Original Paper

Climate resilience to floods on rural roads in Cambodia

Monirath Ly, Chunho Yeom

Received: 10 December 2024 | **Accepted:** 24 May 2025 | **Published:** 8 June 2025

Keywords: climate resilience; flood-prone; flood resilience; rural road vulnerability; flood risk assessment.

Abstract. *This article examines the vulnerability of rural roads in Cambodia to flooding, with a focus on enhancing climate resilience through spatial and hydrological analysis. The study utilizes Geographic Information Systems (GIS) and a Rational Method to assess flood risks and identify infrastructure vulnerabilities in Siem Reap Province. Data from a 12-year period (2012–2023) was analyzed to evaluate changes in rainfall intensity and peak discharge, revealing that certain road segments, particularly Siem Reap Roads 03 and 04, are highly susceptible to flooding. GIS-based flood mapping pinpointed flood-prone areas, while the Rational Method provided estimates of peak runoff, helping to identify critical infrastructure segments in need of upgrades. The findings demonstrate that road networks in low-lying areas and near water bodies are particularly vulnerable, with the highest peak discharge recorded in 2020, reflecting the growing impact of climate variability. To mitigate these identified risks, the study recommends infrastructure improvements such as enhanced drainage systems, road elevation, and the use of permeable materials. These results offer valuable insights for policymakers and engineers to prioritize investments and develop climate-resilient infrastructure strategies. Integrating climate resilience into rural road planning allows Cambodia to reduce adverse flood impacts on transportation and fosters sustainable rural development.*

1. Introduction

Flooding remains a significant challenge in Cambodia, particularly in rural areas where agriculture dominates the economy and rural roads play a crucial role in market connectivity. Cambodia's topography, seasonal monsoon rains, and river systems, notably the Mekong and Tonle Sap, make it highly susceptible to severe floods (ADB, 2016; World Bank, 2020). Flood-induced damages disrupt transportation, limit access to essential services, and weaken agricultural productivity, exacerbating economic losses and food insecurity (UNDP Cambodia, 2021). Furthermore, Cambodia faces increasing climate risks, including intensified storms and erratic rainfall patterns, which further threaten infrastructure resilience (IPCC, 2021; NCDM, 2018).

This study focuses on assessing flood risks to rural roads in Cambodia using Geographic Information Systems (GIS) and the Rational Method, a hydrological tool for rainfall-runoff analysis. By integrating GIS spatial data—topography, land use, and rainfall—with hydrological insights, the research identifies flood-prone rural road networks and proposes climate-resilient infrastructure solutions. The study addresses two key questions:

1. How can GIS be effectively applied to assess and enhance climate resilience to floods on rural roads in Cambodia?
2. What role does the Rational Method play in analyzing future flood risks?

The study's findings provide evidence-based recommendations for policymakers and planners, offering sustainable strategies to minimize the socio-economic impacts of flooding and enhance rural road resilience, particularly in agricultural areas (World Bank, 2020; UNFCCC, 2020). The research analyzes flood-prone data from 2013–2020, encompassing major events such as the 2013 and 2020 floods, which caused extensive damage to infrastructure (Voice of America, 2020). By addressing critical vulnerabilities, the study contributes to sustainable development and enhances adaptive capacity in Cambodia's rural communities.

2. Literature Review

Flooding poses a significant challenge to rural regions globally, and Cambodia is no exception. To effectively address this issue, it is essential to examine existing research on flood risks, climate resilience, and infrastructure development. This literature review synthesizes current knowledge on the impacts of seasonal floods in Cambodia, the vulnerabilities of rural infrastructure, and various strategies for enhancing climate resilience. By analyzing these studies, gaps in the existing literature are identified to establish a foundation for developing sustainable solutions tailored to the unique needs of Cambodia's rural communities. This research provides a comprehensive overview of theoretical and empirical research relevant to understanding and mitigating flood risks through resilient infrastructure approaches.

2.1 GIS and spatial analysis

Flooding poses severe challenges to rural road infrastructure in developing countries, including Cambodia, where seasonal floods disrupt livelihoods and economic stability. Geographic Information Systems (GIS) and hydrological models have proven effective in assessing flood risks and guiding infrastructure improvements. Regmi. M. B. and Hanaoka. S. (2011) emphasizes the growing frequency of extreme weather events in Asia and highlight the importance of comprehensive adaptation strategies, including infrastructure upgrades and maintenance (Regmi & Hanaoka, 2011). Similarly, Chinowsky. P. (2013) argues that proactive planning, such as improving road design standards and incorporating flood defenses, reduces long-term climate-related costs (Chinowsky et al., 2013). Combining GIS-based spatial analysis with hydrological tools enables the precise identification of flood-prone areas, providing critical insights for enhancing the resilience of Cambodia's rural road networks.

2.2 Framework development and governance analysis

Effective governance and policy frameworks are essential for building climate-resilient infrastructure. Lebel. L. (2018) observed that Cambodia's adaptation projects prioritized technical solutions, such as road elevation and improved drainage, but often neglected broader governance issues, including community access and planning capacity (Lebel et al., 2018). In contrast, Bollinger. L. A. (2013) proposed a systems-of-systems approach integrating interconnected infrastructure systems to address cascading climate-induced disruptions. This approach emphasizes managing road infrastructure alongside other critical systems, such as agriculture and water management, to create a more comprehensive and resilient adaptation framework for rural Cambodia.

