results show a gradual diversification of the approaches employed. Physically based numerical methods constituted the third most frequent category, with 25 articles (11.26%), whereas 20 studies (9.01%) adopted a comparative or multi-method approach. Other statistical methods, distinct from the specific Hershfield classification, were identified in 14 publications (6.31%). Atmospheric modeling, multifractal methods, and probabilistic methods were each identified in four studies (1.80%), while hybrid methods appeared in three articles (1.35%) and the empirical method in one study (0.45%). Although these approaches accounted for smaller proportions of the literature, their presence indicates an expansion of the methodological field beyond traditionally used procedures.

This diversification also includes the use of storm models and atmospheric simulations capable of representing physical processes that are not explicitly considered in more traditional methods. Collier and Hardaker (1996) proposed an approach based on a convective storm model. For durations shorter than 11 hours, the resulting values were similar to those produced by the procedure then used in the United Kingdom. For durations between 11 and 24 hours, however, the model generated

higher values, a difference attributed to the contribution of mesoscale convective systems that were not adequately represented in previous estimates.

The incorporation of greater physical complexity, however, does not automatically eliminate uncertainties or necessarily imply proportional increases in PMP. Tarouilly et al. (2024) investigated the hypothesis that historical storms may already have exhibited maximum efficiency in converting atmospheric moisture into precipitation. Using an artificial record of approximately 1,150 years and adjusting the ten most severe storms, the authors identified events with efficiencies up to 30% greater and precipitation amounts 32% higher than those of historical storms. After maximization, however, the final PMP estimates were only 8% higher than those obtained from observed events, indicating a degree of convergence between the datasets and showing that greater physical detail does not necessarily produce changes of equivalent magnitude in the final estimates.

Methodological diversification has also extended to the formal quantification of uncertainty in the Hershfield method. Bhatt and Srinivas (2025) developed a framework based on imprecise probability to integrate uncertainties associated with record length and sampling, definition of homogeneous regions, preparation of frequency factors, and construction of envelope curves. The results showed that the relative contribution of each source varied among the basins analyzed, reinforcing that PMP uncertainty cannot be represented by a single component or universal factor.

Taken together, these advances indicate that the methodological evolution of PMP has not occurred through the simple replacement of traditional methods, but rather through reassessment of their assumptions, incorporation of new data sources, and formalization of uncertainty. Statistical and hydrometeorological procedures remain operationally relevant, while atmospheric models, probabilistic methods, and hybrid frameworks broaden the possibilities for interpreting and updating PMP estimates.

3.3. Research purposes and engineering applications

In addition to the methodological approach employed, each of the 222 studies was classified according to its primary purpose, as presented in Fig. 6.

Methodological comparison or development was the predominant purpose, identified in 77 articles, corresponding to 34.68% of the analyzed subset. This result indicates that approximately one-third of the studies primarily aimed to evaluate existing methods, improve estimation procedures, or develop new approaches for PMP estimation.

Climate change assessment was the second most frequent purpose, with 38 studies (17.12%), followed by PMP regionalization and mapping, with 23 articles (10.36%). Together, methodological comparison or development, climate change assessment, and regionalization and mapping comprised 138 publications, equivalent to 62.16% of the estimation studies. This distribution indicates that recent literature is not restricted to the direct production of PMP values but also focuses on reassessing existing procedures, representing the spatial variability of estimates, and evaluating their suitability under future climate conditions.

Updating previously available values represents a particularly relevant application because it allows the incorporation of longer observational records, new extreme events, and additional atmospheric information. In Hong Kong, Lan et al. (2024) combined a statistical method, local moisture maximization, and storm transposition to update point and areal PMP estimates for durations of 4, 6, 12, and 24 hours. The study incorporated precipitation records beginning in 1884, hourly dew-point data, and severe typhoon-related storms in Taiwan. Verification was performed through comparisons with regional records, historical values, and estimates for adjacent areas, demonstrating how different information sources can be integrated to produce values intended for hydraulic structure design.

The 23 studies addressing regionalization and mapping demonstrate that the applicability of PMP also depends on the ability to adequately represent its spatial variability. Pandey et al. (2026) used the CHIRPS satellite precipitation product, with a spatial resolution of 0.05°, to estimate and map daily PMP across Nepal. Comparison with ground observations indicated

satisfactory performance, although the spatial differences identified also highlighted the need for regional validation before satellite products are used in areas of complex terrain. This issue is particularly important in regions with sparse rain-gauge networks, where spatially distributed products can expand the coverage of estimates but do not eliminate the need to assess local biases and limitations.

Direct PMP estimation, dam safety, and hydrological risk assessment occurred with the same frequency, with 16 studies each, individually corresponding to 7.21% of the subset. Probable Maximum Flood estimation was the primary purpose of 11 articles (4.95%), while ten studies (4.50%) focused on updating previously available PMP values. Spillway design was identified in eight publications (3.60%), and flood modeling in seven (3.15%).

When considered jointly, the purposes directly related to dam safety, hydrological risk assessment, Probable Maximum Flood estimation, spillway design, and flood modeling comprised 58 articles, corresponding to 26.13% of the studies that estimated PMP. This proportion demonstrates that, although methodological development occupies a central position in the literature, PMP remains directly linked to engineering problems and the assessment of low-probability, high-impact events.

The relevance of applications related to dam safety arises, among other factors, from the long service life of these structures and the fact that many were designed using climatic and hydrometeorological information available several decades earlier. Chen and Hossain (2019) emphasize that structural integrity represents only one dimension of safety, since the ability to withstand current and future hydrological loads must also be periodically reassessed. For the northwestern United States, the authors projected approximate increases in PMP of 20% under RCP4.5 and 50% under RCP8.5 by the end of the century, indicating that changes in climatic conditions may directly modify the hydrological loads considered in hydraulic safety assessments.

At Batu Dam in Malaysia, Wan Ariffin et al. (2025) demonstrated how future PMP estimates can be incorporated into quantitative assessments of overtopping risk. The authors used regional climate models, different RCP scenarios, and the HEC-HMS hydrological model to simulate PMF and floods associated with different return periods. Future discharges exceeded that considered in the original design, indicating that updating PMP estimates can directly alter risk assessments and the interpretation of the hydraulic safety of existing structures.

The transformation of PMP into PMF represents another critical stage in these applications because changes in precipitation are not necessarily propagated proportionally into peak discharge. Hydrological response also depends on snow accumulation, soil moisture, antecedent conditions, reservoir operation, and watershed characteristics. In five Canadian basins, Clavet-Gaumont et al. (2017) combined changes in spring PMP and snow accumulation, obtaining changes in PMF ranging from approximately – 1.5% to 20%. This range demonstrates that analysis of PMP alone is insufficient to determine the behavior of extreme floods because its transformation into discharge depends on different components of the hydrological system.

Spillway design or safety verification also depends on propagating PMP estimates through hydrological and reservoir models. At Kaeng Krachan Dam in Thailand, Theprasit et al. (2024) analyzed 65 years of data and 190 storm events to estimate PMP, convert it into PMF, and assess the capacity of outlet structures. Although the spillway had sufficient capacity for events associated with high return periods, the estimated PMF produced water levels exceeding the maximum design level, highlighting the importance of evaluating not only the nominal capacity of hydraulic structures but also the integrated reservoir response under extreme conditions.

Flood-modeling studies introduce an additional level of uncertainty because they frequently represent discharges beyond the range used for model calibration. Felder et al. (2017) compared conventional hydrological modeling with a coupled hydrological–hydrodynamic system using 100 plausible spatiotemporal distributions of PMP. The results demonstrate that, in addition to the total magnitude of precipitation, its spatial and temporal distribution can significantly modify hydrological response and simulated impacts, reinforcing that the use of PMP in risk assessments depends not only on the estimated total precipitation but also on how the event is represented in subsequent models.

