

## Review article

# A review of climate change impact assessment and methodologies for urban sewer networks

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## ABSTRACT

Understanding how climate change affects urban sewer networks is essential for the sustainable management of these infrastructures. This research uses a systematic literature review (PRISMA) to critically review methodologies to assess the effects of climate change on these systems.

A scientometric analysis traced the evolution of research patterns, while content analysis identified three primary research clusters: Climate Modelling, Flow Modelling, and Risk and Vulnerability Assessment. These clusters, although rooted in distinct disciplines, form an interconnected framework, where outputs of climate models inform flow models, and overflow data from flow models contribute to risk assessments, which are gaining increasing attention in recent studies. To enhance risk assessments, methods like Gumbel Copula, Monte Carlo simulations, and fuzzy logic help quantify uncertainties. By integrating these uncertainties with a Bayesian Network, which can incorporate expert opinion, failure probabilities are modelled based on variable interactions, improving prediction.

The study also emphasises the importance of factors, such as urbanisation, asset deterioration, and adaptation programs in order to improve predictive accuracy. Additionally, the findings reveal the need to consider cascading effects from landslides and climate hazards in future risk assessments. This research provides a reference for methodology selection, promoting innovative and sustainable urban sewer management.

## 1. Introduction

Urban sewer systems are critical infrastructures that are increasingly vulnerable to the wide-ranging impacts of climate change [1,2]. The mean sea level rise increased by 0.2m from 1901 to 2018, and extreme weather conditions/events, such as heatwaves, heavy rainfalls, draughts, and cyclones have become more frequent and intense in recent years, putting urban infrastructures at risk. There are numerous instances worldwide where urban sewer networks become overwhelmed by extreme weather, including the 2020 Karachi floods [3], the 2020 Zagreb flash flood (Krvavica et al., 2023), the 2021 European floods [4], the 2023 Auckland Anniversary floods [5], the 2024 Nepal floods [6], and the 2023 Volta Region floods in Ghana [7]. These risks are anticipated to significantly increase beyond 2100 [1]. The shifting risks and heightened awareness and concern highlight the importance of developing adaptation strategies that account for climate change alongside other challenges like urbanisation and infrastructure aging [8–12].

Moreover urban infrastructure, particularly sewer systems, is

becoming more susceptible to climate-related risks, such as extreme weather events, rising sea levels, and shifting rainfall patterns [13,14]. These threats can result in sewer system failures, including overflows, increased peak flow, corrosion, and treatment plant inundation in low-lying areas [15–19]. Studies have identified adaptation strategies, including pipe renewals, separation programs, and low-water-use technologies, as critical to mitigating these impacts [20,21]. However, developing these strategies requires interdisciplinary collaboration across various research fields [22–24]. Understanding gaps and overlaps in these fields is vital to formulating effective solutions, particularly by incorporating factors like land use changes and asset deterioration [23, 25–27]. These factors contribute to capacity constraints and elevate the risk of failures, such as overflows, which will be further exacerbated by climate change [28].

### 1.1. Study motivation

Most existing studies primarily concentrate on stormwater or

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combined sewer systems, particularly regarding controlled overflows [16,29,30], reflecting the assumption that these systems are more susceptible to climate change. However, separate sewer networks, which constitute the majority of urban infrastructure in developed countries, have received minimal attention in review studies [16,29,30].

In addition, while many current review papers touch on various indicators and methodologies (e.g., [16,22]), they lack a structured framework to categorise studies by methodologies and interlink the diverse research domains, such as climate modelling, hydraulic flow analysis, and risk assessments in this field. This omission complicates the task of pinpointing essential missing indicators or metrics.

Moreover, few review papers examine the evolution of research efforts over time or provide insights into the way different methodologies and focus areas have developed. They rarely provide visual mapping of research trends or insights into future directions, leaving limited guidance on emerging opportunities and underexplored areas.

Lastly, broader issues, such as the interplay between climate change, urbanisation, and aging infrastructure, are also rarely addressed. Similarly, despite reports from utilities [12], there is a lack of studies that sufficiently demonstrate the role of cascading hazards, such as landslides or disrupted access, on sewer networks and their potential implications due to climate change. It is crucial to highlight where in the risk assessment process these factors should be considered, to understand their dynamics and outline the associated risks.

Based on the abovementioned research gaps, the following research questions were identified for this study.

- What indicators and assessment tools have been commonly used to evaluate the impacts of climate change on separate sewer networks?
- What are the key research trends and methodologies in the field of climate change impacts on separate sewer networks, and how can they be organised into a structured framework to identify gaps and missing indicators?
- How can research fields, such as climate modelling, hydraulic flow analysis, and risk assessments, be categorised and interlinked to enhance the understanding of climate change impacts on sewer networks?
- What emerging challenges, such as urbanisation and aging infrastructure, are influencing the performance of separate sewer networks under climate change, and how can future research address these evolving factors?

The primary objective of this study is to review key research clusters, assessment tools, and methodologies currently employed in evaluating the effects of climate change, focusing on identified indicators. Building on this foundation, the paper aims to develop a structured framework that systematically categorises these methodologies, with a special emphasis on separate sewer systems. In addition, it aims to assess the current state of knowledge, identify gaps, and propose avenues for future research. To bridge theory and practice, the paper presents a practical, step-by-step approach to help network planners evaluate climate risks while considering other critical factors. Lastly, it highlights the need for interdisciplinary collaboration across fields and disciplines to effectively address these complex, interconnected challenges.

### 1.2. Research contribution

This study offers several contributions to the field of climate risk assessment for sewer networks. First, it introduces a novel framework that systematically classifies and interlinks diverse research fields, including climate modelling, flow modelling, and risk and vulnerability assessments, while highlighting their progress trends. This structured classification simplifies the complexity of overlapping research domains and fosters interdisciplinary collaboration.

Second, the study addresses underexplored factors, such as cascading hazards like landslides, urbanisation dynamics that amplify flow, and

asset deterioration that heightens failure risk— all of which are critical to understanding vulnerability.

Another key contribution is the focus on separate sewer networks, an often overlooked yet critical component of urban infrastructure.

Additionally, the study identifies progress trends and knowledge frontiers in the field, providing a roadmap for future research.

Finally, a step-by-step approach is proposed to help network planners assess climate risks and forecast how factors like urbanisation, asset deterioration, and adaptation strategies may exacerbate these risks. The framework is designed to facilitate collaboration across various fields and disciplines, offering a clear structure to manage these interconnected challenges and help planners navigate the complexities of climate impacts and their compounding factors.

## 2. Background

In recent years, researchers have increasingly focused on evaluating the impacts of climate change on sewer networks [16]. Climate and flow modelling have been widely used methods in this research domain [31]. However, the research focus has recently shifted from climate and flow modelling to developing comprehensive risk and vulnerability models for sewer networks [25]. There is an increased trend of studies focusing on the vulnerability assessment of urban drainage networks in the face of climate change [32]. Assessing the vulnerability of the sewer systems is essential in urban water management, especially in terms of developing adaptation and response plans [33]. Advancements in climate and flow modelling have enabled researchers to utilise existing localised models, freeing up resources to enhance risk and vulnerability models by incorporating previously overlooked factors [34].

Bayesian Network Hosseini et al. [35,36], Multi-Criteria Analysis Johnston et al. [37], Impact Matrix [38], Problem tree Analysis Aubin et al. [39], Participatory Rural Appraisal (PRA) [40,41], N-k analysis, Statistical Learning Theory [42] and Complex Network Theory Simone [32] were identified as applicable methods in climate change-related vulnerability and resilience assessment. Furthermore, incorporating a vulnerability index alongside flow modes [33] and the application of vulnerability functions are alternative approaches used for this purpose [43].

The quality and completeness of input data directly influence the reliability of the vulnerability assessment outcomes. For reliable and insightful vulnerability assessments, data quality assurance processes and standardisation of indicators are of utmost importance [21]. Various indicators can be considered in a climate change vulnerability assessment for sewer networks to evaluate the system's susceptibility and potential impacts. Some of the key indicators include the intensity of weather events (Rak et al. [44]), change of urbanisation and land use (Yekenelem Abebe, 2018), hydraulic load and age and condition of infrastructure [45].

## 3. Methodology

This study adopts a mixed-methods approach, integrating both quantitative and qualitative methods [46]. The utilisation of a mixed-methods approach enables the triangulation of data, facilitating a more comprehensive and robust conclusion, even in cases of paradox or contradiction arising from each analysis separately [47–49]. These methods enable mapping the research patterns in previous literature. The research framework, shown in Figure 1 Fig. 1, follows a three-stage approach to investigate resilience assessment in sewer networks. It begins with a scientometric analysis to identify research trends, key authors, and gaps. Next, a systematic literature review evaluates existing assessment tools through structured identification and screening, refining the research question. Finally, content analysis extracts key indicators and approaches for resilience assessment, ensuring a comprehensive understanding of evaluation methods.

