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*Review*

# A Systematic Review: To Increase Transportation Infrastructure Resilience to Flooding Events

**Grace Watson and Jeong Eun Ahn ***

Department of Civil and Environmental Engineering, College of Engineering, Rowan University, Glassboro, NJ 08028, USA
* Correspondence: ahn@rowan.edu; Tel.: +1-(856)-256-5399

**Abstract:** This study investigated literature databases of Google Scholar and Scopus from 1900 to 2021 and reviewed relevant studies conducted to increase transportation infrastructure resilience to flood events. This review has three objectives: (1) determine which natural hazard or natural disaster had the most vulnerability studies; (2) identify which infrastructure type was most prevalent in studies related to flood resilience infrastructure; and (3) investigate the current stage of research. This review was conducted with three stages. Based on stage one, floods have been extremely present in research from 1981 to 2021. Based on stage two, transportation infrastructure was most studied in studies related to flood resilience. Based on stage three, this systematic review focused on a total of 133 peer-reviewed, journal articles written in English. In stage three, six research categories were identified: (1) flood risk analysis; (2) implementation of real-time flood forecasting and prediction; (3) investigation of flood impacts on transportation infrastructure; (4) vulnerability analysis of transportation infrastructure; (5) response and preparatory measures towards flood events; and (6) several other studies that could be related to transportation infrastructure resilience to flood events. Current stage of studies for increasing transportation resilience to flood events was investigated within these six categories. Current stage of studies shows efforts to advance modeling systems, improve data collections and analysis (e.g., real-time data collections, imagery analysis), enhance methodologies to assess vulnerabilities, and more.

**Keywords:** flooding; flood; flood vulnerability; flooding resilience; transportation; transportation network



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## 1. Introduction

A natural disaster is an actual event that causes detrimental effects while a natural hazard is the threat of an event that could cause a detrimental effect [1]. Natural disasters are created by shifts in the Earth's general stability—whether it is movement of plates in the Earth's crust to form an earthquake, excess rain that cannot fully infiltrate into the ground, or extremely dry areas catching fire from the heat. These often create secondary events, such as landslides or mudslides, as a result of a flooding event. While these events are not able to be restrained, it is possible to lessen the impacts and prepare as best as possible [2]. Natural disasters negatively affect people's lives as they can be fatal, economically devastating, and environmentally depleting. This loss of life, damage to important infrastructure, and loss of resources all creates life-changing impacts that are physically, socially, economically, and environmentally damaging. Physical impacts can include damage or contamination to property, built infrastructure, and land. This results in injury, death, and loss of people, structures, animals, and crops [3]. Social impacts can be physical and/or mental health effects or destruction of household structures [3]. Economic losses are interconnected with physical impacts as well, and can be represented by costs associated with repair, replacement, and recovery [3]. Negative environmental impacts are also caused by natural disasters; for example, droughts alter water availability which causes biodiversity crises [4].

Vulnerability connects natural disaster events and the level of their risk by describing the degree that the afflicted places or people may be negatively impacted [5]. There are innumerous classification systems and methods of categorizing natural hazards and natural disasters for different areas of the world and from different sources. The most significant natural hazards and natural disasters of which to investigate vulnerability using lists and indexes by the Center for Disease Control and Protection [6], United States Geological Survey [7], Center for Disease Philanthropy [8], and Federal Emergency Management Agency [1] include, but are not limited to: avalanche, drought, earthquake, extreme temperature, flood, hail, heat wave, hurricane, ice storm, landslide, lightning, strong wind, tornado, tsunami, wildfire, winter weather, and volcanic activity.

Resilience represents the response to and the ability to recoup losses and recover stability after a natural disaster [5]. The Environmental Protection Agency (EPA) stated that focus on preparedness and recovery aligned with smart growth methods can help with a community's response to natural disasters [9]. Resilience, therefore, does not only represent the reaction post-natural disaster, but is largely affected by the awareness and preparedness of a community to their vulnerability to the natural disaster in the first place. The Department for International Development (DFID) stated that overall resilience includes adaptation of livelihoods and infrastructure, anticipation of vulnerability in climate and extreme scenarios, absorption of the effects and response for recovery, and response when the actual events occur [10]. Resilience begins with awareness and protective measures for infrastructure and concludes with disaster response.

Infrastructure is an important part towards the functioning of society, thus improving and maintaining infrastructure in a way that is resilient is important. A process of planning and assessing the vulnerability, designing reasonable resilience actions, implementing these actions in the area, and consistently reviewing and adapting is best advised. Some examples of proactive changes as resilience efforts are green roofs to combat extreme heat in cities or wetlands to help with coastal flooding along shorelines [11].

This review focused on the vulnerability and resilience related to natural disaster events, specifically involving infrastructure that is important to the function of society during and after a natural disaster. For investigating most relevant studies, three stages of the review process were conducted, as seen in Figure 1. The first two stages were to tailor and find the most pertinent studies. Stage one revealed that flooding was the most pertinent natural disaster to investigate based on studies related to types of natural hazard and natural disaster vulnerability. Stage two determined transportation as the most critical infrastructure type in relation to flood resilience. Stage three determined keywords based on the examination of abstracts and titles of relevant studies, and then the final keywords were used to select studies most related to transportation infrastructure resilience to flood events, as directed by stages one and two. The final studies selected were reviewed. These stages are further explained and delineated in the section of Materials and Methods.

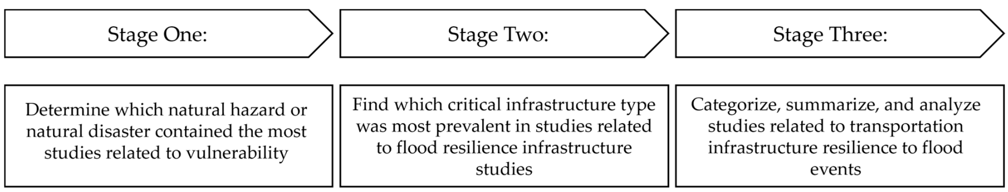


**Figure 1.** Methodological Framework of this Systematic Review.

The following questions were addressed through this review considering the results of the searches of recent research:

(1) Which natural disaster is most pertinent for vulnerability study?
(2) Which aspect of infrastructure should be included in flood resilience study?
(3) What is the current stage of research related to transportation infrastructure resilience to flood events?

## 2. Materials and Methods

This review utilized Google Scholar and Scopus to search for scholarly articles and papers published from 1900 to 2021. Google Scholar searches scholarly literature from articles, theses, and books from multiple publishers, societies, and repositories. It was chosen as a widely used starting ground for scientific research [12]. Scopus is a database of peer-reviewed literature that is collected from journals, books, and conferences regarding science, technology, social sciences, arts, and humanities. It was chosen as it represents a main data source for over three thousand academic and corporate institutions [13]. The results found from these searches were very widespread from a variety of major journals, databases, and websites including: SpringerLink, ASCE, MDPI, Sage Journals, ScienceDirect, and Wiley Online Library. Result totals mentioned below are equivalent to the sum of both database searches' results together. An advanced search was used by one independent reviewer with the criteria of: (1) custom range in the beginning of the review from 1900 to 2021 for Google Scholar and 1961 to 2021 for Scopus since Scopus does not provide data from 1900 to 1960, (2) exclusion of citations and patents results in Google Scholar, and (3) search keywords in the title of the article in both Scopus and Google Scholar. Citations and patents were excluded as these represented sources without publication access and patents were not the format represented in studies for this review. The search criteria within Scopus were limited to article title and within Google Scholar to title only to exclude results of which the topic was not the primary focus. A variety of publications were accepted including articles, journal papers, reports, and theses until the third stage in which only peer-reviewed journal publications in English were considered. As aforementioned, this review contained three stages. Each stage's key features can be seen in Figure 2 and each is explained in greater detail below.

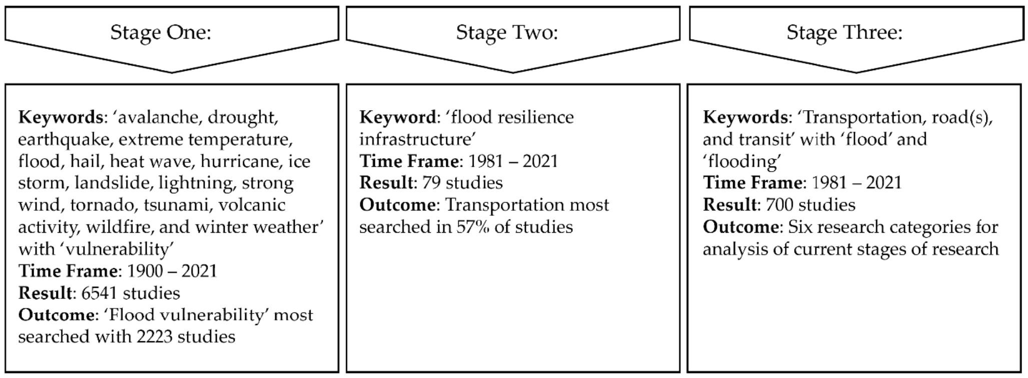


**Figure 2.** Detailed Framework of this Systematic Review.

As mentioned previously, this review initiated with a search to find which natural hazard or natural disaster was most studied regarding vulnerability. Stage one conducted a search with seventeen natural hazards and natural disasters as mentioned above, and the word 'vulnerability,' since vulnerability refers to a possible level of destruction due to a natural disaster. Table 1 presents the number of studies found with each type of natural hazard or natural disaster; a total number of 6541 results were found from all natural disaster vulnerability studies. As seen in Table 1, the amount of studies related to natural hazard and natural disaster vulnerability was nearly zero from 1900 to 1980, but it began to increase from 1981 to 1990. This can be likely attributed to two factors: the increase of occurrence of several natural disasters and efforts to prepare and respond to natural disasters, such as the development of corporations that initiated extensive amounts of studies [14]. Since the 1980's, large corporations including the Centre for Research on the Epidemiology of Disasters (CRED) and the US Agency for International Development (USAID) initiated efforts to investigate natural disasters [14]. These two factors could be linked with climate change, as the early 1980's felt increased temperature and the late 1980's experienced drought and wildfire, and the Intergovernmental Panel on Climate Change was formed in 1989 [15].