Taken together, the results show that the practical application of PMP depends on a sequence of procedures extending from its estimation and regionalization to rainfall–runoff transformation, reservoir operation, and hydraulic modeling. Each of these stages introduces additional sources of uncertainty, meaning that the reliability of the final decision does not depend exclusively on the initial PMP estimate. An integrated assessment of these uncertainties is therefore particularly relevant when the results are used for dam safety, spillway design, and other decisions involving critical hydraulic infrastructure.

3.4. Climate change in PMP estimation

The explicit incorporation of climate change into Probable Maximum Precipitation estimates was identified in 35 studies. Although 38 articles were classified under “climate change assessment” as their primary purpose, only 35 met the specific criteria established for the climate-related subset, namely, the use of future projections and their direct incorporation into PMP estimation, updating, or comparison. This distinction demonstrates that the inclusion of climate change as a study objective does not necessarily imply its quantitative integration into the PMP estimation procedure.

The first publications within this subset appeared in 2013, indicating that the assessment of PMP under future climate conditions represents a relatively recent research area. As shown in Fig. 7, scientific production remained discontinuous during the first few years, with one publication in 2013, three in 2014, and no studies in 2015.

Scientific production intensified from 2017 onward. Between 2017 and 2026, 30 of the 35 studies were published, corresponding to 85.7% of the climate-related subset. The highest annual number was recorded in 2022, with six publications, followed by 2020 and 2025, with five studies each. Four articles were identified in 2017, while 2018 and 2024 each accounted for three publications.

The studies employed different generations of emission scenarios and socioeconomic pathways. Because a single article could use more than one scenario, the frequencies presented in Fig. 8 are not mutually exclusive, and their percentages therefore do not sum to 100%. RCP8.5 was the most frequently used scenario, appearing in 20 studies, corresponding to 57.1% of the analyzed subset. This was followed by RCP4.5, used in 13 studies (37.1%), and SRES A2, reported in eight articles (22.9%).

Among scenarios based on the *Shared Socioeconomic Pathways*, SSP5-8.5 was used in five studies (14.3%), SSP1-2.6 in four (11.4%), SSP3-7.0 in three (8.6%), and SSP2-4.5 in two (5.7%). RCP2.6, RCP6.0, and SRES A1B were each identified in three studies, whereas SRES B1 was used in two articles. The predominance of RCP8.5 indicates that a substantial portion of the literature examined PMP responses under conditions of stronger warming, often in comparison with intermediate or lower-emission pathways. However, the simultaneous use of different generations of scenarios also highlights the methodological and temporal heterogeneity of the literature, which should be considered when making direct comparisons among studies.

Future periods varied widely, ranging from near-term projections to the end of the twenty-first century. To facilitate comparison, the studies were grouped according to the final year of their respective future projection periods. Three studies (8.6%) presented projections ending by 2040, while 11 (31.4%) used final horizons between 2041 and 2060. Nine studies (25.7%) had projection periods ending between 2061 and 2080, and 12 (34.3%) extended their projections into the 2081–2100 interval.

Overall, 21 studies, equivalent to 60.0% of the subset, presented projections with final horizons after 2060. In addition, 32 articles (91.4%) used periods extending beyond 2040, highlighting the predominance of medium- and long-term assessments, particularly those focused on conditions expected during the second half and toward the end of the twenty-first century. This characteristic is particularly relevant to hydraulic infrastructure applications, since dams and other critical structures may remain in operation for several decades, making projected climate changes over their service life relevant to the updating of design estimates. The individual characteristics of the studies, including authorship, publication year, climate scenario, reference period, and future period, are presented in Table 1.

Table 1

Studies that estimated or reassessed Probable Maximum Precipitation considering climate change scenarios.

Authors	Climate scenario	Reference period	Future period
(Rouhani and Leconte, 2018)	SRES-A2 e SRES-A1B.	1961–1990	2041–2070
(Hiraga et al., 2025)	SSP5-8.5	1995–2009	2045–2059
(Liu et al., 2025)	SSP3-7.0	1901–2015	2016–2100
(Gu et al., 2024)	RCP8.5	1950–2005	2006–2100
(Sammen et al., 2022)	RCP8.5	2001–2015	2031–2045
(Hiraga et al., 2025)	SSP2-4.5	2015–2024	2041–2060
(Rousseau et al., 2014)	SRES- A2	1961–2000	2001–2040
(Rastogi et al., 2017)	RCP8.5	1981–2010	2021–2050
(Chan et al., 2024)	SSP1-2.6; SSP3-7.0; SSP5-8.5	1986–2014	2071–2099
(Thuy et al., 2019)	RCP4.5; RCP8.5	1962–2016	2021–2050
(Lee and Kim, 2018)	RCP4.5; RCP8.5	1981–2005	2100
(Liu et al., 2022)	RCP2.6; RCP4.5; RCP6.0; RCP8.5	1979–2005	2061–2100
(Beauchamp et al., 2013)	SRES-A2	1961–2000	2011–2040
(Acierto et al., 2025)	RCP8.5	1951–2011	2051–2100
(Seo et al., 2023)	RCP4.5; RCP8.5	Data through 2020	Through 2100
(Ishida et al., 2018)	RCP4.5; RCP8.5	1950–2011	2099
(Labonté-Raymond et al., 2020)	RCP4.5; RCP8.5	1971–2000	2041–2070
(Sarkar and Maity, 2020)	RCP4.5; RCP8.5	1901–1970	2041–2070
(De Paola et al., 2014)	RCP4.5; RCP8.5	1958–2010	2010–2050
(Abbasnezhadi et al., 2020)	SRES-A2	1971–2000	2041–2070
(Ahmad et al., 2026)	SSP1-2.6; SSP5-8.5	1971–2022	2023–2050
(Afzali-Gorouh et al., 2022)	RCP2.6; RCP4.5; RCP8.5	1988–2017	2019–2048
(Herbozo et al., 2022)	RCP8.5	1975–2015	2011–2070
(Wan Ariffin et al., 2025)	RCP4.5; RCP6.0; RCP8.5	1975–2019	2020–2046
(Lagos-Zúñiga and Vargas M, 2014)	SRES-A2 e B1	1960–1999	2045–2065
(Clavet-Gaumont et al., 2017)	SRES-A2	1971–2000	2041–2070
(Zeroual et al., 2022)	RCP4.5; RCP8.5	1960–2013	2022–2052
(Ben Alaya et al., 2019)	RCP8.5	1951–2000	2001–2050
(Chen, Hossain and Leung, 2017)	RCP8.5	1970–2016	2050–2099
(Lee et al., 2016)	RCP2.6; RCP4.5; RCP6.0; RCP8.5	1981–2005	2006–2100
(Ramak et al., 2017)	SRES-A1B; A2; B1	1970–2000	2011–2039
(Visser et al., 2022a)	SSP1-2.6; SSP2-4.5; SSP3-7.0; SSP5-8.5	1950–2014	2015–2100

Authors	Climate scenario	Reference period	Future period
(Rouhani and Leconte, 2019)	SRES-A2; A1B	1961–1990	2041–2070
(Chen and Hossain, 2019)	RCP4.5; RCP8.5	1970–2016	2050–2099
(Xiong et al., 2024)	SSP1-2.6; SSP5-8.5	1980–2014	2030–2064

The earliest studies within this subset primarily sought to adapt traditional hydrometeorological procedures to information produced by climate models. Rousseau et al. (2014), for example, used simulations from the Canadian Regional Climate Model to update maximum precipitable water and the maximization factor used in PMP estimation in southern Quebec. This type of approach represents an early stage in the incorporation of climate change, in which components traditionally used in maximization procedures are updated on the basis of projected atmospheric conditions.

Subsequent developments expanded the representation of atmospheric processes and the use of physically based models. Rastogi et al. (2017) applied the WRF model to 120 storms in the Alabama–Coosa–Tallapoosa basin and projected increases of approximately 20% in PMP for 2021–2050 and 44% for 2071–2100 relative to 1981–2010. Ishida et al. (2018), using progressive temperature perturbations in the boundary conditions of an atmospheric model applied to the American River basin, also observed a monotonic increase in 72-hour maximum precipitation across the events examined. These results show that atmospheric modeling approaches make it possible to assess not only statistical changes in extremes but also the physical responses of storms to different thermodynamic conditions.