In the first stage of this study, a quantitative scientometric analysis is

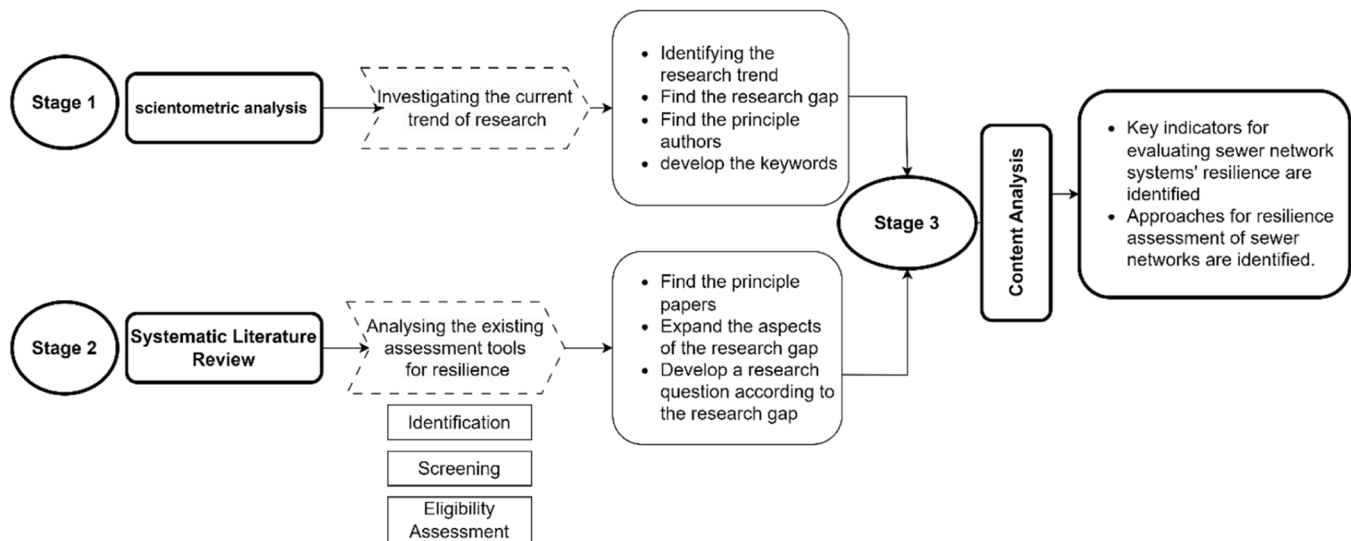


Fig. 1. Research Framework.

utilised to identify a wide array of articles published on vulnerability analysis of sewer networks, fostering a more holistic coverage of the literature on the topic [50]. This approach helps make sense of existing research by creating clear and useful graphs. These graphs offer insights into how up-to-date the topic is, highlight contributions from various researchers, and show key themes in the findings [51]. VOSviewer software tool is chosen for its text-mining capabilities leveraging the visualisation of similarities (VOS) algorithm, which facilitates the creation, visualisation, and examination of bibliometric relationships [52]. The VOS algorithm measures the similarities between items based on data, such as co-authorship in publications or the co-occurrence of keywords within documents. The clustering algorithm is also used to group closely related items. However, the software has limitations, including simplifying network structures, underrepresenting weaker links, and occasionally merging closely related terms inaccurately. Despite these challenges, the tool offered meaningful insights into research trends and gaps, contributing to the understanding of sewer network resilience as it relates to climate change [53].

In stage 2, a qualitative systematic literature review (SLR) provides an in-depth study of the literature and conceptualisation of the key research themes. The aim is to identify the used indicators, approaches and tools in the resilient assessment of sewer networks from climate change impacts [21,54]. The methodology employed in this study follows the reporting guidelines established by PRISMA [55]. PRISMA provides a comprehensive framework comprising a four-phase flow diagram and a 27-item checklist, which makes the review accurate and transparent throughout the process. The PRISMA flow diagram outlines the criteria for identifying, screening, and eligibility assessment and includes relevant reports in the review [56,57].

### 3.1. Identification of relevant articles

In alignment with the research questions outlined in the background section, initially, the following keywords were identified to ensure a comprehensive and structured search of relevant literature in the research domain. Initially, the combination of "resilience," "adaptation," "urban sewer networks," "climate change," and "extreme weather events" were defined as keywords for searching. However, the strategy was later refined by incorporating synonyms, applying truncation, and using Boolean logic to enhance inclusivity. This approach ensured a broader and more representative collection of relevant studies for the scientometric analysis. SCOPUS was the designated search engine to navigate the relevant research papers due to its quality and reliability and its

available visualisation tools [58]. To minimise selection bias, Google Scholar was employed to cross-check results, ensuring no relevant studies were overlooked. Methodological bias was further mitigated through a critical evaluation of each study's objectives, methods, and findings to ensure relevance and reliability. Although the screening was conducted by a single reviewer, subjective bias was minimised by applying explicit inclusion/exclusion criteria in sequential rounds and documenting decisions at each stage. For example, studies that focused solely on buildings, roads, or stormwater infrastructure rather than sewer systems were explicitly excluded and noted in the screening process. Water Switzerland and Sustainable Cities And Society were the most significant source of articles related to the research question, followed by the Journal of Hydrology, Journal Of Environmental Management and Water Resources Management. Subsequently, the newly identified keywords from the scientometric phase were incorporated into the search and integrated into the screening process. However, it is noteworthy that, during this review, no additional papers were found through the inclusion of these keywords.

### 3.2. Screening

The next stage of the PRISMA process involves a thorough examination of the selected papers, with a focus on highlighting the key findings of each article.

The screening process was conducted in Scopus as the primary database in multiple rounds:

- **Initial Screening:** Broad keywords were applied to ensure comprehensive coverage of relevant studies. Studies clearly meeting the exclusion criteria (e.g., non-relevant infrastructure or focus areas) were removed.
- **Detailed Screening:** Full-text reviews were conducted to assess relevance, and terms used interchangeably (e.g., "urban sewer networks" and "wastewater systems") were standardised to maintain consistency with the inclusion criteria.
- **Final Selection:** All remaining studies were re-evaluated to ensure alignment with the predefined inclusion and exclusion criteria.

The results from Scopus were cross-checked in Google Scholar to confirm that no significant studies were missed, ensuring the completeness of the review.

### 3.3. Eligibility assessment

This stage is to ensure that the selected articles are aligned with the research topic. Therefore, certain exclusion and inclusion criteria (EC/IC) have been specified in this research as follows:

**Inclusion criteria:**

- Studies that investigate the impacts of climate change on urban sewer networks, incorporating both combined and separate sewer systems, including linear infrastructure (pipelines) and pumping stations.
- Studies focusing on the resilience of urban sewer networks to the impacts caused by climate change.
- Studies that integrate interdisciplinary methodologies, such as climate modelling, hydraulic analysis, risk assessment, and vulnerability analysis, to assess the vulnerability of urban sewer networks to climate-related stressors
- Studies published in peer-reviewed journals

**Exclusion criteria:**

- Studies that did not focus on the impact of climate change on urban sewer networks.
- Studies that focus on other types of infrastructure, such as treatment plants, buildings or roads, without addressing the sewer networks (pipelines and pump stations).

- Studies that focus on the effects of extreme weather events on human health or the environment without examining their impact on urban sewer networks.
- Studies not published in peer-reviewed journals, including grey literature or conference papers with limited review or validation.

This decision to exclude other types of infrastructures was made to highlight the unique dynamics of sewer networks, which differ significantly from those of other infrastructures, such as roads, bridges and treatment facilities. While roads and bridges are also affected by hydrological factors, such as rainfall and flooding, the interactions within sewer networks—particularly those involving rainfall-induced inflows, runoff infiltration, and groundwater dynamics—introduce distinct challenges. Additionally, the complexities associated with treatment facilities further differentiate their vulnerability to climate change from that of sewer networks, necessitating a targeted approach to effectively address the vulnerabilities within the network.

While the selection criteria may limit insights from related fields, focusing specifically on sewer networks is essential to develop targeted strategies to enhance resilience against climate change. This approach helps ensure that the analysis remains relevant and applicable to the unique challenges faced by sewer systems.

The final selected papers are included in the literature review and have undergone a content analysis to identify the significant trends in the research topic.

Fig. 2

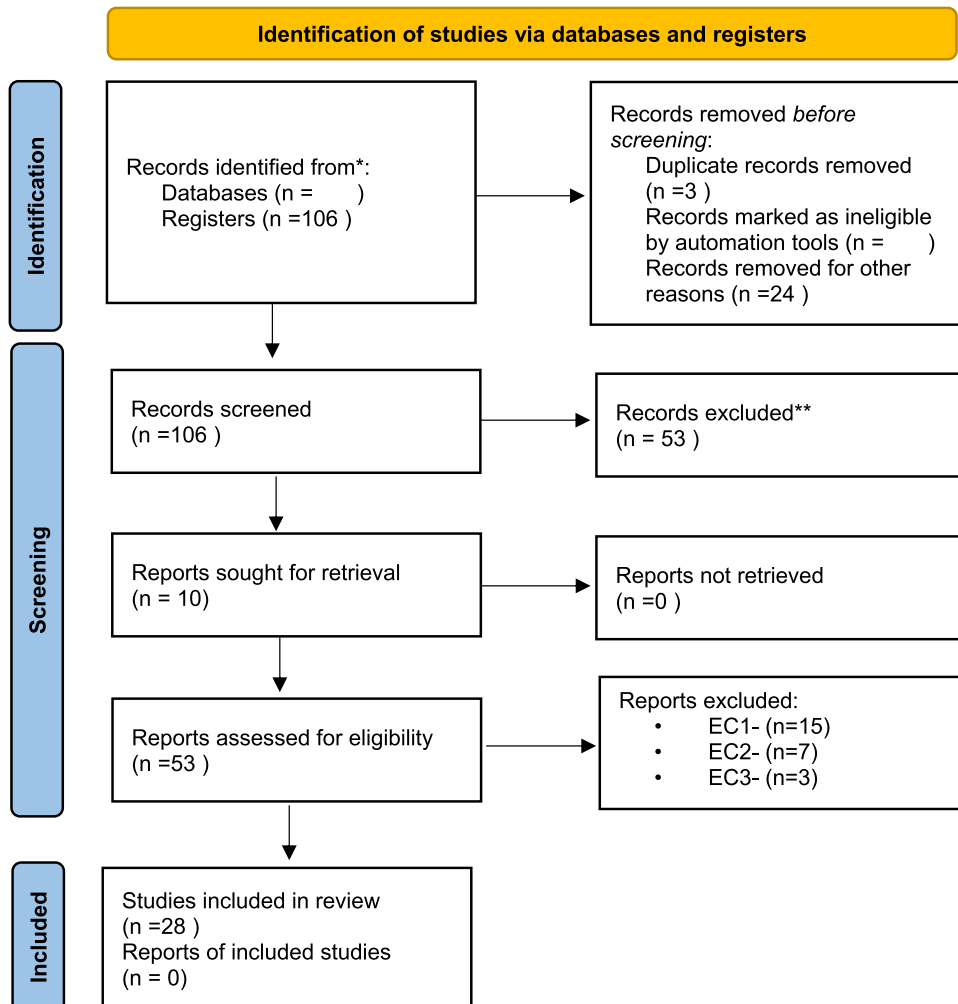


Fig. 2. PRISMA article identification process.