**Table 1.** Natural Hazard and Natural Disaster Vulnerability Study Results over Time from both Google Scholar and Scopus.

| Natural Hazard or Disaster Type | 1900–1960 | 1961–1980 | 1981–1990 | 1991–2000 | 2001–2010 | 2011–2021 | Total |
|---|---|---|---|---|---|---|---|
| Avalanche | 0 | 1 | 0 | 0 | 13 | 21 | 35 |
| Drought | 1 | 2 | 12 | 39 | 164 | 1165 | 1383 |
| Earthquake | 0 | 4 | 19 | 49 | 232 | 973 | 1277 |
| Extreme Temperature | 0 | 0 | 0 | 0 | 0 | 25 | 25 |
| Flood | 0 | 1 | 4 | 26 | 236 | 1956 | 2223 |
| Hail | 0 | 0 | 1 | 0 | 2 | 8 | 11 |
| Heat wave | 0 | 0 | 0 | 0 | 8 | 52 | 60 |
| Hurricane | 0 | 0 | 1 | 3 | 89 | 260 | 353 |
| Ice storm | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Landslide | 0 | 0 | 2 | 3 | 49 | 374 | 428 |
| Lightning | 0 | 8 | 10 | 2 | 10 | 29 | 59 |
| Strong wind | 0 | 0 | 0 | 0 | 2 | 4 | 6 |
| Tornado | 0 | 0 | 0 | 0 | 11 | 45 | 56 |
| Tsunami | 0 | 0 | 0 | 5 | 141 | 357 | 503 |
| Volcanic activity | 0 | 0 | 0 | 0 | 9 | 5 | 14 |
| Wildfire | 0 | 0 | 0 | 0 | 9 | 93 | 102 |
| Winter weather | 0 | 0 | 0 | 0 | 0 | 5 | 5 |

As seen in Table 1, ‘flood vulnerability’ was the most prominent with 2223 results, which confirmed this as the most decisive direction to conduct the rest of the review. The next highest was ‘drought vulnerability’ with 1383 results, and all others had lower result totals. Since studies regarding the vulnerability of floods represented the natural disaster with the highest amount of studies from a total of seventeen natural hazard and natural disaster vulnerability searches, flood was chosen as the natural disaster to further investigate. Figure 3 presents a similar trend as all natural hazards and natural disasters observed; flood vulnerability studies also increased rapidly after the 1980′s. Therefore, the authors further focused on the time frame of database from 1981 to 2021 to conduct the remainder of this review.

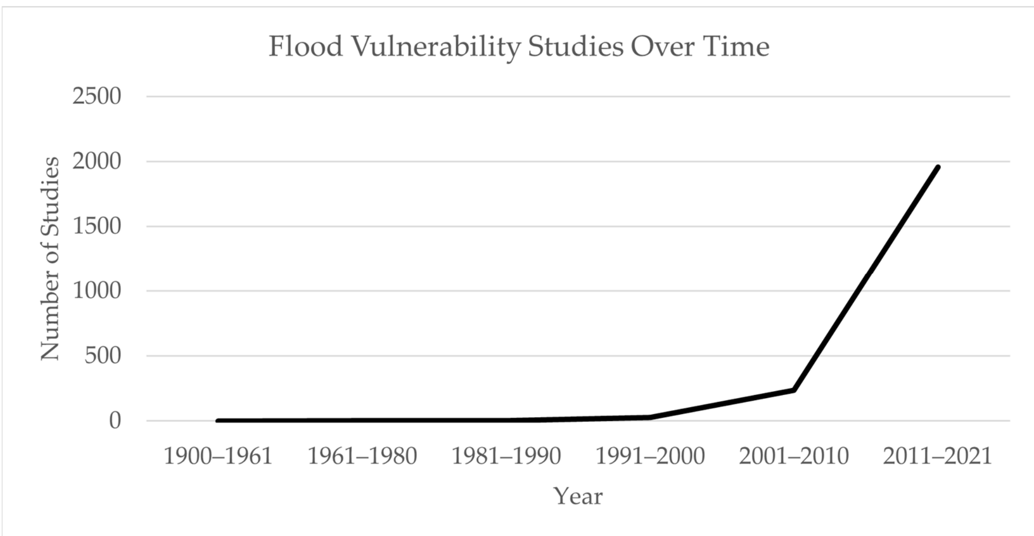


**Figure 3.** Flood Vulnerability Study Results over Time from both Google Scholar and Scopus.

With stage two, this review persisted to find which infrastructure was most studied with flood resilience. Resilience is one of the key aspects to consider with floods since it accommodates proper management of floodwater during flooding events which lessen risk to people and infrastructure [16]. Increasing resilience is crucial to ensure the well-being of communities that are affected by flood events, and infrastructure is a component that affects resiliency of the communities. To influence resilience of communities, infrastructure handles, withstands, and restores operability to floods and thus requires alterations, changes, and proper development to handle these events. Since climate change has increased the intensity and frequencies of floods, infrastructure resilience is a high priority. This study considered critical infrastructure including the chemical, commercial facilities, communications, critical manufacturing, dams, defense industrial base, emergency services, energy, financial services, food and agriculture, government facilities, healthcare and public health, information technology, nuclear, transportation, and water and wastewater systems sectors [17].

Stage two used the keyword phrase 'flood resilience infrastructure.' Results from the search keyword phrase 'flood resilience infrastructure' totaled to 79 results. 55 results were considered since 24 results were repeated between the two databases. Each study was screened, and these 55 studies were categorized by the primary types of critical infrastructure which were involved in the study: transportation, wastewater treatment, water supply, energy, green infrastructure, health care, housing, communications, and emergency services. Transportation was focused on in 57% of these studies, wastewater treatment in 42%, energy in 34%, water supply in 32%, green infrastructure in 23%, health care in 21%, communications in 21%, housing in 19%, and emergency services in 8%. Many articles featured more than one type of infrastructure, so total percentages are not one hundred. Since transportation was the most prevalent infrastructure type, this was considered in relation to floods and resilience studies for the rest of the review.

In stage three, this study searched literature related to transportation infrastructure resilience to flood events. Based on titles and abstracts, final keywords (i.e., 'transportation', 'road(s)', and 'transit' with 'flood' and 'flooding') were determined. Authors included 'flood' and 'flooding' in keywords since these terminologies have slightly different definitions, and either is commonly used in studies of transportation infrastructure resilience to flood events. Flood is the natural disaster itself while flooding is the act of the natural disaster occurring. Furthermore, an option used by the authors within Google Scholar to search relevant studies was including the exact keywords in the title of the article. By using keyword combinations with 'flood' and 'flooding', the authors included all relevant studies. The searches yielded a total of 700 studies: 475 studies with 'flood' and 236 studies with 'flooding.' 'Road' and 'roads' were used for the same reason with Google Scholar.

This review then checked these 700 studies and excluded 566 studies. The accepted studies for this third stage were: (1) written in English and (2) peer-reviewed published journal publications with available access. Conference proceedings, books, reports, or academic papers (i.e., thesis or dissertation) were not included. Irrelevant studies (e.g., habitat modification due to road-killed snakes caused by summer flooding) were also excluded. Therefore, a total of 133 studies were further investigated.

Based on reviewing abstracts of these 133 studies, this study first determined six main research categories as they relate to transportation infrastructure resilience to flood events. These studies were categorized as aligned with the Infrastructure Resilience Planning Framework (IRPF) established by the Cybersecurity and Infrastructure Security Agency (CISA), as seen in Figure 4. The IRPF consisted of 5 total steps: (1) Lay the Foundation; (2) Critical Infrastructure Identification; (3) Risk Assessment; (4) Develop Actions; and (5) Implement and Evaluate. This framework supported the Federal Management Agency (FEMA) National Mitigation Investment Strategy and the U.S. Government Accountability Office (GAO) Disaster Resilience Framework. Therefore, this framework is applicable to any of the sixteen critical infrastructure types, including transportation infrastructure [18].