2.3 Resilience approach and vulnerability

Building resilience to climate change requires addressing both physical and socio-economic vulnerabilities. Phy. S. R. (2022) highlights the need for comprehensive flood hazard mapping and risk assessments to develop targeted resilience strategies. Meanwhile, Natarajan. N. (2019) introduce the concept of "climate precarity," which underscores structural and economic constraints that leave marginalized rural communities unable to adapt effectively (Natarajan et al., 2019). Involving local communities in adaptation strategies, as advocated by Odemerho. F. O. (2015) enhances the sustainability and effectiveness of flood management (Odemerho, 2015). However, Ogunbode. C. A. (2019) caution that communities' short-term resilience to frequent floods may lead to complacency, reducing motivation for systemic, long-term improvements. These studies demonstrate the need for inclusive strategies that address both physical infrastructure and the social factors contributing to vulnerability Ogunbode. C. A. (2019). A combination of structural and non-structural measures is essential to adapt to evolving flood risks. Wilby and Keenan (2012) emphasize the importance of integrating engineering solutions, such as elevated roads and improved drainage systems, with adaptive management policies to ensure flexibility in response to changing flood patterns. In Cambodia, the UNDP's PCRWM project D'Agostino. A. L. (2011) highlights the significance of incorporating climate risks into governance and infrastructure planning. This project demonstrates that long-term resilience requires both technical solutions and community-driven approaches to enhance rural road infrastructure's capacity to withstand future floods (D'Agostino & Sovacool, 2011).

The literature highlights critical gaps in Cambodia's flood management strategies, particularly the need for integrated technical, governance, and community-driven approaches. GIS and hydrological models provide essential tools for identifying flood risks, while governance frameworks and inclusive resilience strategies ensure long-term sustainability. Addressing these gaps will enhance the resilience of Cambodia's rural roads, reducing socio-economic vulnerabilities and supporting sustainable connectivity amid increasing climate risks.

3. Methodology

3.1 Geographical information system (GIS) and rational method

This research adopts a methodological approach combining Geographic Information System (GIS) tools and the Rational Method to assess the vulnerability and climate resilience of rural roads in Cambodia to flood events. With the increasing frequency and severity of floods due to climate change, particularly in Southeast Asia, robust spatial and hydrological analysis is essential. GIS facilitates the integration of spatial data, including flood hazard maps, rainfall data, and road networks, to identify high-risk areas. The Rational Method estimates peak discharge to evaluate flood impacts on road infrastructure. This combined approach provides a comprehensive framework for understanding flood risks, enabling policymakers and planners to prioritize interventions and enhance flood mitigation strategies.

 http://dx.doi.org/10.13135/2384-8677/11406

3.1.1 GIS data collection

Data collection for this research involved multiple stages and sources to ensure robustness and reliability. The following methods will be employed with Geospatial Data including Road Network Data that collected as shapefiles or other vector data of the rural road networks from local authorities, such as the Cambodian Ministry of Rural Development (MRD) or OpenStreetMap. Moreover, the uses of The Shuttle Radar Topography Mission (SRTM) raster image for Cambodia, as shown in Figure 1: Shuttle Radar Topography Mission (SRTM) Map of Cambodia, is used to map elevation changes and analyze watershed impacts on flood-prone rural roads.

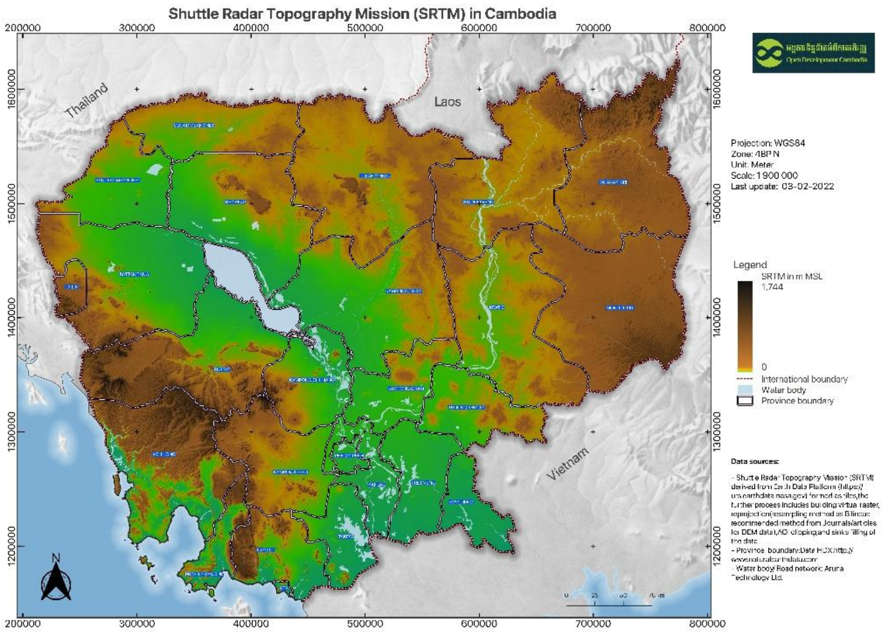

Figure 1. Shuttle Radar Topography Mission (SRTM) Map Cambodia Source: Open Development Cambodia

Furthermore, Figure 2: Cambodia Floods Map 2020 is used to show the flood map that was created to identify the specific harmfulness of the flood-prone toward the province regions of Cambodia around the Tonle Sap River. The data of floods detected water areas was conducted by the ASIA Sentinel in 2020 as shown in Figure 3: Cambodia's Flood Dataset.