Despite the predominance of projected increases, the magnitude of change varied substantially across regions, scales, methods, and scenarios. Chen et al. (2017) projected that PMP in the northwestern United States could increase by approximately $50\% \pm 30\%$ by 2099 under RCP8.5. In northeastern Vietnam, Thuy et al. (2019) found that the relationship between temperature and extreme precipitation approached or exceeded the Clausius–Clapeyron rate up to certain thresholds but weakened at higher temperatures. This behavior demonstrates that increases in temperature or moisture availability cannot automatically be translated into a linear PMP change factor because precipitation response also depends on dynamic processes and storm organization.

Comparison among scenarios likewise revealed non-monotonic responses. In Hong Kong, Chan et al. (2024) projected increases in 24-hour, 10-km² PMP of 30.8% under SSP1-2.6, 8.3% under SSP3-7.0, and 35.6% under SSP5-8.5 for 2071–2099. The magnitude of the response reflected interactions among extreme precipitation, maximum dew point, storm-associated dew point, and differences among the climate models employed. Thus, a pathway associated with stronger climate forcing does not necessarily produce a proportionally larger PMP response in every application.

In Utah, Gu et al. (2024) associated an increase of approximately 3.43°C in dew-point temperature under RCP8.5 with an average increase of 39% in 24-hour, 259-km² PMP. This result reinforces the importance of future moisture availability in hydrometeorological procedures but also demonstrates that its influence must be evaluated within the atmospheric and regional context in which maximization is performed.

Liu et al. (2025) advanced the joint representation of nonstationarity and uncertainty by integrating a stochastic precipitation generator, a nonstationary GEV model, and 50 members of a global climate model. PMP was estimated as a quantity associated with a specified annual exceedance probability rather than as an invariant upper bound. For an annual probability of 10^{−4}, increases of 15% to 25% were projected between 2020 and 2100, depending on area and duration, whereas the PMFs of two tributaries increased by 35% and 36%. This approach represents an important conceptual shift by linking PMP to evolving climate conditions and the explicit representation of uncertainty rather than treating it exclusively as a deterministic and temporally fixed value.

Studies based on physical modeling also demonstrated that moisture maximization does not always result in increased precipitation. Hiraga et al. (2025) found that directly increasing relative humidity enhanced convective stability and suppressed the organization of certain mesoscale systems. This finding highlights that interactions between thermodynamic

and dynamic processes can constrain the precipitation response, challenging procedures that assume a direct and invariant relationship between greater moisture availability and greater extreme precipitation.

Moreover, although most studies indicated future increases in PMP, this behavior was not universal. Afzali-Gorouh et al. (2022) projected reductions ranging from approximately 14% to 38% for the southeastern Caspian Sea region, depending on the future period considered. The existence of projected decreases, together with non-monotonic responses across scenarios, reinforces that future PMP changes cannot be represented by a single direction or magnitude that is universally applicable across regions.

Taken together, these findings do not support the application of a universal climate change adjustment factor to PMP. Both the magnitude and direction of projected changes depend on regional climate, precipitation duration, storm type, emission scenario, climate model, and the representation of atmospheric processes. Climate-informed updating of PMP therefore requires regionalized and methodologically explicit approaches capable of representing different sources of variability and uncertainty and incorporating new climate information as it becomes available.

3.5. Nonstationarity and implications for PMP estimation

Nine studies reported statistical or modeling evidence of nonstationarity in PMP, extreme precipitation, or variables directly used in or explicitly related to its estimation, as summarized in Table 2. The assessment procedures included trend tests, statistical comparisons between periods, change-point detection methods, and extreme-value models with parameters dependent on time or climatic covariates.

Table 2

Summary of studies reporting evidence of nonstationarity in PMP, extreme precipitation, or variables directly used in or explicitly related to its estimation

Title	Authors and year	Country or region	Period analyzed	Method used to assess nonstationarity
A Nonstationary Probabilistic Approach for Probable Maximum Precipitation Estimation Based on Global Climate Model Large Ensembles	Liu et al. (2025)	Upper Red River Basin, south-central United States	1901–2100	Non-stationary GEV model
Development of a methodology to evaluate probable maximum precipitation (PMP) under changing climate conditions: Application to southern Quebec, Canada	Rousseau et al. (2014)	Southern Quebec, Canada, with application to the Kénogami and Yamaska basins	1961–2100	Mann–Kendall test
Probable maximum precipitation in a warming climate over North America in CanRCM4 and CRCM5	Ben Alaya et al. (2020)	North America	1951–2100	Non-stationary bivariate GEV model
Historical trend of probable maximum precipitation in Utah and associated weather types	Gu et al. (2022)	Utah, United States	1981–2018	Mann–Kendall test
Analysis of uncertainty and non-stationarity in probable maximum precipitation in Brazos River basin	Lee and Singh (2020)	Brazos River Basin, Texas, United States	1940–2013	Mann–Kendall test
Hurricane Harvey Highlights: Need to Assess the Adequacy of Probable Maximum Precipitation Estimation Methods	Kao et al. (2019)	U.S Gulf Coast, with emphasis on Houston, Texas	1949–2017	Time series linear regression
The Impact of Climate Change on Operational Probable Maximum Precipitation Estimates	Visser et al. (2022)	Australia, including 546 large dams	1960–2018	Mann–Kendall test
Dynamic and thermodynamic drivers of extreme precipitation under nonstationarity: implications for probable maximum precipitation across North America	Islam and Najafi (2026)	North America	1940–2021	Mann–Kendall test
Estimation of probable maximum precipitation at three provinces in Northeast Vietnam using historical data and future climate change scenarios	Thuy et al. (2019)	Bac Kan, Thai Nguyen, and Tuyen Quang provinces, northeastern Vietnam	1971–2000	At Most One Change (AMOC), Pruned Exact Linear Time (PELT), and Binary Segmentation (BinSeg).

The results revealed three main forms of confirmation. Liu et al. (2025), Rousseau et al. (2014), Ben Alaya et al. (2020), Islam and Najafi (2026) employed nonstationary statistical models in which the parameters of extreme-value distributions varied over time or as functions of atmospheric covariates. Gu et al. (2022), Lee and Singh (2020), Kao et al. (2019) and Visser et al. (2022) confirmed changes using tests applied to historical series of PMP or variables used in its estimation. Thuy et al. (2019), in turn, employed change-point detection methods for variables related to moisture maximization.

The formal confirmation of nonstationarity in only nine of the 354 articles, approximately 2.5% of the corpus, demonstrates that statistical investigation of the temporal evolution of PMP and its components still occupies a limited position in the literature. This result does not mean that the remaining studies demonstrated stationarity, but rather that few applied tests, models, or criteria capable of statistically confirming temporal changes. Therefore, the low frequency observed should be interpreted as a limitation in the formal assessment of the stationarity assumption rather than as evidence of temporal stability of PMP across most of the literature.

In eight of the nine studies, the identified changes were directly or indirectly associated with increases in PMP. The magnitude of these changes varied according to region, period analyzed, precipitation duration, and method employed. This variability reinforces that nonstationarity does not manifest uniformly and that its influence on PMP depends on both local climatic characteristics and the components considered in the estimation procedure.

One of the most direct lines of evidence was presented by Lee and Singh (2020) for the Brazos River basin. By comparing the periods 1940–1976 and 1977–2013, the authors identified significant increases of 19.5 mm in record 24-hour precipitation and 22.3 mm in PMP. Nonstationarity accounted for 31.4% of the total uncertainty, whereas methodological choice accounted for 53.5% and topography for 15.1%. This result demonstrates that temporal change can represent a substantial component of the total uncertainty in PMP estimates, although it is not necessarily the dominant source.

