Journal of Infrastructure Planning and Engineering Vol. 4, No. 1, Year 2025, pp 45 - 53

JIPE Journal of Infrastructure Planning and Engineering

Journal of Infrastructure Planning and Engineering

Journal homepage: https://ejournal.warmadewa.ac.id/index.php/jipe

Assessing the role of satellite precipitation products in urban flood risk management in Germany

Arne Finger[1*], Jonas Lutz[1], Putu Aryastana[2, 3]

[1]Hamm-Lippstadt University of Applied Sciences, Marker Allee 76-78, Hamm, 59063, Germany
[2]Master Program of Infrastructure and Environmental Engineering, Warmadewa University, Denpasar, 80239, Indonesia
[3]Department of Civil Engineering Warmadewa University, Tanjung Bungkak, Denpasar, 80239, Indonesia
* arnefinger1@gmail.com

Received on 29 April 2025, accepted on 9 May 2025

ABSTRACT

Urban areas in Germany face increasing hydrological challenges due to climate change, extreme precipitation events, and the expansion of impervious surfaces. Traditional rainfall monitoring systems, such as rain gauges and radar networks, often fall short in capturing the spatiotemporal variability of urban precipitation, particularly in regions with complex topography or during high-intensity events. Satellite precipitation datasets such as IMERG, TRMM, CMORPH, GSMaP, and PERSIANN have emerged as essential tools for enhancing urban flood risk management. This paper evaluates the performance, limitations, and future prospects of these datasets in the context of Germany's urban environments. Key limitations include resolution constraints, latency, and accuracy issues related to orographic and winter precipitation. Nonetheless, recent advancements in machine learning, data fusion with ground-based systems like RADOLAN, IoT sensor integration, and downscaling techniques show significant promise in overcoming these challenges. The study highlights the potential of multi-sensor satellite systems and real-time data assimilation to improve predictive accuracy in urban hydrology. The findings emphasize the need for continued technological innovation and inter-operable data infrastructures to support climate-resilient urban water management strategies.

Keywords: GPM; flood risk management; rainfall; satellite precipitation products; urban hydrology.

1 Introduction

The management of urban flood risks in Germany is of profound significance, especially as the nation grapples with the dual challenges of climate change and urbanization. As urban landscapes, characterized by increasingly impermeable surfaces, expand, the nature of hydrological responses to precipitation events becomes more complex. Traditional urban drainage systems, which were primarily designed based on historical rainfall data, are now frequently overwhelmed by the intensity and frequency of extreme precipitation events associated with climate change. It is within this context that the integration of advanced satellite precipitation products becomes paramount. These products, such as the Integrated Multi-satellite Retrievals for GPM (IMERG) and the Climate Prediction Center Morphing Technique (CMORPH), offer an innovative approach to enhancing rainfall monitoring and improving urban flood risk management in cities like Berlin, Hamburg, and Munich, where the incidence of flooding is notably observed [1].

In Germany, the recent catastrophic floods, such as those in 2021, demonstrate the urgent need for accurate and timely precipitation data. Flooding driven by heavy rainfall causes significant infrastructural damage and poses risks to public safety, making effective risk management crucial [2]. Traditional rain gauges and operational radar networks, like the RADOLAN system, while useful, suffer from inherent limitations, including inconsistent spatial coverage and inaccuracies during severe weather. On the other hand, satellite precipitation datasets provide comprehensive, high-resolution data that are critical for understanding rainfall distribution over urban areas [3]. Through consistent coverage across complex terrains, these products facilitate better predictions of surface runoff

DOI: https://doi.org/10.22225/jipe.4.1.2025.45-53 E-ISSN: 2829-5153

and flooding risks, thus offering vital information to inform policies and urban planning initiatives aimed at mitigating flood impacts [1].

The efficacy of satellite data in enhancing flood risk management in urban areas has been underscored in various studies. For instance, the integration of IMERG data with traditional radar systems has shown promising results in increasing the accuracy of rainfall estimations during extreme events, which is essential for effective flood forecasting [4]. Moreover, satellite-based observations can significantly improve hydrological models used for urban flood simulation, particularly in situations lacking ground-based precipitation data. By allowing for a more robust analysis of rainfall patterns, these satellite products contribute to a deeper understanding of localized hydrological dynamics [5]. Evidence suggests that combining these satellite observations with machine learning algorithms enhances their reliability and spatial resolution, thereby providing more actionable insights for urban flood management [6].

Furthermore, advancements in machine learning algorithms have revolutionized how satellite data can be utilized in urban hydrology. These methodologies facilitate the fusion of satellite-derived information with ground observations, effectively minimizing biases that can arise from either data source alone. Such integrative approaches are particularly beneficial in regions with complex topographies, a common challenge in Germany, where urban settings often funnel rainfall into sudden, intense flow paths [7]. Additionally, techniques such as downscaling allow for higher spatial resolution estimates from coarser satellite data, adapting these inputs for urban scenarios where precise flooding forecasts are critical [8]. Recent studies have focused on downscaling IMERG data to a 1 km resolution, making it more suitable for local applications and enhancing its usability in urban flood risk assessments [4].

Germany's diverse climatic regions further complicate urban flood risk management. Cities situated in different topographies may experience varying hydrological responses to similar precipitation events, underscoring the necessity for localized forecasting systems. By employing satellite precipitation products, cities can derive better hydrological insights and develop adequate disaster preparedness strategies [9]. The ability to accurately assess and predict flooding from these data sources transforms urban planning into a proactive rather than reactive process, offering substantial potential benefits for community resilience [10].