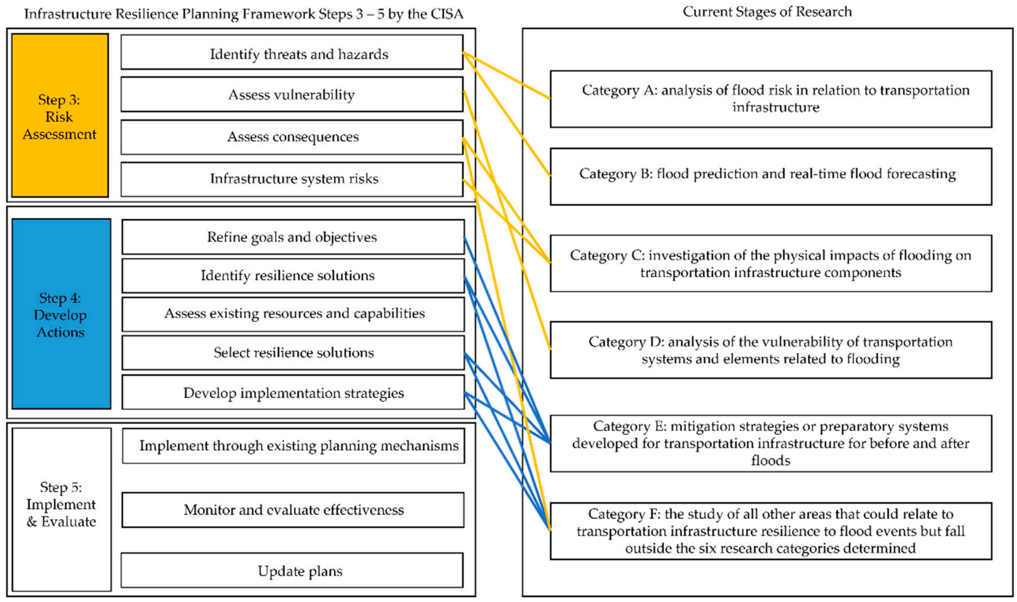


**Figure 4.** Category Association with the Infrastructure Resilience Planning Framework.

This framework is a flexible guidance to help lay the groundwork for success, prioritize critical infrastructure, understand risk, identify opportunities to improve resilience, and influence decision-making related to resilience for planning and investment decisions. Since this framework expressed this flexibility with its use, the first two steps were covered by the first two stages of this review as transportation infrastructure was determined as the main area for stage three.

Research category A: analysis of flood risk in relation to transportation infrastructure. Recognition of flood risk is imperative to help future planning and investment decisions related to resiliency of transportation infrastructure [19].

Research category B: flood prediction and real-time flood forecasting. According to Fan, C., et al. (2020), accurate flood forecasting would increase transportation resiliency that allows emergency managers, public officials, and other decision-makers to have more accurate and real-time flood prediction data [20].

Research category C: investigation of the physical impacts of flooding on transportation infrastructure components. The World Economic Forum (2015) noted that proper assessment, understanding, and explanation of the existing risks of flooding is beneficial to heighten resilience to floods. For a proper response method to be established for floods, the problem itself must first be identified [21].

Research category D: analysis of the vulnerability of transportation systems and elements related to flooding. As stated by Colon, C., et al. (2020), transport systems hold high vulnerabilities and are important before and after flooding events. By evaluating vulnerability of components of the transport network, prioritization of resilience efforts can be made to benefit economics and general function [22].

Research category E: mitigation strategies or preparatory systems developed for transportation infrastructure for before and after flood events. As Gersonius, B., et al. (2016) noted, resilience strategies utilize prevention and preparedness measures to reduce effects and risks of flooding [23]. Improving effectiveness of design standards for more resilient transportation infrastructure, disaster recovery plans, and consideration of better planning measures for redundancy and flexibility of transportation infrastructure is critical to improve [19,24,25].

Research category F: the study of all other areas that could relate to transportation infrastructure resilience to flood events but fall outside the six research categories determined.

As discussed above, six research categories were aligned with Steps 3 and 4 of the IRPF. Categories A and B worked for identifying threats and hazards. Category C applied to assess consequences and infrastructure system risks. Category D represented assess vulnerability. Category E worked for refining goals and objectives, identifying and selecting resilience solutions, and developing implementation strategies. Category F applied to assess consequences, identify resilience solutions, select resilience solutions, and develop implementation strategies. There is a research gap for assessing existing resources and capabilities, implementing through existing planning mechanisms, monitoring and evaluating effectiveness, and updating plans. This is discussed in greater detail in the Discussion section. This final stage of the review investigated 133 studies, which consist of 17 studies in Category A, 11 studies in Category B, 29 studies in Category C, 25 studies in Category D, 20 studies in Category E, and 31 studies in Category F.

## 3. Results

As aforementioned in the Materials and Methods section, a final 133 studies were investigated to review the studies conducted to increase transportation infrastructure resilience to flood events. Tables 2–7 present these 133 studies including the title, year of publication, authors, country of study area conducted, and the journal published within for each category. All studies are listed in a publication year order. In case a study did not apply to a specific area, the country of study area was presented as N/A.

Table 2 represents the 17 studies within research category A, regarding flood risk correlated to transportation infrastructure [26–42].

**Table 2.** 17 Studies of category A.

| Study Number: | Study Title: | Year: | Authors: | Country of Study Area: | Journal: |
|---|---|---|---|---|---|
| 1 | Flood analysis and hydraulic competence of drainage structures along Addis Ababa light rail transit [26] | 2021 | Kiwanuka, M., et al. | Ethiopia | *Journal of Environmental Science and Sustainable Development* |
| 2 | Flooding and its relationship with land cover change, population growth, and road density [27] | 2021 | Rahman, M., et al. | Bangladesh | *Geoscience Frontiers* |
| 3 | Flood risk assessment using the CV-TOPSIS method for the Belt and Road Initiative: an empirical study of Southeast Asia [28] | 2020 | Yan, A., et al. | Asia | *Ecosystem Health and Sustainability* |
| 4 | Assessing flood probability for transportation infrastructure based on catchment characteristics, sediment connectivity and remotely sensed soil moisture [29] | 2019 | Kalantari, Z., et al. | Sweden | *Science of The Total Environment* |
| 5 | A Method for Urban Flood Risk Assessment and Zoning Considering Road Environments and Terrain [30] | 2019 | Chen, N., et al. | China | *Sustainability* |
| 6 | Changes concerning commute traffic distribution on a road network following the occurrence of a natural disaster—The example of a flood in the Mazovian Voivodeship (Eastern Poland) [31] | 2019 | Borowska-Stefańska, M., et al. | Poland | *Transportation Research Part D: Transport and Environment* |
| 7 | Analysis of Flood Vulnerability and Transit Availability with a Changing Climate in Harris County, Texas [32] | 2019 | Pulcinella, J. A., et al. | USA | *Transportation Research Record: Journal of the Transportation Research Board* |
| 8 | Flood risk analysis for flood control and sediment transportation in sandy regions: A case study in the Loess Plateau, China [33] | 2018 | Guo, A., et al. | China | *Journal of Hydrology* |

**Table 2.** *Cont.*

| Study Number: | Study Title: | Year: | Authors: | Country of Study Area: | Journal: |
|---|---|---|---|---|---|
| 9 | A Location Intelligence System for the Assessment of Pluvial Flooding Risk and the Identification of Storm Water Pollutant Sources from Roads in Suburbanised Areas [34] | 2018 | Szewrański, S., et al. | Poland | *Water* |
| 10 | The Increased Risk of Flooding in Hampton Roads: On the Roles of Sea Level Rise, Storm Surges, Hurricanes, and the Gulf Stream [35] | 2018 | Ezer, T. | USA | *Marine Technology Society Journal* |
| 11 | Flood probability quantification for road infrastructure: Data-driven spatial-statistical approach and case study applications [36] | 2017 | Kalantari, Z., et al. | Sweden | *Science of The Total Environment* |
| 12 | Climate change in asset management of infrastructure: A riskbased methodology applied to disruption of traffic on road networks due to the flooding of tunnels [37] | 2016 | Huibregtse, E., et al. | N/A | *European Journal of Transport and Infrastructure Research* |
| 13 | Modeling flash floods in southern France for road management purposes [38] | 2016 | Vincendon, B., et al. | France | *Journal of Hydrology* |
| 14 | A method for mapping flood hazard along roads [39] | 2014 | Kalantari, Z., et al. | Sweden | *Journal of Environmental Management* |
| 15 | Flash flood risk estimation along the St. Katherine road, southern Sinai, Egypt using GIS based morphometry and satellite imagery [40] | 2011 | Youssef, A. M., et al. | Egypt | *Environmental Earth Sciences* |
| 16 | Development of a screening method to assess flood risk on Danish national roads and highway systems [41] | 2011 | Nielson, N. H., et al. | Denmark | *Water Science & Technology* |
| 17 | The Environmental Impact of Flooding on Transportation Land Use in Benin City, Nigeria [42] | 2010 | Adebayo, W. O. and Jegede, O. A. | Nigeria | *African Research Review* |

Within category A, which is the flood risk analysis studies, hydrological and/or hydrodynamic modeling were often utilized to analyze flood depths. Geospatial tools were then used to display these depths which translated to flood risks. Sanyal, J., et al. (2014) used a hydrological model (HEC-HMS) to determine how land use and land cover change affected a sub-catchment and influenced the flood risk [43,44]. Kiwanuka, M., et al. (2021) conducted hydrological analysis using HEC-HMS along several roadways in Addis Ababa City, Ethiopia. Geospatial tools then helped to display the physical aspects of elevation data [26,44]. Szewrański, S., et al. (2018) developed a location intelligence system, extended from the Pluvial Risk Flood Assessment Tool. It included spatial and temporal pluvial flood analysis, elevation, and hydrologic analyses. This was used to find runoff depths and distribution of flood risks in Wrocław, Poland [34]. Nielson, N. H., et al. (2011) investigated flood risk in Jutland, Denmark with the 1-D hydrodynamic model, Mike Urban [41,45]. Geospatial methods illustrated elevation-based depressions of land surfaces that experienced flooding [41]. Youssef, A. M., et al. (2011) investigated qualitative flash flood risk analysis by incorporating remote imagery and physical data in geospatial systems in Sinai, Egypt. Morphometric analysis of the individual sub-basins was evaluated to determine the hazard from flash floods [40]. Through many of these studies, drainage systems (i.e., culverts, drains) were influential characteristics in affecting flood risk [26,34,40,41].