Hurricane Harvey provided operational evidence of the consequences of retaining estimates derived from specific historical periods. Kao et al. (2019) found that the 72-hour precipitation associated with the event partially exceeded the values reported in HMR 51 over large areas. The authors also identified increasing trends in annual maximum precipitable water and dew-point temperature along the U.S. Gulf Coast since 1949. These findings indicate that operational values established from particular historical conditions may no longer adequately represent atmospheric conditions observed subsequently.

Nonstationarity in atmospheric components was also identified at the continental scale. Visser et al. (2022) applied the Mann–Kendall test and Theil–Sen slope estimator to maximum persisting dew-point temperatures across Australia between 1960 and 2018. Large portions of the country exhibited positive trends, with values exceeding 0.3°C per decade in parts of the southern and southeastern coastal regions. Because persisting dew point is used to derive maximum precipitable water, changes in this variable may directly modify maximization factors and, consequently, operational PMP values.

Not all studies included in the subset directly recalculated PMP. Islam and Najafi (2026) for example, demonstrated that the distribution of annual maximum precipitation depended on atmospheric covariates, indicating the need to incorporate dynamic and thermodynamic controls into estimation methodologies. This type of evidence is relevant because it shows that nonstationarity may affect not only the final PMP estimate but also the variables and distributions used in its determination.

Incorporating nonstationarity, however, does not imply that stationary models should automatically be abandoned. Models with time-varying parameters or parameters conditioned on climatic covariates are more complex and may produce unstable estimates when fitted to short records.

The choice between stationary and nonstationary formulations should therefore be supported by statistical testing, performance comparison, physical consistency, and uncertainty assessment. In some situations, the greater complexity of a nonstationary model may not be justified by the quantity or quality of the available information.

Taken together, the evidence analyzed supports the explicit definition of climate reference periods, periodic updating of observational datasets and operational values, comparison between stationary and nonstationary models, and transparent reporting of associated uncertainties.

This perspective allows PMP to be treated as an estimate that can be updated over time for risk-management purposes rather than as a fixed value disconnected from evolving atmospheric conditions. For hydraulic structures with long service lives, this issue becomes particularly important because the stationarity assumption is no longer merely a statistical choice but may directly influence the adequacy of the values used for design and safety reassessment.

3.6. Scientific gaps and future directions

The analysis of limitations, unresolved issues, and recommendations reported in the studies allowed five major areas of challenge for advancing Probable Maximum Precipitation estimation to be identified: (i) historical records and storms; (ii) atmospheric parameters and physical processes; (iii) uncertainty, subjectivity, and methodological choice; (iv) spatial data, regionalization, and validation; and (v) climate change and nonstationarity.

Table 3

summarizes these areas and presents representative studies from each category, together with the main gaps and future directions identified. The complete list of articles included in the qualitative synthesis, including the identified gaps, explicit recommendations, and their respective textual evidence, is provided in Supplementary Table S1.

Thematic axis	Representative studies	Main identified gaps	Future directions
Historical records and storms	Johnson and Smithers (2019); Liao and Barros (2026)	Short, incomplete, or poorly representative historical records; limited number of extreme storms; low availability of subdaily and atmospheric data; difficulty in characterizing rare events and complex orographic conditions.	Maintain and expand observational networks; continuously update storm catalogs; increase the availability of subdaily data; incorporate new extreme events; and integrate observations with high-resolution products
Atmospheric parameters and physical processes	Chen and Bradley (2006); Wasti et al. (2025); Islam and Najafi (2026)	Simplified representation of extreme precipitation based on moisture availability; limitations of surface dew point as a representation of the atmospheric column; assumption of a linear proportional relationship between precipitable water and precipitation; incomplete representation of dynamic processes.	Integrate thermodynamic and dynamic variables, including precipitable water, atmospheric instability, moisture convergence, wind, and vertical motion; investigate nonlinear relationships; and use higher-resolution observations and atmospheric models.
Uncertainty, subjectivity, and methodological choice	Micovic et al. (2015); Lee and Singh (2020); Bhatt and Srinivas (2025)	Sensitivity of estimates to method selection, sampling, treatment of extremes, regional delineation, envelope curves, and expert judgment; still incomplete quantification of the different sources of uncertainty.	Jointly quantify multiple sources of uncertainty; use multi-method comparisons and <i>ensembles</i> ; represent PMP as a range, distribution, or set of values; and propagate uncertainties into PMF, spillway design, and dam safety assessments.
Spatial data, regionalization, and validation	Yang et al. (2018); Lagos-Zúñiga and Vargas (2014); Xiong et al. (2024)	Low station density; insufficient representation of complex terrain; differences in resolution and coverage among stations, satellites, reanalyses, gridded datasets, and climate models; limitations in regionalization and independent validation.	Integrate multiple data sources; increase spatial and temporal resolution; regionally assess product biases; develop regionalized procedures; conduct independent validation; and accompany estimates with sensitivity and uncertainty analyses.
Climate change and nonstationarity	Rousseau et al. (2014); Visser et al. (2022); Liu et al. (2025)	Continued reliance on the stationarity assumption; use of operational values derived exclusively from historical climate; limited representation of changes in atmospheric processes; dependence on a small number of models, scenarios, and covariates; incomplete representation of climate uncertainty.	Compare stationary and nonstationary formulations; use physically interpretable covariates; employ climate <i>ensembles</i> and multiple scenarios; quantify future uncertainty; and periodically update observational databases, technical procedures, and operational PMP values.

Table 3. Synthesis of the main scientific gaps and future directions identified in the literature on Probable Maximum Precipitation estimation.

Note

The studies presented are representative of the main thematic areas identified. The complete list of articles, their identified gaps, explicit recommendations, and corresponding textual evidence is provided in Supplementary Table S1.

Within the first area, the studies showed that the robustness of PMP estimates may be limited not only by record length but also by record completeness, monitoring-network density, temporal and spatial resolution, and the representativeness of the

available extreme events. Cases were identified in which records spanning several decades remained insufficient to stabilize parameters sensitive to the largest events, as well as applications based on only a few historical episodes or incomplete records of dew point, humidity, temperature, wind, and subdaily precipitation. Recommendations focused on maintaining continuous monitoring networks, updating storm catalogs, expanding subdaily observations, and integrating rain-gauge, radar, satellite, and reanalysis data.

Regarding atmospheric parameters and physical processes, the main limitations were associated with representing moisture availability as the primary control on extreme precipitation. Some studies questioned the use of surface dew point as a representation of the entire atmospheric column, the assumption of a linear proportional relationship between precipitable water and precipitation, and the adoption of maximization limits based predominantly on expert judgment. Gaps were also identified in the joint consideration of convective instability, moisture convergence, wind, precipitation efficiency, orography, and other dynamic components. In response, the authors recommended multifactorial and regionalized approaches supported by observations and higher-resolution atmospheric models.

Methodological limitations also involved the sensitivity of PMP to method selection, treatment of extreme values, choice of probability distribution, construction of envelope curves, and transfer of frequency factors across climatically distinct regions. The theoretical PMP is not directly observable, which complicates the determination of a reference value against which estimates can be validated. In this context, the studies recommended comparisons among different methodological families, validation using independent data sources, sensitivity analysis, and presentation of PMP as a range, distribution, or ensemble of values rather than as a single deterministic estimate. Propagation of meteorological and statistical uncertainties into PMF estimation, spillway design, and dam safety assessments was also recommended.

Spatial gaps were primarily associated with low monitoring-network density, concentration of stations in easily accessible areas, inadequate representation of mountainous terrain, and the combination of products with different resolutions, periods, and interpolation procedures. Satellite products, reanalyses, and gridded datasets were recognized as important alternatives for poorly monitored regions, although their use remained dependent on regional assessment of biases and their ability to reproduce the most extreme events. Recommendations included expanding monitoring networks, integrating multiple data sources, applying high-resolution regional models, and producing spatially distributed estimates accompanied by uncertainty assessment.