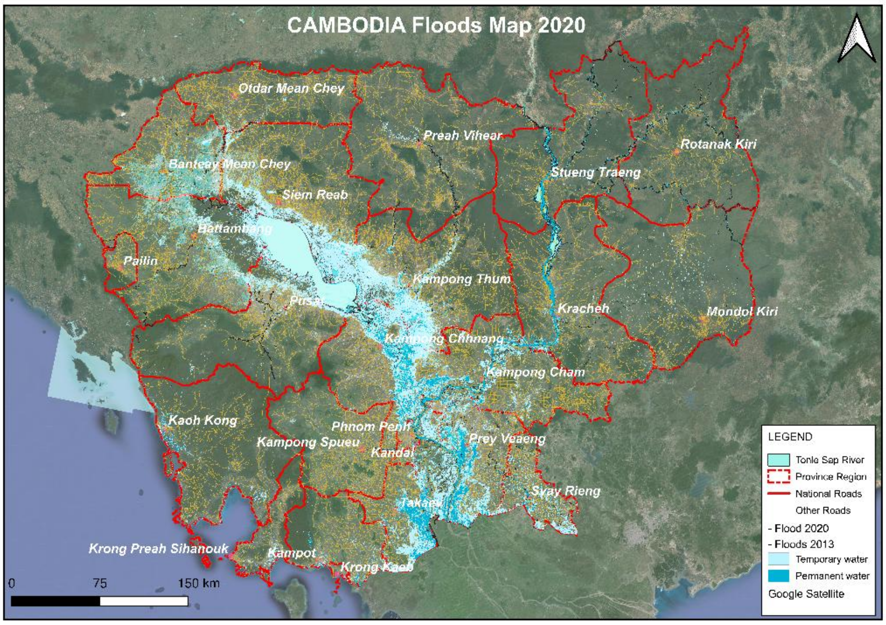

Figure 2. Cambodia Floods Map 2020. Source: Map Created by Monirath Ly, 2024. Dataset sources from Open Development Cambodia

This study utilizes Geographic Information System (GIS) tools to analyze flood impacts on rural roads in Cambodia, providing visual differentiation between affected and unaffected road segments using color-coded symbology. By overlaying flood risk maps with infrastructure maps, the study identifies vulnerable road sections, bridges, and critical infrastructure. Topographic data, generated from Digital Elevation Models (DEMs) derived from SRTM maps, are used to analyze surface elevations, slopes, and delineate catchment areas to understand water flow patterns during floods. Spatial road network data, collected from the Ministry of Rural Development, are processed in GIS to assess intersections with flood-prone zones. Historical rainfall records, annual precipitation, and flood maps from meteorological stations are integrated into GIS for a comprehensive assessment. By combining these datasets and advanced

GIS-based analysis, the study develops a clear understanding of current vulnerabilities and proposes effective climate-resilient infrastructure solutions for rural roads in Cambodia. This structured methodology emphasizes spatial analysis and hydrological integration to inform sustainable flood mitigation strategies.

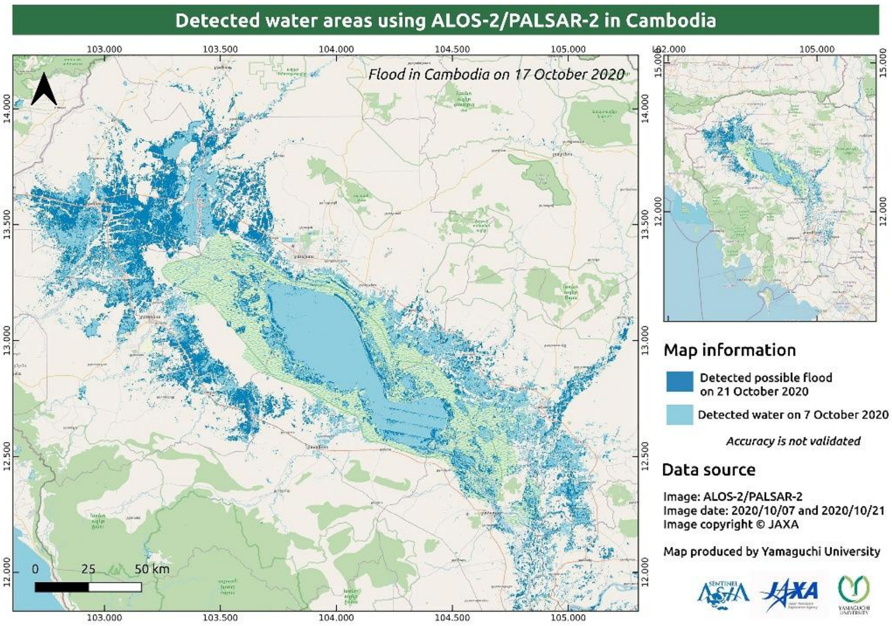

Figure 3. Cambodia's Flood Dataset Source: Open Development Cambodia, 2020/ ASIA Sentinel, 2020/ Image JAXA, 2020

3.1.2 Rational method data collection

The Rational Method is a widely used hydrological tool for estimating peak discharge in small watersheds and is highly relevant for assessing the flood risk on rural roads in Cambodia. This method determines the potential floodwater volume that could impact the rural infrastructure during heavy rainfall events. Moreover, the purpose of this method is to estimate the peak runoff form a catchment area during a rainfall period, which is essential for evaluating the potential flood risk. Additionally, understanding how much water could accumulate and impact the road network is critical for building climate resilience.

Below is the formula and key parameters of Rational Method:

$$Q = C * i * A$$

Q is the peak discharge (in cubic meters per second, m^3/s)

C is the runoff coefficient, which represents the proportion of rainfall that turns into runoff based on land use and surface conditions.

i : is the rainfall intensity (in millimeters per hour, mm/h) for a specified duration and return period, critical for the analysis of extreme rainfall events that may cause flooding.

A is the catchment area (in square kilometers, km^2) contributing to the runoff.

This method is particularly useful for identifying sections of the road network that are vulnerable to overtopping, erosion, or being submerged during a flood.

In this method the data that uses for the runoff coefficient (C) is the chosen type of land cover for calculation is shown in Table 1: Coefficient by type of land cover.