Furthermore, there are several other efforts to investigate the flood risk. For example, Yan, A., et al. (2020) investigated historical flood risks in 11 countries within Southeast Asia, using the CV (coefficient of variation) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) methods. The CV method was utilized to find weights of the indicators for the flood risk assessment, and the TOPSIS method assessed the flood risk by utilizing a decision matrix [28]. Chen, N., et al. (2019) used a road risk zoning model that determined submerged depths, assessed urban flood risk with a neural network algorithm, and created flood risk maps. Spatial distribution of this flood risk varied greatly among the cities in the Chang-Zhu-Tan Urban Agglomeration (CZTUA), China [30]. Kalantari, Z., et al. (2017) utilized spatial analysis with ArcHydro to obtain the physical characteristics of the watershed and used statistical methodology (i.e., regression models) to determine and display flood probability in Västra Götaland and Värmland counties of Sweden [36,46]. Sanyal, J. and Lu, X. (2004) reviewed applications of remote imagery and spatial analysis for flood management and highlighted the importance of accurate analysis of flood depths for flood hazard mapping. This application was recommended to understand impacts of monsoons which are strong winds prevalent in south and southeastern Asia that can bring rains [47]. Islam, A., and Barman, S. D. (2020) considered morphometric characteristics (e.g., basin areas, stream number and length) to measure the floods of the Mayurakshi River, India [48]. Islam, A. and Ghosh, S. (2021) created a community-based risk assessment for riverine floods in the Rarh Plains, India that utilized the analytical hierarchy process (AHP). Flood depth was used as the determiner for flood hazard and demographic, social, infrastructure, and economic characteristics were considered [49].

Table 3 represents the 11 studies related to flood prediction and real-time flood forecasting which is Research category B [20,50–59].

**Table 3.** 11 Studies of category B.

| Study Number: | Study Title: | Year: | Authors: | Country of Study Area: | Journal: |
|---|---|---|---|---|---|
| 1 | Flash flood susceptibility prediction mapping for a road network using hybrid machine learning models [50] | 2021 | Ha, H., et al. | Vietnam | *Natural Hazards* |
| 2 | Estimating Flood Inundation Depth along the Arterial Road Based on the Rainfall Intensity [51] | 2021 | Suharyanto, A. | Indonesia | *Civil and Environmental Engineering* |
| 3 | A network percolation-based contagion model of flood propagation and recession in urban road networks [20] | 2020 | Fan, C., et al. | USA | *Scientific Reports* |
| 4 | Validating an Operational Flood Forecast Model Using Citizen Science in Hampton Roads, VA, USA [52] | 2019 | Loftis, J. D., et al. | USA | *Journal of Marine Science and Engineering* |
| 5 | Modeling the Impacts of Sea Level Rise on Storm Surge Inundation in Flood-Prone Urban Areas of Hampton Roads, Virginia [53] | 2018 | Castrucci, L. and Tahvildari, N. | USA | *Marine Technology Society Journal* |
| 6 | A Case Study for the Application of an Operational Two-Dimensional Real-Time Flooding Forecasting System and Smart Water Level Gauges on Roads in Tainan City, Taiwan [54] | 2018 | Chang, C., et al. | Taiwan | *Water* |
| 7 | Impact of Sea-Level Rise on Roadway Flooding in the Hampton Roads Region, Virginia [55] | 2017 | Sadler, J. M., et al. | USA | *Journal of Infrastructure Systems* |
| 8 | Estimation of Real-Time Flood Risk on Roads Based on Rainfall Calculated by the Revised Method of Missing Rainfall [56] | 2014 | Kim, E., et al. | Korea | *Sustainability* |
| 9 | Spatially distributed flood forecasting in flash flood prone areas: Application to road network supervision in Southern France [57] | 2013 | Naulin, J., et al. | France | *Journal of Hydrology* |
| 10 | Use of radar rainfall estimates and forecasts to prevent flash flood in real time by using a road inundation warning system [58] | 2012 | Versini, P. | France | *Journal of Hydrology* |
| 11 | Vulnerability of Hampton Roads, Virginia to Storm-Surge Flooding and Sea-Level Rise [59] | 2006 | Kleinosky, L. R., et al. | USA | *Natural Hazards* |

Studies within this category considered historical and current flood threats and/or future scenarios to better predict the flood events. Since having sufficient rainfall and water data would increase the accuracy of the prediction models, there are some related discussions and investigations. Kim, E., et al. (2014) estimated real-time flood risks by investigating historical rainfall and the probability of precipitation in Busan, Korea [56]. Chang, C., et al. (2018) found highly accurate flood forecasts by utilizing a two-dimensional real-time forecasting model with improved water gauges that includes recording and transmission of data. It helps track road inundation in real-time in Tainan City, Taiwan [54]. Naulin, J., et al. (2013) utilized spatial and temporal rainfall estimate data where water gauges were not present in the Gard Region, France and utilized this data with the hydro-meteorological forecasting approach [57]. Loftis, J. D., et al. (2019) validated accuracy for the street-level flood forecasting tool for Virginia, USA by addition of atmospheric wind and pressure data, tidal harmonic predictions, and ocean currents to their hydrodynamic model (SCHISM) and with a citizen science GPS data collection made in Hampton Roads located in Virginia to map the inundated areas as well as validate and improve predictive models for future flooding [52].

Table 4 represents the 29 studies within Research category C, examination of the physical impacts of flood events on transportation infrastructure [60–88].

**Table 4.** 29 Studies of category C.

| Study Number: | Study Title: | Year: | Authors: | Country of Study Area: | Journal: |
|---|---|---|---|---|---|
| 1 | Quantifying Road-Network Robustness toward Flood-Resilient Transportation Systems [60] | 2021 | Tachaudomdach, S., et al. | Thailand | *Sustainability* |
| 2 | Flood Impact Assessments on Transportation Networks: A Review of Methods and Associated Temporal and Spatial Scales [61] | 2021 | Rebally, A., et al. | N/A | *Frontiers in Sustainable Cities* |
| 3 | Flood risk assessment of the European road network [62] | 2021 | van Ginkel, K. C. H., et al. | Europe | *Natural Hazards and Earth System Sciences* |
| 4 | A River Flood and Earthquake Risk Assessment of Railway Assets along the Belt and Road [63] | 2021 | Wang, Q., et al. | Asia | *International Journal of Disaster Risk Science* |
| 5 | Flood impacts on urban transit and accessibility—A case study of Kinshasa [64] | 2021 | He, Y., et al. | Democratic Republic of the Congo | *Transportation Research Part D: Transport and Environment* |
| 6 | Assessment of transportation system disruption and accessibility to critical amenities during flooding: Iowa case study [65] | 2021 | Alabbad, Y., et al. | USA | *Science of The Total Environment* |
| 7 | Towards Resilient Critical Infrastructures: Understanding the Impact of Coastal Flooding on the Fuel Transportation Network in the San Francisco Bay [66] | 2021 | He, Y., et al. | USA | *International Journal of Geo-Information* |
| 8 | Mere Nuisance or Growing Threat? The Physical and Economic Impact of High Tide Flooding on US Road Networks [67] | 2021 | Fant, C., et al. | USA | *Journal of Infrastructure Systems* |
| 9 | A systematic assessment of the effects of extreme flash floods on transportation infrastructure and circulation: The example of the 2017 Mandra flood [68] | 2020 | Diakakis, M., et al. | Greece | *International Journal of Disaster Risk Reduction* |
| 10 | Probabilistic modeling of cascading failure risk in interdependent channel and road networks in urban flooding [69] | 2020 | Dong, S., et al. | USA | *Sustainable Cities and Society* |
| 11 | A physically based spatiotemporal method of analyzing flood impacts on urban road networks [70] | 2019 | Li, Y., et al. | USA | *Natural Hazards* |
| 12 | Assessing the knock-on effects of flooding on road transportation [71] | 2019 | Pyatkova, K., et al. | Spain | *Journal of Environmental Management* |