Moreover, integrating satellite precipitation data into urban flood risk management frameworks can support the development of sustainable urban drainage systems (SUDS). Meta-analyses have demonstrated that SUDS can mitigate flood risks associated with heavy rain events, providing robust evidence for their effectiveness in urban planning [6]. In Germany, Finger et al. [11] emphasize the importance of linking SUDS with Integrated Water Resources Management (IWRM) to address urban water challenges more holistically, particularly when supported by high-resolution precipitation data. The synthesis of satellite data with SUDS designs may enhance the efficiency of these systems, building more robust infrastructures that can cope with the anticipated increases in rainfall intensity due to climate change [3]. Therefore, employing such data not only allows for improved flood risk predictions but also aids decision-makers in establishing practical, long-term flood mitigation measures [12].

Critically, the benefits of satellite precipitation products extend beyond immediate flood risk assessment; they also contribute to broader climate adaptation and resilience strategies. As urban populations continue to grow, understanding the implications of climate impacts becomes pivotal for creating sustainable urban environments [2]. The identification of trends in rainfall and discharge data allows stakeholders to anticipate future challenges and adapt infrastructure and policies accordingly [13]. By enabling a more detailed analysis of hydrological phenomena at urban scales, satellite precipitation products pave the way for a more integrated approach to flood risk management that encompasses not only technological innovations but also policy reforms [7], [14].

In summary, the integration of satellite precipitation datasets into urban flood risk management practices in Germany demonstrates considerable promise. Through their high-resolution, comprehensive datasets, these tools enable more effective predictive capabilities in managing urban flood risks. The coupling of satellite data with ground-based observations, enhanced by advancements in machine learning and downscaling methodologies, strengthens flood forecasting accuracy and enables quick adaptations to changing climate conditions. Consequently, leveraging satellite precipitation products emerges as a vital strategy in addressing urban flooding challenges, ultimately contributing to the resilience and sustainability of urban areas in Germany and beyond.

2 Role of Satellite Data

The utilization of satellite precipitation datasets in urban hydrology and rainfall modeling represents a transformative advancement in flood risk management, particularly evident in Germany's increasingly complex urban environments. As urbanization continues to exacerbate issues of stormwater runoff and flooding, integrating satellite-based data into hydrological assessments is essential for improving management strategies and mitigating risks associated with extreme precipitation events. Datasets such as the Global Precipitation

Measurement (GPM), Integrated Multi-satellite Retrievals for GPM (IMERG), and the Tropical Rainfall Measuring Mission (TRMM) are pivotal due to their global coverage and high temporal resolution, serving to address the limitations of traditional rainfall measurement systems that often overlook the nuanced precipitation patterns characteristic of urban areas Tarpanelli et al. [1].

A significant advantage of satellite precipitation datasets lies in their ability to provide comprehensive coverage of rainfall events, particularly in areas where ground-based observation networks are sparse. Germany's diverse topography including mountainous regions and densely populated urban centers necessitates data sources that can accurately represent rainfall across varying landscapes. For instance, the IMERG dataset, with its spatial resolution of 0.1° and a temporal resolution of 30 minutes, offers critical insights into precipitation patterns that can influence urban flooding [6]. Studies demonstrate that IMERG effectively tracks extreme rainfall events throughout Europe, including Germany, thereby facilitating timely hazard warnings and enhancing urban resilience by informing infrastructure planning [7].

As flooding exacerbates with increasing impervious surfaces in urban areas, satellite precipitation datasets are crucial for predicting flood events. The GPM mission, particularly its product IMERG, has been widely leveraged in flood forecasting, evidenced by its integration into high-resolution hydrological models that optimize flood prediction accuracy [3]. Noteworthy findings indicate that the combination of satellite data with traditional radar sources, such as RADOLAN, enhances flood risk assessment by effectively detecting extreme rainfall events pivotal for accurate flood modeling [5]. For example, studies have shown significant improvements in flood risk evaluations in cities like Hamburg and Berlin, where satellite data have informed real-time decision-making processes during periods of extreme rainfall [15].

Furthermore, satellite precipitation datasets provide long-term records that significantly reinforce the resilience of urban hydrological models. Such datasets facilitate the analysis of trends in precipitation linked to climate change, thereby informing adaptive strategies to manage flood risks in urban setups. By highlighting variabilities in precipitation patterns, these datasets can also guide the improvement of drainage systems and the establishment of early-warning systems for urban flooding events [2]. The integration of these data sources into hydrological models enhances the accuracy of simulating rainfall-runoff processes, which is vital for effective urban water management under the strains of climate variability [16].

Advanced downscaling techniques further democratize the benefits of satellite precipitation datasets by converting coarse-resolution data into high-resolution inputs suitable for urban modeling. Such methodologies that leverage cloud attributes alongside ancillary data significantly enhance the spatial accuracy required to effectively forecast urban hydrological behavior. Recent studies successfully downscaled IMERG data to a resolution of 1 km, demonstrating improved capabilities to simulate urban hydrological processes with greater precision [4]. This advancement is particularly relevant in Germany's urban environments, where detailed hydrological modeling is essential for both mitigation strategies and urban planning [17].

Moreover, the unique interactions between urban heat island (UHI) effects and precipitation patterns pose additional challenges in urban environments. Satellite precipitation datasets allow for detailed examinations of how urbanization affects local rainfall characteristics, such as intensity and distribution. IMERG data have been utilized to assess UHI impacts in German cities, revealing critical insights into the necessity for adaptive urban resilience strategies to accommodate hydrological responses influenced by these phenomena [13]. Thus, the integration of satellite datasets into urban planning efforts not only informs immediate flood risk management but also fosters a broader understanding of climate interactions and urban hydrology.