### 3.4. Content analysis

During this stage, the research themes were examined using a context analysis method, which was adapted from Jelodar et al. [59]. This approach involves assessing the data's alignment with the study questions by evaluating criticality, citation, and the significance of the literature.

The criticality assessment produces a numerical rating based on the language used in the text. The analysis was performed utilising NVivo 20 as a reliable multipurpose tool to analyse qualitative data [60], with scores ranging from 1 (indicating low criticality) to 5 (indicating high criticality). For instance, a score of 5 means the research is about creating new tools or ideas that push the knowledge boundaries. A score of 1 means the research uses simple examples that don't match real-world situations. In this study, factors contributing to the enhancement of current knowledge and utilised to refine sewer network risk and vulnerability assessments received the highest criticality rating, while the remaining factors were comparatively rated lower.

In addition, the significance of each indicator in the literature was defined by Eq. (1), which is measured by dividing, citing, the number of times each theme has been mentioned, in different searched items, and by the total number of articles selected after checking eligibility.

$$\text{Significance in literature} = \frac{\text{Citing}}{\text{Total number of articles}} \quad (1)$$

The relationship between criticality and significance in the literature determines whether the theme stands alone as a valid concept or needs to be integrated with other themes. Similar topics with close significance and relevance were grouped together to make the categories simpler,

resulting in a final set of refined themes.

The insights from scientometric analysis were iteratively cross-verified with themes emerging from content analysis. For instance, clusters like 'risk assessment' identified through co-occurrence networks were consistently reflected in content analysis, which included detailed discussions on GIS systems and adaptation plans. In contrast, terms like "flow modelling" appeared less prominently in the scientometric networks. However, content analysis revealed this concept through the categorisation of different types of models, such as groundwater fluctuation models and network hydraulic and hydrological simulations, into the broader cluster of flow models.

## 4. Findings and discussion

The scientometric and content analysis findings outline trends in the understanding of indicators and methodologies for integrating climate change impacts into sewer network risk and vulnerability assessments. The study begins by describing and discussing the identified indicators, followed by an examination of the methodologies used to apply them.

### 4.1. Scientometric analysis

The research span was investigated by evaluating three key indicators: generalisability, contemporaneity, and alignment of the selected papers with the research question.

The first indicator assesses the global significance of the issue and its ability to captivate researchers worldwide. Fig. 3 visualises these global contributions, derived from an analysis of 256 journal articles in the SCOPUS database, revealing key trends in research focus on the

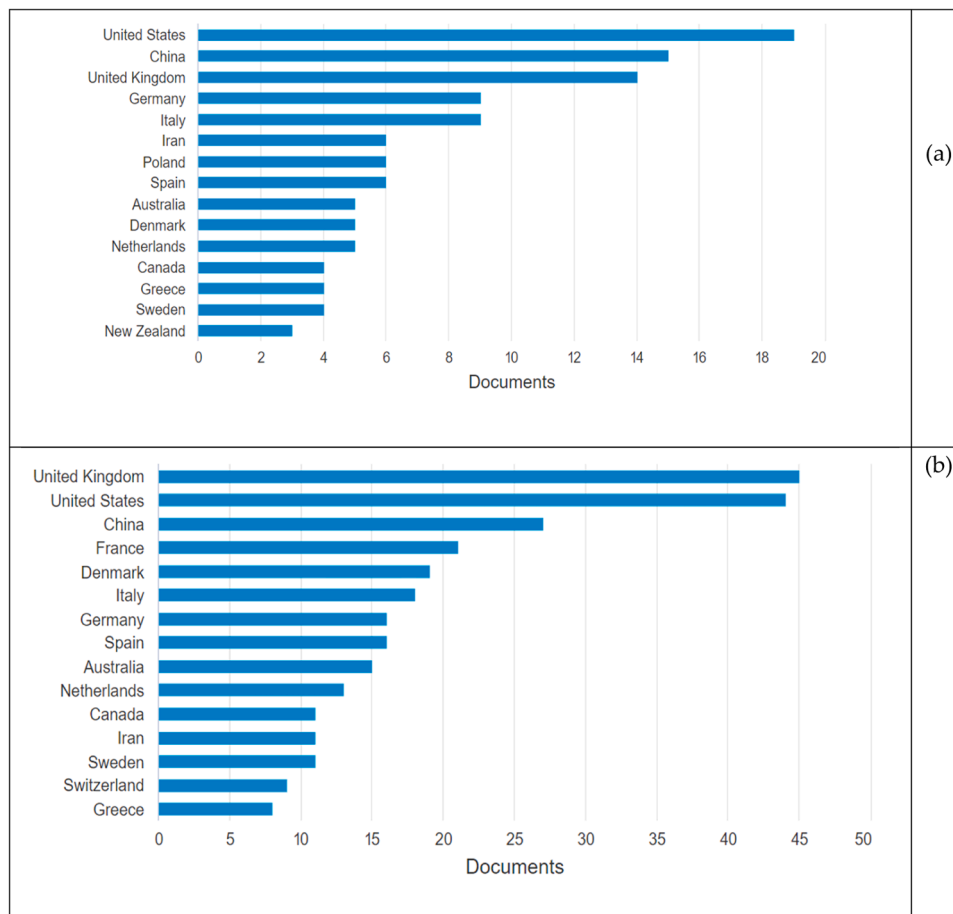


Fig. 3. Visualisation of the collaborative countries to the research area (a) Total contributions from 2000 to current trends, (b) A deeper look at contributions from the past three years.

resilience of sewer networks in the face of climate change.

- Fig. 3(a): Displays the overall contributions from 2000 to the present, providing a historical perspective on global research involvement. The chart highlights the gradual increase in global research interest, showing the growing recognition of the issue across the world.
- Fig. 1(b): Refines the analysis by focusing on the last three years, showing a sharper rise in publications and demonstrating the heightened urgency and interest in this area of research, particularly in New Zealand.

The subsequent criterion involves assessing the validity and contemporaneity of the research, ensuring it remains current and relevant. Fig. 4 shows a steady rise in publications over the years, indicating growing interest in the topic. The average number of publications over three-year periods continues to increase.

The last indicator in scientometrics, the analysis of keyword co-occurrence, is performed to gain valuable insights into the patterns of association and relationships among different keywords within a body of scholarly literature.

Fig. 5 presents a keyword co-occurrence network created with VOSviewer, illustrating relationships among frequently used terms in the literature. Each node represents a keyword, with its size indicating frequency, while links that show co-occurrence relationships and colours denote different research themes based on clustering.

The analysis identifies four interconnected research themes. The first theme, Extreme Events and Climate Modelling, in blue, focuses on predicting extreme rainfall and flooding, utilising them as input for tools like the Storm Water Management Model (SWMM) and emphasising concepts, such as precipitation intensity and uncertainty analysis. The second theme, Urban Water Systems Modelling, shown in red, involves simulating urban water systems, particularly through green infrastructure and climate modelling, employing spatial and time series analyses to monitor climate variable changes, especially in rainfall.

The third theme, SLR and groundwater infiltration, represented in yellow, examines the interactions between SLR and groundwater processes, with I&I as a significant indicator affected by SLR. The fourth theme, Vulnerability and Risk Assessment illustrated in green, integrates insights from other clusters into decision-making frameworks to improve climate risk management. These clusters also reveal urbanisation and adaptation strategies as key indicators influencing the climate risks on sewer networks.

## 4.2. Content analysis

The scientometrics confirmed the research gap and identified the keywords for the systematic literature review. The research of the abovementioned keywords and a PRISMA SRL's performance have led to 28 journal papers. The review process and findings were analysed using NVivo software to identify research themes. These themes were further broken down into narrower clusters based on criticality, citation, and significance. The findings are organised into two groups: (1) indicators used in resilience assessment and (2) methodologies to quantify sewer network resilience.

## 4.3. Indicators used for climate change assessment in sewer networks

The reviewed studies have employed a diverse range of indicators. While some studies utilised a select few, others incorporated all known indicators. Additionally, certain papers have innovatively identified novel indicators to assess the climate change impacts on sewer networks. The findings from the analysis of literature regarding the indicators used to assess the climate change impacts on sewer networks are summarised in Table 1. These indicators are identified based on the climate hazards outlined in the literature review, the documented direct and indirect impacts of these climate factors on the sewer systems and consideration of additional influential factors that may affect network performance in the context of future climate change.

The identified indicators can be grouped into three primary sub-categories. The first category comprises climate impacts like shifts in rainfall intensity, temperature, wind patterns, sea level rise, groundwater fluctuations, drought, and intensified weather events. The second category focuses on the implications of these changes on sewer systems, including overflow, diminished network efficiency, infrastructure damage, water quality issues, elevated maintenance expenses, public health concerns, and social and cultural impacts. Lastly, supplementary factors are recommended to be taken into account alongside Climate-Care to enhance prediction accuracy.