**Table 4.** *Cont.*

| Study Number: | Study Title: | Year: | Authors: | Country of Study Area: | Journal: |
|---|---|---|---|---|---|
| 13 | Analysis of Transportation Disruptions from Recent Flooding and Volcanic Disasters in Hawaii [72] | 2019 | Kim, K., et al. | USA | *Transportation Research Record* |
| 14 | The characteristics of road inundation during flooding events in Peninsular Malaysia [73] | 2019 | Ismail, M. S. N., et al. | Malaysia | *International Journal of GEOMATE* |
| 15 | A topological characterization of flooding impacts on the Zurich road network [74] | 2019 | Casali, Y. and Heinimann, H. R. | Switzerland | *PLoS ONE* |
| 16 | Local floods induce large-scale abrupt failures of road networks [75] | 2019 | Wang, W., et al. | China/USA | *Nature Communications* |
| 17 | Integrated Framework for Risk and Resilience Assessment of the Road Network under Inland Flooding [76] | 2019 | Zhang, N. and Alipour, A. | USA | *Transportation Research Record: Journal of the Transportation Research Board* |
| 18 | Modeling the traffic disruption caused by pluvial flash flood on intra-urban road network [77] | 2018 | Li, M., et al. | China | *Transactions in GIS* |
| 19 | MobRISK: a model for assessing the exposure of road users to flash flood events [78] | 2017 | Shabou, S., et al. | France | *Natural Hazards and Earth System Sciences* |
| 20 | Impact of dam failure-induced flood on road network using combined remote sensing and geospatial approach [79] | 2017 | Foumelis, M. | Greece | *Journal of Applied Remote Sensing* |
| 21 | The impact of flooding on road transport: A depth-disruption function [80] | 2017 | Pregnolato, M., et al. | UK | *Transportation Research Part D: Transport and Environment* |
| 22 | Stochastic modeling of road system performance during multihazard events: Flash floods and earthquakes [81] | 2017 | Wisetjindawat, W., et al. | Japan | *Journal of Infrastructure Systems* |
| 23 | Evaluating the impact and risk of pluvial flash flood on intra-urban road network: A case study in the city center of Shanghai, China [82] | 2016 | Yin, J., et al. | China | *Journal of Hydrology* |
| 24 | Deterioration of flood affected Queensland roads—An investigative study [83] | 2016 | Sultana, M., et al. | Australia | *International Journal of Pavement Research and Technology* |
| 25 | Robustness of road systems to extreme flooding: using elements of GIS, travel demand, and network science [84] | 2016 | Kermanshah, A. and Derrible, S. | USA | *Natural Hazards* |
| 26 | The Effect of Flash Flood on the Efficiency of Roads Networks in South Sinai, Egypt. Case Study (Nuweiba-Dahab Road) [85] | 2015 | Hegazy, I. R., et al. | Egypt | *International Journal of Scientific Engineering Research* |
| 27 | Road assessment after flood events using non-authoritative data [86] | 2014 | Schnebele, E., et al. | USA | *Natural Hazards and Earth System Sciences* |
| 28 | GIS-based estimation of flood hazard impacts on road network in Makkah city, Saudi Arabia [87] | 2012 | Dawod, G. M., et al. | Saudi Arabia | *Environmental Earth Sciences* |
| 29 | Impacts of flooding and climate change on urban transportation: A systemwide performance assessment of the Boston Metro Area [88] | 2005 | Suarez, P., et al. | USA | *Transportation Research Part D: Transport and Environment* |

Remote imagery and sensing were featured in multiple studies, showing that visualization can be included in the measurements and analysis of flood impacts. Spatial analysis was one method for representation of the effects on transportation infrastructure from floods. Foumelis, M. (2017) investigated road segments impacted by flood events, from the Sparmos dam failure in Larissa, Central Greece via geospatial analysis and remote sensing. This was based upon the flood depths along these roads to imply damages [79].

Fant, C., et al. (2021) inspected delay as impacts on traffic corridors caused by high tide flooding in the East, Gulf, and Pacific coastal regions of the USA. This study utilized geospatial analysis for the representation of the flood impacts on road networks with traffic volume data [67]. Yin, J., et al. (2016) assessed the impacts of pluvial floods on a road network by utilizing geospatial tools. This study developed an algorithm to determine the start and end time of the flooding on the roadways. The results of the algorithm allowed this study to quantify the interruptions to the roadways in Shanghai, China [82].

Transportation network impacts of accessibility and mobility are crucial to evaluate as they represent the functionality of the roadways. These were measured by investigating delay, vehicle speed, or ability to traverse the road in the flood. Casali, Y. and Heinimann, H. R. (2019) considered the roads (edges) and intersections (nodes) of road infrastructure to determine accessibility of each node in Zurich, Switzerland and determined that flood events affect topological properties of the roadways [74]. Suarez, P., et al. (2005) considered the effects of climate change to analyze the impacts on the performance of an urban transportation network in the Boston Metro Area, USA. This study measured accessibility and mobility by considering increased delay and loss of trips [88].

Social and economic impacts were considered by some studies to investigate the impacts to accessibility and mobility, showing that flood impacts extend beyond physical attributes of the transportation infrastructure. Pregnolato, M., et al. (2017) developed a correlation between depth of flood and vehicle speed in a case study in Newcastle upon Tyne, UK. This study revealed that there are wide variety of potential impacts of flood events on accessibility and mobility, such as with safety, disruption, and economic, and social impacts [80]. He, Y., et al. (2021) found the impacts of floods by combining transit feed datasets, surveys, and flood maps to show disruptions from floods which led to delay in mobility and loss of accessibility to jobs, especially to low-income individuals. Floods impact individuals, particularly the disadvantaged, at a higher proportion in Kinshasa, Democratic Republic of the Congo [64]. Islam, A., et al. (2022) investigated social and economic vulnerabilities for the Mayurakshi River Basin, India. This study deployed questionnaire surveys to the general public for understanding their experiences with floods. This study also conducted spatial analysis for investigating flood depth, duration, and inundation area [89].

Table 5 represents the 25 studies related to the analysis of the vulnerability of transportation systems and elements related to flooding, which is research category D [90–114].

**Table 5.** 25 Studies of category D.

| Study Number: | Study Title: | Year: | Authors: | Country of Study Area: | Journal: |
|---|---|---|---|---|---|
| 1 | Use of flash flood potential index (FFPI) method for assessing the risk of roads to the occurrence of torrential floods—part of the Danube Basin and Pek River Basin [90] | 2021 | Markovic, M., et al. | Serbia | *International Journal for Traffic and Transport Engineering* |
| 2 | BIM-GIS-DCEs enabled vulnerability assessment of interdependent infrastructures—A case of stormwater drainage-building-road transport Nexus in urban flooding [91] | 2021 | Yang, Y., et al. | N/A | *Automation in Construction* |
| 3 | Vulnerability patterns of road network to extreme floods based on accessibility measures [92] | 2021 | Papilloud, T., et al. | Switzerland | *Transportation Research Part D: Transport and Environment* |
| 4 | Impact of the Change in Topography Caused by Road Construction on the Flood Vulnerability of Mobility on Road Networks in Urban Areas [93] | 2021 | Mukesh, M. S. and Katpatal, Y. B. | India | *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering* |
| 5 | Measuring urban road network vulnerability to extreme events: An application for urban floods [94] | 2021 | Morelli, A. B. and Cunha, A. L. | Brazil | *Transportation Research Part D: Transport and Environment* |

**Table 5.** *Cont.*

| Study Number: | Study Title: | Year: | Authors: | Country of Study Area: | Journal: |
|---|---|---|---|---|---|
| 6 | Measuring the dynamic evolution of road network vulnerability to floods: A case study of Wuhan, China [95] | 2021 | Liu, J., et al. | China | *Travel Behaviour and Society* |
| 7 | Multi-facilities-based road network analysis for flood hazard management [96] | 2021 | Chakraborty, O., et al. | India | *Journal of Spatial Science* |
| 8 | Relative sea level rise impacts on storm surge flooding of transportation infrastructure [97] | 2021 | Tahvildari, N. and Castrucci, L. | USA | *Natural Hazards Review* |
| 9 | Flood exposure analysis of road infrastructure—Comparison of different methods at national level [98] | 2020 | Papilloud, T., et al. | Switzerland | *International Journal of Disaster Risk Reduction* |
| 10 | Assessment of Transportation System Vulnerabilities to Tidal Flooding in Honolulu, Hawaii [99] | 2020 | Shen, S. and Kim, K. | USA | *Transportation Research Record* |
| 11 | Characterization of vulnerability of road networks to fluvial flooding using SIS network diffusion model [100] | 2020 | Abdulla, B., et al. | USA | *Journal of Infrastructure Preservation and Resilience* |
| 12 | Hierarchical Approach for Assessing the Vulnerability of Roads and Bridges to Flooding in Massachusetts [101] | 2020 | Barankin, R. A., et al. | USA | *Journal of Infrastructure Systems* |
| 13 | Flood evacuation and rescue: The identification of critical road segments using whole-landscape features [102] | 2019 | Helderop, E. and Grubesic, T. H. | USA | *Transportation Research Interdisciplinary Perspectives* |
| 14 | Assessment of Road Vulnerability to Flood: A Case Study [103] | 2019 | Babalola, A. M. and Abilodun, O. K. | Nigeria | *International Journal of Research in Engineering and Science* |
| 15 | Vulnerability assessment of urban road network from urban flood [104] | 2018 | Singh, P., et al. | India | *International Journal of Disaster Risk Reduction* |
| 16 | A multi-objective framework for analysis of road network vulnerability for relief facility location during flood hazards: A case study of relief location analysis in Bankura District, India [105] | 2018 | Chakraborty, O., et al. | India | *Transactions in GIS* |
| 17 | Analysis of Transportation Network Vulnerability under Flooding Disasters [106] | 2015 | Chen, X., et al. | USA | *Transportation Research Record: Journal of the Transportation Research Board* |
| 18 | Identification and Prioritization of Critical Transportation Infrastructure: Case Study of Coastal Flooding [107] | 2015 | Lu, Q., et al. | USA | *Journal of Transportation Engineering* |
| 19 | Adaptation to flooding and mitigating impacts of road construction—a framework to identify practical steps to counter climate change [108] | 2015 | Mallick, R. B., et al. | N/A | *The Baltic Journal of Road and Bridge Engineering* |
| 20 | Evaluating the Prioritization of Transportation Network Links under the Flood Damage: by Vulnerability Value and Accessibility Indexs [109] | 2013 | Khaki, A. M., et al. | Iran | *International Journal of Scientific Research in Knowledge* |
| 21 | Vulnerability of population and transportation infrastructure at the east bank of Delaware Bay due to coastal flooding in sea-level rise conditions [110] | 2013 | Tang, H. S., et al. | USA | *Natural Hazards* |
| 22 | Assessment of the susceptibility of roads to flooding based on geographical information—test in a flash flood prone area (the Gard region, France) [111] | 2010 | Versini, P., et al. | France | *Natural Hazards and Earth System Sciences* |
| 23 | Flood risk: a new approach for roads vulnerability assessment [112] | 2010 | Benedetto, A. and Chiavari, A. | Italy | *WSEAS Transactions on Environment and Development* |