While the potential of satellite precipitation products is substantial, challenges do persist, particularly concerning their application in urban hydrology. The spatial resolution of datasets such as IMERG, although high, can still be insufficient for capturing localized phenomena inherent to urban landscapes, often leading to biases in rainfall estimates [18]. Additionally, satellite estimates have been found to overestimate rainfall during light precipitation events and underestimate it during heavier rainfall, thereby influencing the reliability of hydrological models [11]. Addressing these inaccuracies through improved algorithms and combined methodologies that leverage both satellite and ground data represents a critical avenue for enhancing the effectiveness of urban flood management strategies [19].

Future advancements in satellite technology, including the upcoming European Space Agency's Earth Explorer missions, anticipate resolutions that may reach up to 1 km and provide updates as frequently as every five minutes. These innovations promise to significantly enhance the granularity and reliability needed for effective urban hydrological modeling and flood risk assessments [8]. By equipping urban planners and hydrologists with more precise data, the next generation of satellite missions will likely transform how urban water management problems are approached, thereby enabling better-informed decision-making in the face of increasing flooding risks due to climate change [10].

In summary, the advent of satellite precipitation datasets represents a critical innovation in urban flood risk management in Germany. These datasets not only enhance the precision of flood predictions but also provide the necessary historical context for understanding shifts in rainfall patterns due to climate change and urbanization. Through the integration of GPM, IMERG, and other relevant satellite products into urban hydrological assessments, effective frameworks for managing urban flood risks can be established. Furthermore, ongoing advancements in satellite technology and data processing hold the potential to further refine these approaches, ultimately facilitating enhanced resilience in urban environments.

3 Evaluation of Products

The assessment of satellite precipitation datasets in urban hydrology, especially within the unique geographical and socio-hydrological context of Germany, reveals critical insights into their effectiveness, challenges, and prospective enhancements. Satellite precipitation products such as IMERG (Integrated Multi-satellite Retrievals for GPM), TRMM (Tropical Rainfall Measuring Mission), CMORPH, GSMaP, and PERSIANN mark significant advancements over ground-measured data, thereby providing essential tools for disaster management, climate adaptation, and flood risk reduction in urban settings. However, a comprehensive evaluation of these products is necessary to fully understand their strengths and limitations.

One of the primary metrics for evaluating satellite rainfall estimates is their accuracy when compared to traditional ground-based measurements. IMERG has emerged as a well-validated product known for its global coverage and high temporal resolution, making it particularly suitable for urban hydrology Ponukumati et al. [20]. However, studies have highlighted that IMERG tends to underestimate rainfall, especially during brief but intense precipitation events typical of urban flooding scenarios in Germany. This underestimation can lead to significant inaccuracies in flood risk assessments, which was particularly evident when IMERG was evaluated against the RADOLAN radar datawhere significant biases were observed during convective storms [21]. Similar findings indicate that while IMERG provides reliable rainfall trends, its ability to represent the spatial variability of precipitation remains a challenge [22].

Alternatives such as CMORPH and PERSIANN also present similar accuracy-related issues. CMORPH, while offering high temporal resolution, is criticized for overestimating light rainfall and underestimating heavier events, reflecting inadequacies in its hydrological modeling capabilities [23]. PERSIANN, particularly in the context of Germany's diverse mountainous terrain, fails to accurately capture complex precipitation dynamics critical for urban areas facing challenges from orographic rainfall [24]. The underrepresentation of precipitation dynamics in mountainous areas suggests a need to refine these products for effective urban flood management.

Urban hydrology fundamentally requires high spatial and temporal resolution data, which are essential for capturing localized rainfall patterns. IMERG often receives praise in this area due to its spatial resolution of 0.1° and frequent updates every 30 minutes, aligning well with the monitoring prerequisites for urban precipitation anomalies. Nevertheless, such specifications still fall short compared to ground-based networks like RADOLAN that provide ultra-high-resolution data necessary for modeling small urban catchments [25]. TRMM, despite its valuable long-term precipitation records, does not offer the spatial resolution required for urban studies, making it less relevant for immediate urban hydrological applications [26]. CHIRPS offers robust historical datasets, yet its coarser resolution limits its effectiveness in finely-tuned urban hydrological contexts [27]. Nevertheless, the high temporal resolution of GSMaP and CMORPH, while beneficial, is offset by spatial constraints that challenge their utility in concentrated urban analyses.

The incorporation of advanced downscaling techniques has emerged as a leading approach to enhance the resolution of satellite datasets for urban hydrological modeling. For instance, work demonstrating the downscaling of IMERG data to a resolution of 1 km has shown significant improvements in modeling urban hydrological processes [28]. Moreover, combining satellite-based findings with ground-based observations can further address the inherent resolution shortcomings of individual datasets, allowing for a more comprehensive urban flood risk management framework [29].

The integration of machine learning algorithms also plays a pivotal role in improving satellite precipitation estimates. Studies have reported success in utilizing machine learning to fuse IMERG with RADOLAN data, resulting in substantial enhancements in rainfall estimation accuracy [22]. This methodology optimally exploits the strengths of both satellite and ground-based data, thereby enabling urban planners and hydrologists to derive more accurate and reliable rainfall forecasts essential for flood preparedness and management.

Notwithstanding the promising capabilities of satellite datasets, notable limitations persist. The underrepresentation of extreme rainfall events critical to flood risk assessments poses a crucial challenge. Datasets like IMERG often fail in delineating the intensity and spatial characteristics of convective storms, which are necessary for accurate hydrological modeling in urban contexts, potentially compromising urban flood resilience [30]. Furthermore, the latency associated with satellite data processing can impede real-time applications, essential for swift responses during flood events. Although products like IMERG are designed for near-real-time updates, the delays can hinder their efficacy in early warning systems that require instantaneous data input [23].