Finally, studies grouped under the climate change and nonstationarity area highlighted limitations associated with the continued use of parameters, distributions, maximization factors, and operational values derived exclusively from the historical climate. Projected responses varied according to the model, scenario, resolution, *downscaling* method, precipitation duration, storm type, and covariate considered. Recommendations included comparing stationary and nonstationary formulations, using physically interpretable covariates, applying climate and atmospheric ensembles, considering multiple scenarios, and periodically updating datasets, guidelines, and operational PMP values. Taken together, the evidence indicates the need for regionalized, reproducible, and physically based procedures capable of representing temporal changes in parameters, explicitly characterizing uncertainties, and accounting for changing climatic conditions over the service life of hydraulic structures.

3.7. Limitations of the review

The search strategy was based on the exact expression “Probable Maximum Precipitation” and restricted to the Scopus and Web of Science databases. Although this approach provided high specificity in identifying studies directly related to PMP, articles using alternative terminology or addressing equivalent procedures without explicitly using this expression may not have been retrieved. Therefore, complementary search strategies and the inclusion of additional bibliographic databases could broaden the coverage of the literature.

Another limitation concerns full-text availability. After integration of the databases and removal of duplicate records, 422 unique records remained for assessment. Of these, 68 were excluded from the full-text analysis because their complete

content could not be located or accessed, resulting in a final corpus of 354 articles. This exclusion may have introduced availability bias, particularly with respect to older or less accessible publications. Consequently, the findings of this review represent the set of studies retrieved through the adopted search strategy and available for full-text assessment.

In addition, to allow comparisons among categories and avoid double counting, each article was assigned to a single predominant methodological approach and a single primary purpose. This strategy facilitated the quantitative synthesis of the results but may simplify the representation of studies that combined different methods or simultaneously addressed multiple applications. Therefore, the frequencies reported for these classifications should be interpreted as representing the predominant characteristic of each article rather than as an exhaustive description of all procedures and objectives addressed within it.

The bibliometric analysis of term frequency also has a specific limitation because synonyms and terminological variants in the Keywords field were not standardized. Thus, different forms of the same concept, such as “probable maximum precipitation”, “probable maximum precipitation (PMP)”, and “PMP”, were counted separately. This decision preserved the original form of the keywords but may have fragmented the frequency of certain concepts in the thematic representation.

Finally, publications from 2026 were considered only through July 31, according to the search cutoff date. Consequently, the number of articles published in that year is not directly comparable with that of complete years and should not be interpreted as indicating a decline or definitive change in scientific production.

4. CONCLUSION

This review demonstrates that research on Probable Maximum Precipitation has undergone substantial expansion and diversification in recent decades, both in its geographical distribution and in the approaches used for its estimation. Of the 354 articles subjected to full-text review, 222 produced new PMP estimates, indicating that a substantial proportion of the retrieved literature effectively contributed to the generation, updating, or quantitative comparison of these values. Despite the recent expansion of the field, scientific production remains geographically concentrated, while new countries and multinational studies have become increasingly represented in the literature.

Taken together, the evidence analyzed indicates a transition from a predominantly static and deterministic conception of PMP toward more regionalized, physically based, uncertainty-transparent, and updateable approaches as new observations and climate information become available. This transition does not imply that traditional methods should be automatically abandoned, but rather that their assumptions, parameters, and suitability under observed and projected conditions should be continuously reassessed. In this context, the main contribution of this review lies in integrating, within a single synthesis, the evolution of scientific production, estimation methods, applications, climate change, nonstationarity, and research gaps, demonstrating that the future development of PMP depends on the integration of statistical robustness, physical consistency, temporal updating, and applicability to engineering decision-making.

5. CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Gabriel Adão Zechini da Silva: Conceptualization; Methodology; Investigation; Data curation; Formal analysis; Visualization; Validation; Writing – original draft; Writing – review & editing.

Diogo Costa Buarque: Conceptualization; Methodology; Investigation; Formal analysis; Validation; Supervision; Writing – review & editing.

Murilo Brazzali Rodrigues: Conceptualization; Methodology; Investigation; Formal analysis; Validation; Writing – review & editing.

Declarations

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION PROCESS

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with English-language translation, readability, and linguistic editing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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DATA AVAILABILITY

The bibliographic records analyzed in this review were retrieved from Scopus and Web of Science Core Collection according to the search strategy described in the Methodology. The main data supporting the qualitative synthesis are provided in the Supplementary Material.

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Figures

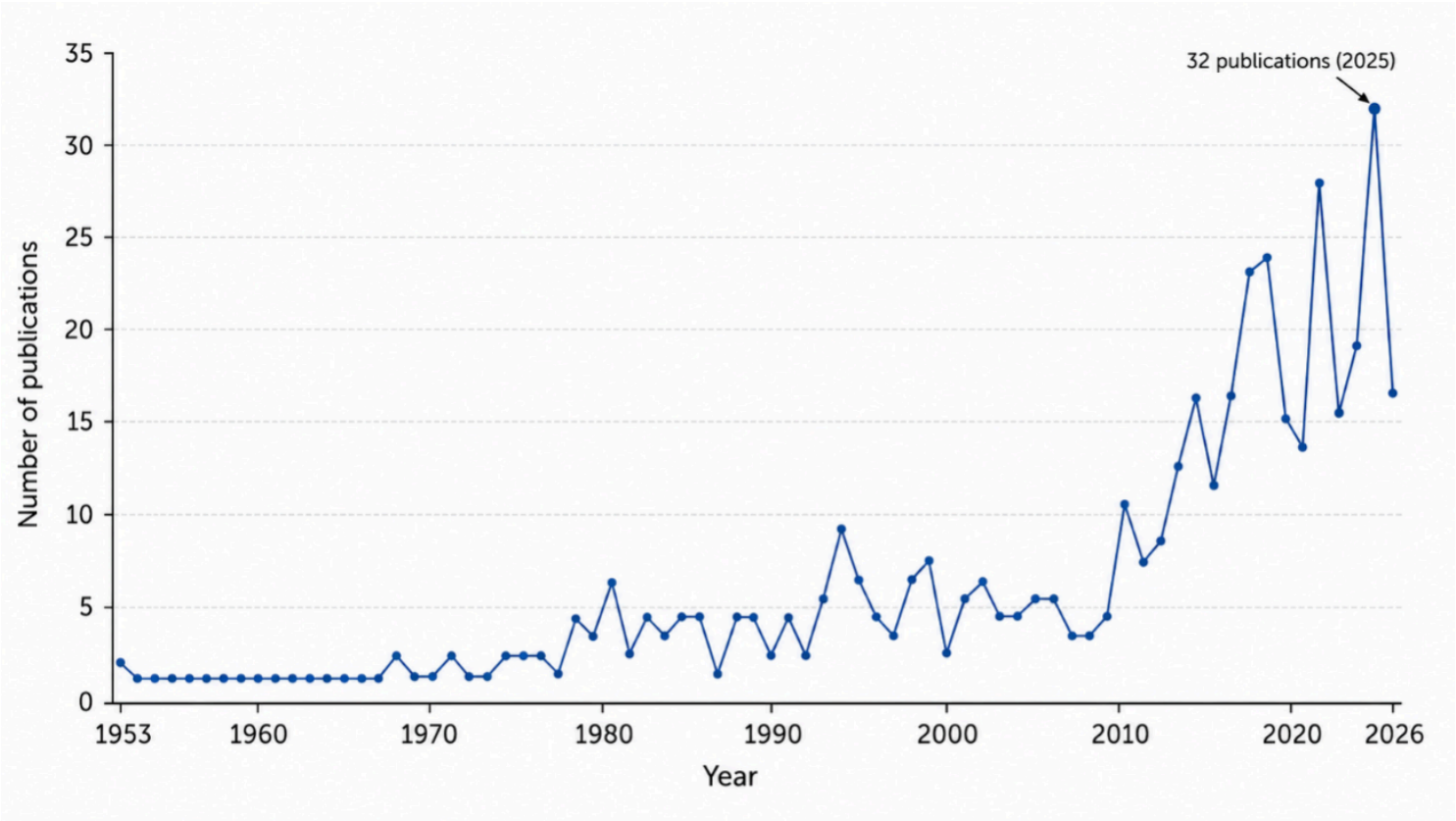


Figure 1

Annual evolution of scientific publications on Probable Maximum Precipitation from 1953 to 2026.