Change in rainfall characteristics was considered as the key climate change impact causing overflow in the combined sewer network [61]. Likewise, [62] considered rainfall amount and intensity as their key indicator to assess the implications of climate change on the sewer network. On the other hand, Friedrich and Kretzinger [45] considered sea level rise (SLR) as the primary climate impact to assess the vulnerability of the coastal sewer networks. Loss of infrastructures, structural damage, and network hydraulic performance were other key indicators covered in their study. Followed by Fung and Babcock [67] that

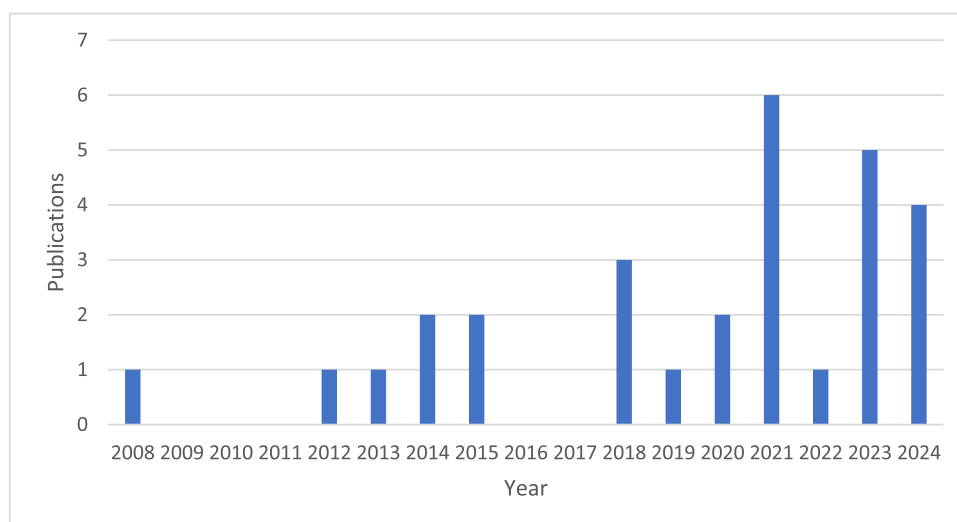


Fig. 4. Research trends over time.

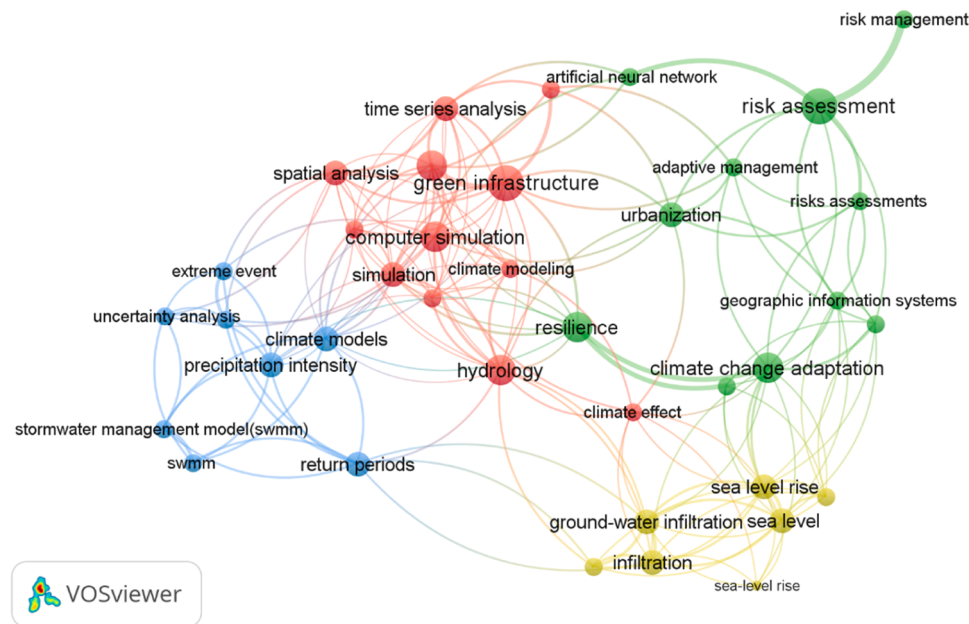


Fig. 5. Keyword Co-occurrence.

considered groundwater level, pipe characteristics, and structural defects as indicators to estimate the impacts of SLR on the network.

In addition, Hughes et al. [22] identified rising sea levels and changing rainfall patterns as the most severe climate hazards affecting New Zealand's wastewater systems, while temperature fluctuations and increased wind are expected to have less of an impact.

#### 4.4. Methodologies used for climate change impact assessment for sewer networks

The results of the content analyses based on the criteria mentioned in the methodology section are summarised in

**Table 2.** Through a comprehensive analysis of the selected articles, 27 distinct methodologies were discovered for the purpose of integrating climate change considerations into sewer network assessments. By carefully evaluating their criticality and significance in the literature and observing the connections between these methodologies, they were subsequently categorised into three main clusters: Climate modelling, Flow Modelling, and Risk and Vulnerability Assessments. Each cluster consists of various methodologies and methods to evaluate the impacts of climate change on sewer systems. The clusters are summarised in Fig. 6. These methodology categories are often used as supplementary together. Climate modelling methods are frequently used to provide inputs for hydraulic/hydrological models. Additionally, risk-based frameworks and vulnerability studies incorporate outputs from flow models, using them as indicators in assessing the potential risks.

#### 4.5. Climate modelling

General circulation models (GCMs) are essential for projecting climate change, as they simulate atmospheric processes under various emission scenarios [21]. For example, [62] used GCMs to assess combined sewer overflows under two carbon emission scenarios. Results showed that climate change increases total annual rainfall while decreasing bathing season rainfall. In a high-emission scenario, the HadCM3 model predicted increased frequency and volume of overflows, although variations existed among models and emission scenarios.

[68] utilised four GCMs across three climate scenarios to forecast temperature and precipitation in the Tasuj Plain, Iran (2022–2050). Findings indicated rising temperatures and reduced rainfall, leading to

groundwater decline in semi-arid areas, a consistent outcome across models.

Regional climate models provide localised climate data by downscaling outputs from GCMs. To achieve fine-scale resolution suitable for hydraulic/flow modelling, further spatial downscaling and temporal disaggregation is necessary [21,25]. Abdellatif et al. [62] applied downscaling to create hourly rainfall data from 40 years of daily observations, selecting a representative 10-year time series. High-resolution (5-minute) rainfall data was then generated for input into flow models, simulating runoff to analyse overflow volume, frequency, and water quality. Similarly, Semadeni-Davies et al. [21] used 5-minute disaggregated relative humidity data to study climate change and urbanisation impacts on Helsingborg City's sewer system.

Artificial neural network (ANN) methods have been employed to downscale coarse rainfall data to local levels for assessing mixed sewer system impacts [63]. However, the approach showed limitations in providing sufficient certainty due to GCM constraints.

Alternatively, Hamidi et al. [65] used a copula-based simulation to model spatial extreme rainfall fields, assessing urban runoff and treatment plant resilience. The study emphasised the importance of accounting for spatial rainfall variability, as assuming uniform rainfall across grid cells could overestimate runoff.

Gogien et al. [25] developed a regional climate model in southern France to generate fine-scale data for combined sewer network modelling. By integrating past rainfall data with climate projections, the study predicted future rainfall series for hydraulic modelling. Overflow volumes increased by 13 % to 52 % across models, although no clear trend was observed in overflow frequency. The study highlighted the limitations of existing climate models in capturing extreme weather events due to their special and temporal resolution and challenges in simulating the convection process, and called for advancements in climate modelling. Abebe and Tesfamariam [34] used a web-based updating tool to downscale the existing rain data and generate the IDF curves incorporating the climate change impacts.

Shared Socio-economic Pathways (SSPs) were used to assess the performance of the combined sewer systems based on long-term rainfall time series. SSPs focus on how human decisions shape emissions and resilience. They are used with climate scenarios together to explore the combined impact of human choices and climate change [73].

**Table 1**  
lists of identified indicators in the SLR.

Item	Study	Indicators																
		Changes in Rainfall Intensity	Sea Level Rise	Changes in Temperature	Drought	Changes in the Wind Patterns	Extreme Weather Events	Overflow/Surcharge	Hydraulic Performance of The Network	Infrastructure Damage	Structural Damage	Water Quality	Increased Maintenance Costs	Public Health Risks	Social/Cultural Levels	Groundwater	Urbanisation and Land Use Changes:	Asset Deterioration
1	Semadeni-Davies et al. [21]	●					●	●			●					●		
2	Friedrich and Kretzinger [45]		●					●	●	●								
3	Fu and Kapelan [61]						●											
4	Veronesi et al. [11]	●					●	●			●	●	●					
5	Abdellatif et al. [62]	●					●				●							
6	Abdellatif et al. [63]	●					●		●									
7	Noi and Nitivattananon [41]											●	●	●				
8	Kleidorfer et al. [64]						●	●										
9	Hamidi et al. [65]	●					●	●										
10	Liu et al. [66]		●					●		●							●	
11	Mahaut and Andrieu [24]	●						●								●	●	●
12	Fung and Babcock [67]		●	●				●	●			●			●			
13	Kool et al. [23]		●					●	●	●		●				●		●
14	Ghazi et al. [68]	●		●											●			
15	Rak et al. [44]						●											
16	Szeląg et al. [69]	●					●											
17	Mohammed et al. [70]	●						●	●									●
18	Rahmoun et al. [71]	●						●			●							
19	Gogien et al. [25]	●		●				●	●	●								
20	Abebe and Tesfamariam [34]	●						●	●							●	●	
21	Sangsefidi et al. [72]	●	●					●	●			●			●			
22	Wang et al. [73]	●						●	●	●								
23	Roseboro et al. [74]	●						●										●
24	Rodriguez et al. [75]	●						●	●	●								●
25	Rodriguez et al. [76]	●						●	●	●								●
26	Cavadini et al. [77]	●						●	●	●			●					●
27	Aziz et al. [78]	●						●	●	●					●		●	
28	Stamou et al. [79]	●	●	●	●			●			●					●	●	●