**Table 5.** *Cont.*

| Study Number: | Study Title: | Year: | Authors: | Country of Study Area: | Journal: |
|---|---|---|---|---|---|
| 24 | Development an accessibility approach to rank the transportation network components during the occurrence of flood crisis (Golestan province case study) [113] | 2010 | Khaki, A. M., et al. | Iran | *Australian Journal of Basic and Applied Sciences* |
| 25 | Landslide and flood hazard index for mountain roads an example from the Stura di Demonte Valley, Italy [114] | 2000 | Barisone, G. and Onori, A. | Italy | *Journal of Nepal Geological Society* |

Inclusion of the interconnected infrastructure elements and display with spatial analysis was important for heightened accuracy in vulnerability analysis. Yang, Y., et al. (2021) combined building information modeling, geographic information system, and domain-specific computational engines to investigate vulnerabilities of infrastructure, specifically a stormwater drainage-building-road transport combination during urban flooding from extreme rainfall. This allowed for the investigation of all the affected infrastructure systems to generate a reliable vulnerability study [91]. Sanyal, J. and Lu, X. (2005) investigated vulnerability of rural settlements in Gangetic West Bengal, India by observing presence of flood and proximity to elevated areas. This was conducted with remote imagery and displayed with spatial analysis [115].

Since accessibility and mobility were also major factors impacting levels of vulnerability, several studies within this category considered them. These studies are distinct from category C, as they investigated the road network's vulnerability based on the impacts and transportation network information. For example, Papilloud, T., et al. (2021) investigated the vulnerability of road networks based on modified accessibility measures which included populations affected by floods, opportunities, and shortest travel time in Bern, Switzerland [92]. Khaki, A. M., et al. (2013) assessed road vulnerability by considering an accessibility index in the Golestan province, Iran. This was accomplished by using flood analysis with flood peak volume and flood frequency as well as traffic volume modeling which enabled them to estimate the traffic volume and travel time [109]. Shen, S. and Kim, K. (2020) assessed the vulnerability of road networks and zones that needed traffic analysis were ranked by change in accessibility in response to tidal flooding in Honolulu, Hawaii, USA. This study used spatial analysis, population, and trip information to show the exposure and disruptions [99]. Singh, P., et al. (2018) assessed the vulnerability of urban road networks in Bangalore, India with hydrodynamic modeling and spatial analysis with 10-year and 100-year flood return periods. They found a relationship between flood depth and vehicle speed reduction to quantify vulnerability [104].

Table 6 represents the 20 studies within Research category E, the response approaches or preparation methods towards involving transportation infrastructure with flood events [116–135].

**Table 6.** 20 Studies of category E.

| Study Number: | Study Title: | Year: | Authors: | Country of Study Area: | Journal: |
|---|---|---|---|---|---|
| 1 | A multi-step assessment framework for optimization of flood mitigation strategies in transportation networks [116] | 2021 | Zhang, N. and Alipour, A. | USA | *International Journal of Disaster Risk Reduction* |
| 2 | When floods hit the road: Resilience to flood-related traffic disruption in the San Francisco Bay Area and beyond [117] | 2020 | Kasmalkar, I. G., et al. | USA | *Science Advances* |
| 3 | Highways protection from flood hazards, a case study: New Tama road, KSA [118] | 2020 | Fathy, I., et al. | Saudi Arabia | *Natural Hazards* |

**Table 6.** *Cont.*

| Study Number: | Study Title: | Year: | Authors: | Country of Study Area: | Journal: |
|---|---|---|---|---|---|
| 4 | Selection of the best alternative for a road project to replace a section in a flood-prone area using GIS and AMC tools [119] | 2020 | Zaoui, M., et al. | Algeria | *Journal of Materials and Engineering Structures* |
| 5 | Median Road Revitalization as an Alternative Way to Overcome Flood on Jalan Asrama, Helvetia, Medan— Indonesia [120] | 2020 | P. K., S. S., et al. | Indonesia | *International Journal of Architecture and Urbanism* |
| 6 | Design of a decision support system for emergency transportation during an Asean economics community flood [121] | 2019 | Meethom, W. | Vietnam/Thailand | *Suranaree Journal of Science & Technology* |
| 7 | Road flood warning system with information dissemination via social media [122] | 2019 | Abana, E., et al. | N/A | *International Journal of Electrical and Computer Engineering* |
| 8 | Gabion wall used in road construction and flood protection embankment [123] | 2019 | Utmani, N., et al. | Pakistan | *Journal of Civil Engineering and Environmental Sciences* |
| 9 | A cloud-based flood warning system for forecasting impacts to transportation infrastructure systems [124] | 2018 | Morsy, M. M., et al. | USA | *Environmental Modelling & Software* |
| 10 | Enhancing dialogue between flood risk management and road engineering sectors for flood risk reduction [125] | 2018 | Huang, G. | Japan | *Sustainability* |
| 11 | Prioritization of Climate Change Adaptation Interventions in a Road Network combining Spatial Socio-Economic Data, Network Criticality Analysis, and Flood Risk Assessments [126] | 2018 | Espinet, X., et al. | Mozambique | *Transportation Research Record* |
| 12 | Framework, approach and process for investment road mapping: a tool to bridge the theory and practices of flood risk management [127] | 2016 | Osti, R. | N/A | *Water Policy* |
| 13 | Development of a post-flood road maintenance strategy: case study Queensland, Australia [128] | 2015 | Khan, M. U., et al. | Australia | *International Journal of Pavement Engineering* |
| 14 | A flood lamination strategy based on transportation network with time delay [129] | 2013 | Nouasse, H., et al. | N/A | *Water Science & Technology* |
| 15 | Emergency Management and Planning Framework of Transportation Evacuation for Urban Flood Calamity [130] | 2013 | Yu, H. and An, S. | N/A | *Applied Mechanics and Materials* |
| 16 | Soil stabilisation with lime-activated-GGBS—A mitigation to flooding effects on road structural layers/embankments constructed on floodplains [131] | 2012 | Obuzor, G. N., et al. | N/A | *Engineering Geology* |
| 17 | Application of a distributed hydrological model to the design of a road inundation warning system for flash flood prone areas [132] | 2010 | Versini, P., et al. | France | *Natural Hazards and Earth System Sciences* |
| 18 | Flood risk management and planning policy in a time of policy transition: the case of the Wapshott Road Planning Inquiry, Surrey, England [133] | 2009 | Tunstall, S., et al. | England | *Journal of Flood Risk Management* |
| 19 | Optimization of transportation networks during urban flooding [134] | 2007 | Ferrante, M., et al. | Italy | *Journal of the American Water Resources Association* |
| 20 | Design of Flood Protection for Transportation Alignments on Alluvial Fans [135] | 1992 | French, R. H. | N/A | *Journal of Irrigation and Drainage Engineering* |

Some studies discussed and developed methodologies for developing preparedness and response strategies. Abana, E., et al. (2019) developed a road flood warning system that provided real-time flood information from ultrasonic sensors. This allowed road users to be informed of the flood depth and passable roads. This study designed that data was portrayed through social media for ease of road user access [122]. Fathy, I., et al. (2020) planned flood relief measures by investigating the flood quantity and distribution as well as stream ways and stream sizes. This study proposed seven new channels and two new culverts for King Abdul-Aziz Highway, Kingdom of Saudi Arabia to help alleviate flood impact [118]. Obuzor, G. N., et al. (2011) investigated use of waste and by-product material in geomaterials, which would help with sustainable technologies and could provide structurally sound, environmentally-friendly, and economic results for roadways in flood-prone areas [131]. Das, S. and Bandyopadhyay, S. (2022) discussed the Millennium Flood in India and the benefit of shelters built at higher elevations to reduce the risk of floods [136].

Some studies evaluated mitigation methods and frameworks that help decide the better implementations to increase transportation resilience. Zhang, N. and Alipour, A. (2021) utilized a segment of a real transportation network to evaluate mitigation strategies for raising the roadway elevation guided by assessment of costs, traffic delay, and traffic volume impacted due to a flood [116]. Espinet, X., et al. (2018) developed a methodology to prioritize mitigation methods for transportation infrastructure to climate change effects in Mozambique and found the benefits, redundancies, and disruption-based costs from floods. This was based on socio-economic criticality and the current and future risk to the roadways [126].

Table 7 represents the 31 studies within Research category F, the study of all other areas that could relate to transportation infrastructure resilience to flood events but fall outside the six research categories determined [137–167].