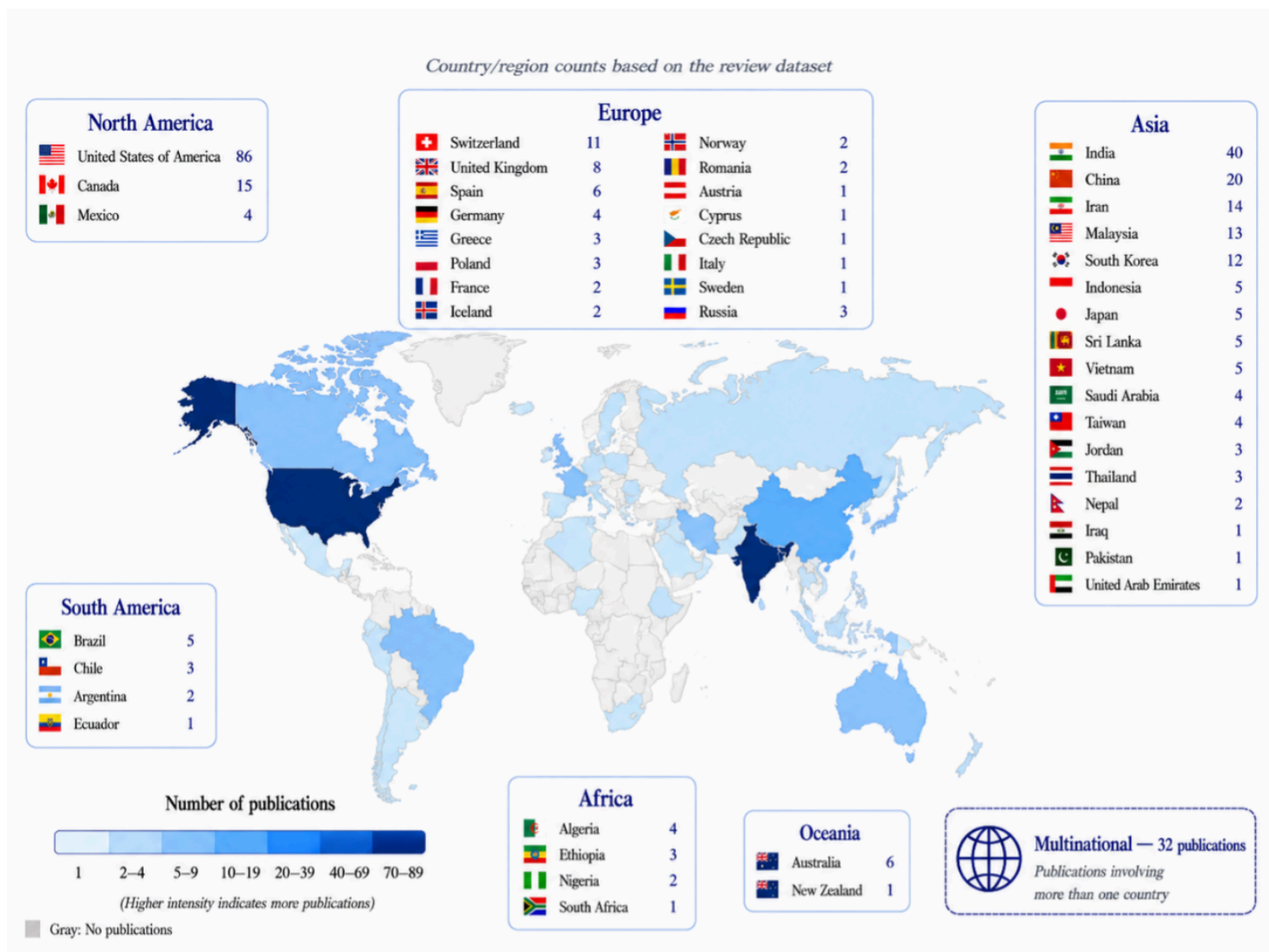


Figure 2

Geographical distribution of articles on Probable Maximum Precipitation according to the country or region in which the study was conducted.

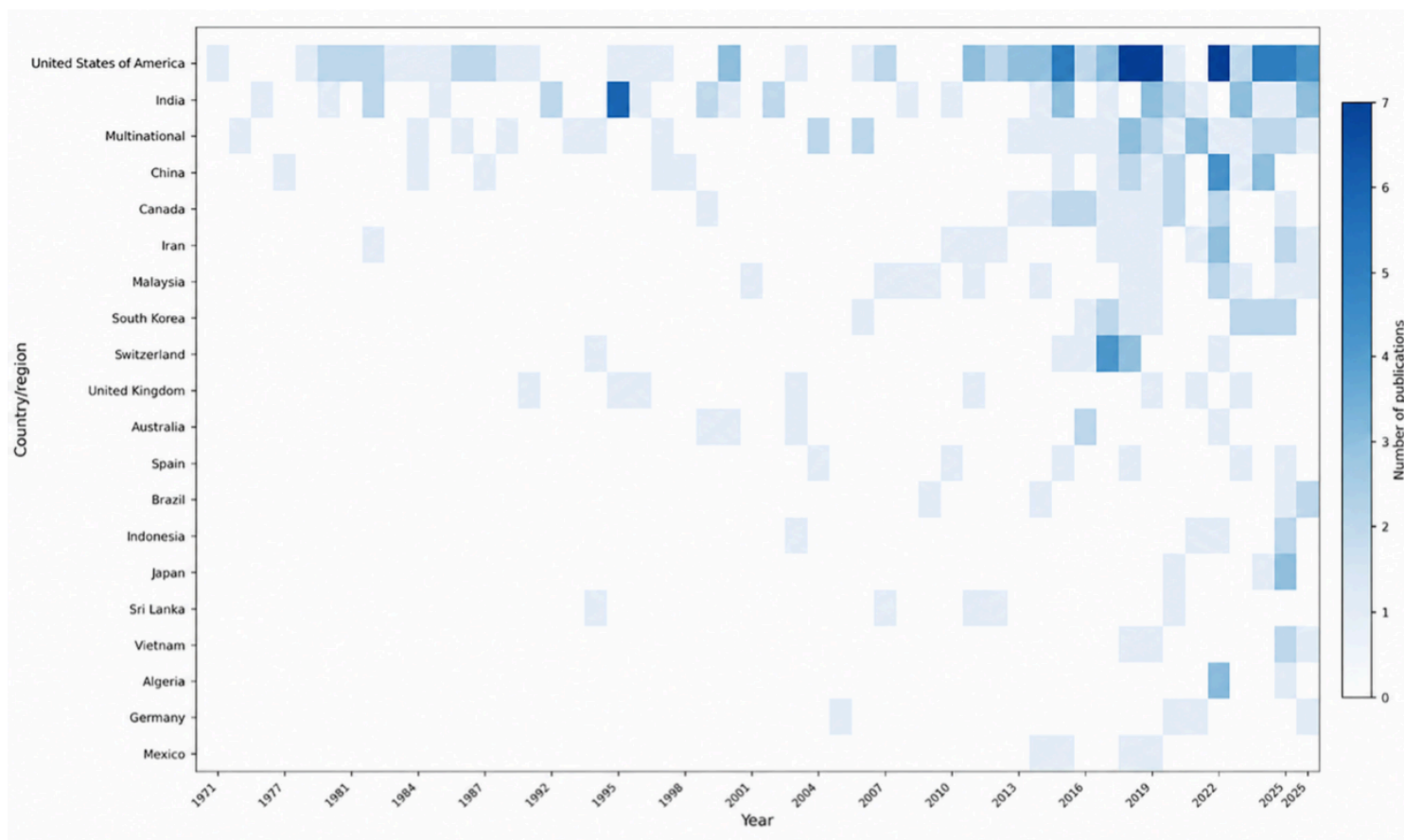


Figure 3

Temporal distribution of publications on Probable Maximum Precipitation among the 20 countries or regions with the highest numbers of publications in the analyzed corpus.