**Table 2**  
Content Analysis results.

Methodologies used for climate change assessment in sewer networks	Criticality	Citing	Significance in literature	Avg criticality	Total citing	Significance in literature	Cluster
Online Tools Updating IDF Curves	1	18	0.9	2.75	178	8.9	Climate modelling
Spatial Downscaling	5	27	1.35				
Generalized Linear Models (GLM)	1	21	1.05				
Artificial Neural Network (ANN)	4	48	2.4				
Least Square Support Vector Machine (LSSVM)	2	13	0.65				
Nonlinear Autoregressive Network With Exogenous Inputs (Narx) Model	2	13	0.65				
Nonparametric Statistic Test	4	23	1.15				
Temporal Disaggregation	3	15	0.75				
Hydrological Modelling	4	61	3.05	3.49	291	14.55	
Storm Water Management Model	4.2	56	2.8				
Modelling Groundwater Level Fluctuations	4.5	21	1.05				Hydraulic/Hydrology Modelling
Uncertainty Analysis	4.2	33	1.65				
Sanitary Sewer Overflow Analysis and Planning (SSOAP) Toolbox	2	14	0.7				
Long-Term Continuous Hydraulic Modelling	3.8	61	3.05				
Copula-Based Analysis	3.2	31	1.55				
Fuzzy set & systems	2	14	0.7				
GIS and Multi-Criteria Analysis	3	49	2.45	3.39	382	19.1	
Risk-Based Framework	4.2	91	4.55				
Dynamic Adaptation Managed Retreat	4	20	1				
Vulnerability Assessment Framework	4.8	31	1.55				
Dynamic Bayesian network	4.8	38	1.9				Vulnerability and Risk Assessment
Impact Matrix	3	20	1				
Problem tree Analysis	3	20	1				
Participatory Rural Appraisal (PRA)	4	20	1				
Dynamic Adaptive Pathway Planning (DAPP)	3	20	1				
Surveys and Stakeholder Engagement	2.5	62	3.1				
Maximum Simulated Likelihood Estimation	1	11	0.55				

#### 4.5.1. Risk and vulnerability assessment

The vulnerability of sewer systems to climate change impacts is defined differently. In addition to several definitions, multiple assessment methods and indices have been developed to assess the different aspects of climate change affecting sewer networks. In a study by Friedrich and Kretzinger [45], the vulnerability was considered a limit that the system is susceptible to failure or cannot operate. The coastal sewer system vulnerability to a 2.8m sea level rise was assessed in the eThekweni Municipal Area in South Africa. They used GIS and multi-criteria analysis techniques to evaluate the system's vulnerability by identifying the assets with high vulnerability for prioritising adaptations and further intervention programs. Similarly, in Vietnam's Dong Nai River basin, vulnerability was assessed by selecting tools and techniques through a literature review. Criteria were established to develop a vulnerability assessment framework, and the tools' effectiveness was evaluated via focus group discussions for both regional and local applications. A rapid vulnerability assessment was conducted at a regional level, and a full vulnerability assessment at a local level. The results highlighted the need for a combination of tools for effective local-level assessments, with Participatory Rural Appraisal (PRA) identified as a critical method. The study addressed economic, environmental, and social climate risks in three steps: identifying key risk factors, assessing system vulnerability, and evaluating adaptation measures to enhance resilience [41].

Rak et al. [44] used three weather data indices—hot day index, frost day index, and daily rain index—to assess the vulnerability of water systems in Poland to weather-related risks. The study found that the water and wastewater systems are highly vulnerable, with intense rainfall leading to sewer overflows and increased hot days resulting in higher water usage. A nonparametric statistical test identified trends, revealing that the number of hot days is increasing, though this factor has the least occurrence frequency among other factors. Sangsefidi et al. [72] developed a vulnerability index (SSVI) to prioritise sewer repairs, considering factors like structural damage and risk of overflows. The index combined CCTV inspection data with factors, such as the severity of damage (rated as slight, moderate, or high), groundwater presence

around defective pipes, and the likelihood of overflow issues at sewer junctions. Each defective pipe was assigned a priority level—low, moderate, high, or urgent—indicating the urgency of repairs needed.

A crucial aspect of vulnerability assessment is ensuring the continuity of minimum service levels across different components of the system, especially in the event of a failure at a specific location. This ensures that unaffected areas maintain service even if other sections of the sewer system are compromised [43,32].

Stamou et al. [79] conducted a vulnerability assessment of water infrastructure in the Mediterranean region in four steps. First, an exposure analysis was carried out to identify climate hazards relevant to the sewer system locations. This was followed by a sensitivity analysis, which assessed the system's sensitivity to these hazards, considering on-site assets, inputs, outputs, transport links, and social and environmental impacts. Next, the system's adaptive capacity to the identified hazards was evaluated, and finally, a vulnerability analysis was performed, integrating the results of the previous steps to determine the overall vulnerability of the system.

Risk assessments are typically built upon vulnerability assessments by understanding the weaknesses of the system [80]. Risk assessment for climate change on sewer networks aims to identify, quantify, and analyse the potential risks due to climate-related factors on the networks. These factors, such as changes in precipitation, wind and temperature, rising sea levels, and extreme weather events, can affect the network performance and adversely affect the surrounding environment and communities served by these networks. Some studies considered the associated risk of a single climate change hazard, while others considered a combination of multiple factors or even the consequences of malfunctioning or failure of the systems due to these hazards.

A risk assessment model was used to predict the impact of climate change on the sewer system in the Wigan catchment, which includes combined, separate, and partially separate networks. The model integrated geographical information and flow data to assess the risk of wastewater surcharge and flooding. Results showed that between 2020 and 2080, the number and volume of surcharging manholes increased in winter under a high-emission scenario, with total winter flooding

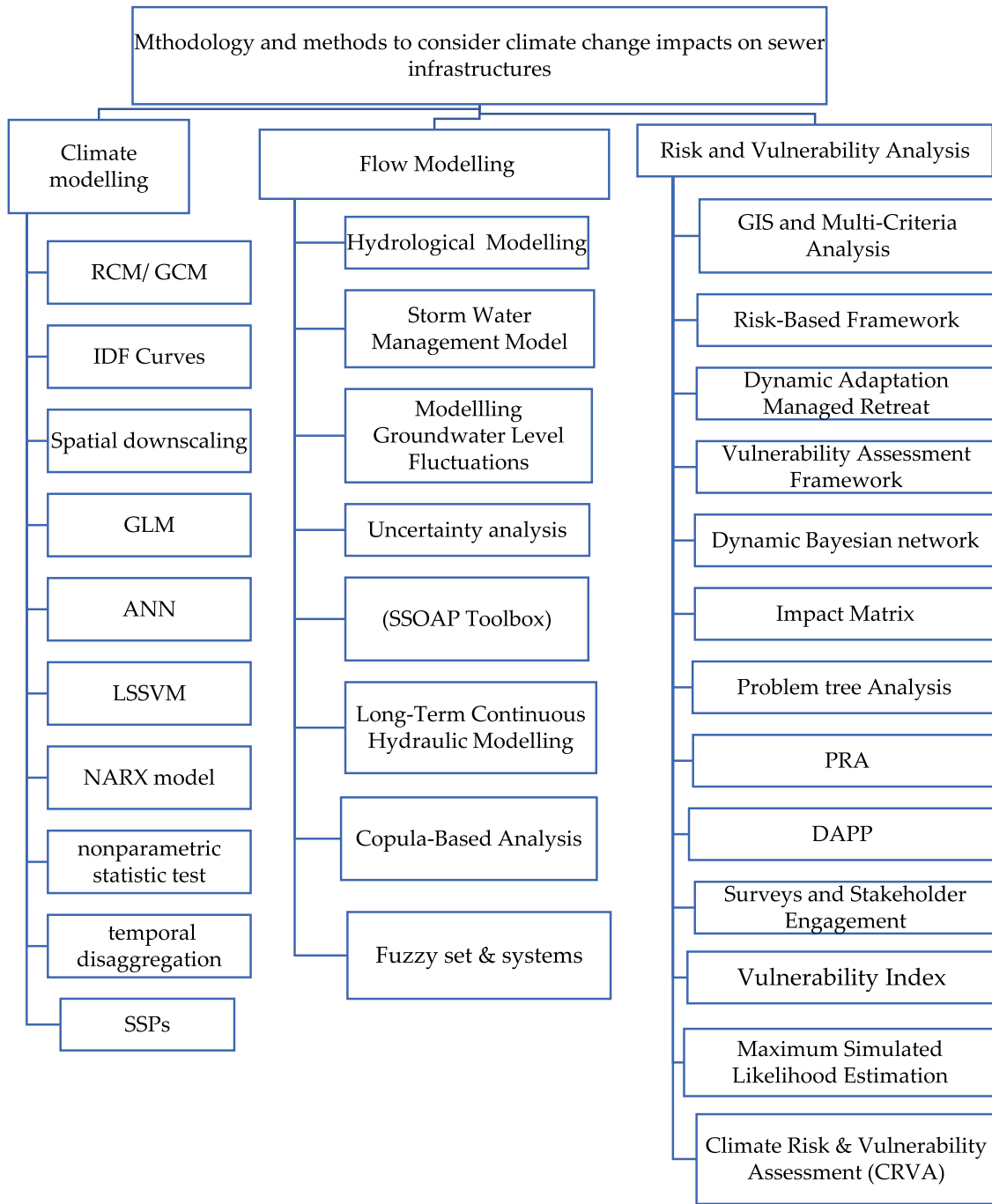


Fig. 6. Methodology and methods to incorporate climate change impacts on sewer networks.

volume rising up to 1.9 times the current situation. However, the risk of overflow was expected to decrease in summer [63].