Moreover, the reliance on indirect measurements from satellite sensors creates significant challenges. For example, misclassifying snow as rain during winter storms can lead to erroneous precipitation estimates, particularly in Germany's mountain areas where mixed-precipitation events are common. Such inaccuracies necessitate caution in deploying these products for precise hydrological forecasting and infrastructure design during winter months [24].

Proposed remedies to these issues include advancements in sensor technology and ongoing developments in satellite missions, notably from the European Space Agency (ESA). These upcoming missions promise to enhance the spatial and temporal resolution of precipitation observations, ultimately addressing existing gaps and improving flood risk management capabilities in urban areas [31]. Additionally, emerging innovations such as multi-sensor satellite systems that triangulate data from infrared, microwave, and radar sources could provide more reliable precipitation estimates, particularly during extreme weather, and for assessing precipitation in diverse topographies [32].

In conclusion, while satellite precipitation datasets represent a valuable resource for urban hydrology and flood risk management in Germany, a nuanced evaluation reveals both their potentials and limitations. The discrepancies observed between satellite estimates and ground-based measurements underscore the importance of continued refinement and integration of emerging technologies and methodologies. Ongoing advancements promise to bolster the efficacy of satellite products, augmenting urban resilience against flooding and facilitating improved management strategies in an era of changing climate. The performance of satellite precipitation can be seen at the Table 1.

Table 1. The performance satellite precipitation products in Germany

Satellite Precipitation Products	Spatial Resolution	Temporal Resolution	Application in Urban Hydrology	Performance	References
IMERG	0.1° (~10 km)	30 minutes	Suitable for monitoring urban rainfall anomalies and hydrological modeling.	Performs well in detecting extreme rainfall but underestimates high-intensity events in urban environments.	Ponukumati et al. (2023) [20], Montes et al. (2021) [22]
TRMM	~25 km	3 hours	Useful for long-term precipitation records but lacks urban-scale resolution.	Limited spatial resolution for urban hydrology applications; useful for regional studies.	Lasminto (2024) [25]; Sharma et al. (2017) [26]
GSMaP	~0.1° (~10 km)	Hourly	Effective for temporal analysis and event monitoring.	High temporal resolution; struggles with fine-scale urban variability and extreme rainfall events.	Zhuang et al. (2023) [8]; Montes et al. (2021) [22]
PERSIANN	~25 km	Daily	Used for regional hydrology and climate studies.	Challenges in capturing precipitation in complex terrains, particularly in mountainous regions of Germany.	Megantara et al. (2022) [24]
CHIRPS	0.05° (~5 km)	Daily	Valuable for historical trend analysis and stream-flow simulation.	Coarse temporal resolution; limited applicability in urban settings due to coarse resolution.	Hordofa et al. (2021) [27]
RADOLAN	~1 km	5 minutes	Ground-based radar dataset; complements satellite data in urban settings.	High spatial and temporal resolution; prone to errors in complex terrains and limited by coverage gaps.	Montes et al. (2021) [22]; Finger et al. (2023) [11]
Earth Explorer Programs	1 km (planned)	5 minutes	Emerging missions aim to enhance fine-scale urban precipitation modeling.	Promising future advancements in accuracy and resolution for urban hydrology applications.	Adem et al. (2023) [31]

4 Limitations and Opportunities

The integration of satellite precipitation products with urban flood risk management strategies in Germany holds substantial promise for enhancing hydrological forecasting and resilience against flood events. However, understanding the limitations faced by these datasets in urban environments, particularly given Germany's varied topography and climatic conditions, is crucial. This section discusses these limitations while simultaneously highlighting the opportunities for future advancements in satellite precipitation data applications shown in Table 2.

One significant challenge in utilizing satellite precipitation data in Germany stems from the country's diverse topography. Ranging from flat plains to the mountainous Bavarian Alps, the varied terrain introduces complexities in accurately measuring precipitation, particularly the orographic effects where precipitation intensifies as moist air ascends over mountains. Satellite products like TRMM and IMERG have been found inadequate in capturing these phenomena, as their resolution might not sufficiently reflect the enhanced precipitation that occurs in such regions [33]. Indirect measurements based on cloud properties, such as temperature and moisture content, further complicate the estimation accuracy, particularly in areas that experience substantial snowfall during winter. Winter precipitation misclassifications where snow is erroneously categorized as light rain are common, negatively impacting models relying on satellite data for hydrological assessments in colder regions of Germany [34].

Real-time application capabilities pose another challenge. Effective flood forecasting and emergency response systems heavily depend on high temporal resolution from satellite datasets. While products such as IMERG and GSMaP provide near-real-time updates, inherent processing delays limit their efficacy in urgent scenarios. Typically, data availability lags a few hours after observation, which may miss critical flash floods that require immediate attention [35]. Furthermore, the tension between spatial and temporal resolution remains prominent; high spatial resolution products, which would capture localized rainfall events crucial in urban flooding contexts, might sacrifice temporal resolution for instance, providing less frequent updates ultimately hindering their applicability in dynamic urban environments.

The reliance on indirect measurements, especially utilizing microwave and infrared radiation, introduces uncertainties in precipitation estimation accuracy. Satellite estimates can misrepresent rainfall amounts, particularly when atmospheric conditions are complicated by low temperatures and winter precipitation dynamics, as seen with datasets like PERSIANN [36]. Moreover, the tendency of satellites to either overlook lighter rainfall events or misclassify them can undermine model accuracy in flood predictions, especially in urban areas with impervious surfaces, where even minor precipitation changes can directly impact runoff [37].