Table 1. Coefficient by type of land cover. Source: SEADRM II Training Program, 2021

Type of Soil and Landuse	Average Slope		
	Mild	Medium	Steep
	(0-4%)	(4-10%)	(>10%)
Rocky, heavy clay	0.6	0.75	0.85
Intense cultivation, loamy, clay soils	0.5	0.6	0.7
Grass cover	0.4	0.5	0.6
Dense Vegetation	0.05	0.15	0.25

Analyzing Rainfall events by the rainfall intensity (i) is a critical input derived from historical rainfall data that helps assess the flood risk during heavy rainfall events, which become more frequent due to climate change. The data that is used for this calculation is from the historical rainfall intensity of Siem Reap Province for 12 years periods from 2012 until 2023. By estimating peak discharge, the Rational Method helps determine whether the existing drainage systems along rural roads are sufficient to handle expected floodwaters. If the calculated discharge exceeds the drainage capacity, it indicates potential vulnerabilities in the road's flood resilience. Moreover, the method implemented across various segments of rural roads, the results can be used to identify critical segments that are highly susceptible to flooding. These sections can then be prioritized for upgrades, such as improved drainage systems or elevation changes, to enhance resilience.

In summary, the Rational Method is a key tool for quantifying flood risks to rural roads by estimating peak discharge during extreme rainfall events. Integrated with GIS, it enables comprehensive flood risk analysis by mapping watersheds using DEMs to delineate catchment areas and identify runoff boundaries. Hydrological parameters, such as peak discharge, are input into GIS to spatially highlight flood-prone zones. By overlaying peak discharge data with road networks, critical road segments—such as those in high-discharge catchments or low-lying areas—are identified, guiding targeted flood mitigation strategies.

4. Data analysis

This article analyzes the vulnerability of rural roads in Cambodia to flooding and evaluates their climate resilience amid increasing climate variability and extreme rainfall events. By integrating Geographic Information Systems (GIS) for spatial flood analysis with the Rational Method for hydrological modeling, the study assesses runoff potential and flood exposure. Key datasets, including historical rainfall records, flood events, topographical data, and road network characteristics, are used to identify vulnerable road segments and prioritize adaptation measures. The research outlines data pre-processing methods, GIS-based analysis, and hydrological modeling approaches, providing insights into strategies for enhancing road resilience and improving flood management in Cambodia's flood-prone regions.

4.1 GIS data analysis

This study conducted a Geographic Information System (GIS)-based spatial analysis to assess the vulnerability of rural roads in Cambodia to flooding, focusing on Siem Reap Province. By integrating datasets such as topography, flood-prone maps, and road networks, the analysis identifies the specific rural road segments most at risk. The project area and road networks were visually presented in Figure 4: Road Map Project area in Siem Reap Province.

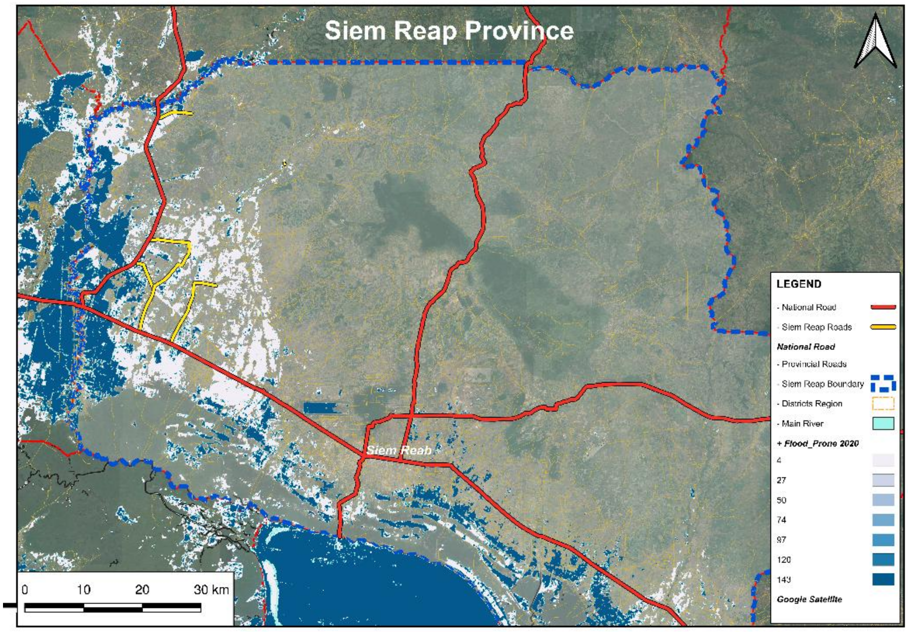

Figure 4. Road Map Project area in Siem Reap Province. Source: Map Created by Monirath Ly, 2024

The GIS analysis overlaid rural road data with flood-prone zones to create a clear spatial representation of high-risk road segments. Specific roads in Siem Reap were analyzed individually to show varying levels of flood exposure. Each road overlay map highlights vulnerable segments, enabling focused analysis and prioritization for flood mitigation interventions shows in Figure 5, Figure 6, Figure 7, and Figure 8, that is clearly identified the location of the overlaying roads networks with the flood prone dataset on the map view.

The maps clearly demonstrate the spatial relationship between roads and flood-prone areas. Darker colors represent higher flood risk (up to 143 cm water level), while lighter shades denote lower flood levels (starting at 4 cm). This visual differentiation is critical for prioritizing road segments that require immediate interventions, such as improved drainage systems, road elevation, or other flood-resilient measures.