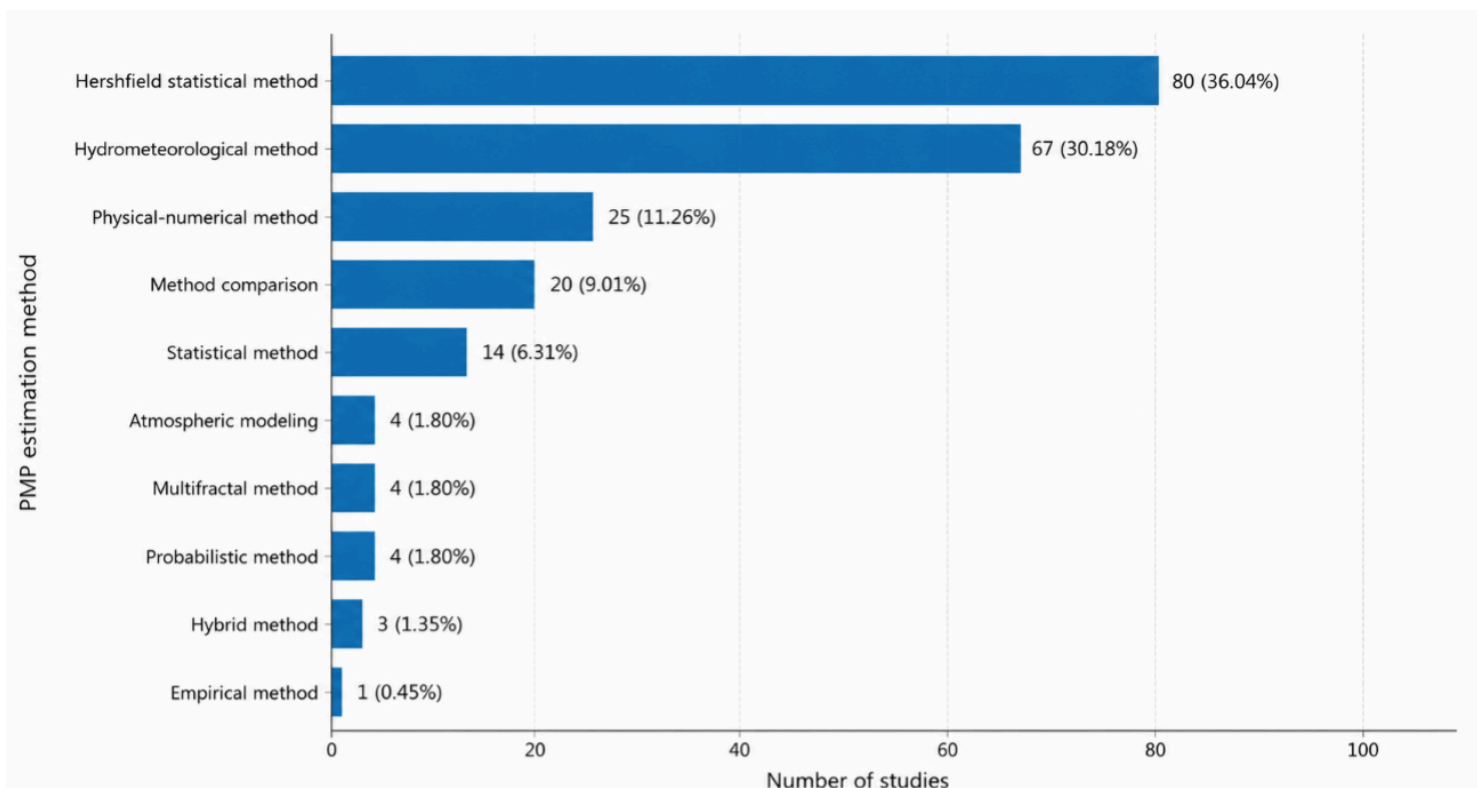


Figure 5

Distribution of methodological approaches used in studies that produced Probable Maximum Precipitation estimates.

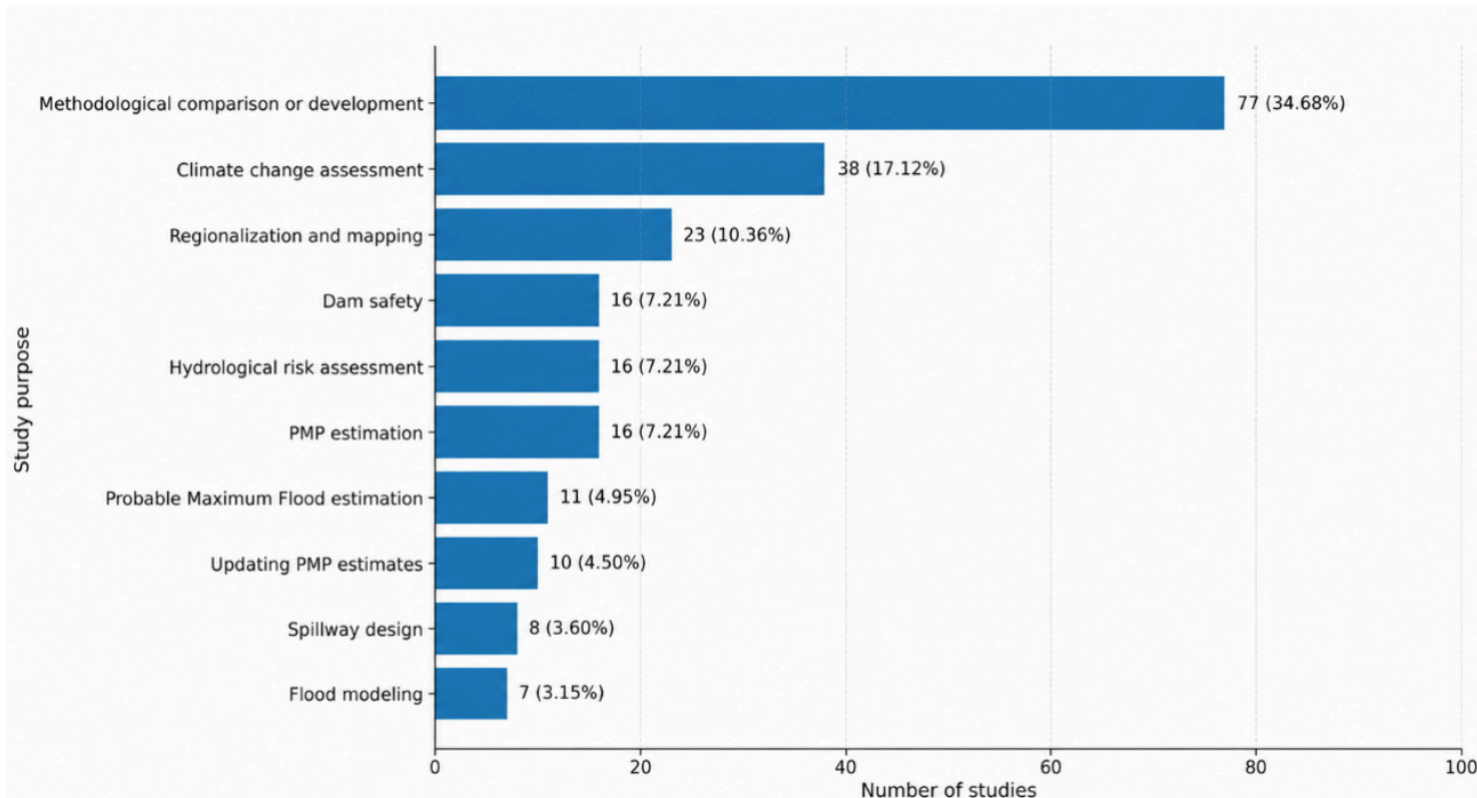


Figure 6

Primary purposes of studies that produced new Probable Maximum Precipitation estimates.