Despite substantial advances made by integrating satellite data with ground observational systems, challenges remain. The RADOLAN radar system in Germany, which provides robust precipitation estimates, also has shortcomings related to coverage gaps and inaccuracies, particularly in difficult-to-access mountainous locations. While integrating RADOLAN data with satellite information can enhance spatial coverage and reduce bias, this fusion is not straightforward. Differences in spatial and temporal resolutions between radar and satellite observations often lead to discrepancies in hydrological models [38]. Ground-based stations themselves are not devoid of limitations; often, they are sparsely distributed in rural areas and face calibration issues that could affect reliability [39].

Long-term data consistency is critical for climate trend analysis and understanding precipitation variability. However, while satellite products like TRMM and IMERG provide essential data, their historical records are limited. The TRMM mission, notably ending in 2015, concentrated primarily on tropical regions and thus cannot provide the necessary urban hydrological insights required for comprehensive flood mitigation planning across Germany [40]. IMERG, although more current, lacks extensive historical datasets that would facilitate robust long-term climate trend analysesthe importance of which cannot be overstated for urban planners tasked with infrastructure resilience under future climate extremes [33].

Despite these limitations, there are several opportunities for enhancing satellite precipitation products' usability and effectiveness in urban hydrology. Increasing both spatial and temporal resolution through advancements in satellite sensor technology is a key avenue. The European Space Agency's Sentinel missions, for example, are equipped with high-resolution sensors designed to improve spatial coverage, permitting finer representation of small-scale precipitation events typical in densely populated urban environments [41]. Furthermore, leveraging downscaling techniques can refine coarse-resolution satellite data to higher resolutions applicable for urban hydrological modeling, thereby improving both accuracy and usability [42].

Additionally, the integration of machine learning strategies stands to revolutionize the assimilation of multiple data sources satellite imagery, radar data, and ground-based measurements thereby improving precipitation estimation significantly. Machine learning techniques can learn to correct biases found in satellite data while enhancing the predictive capability of urban hydrology models [43]. Utilizing such algorithms to synthesize IMERG with RADOLAN data has shown promise, leading to more reliable rainfall estimates suitable for real-time urban applications [44].

The increasing deployment of Internet of Things (IoT) sensors within cityscapes provides an unparalleled capacity to enhance precipitation estimates when combined with satellite-derived data. By integrating real-time data from local sensors, urban hydrology models can yield more granular and accurate precipitation inputs, particularly beneficial in cities like Munich that have developed extensive sensor networks for environmental monitoring [45].

The pursuit of next-generation multi-sensor satellite systems represents another significant opportunity for addressing urban hydrological challenges. Systems that can unify multiple data types microwave, infrared, and radar will provide a more exhaustive overview of precipitation conditions and improve rainfall classification accuracy, essential for urban flood management [46]. Future satellite platforms equipped to differentiate between various precipitation types rain, snow, and mixed conditions could enhance reliability, particularly during harsh winter months in Germany where current systems struggle with accurate precipitation estimation [47].

Real-time data assimilation for urban hydrology is poised to dramatically enhance the precision of flood forecasting and rainfall modeling. By integrating up-to-date satellite precipitation data into hydrological models, anticipated changes in flooding conditions could be captured dynamically. This on-the-fly model adjustment would improve predictive accuracy, offering significant benefits in fast-paced urban environments where hydrological conditions can shift rapidly [48]. This methodology has been successfully employed in flood forecasting in regions such as the United States and Japan, and its application in German urban centers like Hamburg and Cologne could significantly mitigate risks associated with localized flash floods.

The trend towards developing high-resolution satellite products with improved downscaling techniques is encouraging, addressing the spatial resolution gaps of current datasets such as IMERG and TRMM. As urban environments experience intensified and localized rainfall events, the demand for high-resolution satellite precipitation data grows correspondingly [49]. Innovative downscaling methods, utilizing cloud attributes for finer resolution estimates, would enhance the reliability of precipitation inputs into urban hydrological models, adapting to urban dynamics and crafting flooding mitigation strategies tailored to local climates [50].

Importantly, broadening the accessibility and interoperability of satellite precipitation datasets remains fundamental in overcoming existing barriers. With data increasingly available through platforms like NASA's EOSDIS and ESA's Copernicus, ensuring that satellite-derived information is shared in open-access formats fosters integration with local urban water management systems [51]. This synergy is crucial, enabling the development of decision-support tools for urban flood forecasting and real-time risk assessments, ultimately allowing cities to adapt to shifting precipitation patterns brought on by a changing climate.

In summary, while the current limitations of satellite precipitation products present noteworthy challenges in the context of urban flood management in Germany, they also offer substantial opportunities driven by innovation and technology advancements. By enhancing data resolution, integrating machine learning techniques, and fostering collaborative environments through improved accessibility, the potential for satellite datasets to transform urban hydrology remains significant.

Table 2. The limitation and opportunities of satellite precipitation products

Limitations	Opportunities
Satellite data struggles with fine-scale urban rainfall variability.	Increase spatial resolution using advanced sensors and downscaling techniques.
Difficulty capturing orographic effects in mountainous areas.	Utilize multi-sensor integration and improved retrieval algorithms for complex terrains.
Delays in near-real-time data hinder emergency responses.	Reduce latency with rapid data processing and integration of predictive weather models.
Trade-offs between spatial and temporal resolution reduce accuracy.	Develop satellites with combined high spatial and temporal resolution capabilities.
Errors in detecting precipitation type, especially snow vs. rain.	Introduce advanced sensors capable of detecting various precipitation phases.
Inconsistent detection of light rainfall or drizzle.	Apply machine learning to correct biases and integrate ground-based sensor data.
Sparse ground-based stations limit validation efforts in rural areas.	Fuse satellite data with IoT sensors and localized ground networks for enhanced accuracy.
Limited historical satellite data for long-term trend analysis.	Combine satellite data with high-resolution climate models for comprehensive climate trend studies.
Challenges in integrating satellite and radar data due to discrepancies.	Apply machine learning for seamless multi-source data fusion and enhanced urban hydrology modeling.
Accessibility issues for satellite data and interoperability challenges.	Promote open-access platforms and standardized data integration tools for urban planning applications.