Studies have also integrated predictive and resilience-focused approaches. Liu et al. [66] developed a failure model to assess the probability of structural failure of pipes causing infiltration into the sewer system. The model considered factors like pipe characteristics and environmental conditions (e.g., ground formation and water table level) and calculated the failure risk for each pipe. Infiltration risk was then determined by combining the failure risk with outputs from a water table model.

Hughes et al. [22] assessed New Zealand’s sewer network vulnerability to climate change, defining risk as the interaction of hazard, exposure, and vulnerability. The study found that systems are vulnerable due to lack of climate change consideration in design, especially in

coastal and low-lying areas. It recommended integrating climate change impacts and other challenges like growth and land use into a comprehensive risk assessment plan.

Abebe and Tesfamariam [34] developed a risk-based framework to allocate a risk score to the stormwater pipes in Vernon, Canada, considering hydraulic capacity and pipe deterioration. This framework helps asset managers prioritise maintenance and intervention efforts. The PACP (Pipeline Assessment and Certification Program) method was used to assess pipe conditions, with the structural rating index estimating deterioration. The risk score incorporates both the likelihood of failure and the consequences. A Dynamic Bayesian Network (DBN) was applied to evaluate likelihood of failure based on the interdependencies of observed variables, including pipe condition, hydraulic capacity, land cover, and rainfall intensity.

Risk assessments are essential for developing adaptation strategies to enhance the resilience of sewer systems to climate change. Given the uncertainties in assessing climate impacts, suitable approaches are needed to support decision-making under uncertain conditions [81]. Kool et al. [23] proposed a dynamic adaptive pathway planning (DAPP) approach to address uncertainties and manage retreat for stormwater and wastewater infrastructure impacted by sea level rise in Hutt City, NZ. Stakeholders identified thresholds for adaptation, using workshops and the Circle Tool to assess cascading effects and interdependencies. Flood risk mapping combined a 1 % Annual Exceedance probability (AEP) flood level with a 0.1m sea level rise (SLR) increase to identify at-risk assets. Three thresholds for SLR were established, which were associated with the performance of the gravity system, pump stations and overall system performance. Area-specific adaptation options and strategies were identified and consolidated into pathway portfolios that included distinct retreat phases to avoid reaching these thresholds. The research emphasises the importance of recognising the community's adaptation capacity as a crucial signal in the decision-making process.

Rodriguez et al. [75] developed stress-strain curves to evaluate the performance of sewer networks under varying stress conditions. This approach aimed to establish a relationship between rainfall (as the stress) and combined sewer overflows (as the strain). The area under the curves was used as an indicator of system resilience, with larger areas representing higher resilience. Resilience scores were calculated individually for each performance metric, and the overall system resilience was determined by averaging the resilience values across all metrics [76]

Aziz et al. [78] set some criteria, such as (1) pipes with more than 85 % flow and (2) Number of manholes with a freeboard less than 2m to assess the risk of climate change on the performance of the separate sewer system.

A new methodology for Climate Risk And Vulnerability Assessment (CRVA) was developed to assess the impacts of climate change on water infrastructures in the Mediterranean Region. The approach involved identifying hazards, establishing baselines, and assessing risk through three steps: evaluating hazard likelihood occurring in the system's lifespan, analysing consequences of each identified hazard, and combining results in a risk matrix [79].

#### 4.5.2. Flow modelling

Flow models use the output data of climate models after downscaling and disaggregations to simulate sewer network performance under climate change impact/s models simulate sewer network performance under climate change impacts. These models primarily assess overflow risks and system responses to sea level rise (SLR), rainfall variability, and other climate-driven factors.

When SLR is a significant factor, flow models account for rising groundwater levels that lead to increased infiltration and overflow. For instance, Semadeni-Davies et al. [21] used the DHI MOUSE model to simulate infiltration into a combined sewer network under two climate scenarios and urbanisation storylines, emphasising infiltration effects. Similarly, Liu et al. [66] employed the US EPA Storm Water Management Model (SWMM) to evaluate thresholds for combined sewer overflows (CSOs), incorporating groundwater-sewer interactions. Fung and Babcock [67] modelled groundwater infiltration (GWI) in coastal areas under SLR scenarios using the SSOAP toolbox and flow monitoring data, projecting significant increases in GWI with rising sea levels.

Rainfall variability due to climate change also plays a critical role in sewer system modelling. Sangsefidi et al. [72] used SWMM to analyse the combined impacts of SLR, rainfall changes, and groundwater fluctuations on sewer systems in Imperial Beach, California, projecting a 120 % increase in sewage flow during extreme events. Mohammed et al. [70] similarly employed SWMM to estimate CSO impacts in Iraq, using calibration and validation methods for accuracy. Rahmoun et al. [71] applied SWMM to model combined sewer flow in Algeria, analysing surcharge volumes under different rainfall intensities. Mahaut and

Andrieu [24] developed empirical relationships between overflow and total outflow in Nantes, France, while Roseboro et al. [74] combined rainfall data from CORDEX and CMIP5 to project CSO impacts under various climate scenarios and storm durations.

Other studies used advanced modelling tools like InfoWorks. Abdellatif et al. [63] modelled urban drainage in north-west England, employing rainfall and wastewater flow data to predict overflow volumes. Gogien et al. [25] used continuous hydraulic simulations to assess climate impacts on CSOs, highlighting the advantages of long-term simulations over event-based analyses. Rodriguez et al. [76] similarly emphasised continuous simulations to understand system performance comprehensively.

Various flow modelling tools are employed to simulate sewer network performance. According to Muttill et al. [18], the Storm Water Management Model (SWMM) is the most widely used tool for assessing the impacts of extreme rainfall on sewer overflows, a finding consistent with this study. This popularity can be attributed to the model's capabilities and its open-source and free access. Table 3 provides a comparison of key models used for assessing sewer network performance under climate change scenarios, outlining their applications and the climate scenarios they consider.

Flow models also integrate uncertainty analyses to improve reliability. These uncertainties are broadly classified into stochastic uncertainties, which arise from the inherent variability of phenomena like rainfall depth and duration, and epistemic uncertainties, which stem from imprecise knowledge of model parameters, such as Manning's roughness coefficient and imperviousness. For instance, Kleidorfer et al. [82] highlighted the limitations of hydrodynamic models during a 500-year storm event in Australia. The study revealed that a 1-D hydrodynamic model, based on recorded rainfall data, failed to accurately predict flooding in certain areas as compared to observed water levels and citizen reports. This example underscores the challenges posed by uncertainties in flow models and the need for robust uncertainty analysis.

To address stochastic uncertainties, methodologies like Gumbel copula and Monte Carlo simulations are employed to model random variables and propagate uncertainties through systems [61,83]. Fu's combined framework, which utilises Gumbel Copula, Monte Carlo simulations, and Dempster-Shafer theory, effectively models overflow risks in sewer systems by accounting for both random and imprecise inputs. For epistemic uncertainties, fuzzy logic is used to represent imprecise parameters, while Dempster-Shafer theory provides a framework to combine stochastic and epistemic uncertainties, enabling a comprehensive analysis. The integration of these methodologies is critical for improving the reliability of climate impact assessments. Additionally, methodologies like GLUE (Generalized Likelihood Uncertainty Estimation) and Bayesian estimation are utilised to refine

**Table 3**  
Key Flow Models and Their Applications in Climate-Impact Assessments of Sewer Networks.

Model	Application	Climate Scenarios Considered
SWMM	Used in multiple studies to model stormwater and sewer systems, assess overflow risk, and simulate the impact of climate change on sewer performance (e. g., SLR, rainfall variations).	Sea level rise (SLR), rainfall patterns, combined effects of SLR and groundwater rise.
MIKE URBAN	Applied to model urban drainage systems, including effects of climate change on infiltration and overflow risk.	Climate change, urbanisation, sea level rise.
InfoWorks	Used to model flow, estimate overflow, and predict sewer performance under different rainfall and climate scenarios (e. g., SLR, urbanisation effects).	Rainfall, climate change, urbanisation, SLR.

uncertainty analysis, enabling a probabilistic approach for parameter identification and risk assessment [69]. In his study in Kielce, Poland, Szelag et al. [69] used sensitivity analysis to pinpoint critical parameters, including Manning's roughness coefficient and the percentage of impervious areas, that play a significant role in flood outcomes. These techniques highlight the vital role of uncertainty analysis in enhancing model precision and supporting informed decision-making in urban infrastructure development and climate adaptation planning.

Lastly, Aziz et al. [78] utilised PCSWMM and EPA-SSOAP tools to assess flood risks in Charlottetown's separate sewer network under future population and IDF curve scenarios. Calibrations using metrics like Nash-Sutcliffe Efficiency ensured reliable model performance.

#### 4.5.3. Supplementary factors

In addition to climate change, several interconnected factors influence sewer network performance over time. Urbanisation and land use changes have been identified as significant contributors. Semadeni-Davies et al. [21] found that population growth increases overflow volumes, although climate change has a greater impact, potentially leading to a 318 % increase under extreme scenarios. On the contrary, Mahaut and Andrieu [24] suggested that urbanisation and population growth have a greater influence as compared to climate change on sewer overflows, advocating for densification and separate sewer systems as mitigation strategies.

Sea level rise (SLR) further compounds these risks [2,23]. Kool et al. [23] assessed SLR impacts on wastewater networks in New Zealand, alongside urbanisation, growth and adaptation strategies. Liu et al. [66] incorporated pipe deterioration and structural integrity with SLR to analyse the failure risk. Similarly, [34] examined the interplay of climate change, urbanisation, and asset deterioration for stormwater pipe renewal planning. However, due to the lack of time-dependent condition data, statistical predictions were not feasible, and expert judgment was relied upon. Aziz et al. [78] also considered growth alongside climate change in evaluating sewer overflow risk, incorporating pipe age and roughness but not explicitly addressing asset deterioration.