**Table 7.** 31 Studies of category F.

| Study Number: | Study Title: | Year: | Authors: | Country of Study Area: | Journal: |
|---|---|---|---|---|---|
| 1 | The effect of Ring Road and Railway line on the flooding rate of AqQala city in March 2019 Flood [137] | 2021 | Atabay, S., et al. | Jordan | *Journal of Water and Soil Conservation* |
| 2 | Discharge Prediction at Bahadurabad Transit of Brahmaputra-Jamuna Using Machine Learning and Assessment of Flooding [138] | 2021 | Rabbi, I. I., et al. | Bangladesh | *Journal of Water Resources and Pollution Studies* |
| 3 | Deep Learning Models for Road Passability Detection during Flood Events Using Social Media Data [139] | 2020 | Lopez-Fuentes, L., et al. | N/A | *Applied Sciences* |
| 4 | A New Integrated Scheme for Urban Road Traffic Flood Control Using Liquid Air Spray/Vaporization Technology [140] | 2020 | Wu, D., et al. | N/A | *Sustainability* |
| 5 | Assisting Road Users Exposed to Nuisance Flooding [141] | 2020 | Hannoun, G. J., et al. | USA | *Journal of Transportation Engineering, Part A: Systems* |
| 6 | Building Construction, Road Works and Waste Management: Impact of Anthropogenic Actions on Flooding in Yenagoa, Nigeria [142] | 2020 | Brisibe, W. and Brown, I. | Nigeria | *International Journal of Architectural Engineering Technology* |
| 7 | Towards resilient roads to storm-surge flooding: case study of Bangladesh [143] | 2020 | Amin, S. R., et al. | Bangladesh | *International Journal of Pavement Engineering* |
| 8 | Commuting behavior adaptation to flooding: An analysis of transit users' choices in Metro Manila [144] | 2020 | Abad, R. P. B., et al. | Philippines | *Travel Behaviour and Society* |
| 9 | Influence of road characteristics on flood fatalities in Australia [145] | 2019 | Gissing, A., et al. | Australia | *Environmental Hazards* |
| 10 | Automatic detection of passable roads after floods in remote sensed and social media data [146] | 2019 | Ahmad, K., et al. | N/A | *Signal Processing: Image Communication* |
| 11 | The Long Road to Adoption: How Long Does it Take to Adopt Updated County-Level Flood Insurance Rate Maps [147] | 2019 | Wilson, M. T. and Kousky, C. | USA | *Risk, Hazards and Crisis in Public Policy* |

**Table 7.** *Cont.*

| Study Number: | Study Title: | Year: | Authors: | Country of Study Area: | Journal: |
|---|---|---|---|---|---|
| 12 | Failure of Grass Covered Flood Defences with Roads on Top Due to Wave Overtopping: A Probabilistic Assessment Method [148] | 2018 | Aguilar-López, J. P., et al. | Netherlands | *Journal of Marine Science and Engineering* |
| 13 | An Evaluation Of Soil Condition And Flood Risk For Road Network Of Bangladesh—Compiled From Engineering Soil Maps And Digital Elevation Model [149] | 2017 | Mamun, A. A., et al. | Bangladesh | *IOSR Journal of Mechanical and Civil Engineering* |
| 14 | Flood and substance transportation analysis using satellite elevation data: A case study in Dhaka city, Bangladesh [150] | 2017 | Hashimoto, M., et al. | Bangladesh | *Journal of Disaster Research* |
| 15 | Enhancing the effectiveness of flood road gauges with color coding [151] | 2017 | Jing, F., et al. | N/A | *Natural Hazards* |
| 16 | A study on the use of polyurethane for road flood damage control [152] | 2017 | Radzi, S. M., et al. | N/A | *International Journal of GEOMATE* |
| 17 | A dynamic model for road protection against flooding [153] | 2016 | Starita, S., et al. | England | *The Journal of the Operational Research Society* |
| 18 | Road submergence during flooding and its effect on subgrade strength [154] | 2016 | Ghani, A. N. A., et al. | N/A | *International Journal of GEOMATE* |
| 19 | Assessment of commuters' daily exposure to flash flooding over the roads of the Gard region, France [155] | 2016 | Debionne, S., et al. | France | *Journal of Hydrology* |
| 20 | Safety criteria for the trafficability of inundated roads in urban floodings [156] | 2016 | Kramer, M., et al. | N/A | *International Journal of Disaster Risk Reduction* |
| 21 | Study on the use of obstructing objects to diffuse flood water velocity during road crossing [157] | 2015 | Ghani, A. N. A., et al. | N/A | *International Journal of GEOMATE* |
| 22 | Projected impacts of land use and road network changes on increasing flood hazards using a 4D GIS: A case study in Makkah metropolitan area, Saudi Arabia [158] | 2014 | Dawod, G. M., et al. | Saudi Arabia | *Arabian Journal of Geosciences* |
| 23 | The Relationship between the Urban Road Flood Protection Capacity and the Lake Sandbox Based on Internet of Things [159] | 2014 | Shi, H., et al. | N/A | *Applied Mechanics and Materials* |
| 24 | Urban Flood Reconstruction Using Bloggers' Posting on Road Inundations [160] | 2013 | Mah, D. Y. S., et al. | Malaysia | *Urban Planning and Design Research* |
| 25 | Improved methodology for processing raw LiDAR data to support urban flood modelling—accounting for elevated roads and bridges [161] | 2012 | Abdullah, A. F., et al. | Malaysia | *Journal of Hydroinformatics* |
| 26 | Probabilistic graphical models for flood state detection of roads combining imagery and DEM [162] | 2012 | Frey, D., et al. | South Africa | *IEEE Geoscience and Remote Sensing Letters* |
| 27 | Utilisation of lime activated GGBS to reduce the deleterious effect of flooding on stabilised road structural materials: A laboratory simulation [163] | 2011 | Obuzor, G. N., et al. | N/A | *Engineering Geology* |
| 28 | Urban flooding: one-dimensional modelling of the distribution of the discharges through cross-road intersections accounting for energy losses [164] | 2010 | Kouyi, G. L., et al. | France | *Water Science & Technology* |
| 29 | Water vapor transportation over China and its relationship with drought and flood in the Yangtze River Basin [165] | 2009 | Xingwen, J., et al. | China | *Journal of Geographical Sciences* |
| 30 | Effects of forest roads on flood flows in the Deschutes River, Washington [166] | 2000 | La Marche, J. L. and Lettenmaier, D. P. | USA | *Earth Surface Processes and Landforms* |
| 31 | Effect of maximum flood width on road drainage inlet spacing [167] | 1997 | Wong, T. S. W. and Moh, W. | Singapore | *Water Science & Technology* |

Lopez-Fuentes, L., et al. (2020) developed a single double-ended neural network architecture that analyzed two types of data (i.e., metadata, image) that contained passable roadways from tweets. This enabled analysis of both data simultaneously which reduced processing time that would aid in emergency support by greater understanding of roads in flood events [139]. Ahmad, K., et al. (2019) also used social media as well as satellite imagery to determine which roads were passable during floods [146]. Hannoun, G. J., et al. (2020) established a method of sharing flood information to road users during floods in Virginia Beach, Virginia, USA. This implementation required communication between the traffic management center of flooding presence and the in-vehicle systems to determine if the vehicle was at risk and possible alternative pathways [141].

There are many studies that investigated how floods impact people on the streets. Abad, R. P. B., et al. (2020) found the ways how flooding events affect roadway users by considering altered departure times, mode of travel, or travel cancellation. They conducted a survey with public transit commuters to investigate how flood events within the last ten years impacted their morning commutes in Metro Manila, Philippines [144]. Debionne, S., et al. (2016) evaluated exposure of road users to flooding in the Gard region, France by: (1) combining the density of roads and average distance driven to certain points to find the number of road users and (2) applying a traffic attribution to census data [155].

Main research categories and relevant studies were briefly summarized and explained in this section. The Discussion section will elaborate how each category's studies can be included to contribute to studying the increase of transportation infrastructure resilience to flood events.

## 4. Discussion

Since flood vulnerability is a popularly studied field in scholarly research from 1981 to 2021 and transportation is a very high priority critical infrastructure sector, this review aimed to investigate these areas of research to increase transportation infrastructure resilience to flood events.

This review focused on 133 studies related to increasing transportation infrastructure resilience to flood events and defined six research categories. Through the synthesis of these categories and the wide variety of studies, the current stages of research were investigated. As briefly discussed in Introduction, these six categories were aligned with the Cybersecurity and Infrastructure Security Agency (CISA)'s Infrastructure Resilience Planning Framework (IRPF), especially steps 3 to 5: step 3 is risk assessment, step 4 is develop actions, and step 5 is implement and evaluate [18]. However, the methodologies for implementing some components for increasing resilience transportation infrastructure to flood events need to be further discussed and investigated. For example, as seen in Figure 4, assessment of existing resources and capabilities, implementation through existing planning mechanisms, monitoring and evaluating effectiveness, and updating plans are areas for future studies.

This study reviewed relevant studies within six categories that aligned with steps 3 and 4 of the IRPF. As defined and discussed above, these categories were: (A) analysis of flood risk; (B) flood prediction and real-time flood forecasting; (C) investigation the impacts of flooding on transportation infrastructure; (D) assessment of the vulnerability of transportation systems and elements; (E) mitigation methods and preparatory measures to flood events; and (F) all other study areas that relate to transportation infrastructure resilience to flood events.