5 Conclusion

The integration of satellite precipitation datasets into urban hydrological modeling represents a transformative opportunity for enhancing flood risk management in Germany. As cities face growing challenges from climate change, intensified rainfall events, and rapid urbanization, satellite-based rainfall estimates such as those provided by IMERG, TRMM, GSMaP, and PERSIANN offer vital support for improving the accuracy, timeliness, and spatial coverage of hydrological assessments.

However, limitations remain in the form of spatial and temporal resolution trade-offs, latency in real-time applications, and challenges in capturing orographic and cold-season precipitation dynamics. These constraints underscore the need for ongoing refinement in satellite retrieval algorithms and greater reliance on data fusion techniques that combine satellite data with ground-based observations such as RADOLAN. Particularly in complex urban settings with heterogeneous topography, improving the precision of rainfall detection is essential for predictive modeling and infrastructure planning.

Emerging technologies, including machine learning, IoT-based sensor networks, and multi-sensor satellite missions, offer promising solutions to address current shortcomings. Downscaling techniques that enhance spatial granularity and real-time data assimilation approaches can significantly improve the operational utility of satellite data in urban flood forecasting. Furthermore, the development of accessible, interoperable data platforms can facilitate broader adoption of satellite datasets in municipal-level decision-making.

In summary, while current satellite precipitation products are not without challenges, their continued advancement especially through integration with complementary technologies has the potential to redefine urban hydrological modeling. For Germany, leveraging these innovations is key to developing resilient, data-driven strategies that ensure sustainable urban water management in the face of a changing climate.

References

[1] A. Tarpanelli, G. Schumann, & C. Kittel, "Earth observation data for advancing flood forecasting: eo4flood project",, 2025. https://doi.org/10.5194/egusphere-egu25-6671

[2] M. Alobid, C. Fatih, & I. Szücs, "Trends and drivers of flood occurrence in germany: a time series analysis of temperature, precipitation, and river discharge", Water, vol. 16, no. 18, p. 2589, 2024. https://doi.org/10.3390/w16182589

[3] H. Apel, S. Vorogushyn, M. Farrag, N. Dũng, M. Karremann, H. Kreibichet al., " RIMurban – a generalized gpu-based model for urban pluvial flood risk modelling and forecasting",, 2021. https://doi.org/10.5194/egusphere-egu21-2985

[4] R. Mohanty, C. Chatterjee, & B. Sahoo, "Enhancing accuracy of imerg-e satellite rainfall products for mahanadi river basin using bias-correction methods",, 2025. https://doi.org/10.5194/egusphere-egu25-15074

[5] P. Yaswanth, V. Bindhu, B. Kannan, C. Balaji, & B. Narasimhan, "Performance assessment of high-resolution remote sensing rainfall products and their utility in simulating extreme hydrological events in a peri-urban catchment",, 2022. https://doi.org/10.21203/rs.3.rs-2304860/v1

[6] T. Satriawansyah, M. Adikarya, & M. Fanani, "Meta-analysis of sustainable urban drainage systems (suds) in reducing urban flood risks", IJEET, vol. 2, no. 2, p. 297-303, 2024. https://doi.org/10.61991/ijeet.v2i2.53

[7] Y. Huang, Z. Tian, Q. Ke, J. Liu, M. Irannezhad, D. Fanet al., "Nature-based solutions for urban pluvial flood risk management", Wiley Interdisciplinary Reviews Water, vol. 7, no. 3, 2020. https://doi.org/10.1002/wat2.1421

[8] Q. Zhuang, Z. Zhou, S. Liu, D. Wright, & L. Gao, "The evaluation and downscaling-calibration of imerg precipitation products at sub-daily scales over a metropolitan region", Journal of Flood Risk Management, vol. 16, no. 3, 2023. https://doi.org/10.1111/jfr3.12902

[9] A. Tiwari, K. Cherkauer, F. Marks, W. Tung, & D. Niyogi, "Enhancing hydrological insights for tropical cyclones using satellite precipitation data.",, 2025. https://doi.org/10.5194/egusphere-egu25-11548

[10] H. Li, D. Yang, Z. Zhu, Y. Wei, Y. Zhou, H. Ishidairaet al., "Flood risk analysis of urban agglomerations in the yangtze river basin under extreme precipitation based on remote sensing technology", Remote Sensing, vol. 16, no. 22, p. 4289, 2024. https://doi.org/10.3390/rs16224289

[11] A. Finger, M. Kretz, and D. Penker, "Sustainable Urban Drainage Systems and Integrated Water Resources Management in Germany," Journal of Infrastructure Planning and Engineering, vol. 6, no. 1, pp. 69–72, 2023.