Additionally, these factors can have compounding impacts on each other. For instance, climate change can lead to changes in urbanisation and growth programs, particularly in coastal regions [84,85]. It also can accelerate the deterioration of the pipe networks through alterations in water table levels and fluctuations in air, soil, and water temperatures [34,86].

Beyond physical infrastructure, economic factors, such as rising operational and adaptation costs are also crucial. Climate change impacts extend beyond asset loss, with increased energy demands for pumping and maintenance costs due to fluctuating flows and saltwater intrusion [16,87,88]. The efficiency of adaptation strategies like Blue-Green Infrastructure (BGI) have been assessed based on installation and operational costs over 30 years [77], nevertheless further studies are needed to evaluate long-term financial burdens on sewer utilities.

Cascading hazards, such as landslides, present additional risks. Watercare, Auckland's water service provider, reported severe disruptions following the 2023 flood due to landslides [12]. Addressing these hazards in vulnerability assessments is critical, especially given the uncertainties surrounding climate change projections.

Despite the extensive research on individual supplementary factors, no study has comprehensively assessed the combined effects of urbanisation, adaptation strategies, asset deterioration, and economic risks alongside climate change in wastewater networks. Future research should focus on integrating these elements to improve risk assessments and support strategic infrastructure investments.

Table 4 provides a summary of the key methodologies for assessing climate change impacts on sewer networks, including their data requirements, strengths, limitations and typical applications.

#### 4.6. Limitations and biases

Several limitations of this review should be acknowledged. First, there is a regional bias, with the majority of studies focused on developed countries, which may not fully reflect the challenges faced by developing regions with different infrastructural setups and limited climate data availability. Studies, such as Elmahdi and Jeong [89] suggest significant climate change impacts on developing countries, including overflows, contamination, and higher maintenance costs, emphasising the urgent need for action. Additionally, non-reviewed sources, such as conference papers and industry reports were excluded. Scalability is another concern, as many studies focused on overflow risks from excessive water ingress due to climate change, which may not address other significant threats like droughts and sinkholes in regions with poor groundwater management. Lastly, while technical solutions are emphasised, non-technical measures like policy reforms and community-based adaptation strategies are less explored, limiting the scope of potential adaptation strategies.

### 5. Integrated research framework

To address the research question regarding the interaction between research clusters and the interdependencies of the methods, an integrated conceptual framework, as shown in Fig. 7, was developed to assess the impact of climate change on sewer networks. This framework is based on core research clusters identified through content analysis in section 4. The framework visually represents the interconnections between three key clusters: Climate Modelling, Flow Modelling, and Vulnerability and Risk Assessment. It highlights that these clusters are not isolated they often work in tandem to evaluate the implications of climate change on sewer systems. This integrated approach provides valuable insights into the way these diverse research areas converge when evaluating climate change impacts in real-world case studies while supporting identifying and managing uncertainties that may affect risk assessments.

The framework emphasises that climate modelling provides essential input data for flow modelling, with a focus on climate hazards, such as changes in rainfall patterns, sea-level rise, temperature, and wind. Flow modelling, which includes both network and groundwater models, is key to understanding overflow characteristics, such as volume, frequency, and contamination loads. Network modelling simulates flow in pipe networks, while groundwater models assess infiltration caused by sea-level rise. Regardless of the model used, the goal is the same: to identify overflow characteristics, which are key for vulnerability and risk assessments.

Hybrid approaches can be employed throughout the process to address uncertainties and enhance the accuracy of predictions. For instance, Monte Carlo simulations and copula-based techniques can manage stochastic uncertainties in climate data, while fuzzy logic is useful for addressing flow parameter uncertainties, such as roughness and impervious surfaces. These refined outputs can be integrated with machine learning models like Random Forest and XGBoost to improve the accuracy of risk assessment predictions [90]. Tools like Bayesian networks can also combine expert judgment with simulation results, further refining probabilistic risk predictions and improving overall climate risk assessments.

The scientometric and content analysis highlighted supplementary factors like urbanisation, asset deterioration and adaptation programs as emerging considerations in wastewater network resilience. In order to attain a realistic prediction of the network, it is crucial to consider these factors along with climate change. While some studies have incorporated individual factors in the past, there is a notable absence of research that comprehensively examines the combined impacts of these factors on the sewer network. This gap underscores the need for future investigations in this area. These factors have been highlighted in red to indicate the potential future research area in the framework.

**Table 4**  
Key Methodologies, Data Requirement, Strengths, Limits & Application.

	Methodology	Data Requirements	Strengths	Limitations	Typical Applications	References
<b>Climate Modelling</b>	Spatial Downscaling & Temporal Disaggregation	Climate data from GCM	Provides high-resolution local climate data	Complex requires high-quality input data	Site-specific climate impact analysis	Ghazi et al., [68]; Gogien et al. [25]
	Generalized Linear Models (GLM)	Historical data, meteorological and hydrological data	Flexible, captures nonlinear relationships	Data-intensive, sensitivity to parameter choices	Simulate future rainfall accounting for climate change uncertainties	Abdellatif et al., [62]
	Artificial Neural Network (ANN)	Time-series data, climate and operational data	Can model complex patterns and interactions	Overfitting risk, requires large datasets	Predictive modelling of sewer system performance	Abdellatif et al., [62]; Abdellatif et al., [63]; Ghazi et al. [68]
	Least Square Support Vector Machine (LSSVM)	Climate, rainfall, and flow data	High predictive accuracy, robust to noise	Computationally expensive, sensitive to parameter selection	Applied in regression and classification problems, noisy or high-dimensional data	Ghazi et al. [68]
	Nonlinear Autoregressive Network	Time-series, meteorological, and flow data	Captures nonlinear dynamics and time-varying behavior	Requires large datasets for training, complex setup	Forecasting in temporal dynamic systems	Ghazi et al. [68]
	Nonparametric Statistic Test	Climate and flow data	Useful for analysis without assumptions about data distribution	May not capture extreme events, depends on data quality	Managing stochastic uncertainties in climate data	Rak et al. [44]
<b>Flow Modelling</b>	Shared Socio-economic Pathways (SSPs)	Scenario-based socioeconomic and climate data	Integrates socio-economic and environmental variables	Dependent on assumptions about future development and policies	Long-term planning and scenario analysis	Wang et al. [73]
	Hydrological Modelling	Rainfall, runoff, topographic, and land-use data	Models water flow across catchments	Calibration issues, computationally demanding	Watershed and drainage system impact analysis	Fung and Babcock [67]; Gogien et al., [25]; Szelag et al. [69]
	Network Simulation	Rainfall, land-use, runoff, and system data	Well-established, provides comprehensive flow simulation	Requires calibration issues, computationally demanding	Urban drainage system design and climate impact assessment	Liu et al., [66]; Szelag et al. [69]
	Long-Term Continuous Hydraulic Modelling	Continuous flow, pressure, and operational data	Provides a dynamic, long-term view of sewer system performance	High computational cost, requires continuous data	Infrastructure resilience modelling over time	Gogien et al., [25]; Kleidorfer et al. [64];
	Modelling Groundwater Level Fluctuations	Groundwater level and rainfall data	Captures groundwater changes due to climate variation	Requires detailed local data, slow to simulate	Groundwater management under climate stress	Ghazi et al., [68]; Rahmoun et al. [71]
	Uncertainty Analysis (SSOAP Toolbox)	Climate and system operational data	Quantifies uncertainty in modelling assumptions	Complex to implement, data-heavy	Decision-making under uncertainty	Fung and Babcock [67]; Rahmoun et al. [71]
	Monte Carlo	Probability distributions, system and climate data	Can model uncertainty in inputs and provide a range of possible outcomes	Requires large datasets, computationally intensive	Risk analysis, forecasting, uncertainty modelling	Fu & Kaplan [61]
	Copula-Based Analysis	Climate, system, and risk data	Useful for capturing complex dependencies between variables	Requires large datasets, sensitive to model assumptions	Extreme event modelling, risk analysis	Kapelan (2013); Hamidi et al. [65]
	Fuzzy Set & Systems	Data with uncertainty, climate, and system data	Deals with uncertain or vague data	Requires expertise in fuzzy logic, can be complex to implement	Epistemic uncertainty assessment	Fu and Kapelan [61]
	<b>Vulnerability and Risk Assessment</b>	GIS and Multi-Criteria Analysis	Spatial data, climate, infrastructure, and vulnerability data	Effective for spatial decision-making	Requires large datasets, complex analysis	Infrastructure planning, risk assessment
Risk-Based Framework		Climate, operational, and risk data	Provides systematic risk evaluation	May oversimplify risk factors	Climate adaptation strategies for infrastructure resilience	Fung and Babcock [67]; Liu et al. [66]
Dynamic Adaptation Managed Retreat		Climate data, socio-economic, land-use, and infrastructure data	Helps plan for managed retreat and adaptation	Requires significant planning and stakeholder involvement	Long-term coastal and floodplain management	Abebe et al. [31]
Vulnerability Assessment Framework		Vulnerability, infrastructure, and environmental data	Focuses on assessing vulnerability, identifying weaknesses	Subjective, may overlook emerging risks	Vulnerability analysis for climate adaptation	Friedrich and Kretzinger [45]; Noi and Nitivattananon [41]
Dynamic Bayesian Network		Climate, operational, and risk data	Allows integration of expert opinion	High resource and facility costs limit broader application	Detailed risk assessments at community level	Noi and Nitivattananon [41]
Impact Matrix		Expert opinions and secondary data	Simple to use, helps prioritise impacts	May oversimplify complex interactions	Initial impact assessments	Noi and Nitivattananon [41]
Problem Tree Analysis		Qualitative data from observations and interviews	Identifies and visualises relationships between problems	Limited scope for large areas due to data collection challenges	Community-level assessments	Aubin (2018)