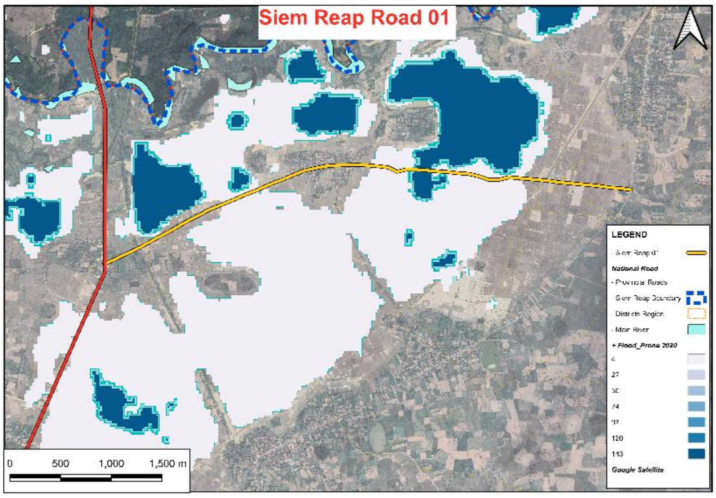

Figure 5. Siem Reap Road 01 map Overlaying Road Track and Flood-Prone

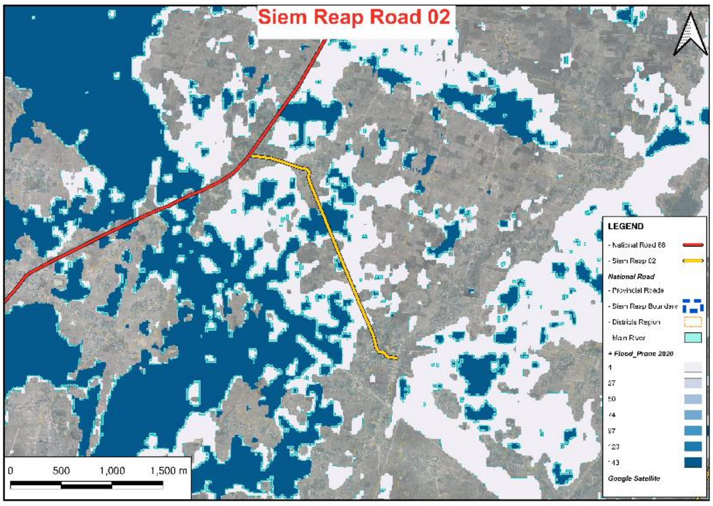

Figure 6. Siem Reap Road 02 map Overlaying Road Track and Flood-Prone

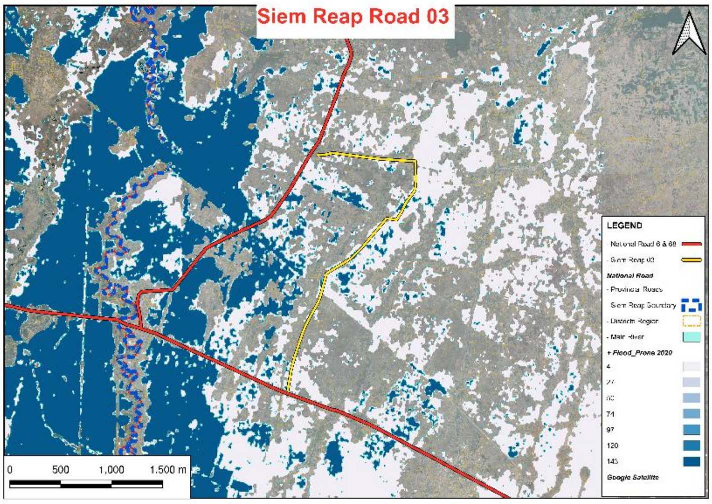

Figure 7. Siem Reap Road 03 map Overlaying Road Track and Flood-Prone

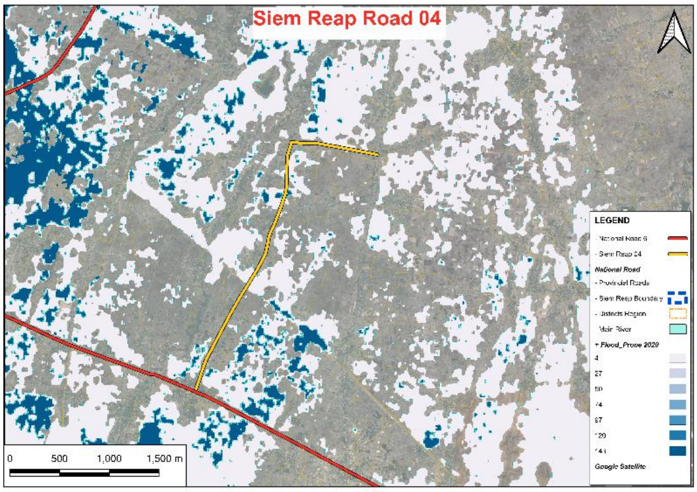

Figure 8. Siem Reap Road 04 map Overlaying Road Track and Flood-Prone

4.1.1 Flood Impact Analysis and Measurement

The flood impact analysis was performed using 30-meter resolution datasets converted into a uniform coordinate system (WGS84/Zone 48 North). The GIS overlay combined road shapefiles and flood-prone raster datasets, enabling the identification of flood-affected road segments using intersection tools. Figures 9 to 12 present detailed analyses of the four selected roads, showing specific locations and lengths of flood-affected segments.