[12] S. Garcia-Rosabel, D. Idowu, & W. Zhou, "At the intersection of flood risk and social vulnerability: a case study of new orleans, louisiana, usa", Geohazards, vol. 5, no. 3, p. 866-885, 2024. https://doi.org/10.3390/geohazards5030044

[13] L. Son, L. Chung, B. Hai, S. ANH, & N. Quang, "Assessing satellite-based precipitation products to create flood forecasting in the da river basin, vietnam", Journal of Geoscience and Environment Protection, vol. 07, no. 11, p. 113-123, 2019. https://doi.org/10.4236/gep.2019.711008

[14] S. Ghomash, H. Apel, K. Schroeter, & M. Steinhausen, "Assessing surface drainage efficiency in urban pluvial flood hazard and risk mitigation: a case study of braunschweig city",, 2025. https://doi.org/10.5194/egusphere-egu24-3076

[15] J. Yin, D. Yu, Z. Yin, M. Liu, & Q. He, "Evaluating the impact and risk of pluvial flash flood on intra-urban road network: a case study in the city center of shanghai, china", Journal of Hydrology, vol. 537, p. 138-145, 2016. https://doi.org/10.1016/j.jhydrol.2016.03.037

[16] K. Javanshour and S. Gülbaz, "Impact assessment of landuse change on peak flowrate by using hydrological model of alibeyköy watershed",, 2019. https://doi.org/10.33422/2nd.rasconf.2019.09.595

[17] L. Netzel, S. Heldt, S. Engler, & M. Denecke, "The importance of public risk perception for the effective management of pluvial floods in urban areas: a case study from germany", Journal of Flood Risk Management, vol. 14, no. 2, 2021. https://doi.org/10.1111/jfr3.12688

[18] S. Mohammed, A. Nasr, & M. MAHMOUD, "Evaluation of the spatiotemporal representation of the gpm satellite precipitation products over diverse climatic regions in ireland",, 2022. https://doi.org/10.5194/egusphere-egu22-8942

[19] P. Laux, D. Feldmann, F. Marra, H. Feldmann, H. Kunstmann, K. Trachteet al., "Future precipitation extremes and urban flood risk under +2°c and +3°c warming: a novel non-stationary climate-hydrodynamic modeling chain for using high-resolution radar data and a convection-permitting climate model ensemble",, 2025. https://doi.org/10.5194/egusphere-egu25-20737

[20] P. Ponukumati, A. Mohammed, & S. Regonda, "Insights on satellite-based imerg precipitation estimates at multiple space and time scales for a developing urban region in india", Journal of Hydrometeorology, vol. 24, no. 6, p. 977-996, 2023. https://doi.org/10.1175/jhm-d-22-0160.1

[21] D. Vázquez-Rodríguez, V. Guerra-Cobián, J. Flores, C. Fonseca, & F. Yépez-Rincón, "Evaluating the performance and applicability of satellite precipitation products over the rio grande–san juan basin in northeast mexico", Atmosphere, vol. 15, no. 7, p. 749, 2024. https://doi.org/10.3390/atmos15070749

[22] C. Montes, N. Acharya, S. Hassan, & T. Krupnik, "Intense precipitation events during the monsoon season in bangladesh as captured by satellite-based products",

Journal of Hydrometeorology, 2021. https://doi.org/10.1175/jhm-d-20-0287.1

[23] D. Moges, A. Kmoch, & E. Uuemaa, " Application of satellite and reanalysis precipitation for hydrological modeling in data-scarce Porijõgi catchment, Estonia",, 2022. https://doi.org/10.5194/egusphere-egu22-6990

[24] A. Megantara, S. Wahyuni, & L. Limantara, "Rationalization of rainfall station density in the jatiroto sub-watershed using ground and satellite rainfall data", Civil and Environmental Science, vol. 005, no. 02, p. 129-143, 2022. https://doi.org/10.21776/ub.civense.2022.00502.3

[25] U. Lasminto, "Reliability of tropical rainfall measuring mission for rainfall estimation in brantas sub-watersheds", International Journal of Geomate, vol. 26, no. 116, 2024. https://doi.org/10.21660/2024.116.4267

[26] V. Sharma, N. Mishra, A. Shukla, A. Yadav, G. Rao, & V. Bhanumurthy, "Satellite data planning for flood mapping activities based on high rainfall events generated using trmm, gefs and disaster news", Annals of Gis, vol. 23, no. 2, p. 131-140, 2017. https://doi.org/10.1080/19475683.2017.1304449

[27] A. Hordofa, O. Leta, T. Alamirew, N. Kawo, & A. Chukalla, "Performance evaluation and comparison of satellite-derived rainfall datasets over the ziway lake basin, ethiopia", Climate, vol. 9, no. 7, p. 113, 2021. https://doi.org/10.3390/cli9070113

[28] L. Brocca, C. Massari, T. Pellarin, P. Filippucci, L. Ciabatta, S. Camiciet al., "River flow prediction in data scarce regions: soil moisture integrated satellite rainfall products outperform rain gauge observations in west africa", Scientific Reports, vol. 10, no. 1, 2020. https://doi.org/10.1038/s41598-020-69343-x

[29] A. Gadêlha, V. Coelho, A. Xavier, L. Barbosa, D. Melo, Y. Xuanet al., "Grid box-level evaluation of imerg over brazil at various space and time scales", Atmospheric Research, vol. 218, p. 231-244, 2019. https://doi.org/10.1016/j.atmosres.2018.12.001

[30] M. Brunetti, M. Melillo, S. Gariano, L. Ciabatta, L. Brocca, G. Amarnathet al., "Performance of satellite rainfall products for landslide prediction in india",, 2022. https://doi.org/10.5194/egusphere-egu22-2757

[31] E. Adem, A. Elfeki, A. Chaabani, S. Hussain, & M. Elhag, "Impact of satellite precipitation estimation methods on the hydrological response: case studies wadi nu'man basin, saudi arabia",, 2023. https://doi.org/10.21203/rs.3.rs-3506255/v1

[32] A. Bodian, A. Dezetter, A. Dème, & L. Diop, "Hydrological evaluation of trmm rainfall over the upper senegal river basin", Hydrology, vol. 3, no. 2, p. 15, 2016. https://doi.org/10.3390/hydrology3020015