(continued on next page)

Table 4 (continued)

Methodology	Data Requirements	Strengths	Limitations	Typical Applications	References
Participatory Rural Appraisal (PRA)	Qualitative data from interviews and discussions	Involves stakeholders, promotes community-based decision-making, captures local knowledge	Subjective, dependent on stakeholder participation, time-consuming	Assessing social aspects of climate change impacts	Fischer [40]; Noi and Nitivattananon [41]
Dynamic Adaptive Pathway Planning (DAPP)	Data from decision-making processes and stakeholders	Involves stakeholders, considers a range of decision factors	Subjective, can lead to decision paralysis	Stakeholder-driven risk management and adaptation planning	Kool et al. [23]
Vulnerability Index	Climate, infrastructure, and socio-economic data	Provides a simplified vulnerability score	Can oversimplify complexity, limited scope	Overall system vulnerability analysis	Sangsefidi (2023)
Maximum Simulated Likelihood Estimation	Survey data	Accommodates different opinions among individuals	Computationally intensive, requires detailed data	Model preference for contribution	Veronesi et al. [11]
Climate Risk & Vulnerability Assessment (CRVA)	Climate, infrastructure, and socio-economic data	Comprehensive risk and vulnerability assessment framework	Requires extensive data and expert input	Long-term climate change adaptation and planning	Stamou (2024)

Overflow and asset loss are the primary risks addressed in vulnerability assessment models. The review indicated that climate change also increases the ongoing running costs to keep the existing assets operational in addition to these factors. These costs extend beyond financial implications and include socio-environmental costs, such as increased carbon footprint due to more power consumption in future. In addition, the effects of climate change on sewer networks can encompass socio-economic risks, such as social health issues due to frequent spills and unsafe water access due to sewage contaminations [22]. This can result in the release of untreated or partially treated wastewater into natural water bodies, increasing the risk to human health, such as antibiotic contamination highlighting the need for effective treatment methods to manage such contaminants in wastewater [91,92].

Some studies highlighted losing assets as a direct result of SLR as one of the indicators for risk and vulnerability assessment. To enhance the comprehensiveness of vulnerability assessments, it is advisable to incorporate losing assets due to cascading hazards and increased running costs as supplementary risk factors.

In practice, the framework can be implemented through the development of multi-disciplinary, collaborative projects that combine expertise from climate scientists, hydraulic engineers, urban planners, and risk assessors. This collaboration can facilitate more accurate predictions and better decision-making for sewer system resilience planning. To provide a more practical context, the following steps can be implemented to assist network planners in assessing the climate risks and forecasting how other factors, such as urbanisation and growth, asset deterioration, and adaptation strategies, will further exacerbate the risks. This will enable planners to design more effective adaptation strategies that incorporate both technical (e.g., infrastructure upgrades) and non-technical (e.g., policy reforms) measures.

- Step 1: The climate modelling component first generates future climate projections based on local GCMs and downscaling techniques.
- Step 2: Flow modelling then simulates how the projected climate impacts (increased rainfall, sea-level rise) affect sewer system performance, identifying overflow hotspots, infiltration risks, and capacity limitations.
- Step 3: Vulnerability and risk assessment evaluates the potential social, environmental, and financial risks from these impacts, considering compound impacts of various hazards and factors, such as costs of maintaining or upgrading the infrastructure.
- Step 4: To improve the accuracy of the risk models, additional factors, such as urbanisation, asset deterioration, and adaptation policies, as well as compounded risk factors, can be integrated into the process according to the framework, following the designated route and location.

### 5.1. Future research

The proposed framework presents an opportunity for future research to validate and assess its implementation in detailed case studies. Additionally, integrating the supplementary factors identified in the framework, as highlighted in red, will foster interdisciplinary collaboration and advance the understanding of sewer network resilience. These factors present significant opportunities for further exploration.

Another key direction is the integration of real-time data into climate risk assessments, enabling more dynamic evaluations of sewer network vulnerabilities. The use of real-time climate and flow data alongside an ongoing inventory of faults and failures that significantly enhance the accuracy of predictions given evolving climate dynamics.

Scenario-based planning for extreme weather events is also another area for further investigation, particularly in light of increasing climate variability. Developing detailed scenarios that incorporate extreme weather indices—such as consecutive wet or dry days, heavy rainfall events, and the combined effects of storms and sea-level rise—will enhance preparedness strategies for sewer networks.

Additionally, it is crucial to examine the socio-economic disparities that influence the resilience of sewer infrastructure, particularly in relation to income levels, urbanisation, and access to resources, especially in developing regions. Research should also explore the role of non-technical solutions, such as community engagement and policy reforms, in enhancing adaptation strategies.

## 6. Conclusion

This study provides a comprehensive review of methodologies used to assess climate change impacts on sewer networks, offering a typological reference for researchers and asset managers. It integrates multiple disciplines—Climate Modelling, Flow Modelling, and Vulnerability and Risk Assessment—highlighting their interconnections. Climate models inform flow models, which in turn generate overflow data, a key risk factor in risk assessments. A conceptual framework is introduced to illustrate these relationships, helping researchers identify gaps and improve interdisciplinary collaboration. Additionally, the framework suggests incorporating factors, such as land use changes, asset deterioration, and adaptation strategies into a dynamic risk-based model will enhance the risk assessment and help to develop effective adaptation strategies. The framework also supports the integration of compound hazards, such as landslides, to enhance risk assessment. Additionally, a typological methodology table is provided to assist researchers and practitioners in applying the framework effectively.

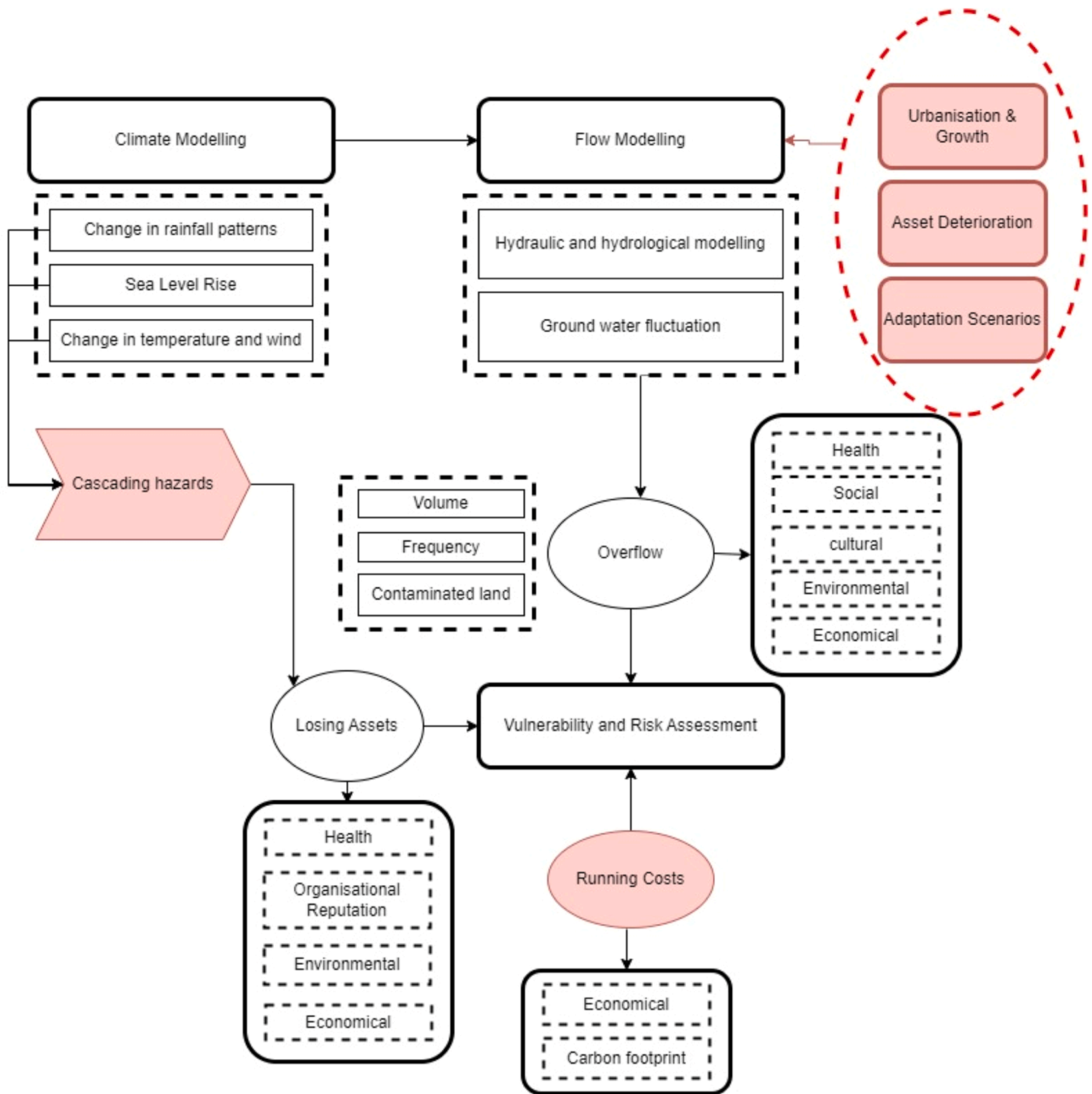


Fig. 7. Climate change and sewer network vulnerability assessment integration framework.

**CRedit authorship contribution statement**

**Amir Masoud Karimi:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Mostafa Babaeian Jelodar:** Writing – review & editing, Supervision, Methodology. **Teo Susnjak:** Writing – review & editing, Supervision. **Monty Sutrisna:** Supervision.

**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.

**Data availability**

Data will be made available on request.

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