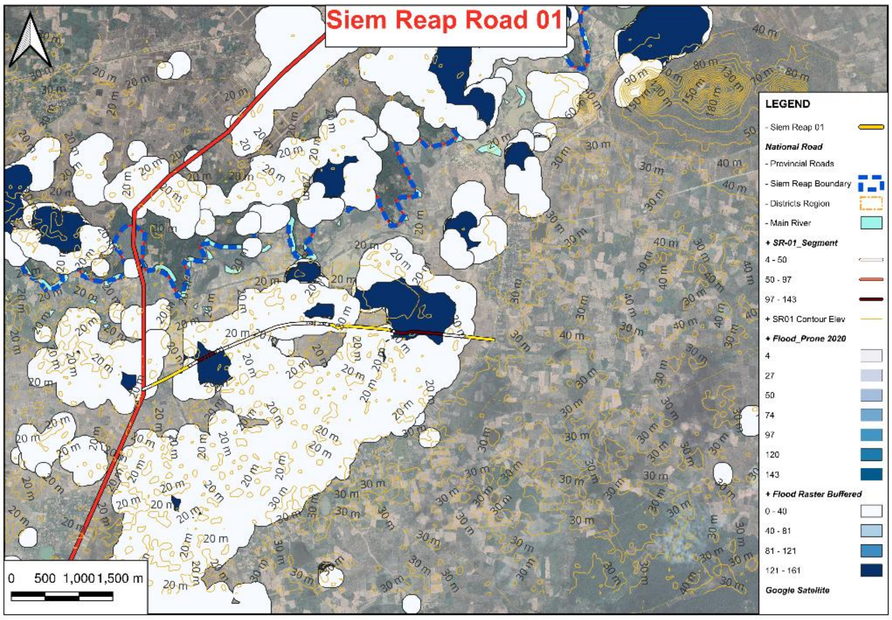

Figure 9. Siem Reap Roads 01 Detail analysis on Flood impacts

The darker flood-prone areas on the maps indicate the riskiest regions, with flood water depths ranging from 4 cm to 143 cm. A 100-meter buffer zone around the flood-affected areas was also analyzed to assess the spatial extent of flood impacts. The specific measurements of flood impacts on the Siem Reap roads were summarized in Table 2 below.

Table 2. Table of Flood Impact Measurement

Road Name	Road Length (m)	Flood Length (m)	Extreme Impact (m)	Medium Impact (m)	Low Impact (m)
Siem Reap 01	5400	3420	1570	130	1720
Siem Reap 02	5500	2500	935.29	170	1394.71
Siem Reap 03	25200	7270	723	240	6307
Siem Reap 04	1500	3955	118	35	3802

This table provides precise measurements of flood-affected road segments, offering critical information for infrastructure planners and decision-makers to prioritize interventions effectively.