In the IRPF, risk assessment (i.e., step 3) includes: (1) identification of the threats and hazards; (2) assessment of vulnerability; (3) assessment of the consequences; and (4) infrastructure risks. This step was focused to collect information that would allow for understanding of the existing risks to help inform implementation measures and development of response actions [18].

Identification of threats and hazards should be considered for current and future applications [18]. This was accommodated by categories A and B of this review. Category

A revealed the threat of floods to the critical infrastructure sector of transportation. Studies in this category contribute to risk assessment of floods. Hydrological and hydrodynamic modeling methods were used to determine flood depths. Visualizations of this can be displayed via spatial analysis, with special attention to drainage infrastructure systems and how this affects the extent of the risk. Category B extended the threat of floods from historical to present to future. With hydrodynamic modeling to understand flood inundations, forecasting and real-time modeling efforts were established. Reliable rainfall data also helped to increase the accuracy of these predictions.

Assessment of vulnerability was based on identifying weaknesses and possible failures. Some key elements of vulnerability noted were accessibility, susceptibility, and recoverability [18]. Category D involved establishment of vulnerability of transportation infrastructure. Vulnerability was assessed by investigating the accessibility of roads and intersections. Traffic volume and traffic time helped to find the exposure and disruptions that would allow for quantification and ranking of the vulnerability.

Assessment of the consequences and infrastructure risks included effects such as on humans, economic, and mission. It also allowed for the highest risks to be identified along the transportation infrastructure [18]. Category C was focused on these aspects of risk assessment. Remote imagery was used to help with visualization of floods on transportation infrastructure. Spatial analysis was utilized to display the risks and impacts (e.g., delay, disruption, change in vehicle speed, ability to use roadway). Economic and social impacts were also noted, beyond physical effects. Some studies from category F could be included here. They focused on the effects to humans directly based on their reactions and exposure to floods.

In the IRPF, developing actions (i.e., step 4) includes: (1) refinement of goals and objectives; (2) identification of resilience solutions; (3) assessment of existing resources and capabilities; (4) selection of resilience solutions; and (5) development of implementation strategies [18].

Refinement of goals and objectives helps observe risks of flooding on the transportation infrastructure as discussed in category E [18]. Identification of resilience solutions to mitigate risks included potential strategies and infrastructure project improvements that could help increase transportation resilience to flood events as addressed in categories E and F [18]. Category E discussed flood forecasting to identify passable roadways for motorists and proposition of drainage and road materials to alleviate flood effects. Category F developed ways to warn road users of flood information. Selection of resilience solutions and the development of implementation strategies were based on vulnerabilities and risks, as discussed in categories E and F [18]. Category E discussed the evaluation of potential mitigation efforts by considering various factors (e.g., climate change, cost analysis, people's safety, environment). Category F discussed employing neural networks and roadway information to detect floods that would guide the warnings issued to road users.

However, this review revealed the knowledge gap in identifying and assessing existing resources and capabilities. Another research gap was observed in step 5 of the IRPF. Assessing existing resources and capabilities was from step 4 of the IRPF. Establishing the baseline of existing resources could help to provide implementation strategies. Some major resources and capabilities that need to be considered are: (1) planning and regulation authorities; (2) existing plans, policies, and programs; (3) administrative and technical skills within the community; and (4) financial resources [18]. Since this review noted a research gap in this area, further strategies and development for identifying existing resources and capabilities by including external public and private sectors could help to increase transportation infrastructure resilience to flood events.

Implementation and evaluation (i.e., step 5 of the IRPF) was also noted as the research gap area by this review. Based on the IRPF, this step 5 includes components of: (1) implementation through existing planning mechanisms; (2) monitoring and evaluation of effectiveness; and (3) updating plans [18]. Implementing through existing planning mechanisms refers to integrating the resilience measures into existing structures (e.g., emergency communications plans, pre-disaster recovery plans, transportation plans) [18]. Monitoring and evaluation effectiveness ensures that resilience measures are reaching their established goals [18]. For updating plans, improvements can be made by incorporating the results of the monitoring and evaluation [18].

To successfully evaluate and implement plans for increasing resilience of transportation infrastructure, studies for the measure of the performance of several planning strategies are also needed. Evaluating the successes of the resilience measures would allow solutions and plans to be better developed for the future. The key aspects of this evaluation and monitoring process would be who would conduct it, the planned time frame, and the process for evaluation. These future study efforts could allow for more successful resilience solutions to flood events [18].

Extending the current stage of research within all six categories can be an area for future research. For example, advancing real-time data analysis (e.g., flood depths, images, metadata) will increase abilities for accurate warning systems and better responses to flood events. Embracing various factors to assess vulnerability would help prioritize preparedness and mitigation strategies that could ensure transportation infrastructure equity.

Analysis of study area for the studies allowed for understanding global efforts. By comparing the amount of studies based on study area, 133 studies were conducted for several countries. As checked based on continent, it revealed that 39 studies were conducted in Asia (i.e., Bangladesh, China, India, Indonesia, Iran, Japan, Jordan, Korea, Malaysia, Pakistan, Philippines, Singapore, Taiwan, Thailand, Vietnam), 32 in North America (i.e., USA), 29 in Europe (i.e., England, Denmark, France, Greece, Italy, Netherlands, Serbia, Spain, Sweden, Switzerland, Poland, UK), 10 in Africa (i.e., Algeria, Democratic Republic of the Congo, Egypt, Ethiopia, Mozambique, Nigeria, Saudi Arabia, South Africa), 3 in Australia, and 1 in South America (i.e., Brazil). This distribution represents that the importance of increasing transportation infrastructure resilience to flood events was recognized and discussed globally. However, it appears that many studies were conducted for Asia and the USA.

The findings and methodologies in studies discussed from this review would be applicable to other coastal areas beyond Asia and USA if they have similar characteristics (e.g., sea-level rise, dense urban development). For example, Asia experiences the impacts of sea-level rise at an extremely high rate, and the USA anticipates to experience 10–12 inches of sea-level rise by 2050 [168,169]. Kim, E., et al. (2014), Chang, C., et al. (2018), Naulin, J., et al. (2013) Loftis, J. D., et al. (2019), Castrucci, L. and Tahvildari, N. (2018), Sadler, J. M., et al. (2017), and Kleinosky, L. R., et al. (2006) utilized hydraulic and hydrodynamic models, remote-sensing, imagery analysis, and more [52–57,59]. These studies would be able to be followed in areas with similar characteristics to better understand and forecast the impacts of sea-level rise.

Asia experiences rapid urbanization along coastlines with high numbers of population and assets, which heightens their vulnerability to floods [170]. The USA has also encountered urbanization and altered environmental aspects of vegetation, land surface, and built infrastructure [171]. This land development reflects the needs of the people living in these urbanized areas and utilizing the transportation networks. As discussed by Abad, R. P. B., et al. (2020), Debionne, S., et al. (2016), and Abana, E., et al. (2019), there are studies that investigate the impacts of floods on people and efforts for preparedness and response strategies are created to increase resilience of transportation during the flood events [122,144,155].

Developing countries transitioning to more urban areas will experience flood effects [170]. As sea-level continues to rise as well as rapid urbanization occurs, flooding will continue to occur worldwide [172]. Therefore, the studies discussed can be applied and adapted by countries worldwide that experience similar characteristics to increase resilience of their transportation infrastructure to flood events in terms of all the categories established.

## 5. Conclusions

This review investigated 133 final studies selected through three stages of review process from Google Scholar and Scopus databases from 1900 to 2021. Flood vulnerability is an extremely important topic in research from 1981 to 2021, and transportation is a critical infrastructure sector that needs enhanced resilience during and after flooding events. The years of 1900 to 1980 did not provide many natural disaster vulnerability studies, but once climate change effects were noticed and began to be studied in the 1980's, there was a quick increase. Therefore, after 1981, there are a lot of needs for studies regarding flooding, flooding vulnerability, and transportation infrastructure resilience to flood events. The current stage of research was analyzed by reviewing 133 studies. These studies were all organized by categories that aligned with the Infrastructure Resilience Planning Framework's risk assessment and develop actions steps. There was a knowledge gap noticed within assessing existing resources and capabilities of step 4 and the components of step 5, the implementation and evaluation step. Advancement of studies regarding this could help to raise resiliency of the transportation infrastructure as determined by this review.

Analysis of flood risk utilizing hydrological and hydrodynamic models as well as spatial analysis is a crucial step towards flood resilience. Flood prediction is also important for investigating flood resilience, as flood depths and extents are an important determiner of transportation infrastructure vulnerability. Additionally, real-time flood models that extend beyond historical flood risk can be helpful towards understanding and recommending flood response methods. Investigation of effects of floods on transportation infrastructure can help create a better visualization of the dangers of flooding and the responses of the transportation sector. Transportation infrastructure vulnerability study can help to understand an area to a greater degree and can help to pivot community focuses where needed for resilience measures and mitigation strategies. Various factors such as social and economic factors as well as accessibility and mobility were included to assess transportation infrastructure vulnerability. Impacted accessibility and mobility were investigated by delay, changes in traffic volumes, and transportation network disruptions. An advancement of assessment of existing resources and capabilities, implementation through existing planning mechanisms, resilience evaluation and monitoring, and plan updating represent the most benefit to increase transportation infrastructure resilience to flood events.

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