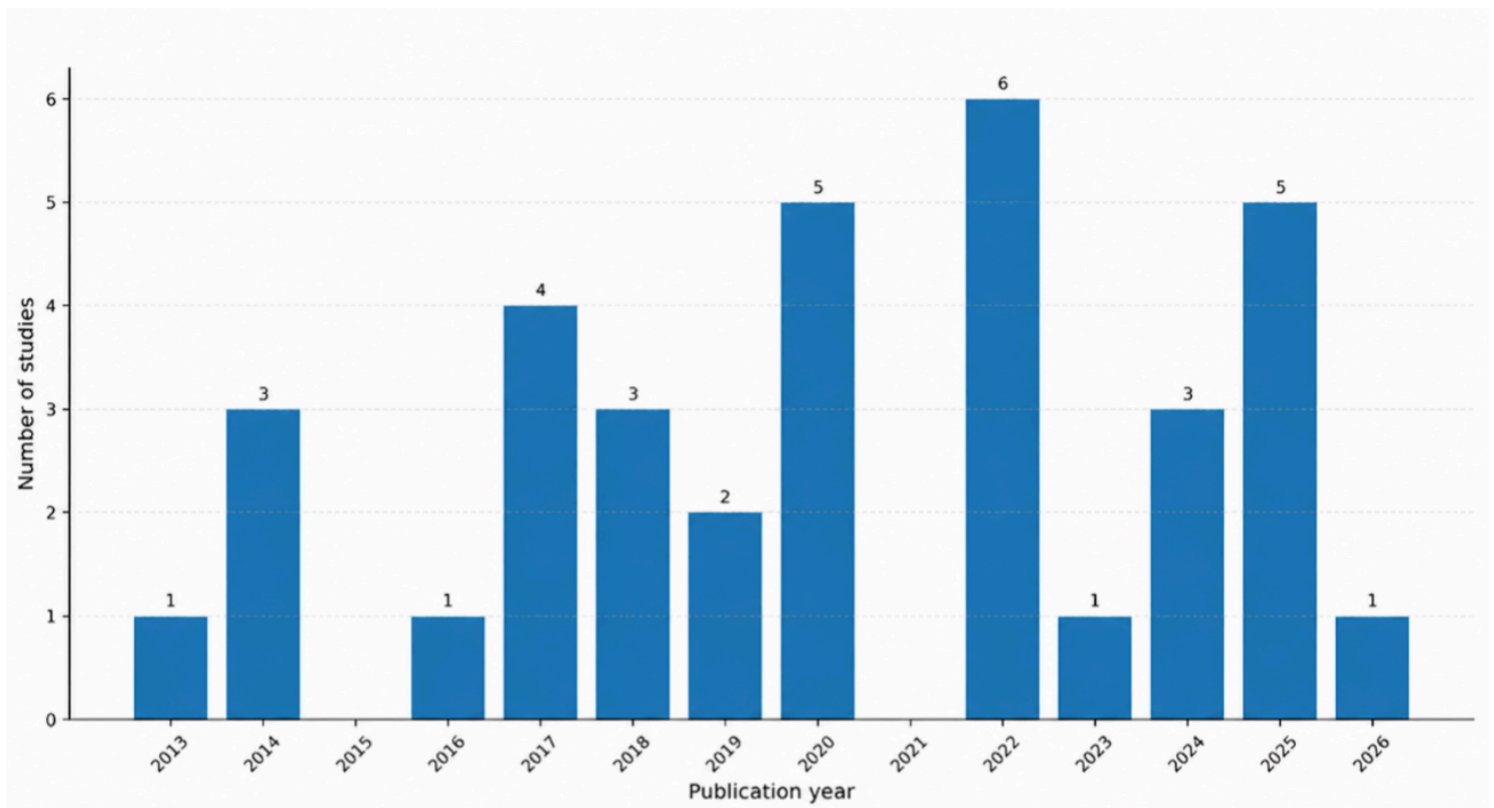


Figure 7

Temporal evolution of studies that estimated or reassessed Probable Maximum Precipitation considering future climate conditions.

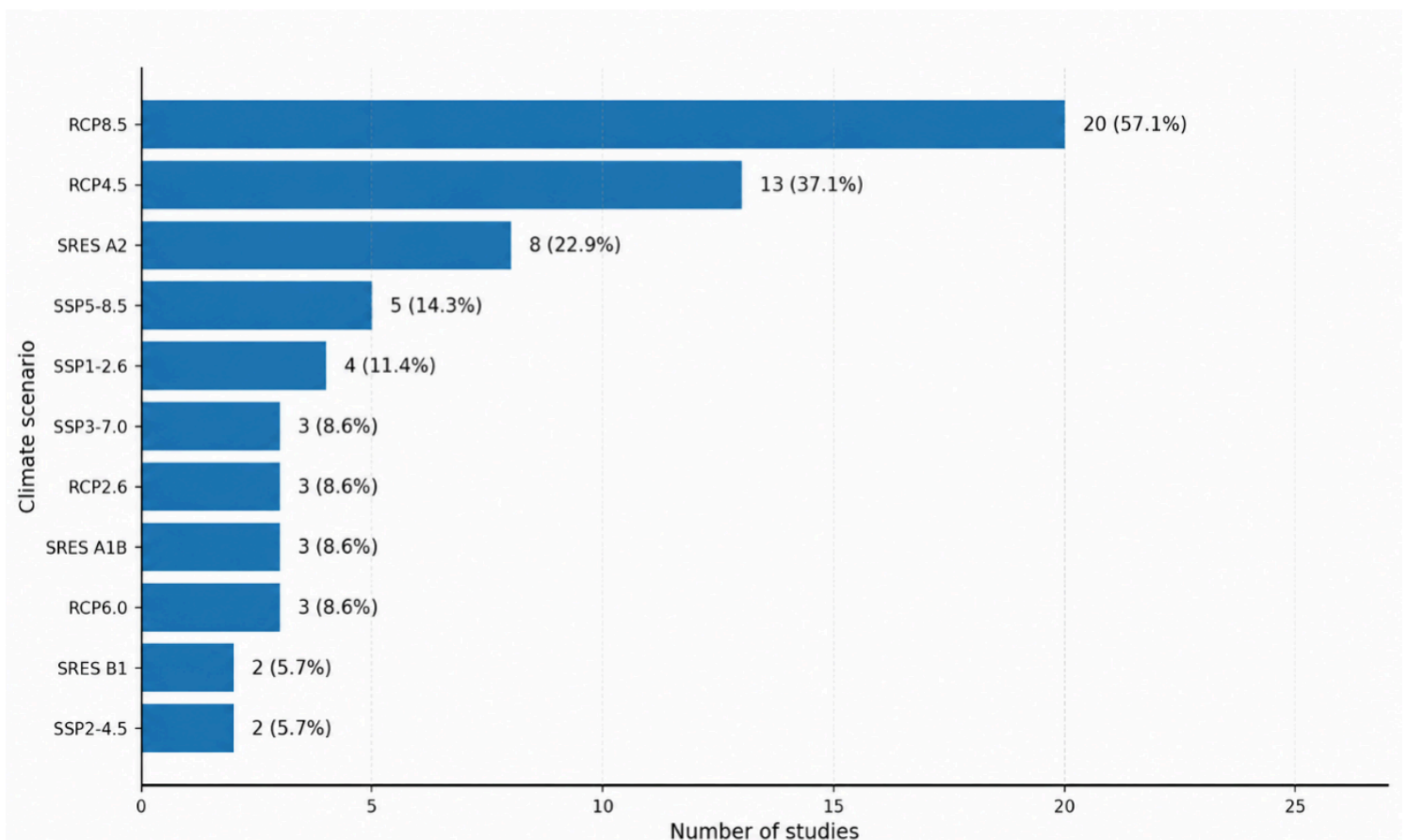


Figure 8

Frequency of climate scenarios used in studies estimating future Probable Maximum Precipitation.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryTableS1.docx](#)