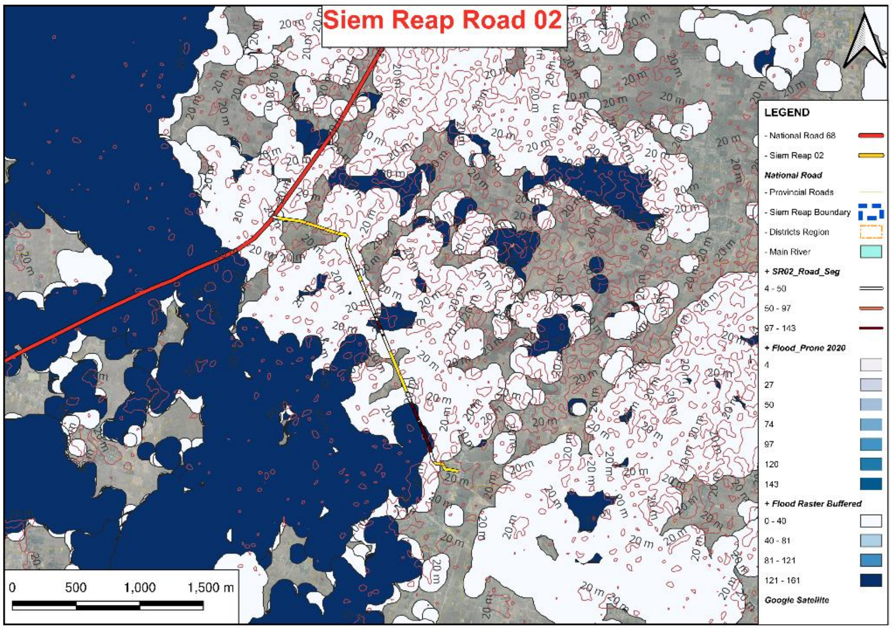

Figure 10. Siem Reap Roads 02 Detail analysis on Flood impacts

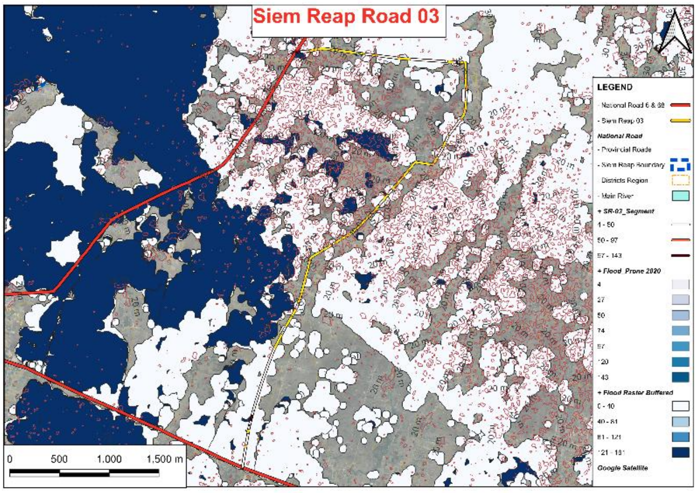

Figure 11. Siem Reap Roads 03 Detail analysis on Flood impacts

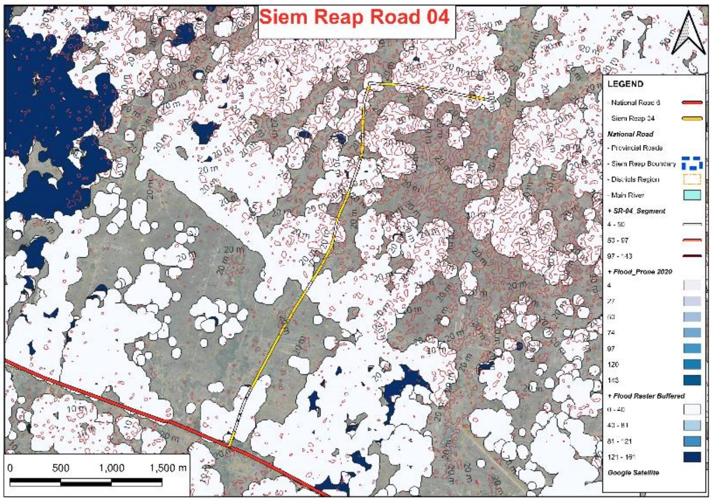

Figure 12. Siem Reap Roads 04 Detail analysis on Flood impacts

4.1.2 Elevation and Slope Analysis

Contour lines were used to analyze the elevation and slope of the areas surrounding the road networks. This slope analysis identifies the direction of water flow across the road and the catchment area contributing to flood risks. The slope data is crucial for applying the Rational Method in hydrological modeling, which requires the calculation of runoff coefficients based on elevation and slope characteristics. The catchment area, visualized using polygons, was measured to determine the flood-prone zone contributing to road flooding. These calculations will be used for further hydrological assessments to propose appropriate flood mitigation measures.

This GIS-based analysis provided a comprehensive assessment of flood vulnerability for rural roads in Siem Reap Province. By mapping flood-prone areas, identifying affected road segments, and integrating elevation and slope data, the study offers a targeted approach for prioritizing road infrastructure improvements. The results highlight specific high-risk zones where flood mitigation strategies, such as improved drainage, road elevation, and adaptive infrastructure planning, are urgently needed to enhance climate resilience in Cambodia's rural areas.

4.2 Rational method data analysis

The Rational Method is applied as a hydrological tool to estimate peak discharge for small catchment areas in Cambodia's flood-prone rural regions. This method combines rainfall intensity, catchment area size, and runoff coefficients to assess water flow volumes during flood events, which critically impact road infrastructure. The results inform targeted resilience strategies, providing a quantitative basis for flood risk mitigation. The Rational Method calculates peak discharge (Q) using the formula:

$$Q = C*i*A$$

where C is the runoff coefficient, i is the rainfall intensity, and A is the catchment area. Table 3: Rainfall Intensity Data shows the total yearly rainfall intensity, calculated into hourly values.

Catchment Area and Runoff Coefficients: The characteristics of each road catchment area were analyzed and listed in Table 4.

Then the results of each road's yearly peak discharge will be shown in Table 5: Yearly Peak Discharge (m^3/s) of Siem Reap Road 01 to Siem Reap Road 04.

Table 3. Rainfall Intensity Data. Source: Department of Meteorology Ministry of Water Resources and Meteorology (MoWRAM), 2023 [Appendix A]

Table 4. Road Flooding Data

Road Name	Road Length (m)	Flood Length (m)	Extreme Impact (m)	Medium Impact (m)	Low Impact (m)	Catchment Area (Sq.KM)	Coefficient
Siem Reap 01	5400	3420	1570	130	1720	7.6	0.4
Siem Reap 02	5500	2500	935.29	170	1394.71	17	0.4
Siem Reap 03	25200	7270	723	240	6307	23.4	0.4
Siem Reap 04	1500	3955	118	35	3802	24.82	0.4

Table 5. Yearly Peak Discharge (m3/s)

Road Name/ Year of Peak Discharge	Siem Reap 01	Siem Reap 02	Siem Reap 03	Siem Reap 04
2012	6.19	13.85	19.06	20.22
2013	7.08	15.84	21.80	23.13
2014	6.28	14.04	19.33	20.50
2015	5.38	12.04	16.57	17.57
2016	7.16	16.01	22.04	23.38
2017	7.08	15.85	21.81	23.14
2018	4.41	9.87	13.59	14.42
2019	6.67	14.91	20.53	21.77
2020	11.34	25.36	34.91	37.03
2021	5.62	12.57	17.30	18.35
2022	5.69	12.74	17.53	18.59
2023	7.00	15.66	21.56	22.87

The analysis highlights that 2020 recorded the highest peak discharge across all four rural roads, with Siem Reap 04 reaching 37.03 m^3/s, emphasizing the need for urgent flood management and infrastructure upgrades. While peak discharge values declined in 2021, a slight increase in 2022 and 2023 indicates continued variability in rainfall and flood risks. Siem Reap 03 and 04 consistently showed high discharge values, marking them as critical areas for prioritized flood resilience interventions. Integrating the Rational Method results with GIS analysis enabled the precise identification of high-risk road segments and visualization of flood severity, aligning hydrological data with spatial flood-prone zones. This combined approach underscores the need for immediate interventions, such as road elevation, improved drainage systems, and embankment stabilization, alongside long-term planning to develop adaptive infrastructure capable of withstanding future extreme rainfall events. The study provides robust insights for policymakers and engineers, emphasizing the importance of targeted infrastructure upgrades to enhance road connectivity and resilience in Cambodia's flood-prone rural regions.