[33] Z. Ma, K. He, X. Tan, J. Xu, W. Fang, Y. Heet al., "Comparisons of spatially downscaling tmpa and imerg over the tibetan plateau", Remote Sensing, vol. 10, no. 12, p. 1883, 2018. https://doi.org/10.3390/rs10121883

[34] J. Xu, Z. Ma, G. Tang, Q. Ji, X. Min, W. Wanet al., "Quantitative evaluations and error source analysis of fengyun-2-based and gpm-based precipitation products over mainland china in summer, 2018", Remote Sensing, vol. 11, no. 24, p. 2992, 2019. https://doi.org/10.3390/rs11242992

[35] T. Pellarin, C. Román-Cascón, C. Baron, R. Bindlish, L. Brocca, P. Camberlinet al., "The precipitation inferred from soil moisture (prism) near real-time rainfall product: evaluation and comparison", Remote Sensing, vol. 12, no. 3, p. 481, 2020. https://doi.org/10.3390/rs12030481

[36] Y. Lyu and B. Yong, "A novel double machine learning strategy for producing high-precision multi-source merging precipitation estimates over the tibetan plateau", Water Resources Research, vol. 60, no. 4, 2024. https://doi.org/10.1029/2023wr035643

[37] G. Scognamiglio, A. Rucci, A. Vaccaro, E. Adirosi, F. Sapienza, F. Giannettiet al., "Deep learning for opportunistic rain estimation via satellite microwave links", Sensors, vol. 24, no. 21, p. 6944, 2024. https://doi.org/10.3390/s24216944

[38] G. Wang, W. Han, S. Ye, S. Yuan, J. Wang, & F. Xie, "Fy-4a/agri infrared brightness temperature estimation of precipitation based on multi-model ensemble learning", Earth and Space Science, vol. 11, no. 2, 2024. https://doi.org/10.1029/2023ea003311

[39] T. Yoshikane and K. Yoshimura, "A bias correction method for precipitation through recognizing mesoscale precipitation systems corresponding to weather conditions", Plos Water, vol. 1, no. 5, p. e0000016, 2022. https://doi.org/10.1371/journal.pwat.0000016

[40] S. Hartke, D. Wright, D. Kirschbaum, T. Stanley, & Z. Li, "Incorporation of satellite precipitation uncertainty in a landslide hazard nowcasting system", Journal of Hydrometeorology, vol. 21, no. 8, p. 1741-1759, 2020. https://doi.org/10.1175/jhm-d-19-0295.1

[41] H. Hung and L. Wang, "Irmerg: enhancing global infrared precipitation estimates with land surface variables and contributing factors analysis using explainable machine learning",, 2025. https://doi.org/10.5194/egusphere-egu25-16863

[42] F. Verdelho, C. Beneti, L. Pavam, L. Calvetti, L. Oliveira, & M. Alves, "Quantitative precipitation estimation using weather radar data and machine learning algorithms for the southern region of brazil", Remote Sensing, vol. 16, no. 11, p. 1971, 2024. https://doi.org/10.3390/rs16111971

[43] H. Han, B. Kim, K. Kim, D. Kim, & H. Kim, "Machine learning approach for the estimation of missing precipitation data: a case study of south korea", Water Science & Technology, vol. 88, no. 3, p. 556-571, 2023. https://doi.org/10.2166/wst.2023.237

[44] G. Papacharalampous, H. Tyralis, A. Doulamis, & N. Doulamis, "Large-scale comparison of machine and statistical learning algorithms for blending gridded satellite and earth-observed precipitation data",, 2023. https://doi.org/10.5194/egusphere-egu23-3296

[45] S. Izanlou, Y. Amerian, & S. Mousavi, "Gnss-derived precipitable water vapor modeling using machine learning methods", Isprs Annals of the Photogrammetry Remote Sensing and Spatial Information Sciences, vol. X-4/W1-2022, p. 307-313, 2023. https://doi.org/10.5194/isprs-annals-x-4-w1-2022-307-2023

[46] M. Altoom, E. Adam, & K. Ali, "Evaluating current satellite sensors in capturing the spatio-temporal rainfall variability across north darfur state, sudan",, 2023. https://doi.org/10.20944/preprints202305.1586.v1

[47] J. Ha, Y. Lee, & Y. Kim, "Forecasting the precipitation of the next day using deep learning", Journal of Korean Institute of Intelligent Systems, vol. 26, no. 2, p. 93-98, 2016. https://doi.org/10.5391/jkiis.2016.26.2.093

[48] T. Chen, " Machine Learning and Deep Learning for Multi-Source Precipitation Integration in the Yangtze River Basin",, 2025. https://doi.org/10.5194/egusphere-egu25-1507

[49] H. Chen, T. Wang, C. Montzka, H. Gao, N. Guo, X. Chenet al., "On the improved ensemble of multi-source precipitation through joint automated machine learning-based classification and regression",, 2023. https://doi.org/10.5194/egusphere-egu23-14002

[50] M. Grecu, G. Heymsfield, S. Nicholls, S. Lang, & W. Olson, "A machine learning approach to mitigate ground clutter effects in the gpm combined radar–radiometer algorithm (corra) precipitation estimates", Journal of Atmospheric and Oceanic Technology, vol. 42, no. 1, p. 17-31, 2024. https://doi.org/10.1175/jtech-d-24-0048.

[51] P. Das, Z. Zhang, S. Ghosh, & H. Ren, "A hybrid ensemble learning merging approach for enhancing the super drought computation over lake victoria basin", Scientific Reports, vol. 14, no. 1, 2024. https://doi.org/10.1038/s41598-024-61520-6