5. Results and Discussion

This study evaluates the vulnerability of Cambodia's rural roads to flooding using Geographic Information Systems (GIS) and hydrological modeling via the Rational Method. The findings provide a detailed assessment of flood-prone areas, spatial patterns of vulnerability, and peak discharge variations over a 12-year period (2012–2023) to inform targeted flood mitigation strategies. Enhancing climate resilience in rural road networks requires collaborative engagement among policymakers, engineers, local communities, and international organizations. The study emphasizes the need for governments to integrate flood resilience into national infrastructure policies, prioritizing investments in flood-prone regions. Additionally, participatory approaches involving local stakeholders can enhance the sustainability of resilience strategies by ensuring community involvement in planning, implementation, and maintenance efforts. Strengthening governance mechanisms, improving data accessibility, and fostering public-private partnerships are critical for scaling up adaptation initiatives effectively.

5.1 Flood-prone identification

The GIS analysis identified flood-prone zones along Siem Reap Roads 01–04 using topographical data, road networks, and historical flood maps. Vulnerable segments were pinpointed by overlaying road tracks with flood zones. Road 01 had 1,570 meters (45.9%) under extreme flood impacts, while Road 02 showed 935.29 meters (37.41%) affected. Road 03, with the largest catchment area (23.4 km^2), experienced 7,270 meters of flooding, including 723 meters classified as extreme. In contrast, Road 04 had high peak discharge but only 118 meters under severe impacts. Spatial patterns revealed roads in low-lying areas or near riverbanks, such as Road 04, exhibited consistent flood exposure, particularly in 2020 (peak discharge of 37.03 m^3/s). Elevation and slope analysis clarified water flow, while a 100-meter buffer confirmed significant water accumulation on Roads 03 and 04, requiring urgent flood management measures.

5.2 Peak discharge runoff results

The Rational Method revealed substantial year-to-year variations in peak discharge across Siem Reap Roads 01–04. 2020 emerged as the most critical year, recording the highest peak discharges due to extreme rainfall. Road 03 experienced 34.91 m^3/s, while Road 04 peaked at 37.03 m^3/s, reflecting the influence of their larger catchment areas and proximity to flood zones. In comparison, Road 01 had moderate peak discharge values ranging from 4.41 m^3/s (2018) to 11.34 m^3/s (2020), while Road 02 fluctuated between 9.87 m^3/s and 25.36 m^3/s. Furthermore, the year 2020 stands out as an anomaly, likely caused by prolonged heavy rainfall or extreme weather events, consistent with global climate change trends. Post-2020, a noticeable decline occurred in 2021, but a slight rebound in 2023 suggests persistent flood risks. Over the 12-year observation, peak discharge increased by 13.13%, indicating intensifying hydrological stress on the rural road network shows in Figure 13: Historical Runoff Data.

5.3 Discussion

The findings from the peak discharge analysis reveal critical implications for flood mitigation and infrastructure planning, particularly for Siem Reap Roads 03 and 04, which consistently experience the highest runoff volumes. These roads require immediate attention, including structural reinforcements, improved drainage systems, and road elevation to withstand increasing water flow. In low-traffic areas, the use of permeable pavements can help reduce runoff while promoting groundwater infiltration. Long-term infrastructure planning must integrate projections of future climate variability, as trends indicate an increasing frequency and intensity of extreme rainfall events. Additionally, maintaining drainage systems, roadbeds, and embankments through regular inspections is essential to prevent costly repairs or disruptions, ensuring the longevity of rural roads and safeguarding rural connectivity against growing climate challenges.

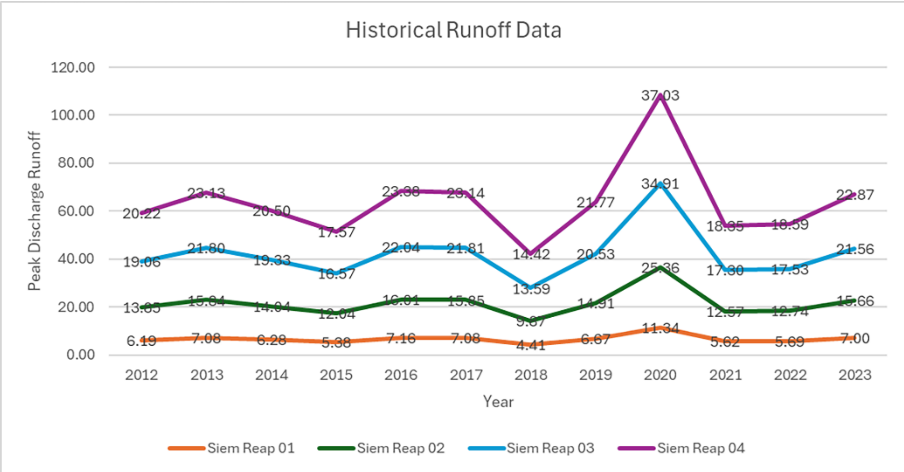

Figure 13. Historical Runoff Data

5.4 Conclusions

The analysis highlights the growing vulnerability of Cambodia's rural roads to flooding, particularly in the Siem Reap region, and underscores the urgent need for proactive infrastructure interventions. Over the 12-year period, peak discharge values fluctuated significantly, with a sharp increase in 2020 due to extreme rainfall events. Roads like Siem Reap 03 and 04 consistently recorded high discharge values, with projections indicating further increases over the next decade, reaching 29.85 m^3/s and 31.66 m^3/s by 2034, respectively. The integration of GIS-based spatial analysis and the Rational Method provided a holistic understanding of flood risks, identifying vulnerable segments and informing targeted solutions such as drainage upgrades, road elevation, and permeable materials. By implementing these adaptive strategies, Cambodia can reduce flood risks, maintain rural connectivity, and support sustainable development amid increasing climate challenges. Moreover, this study extends beyond Cambodia, offering valuable insights for other flood-prone regions. Countries such as Bangladesh, Vietnam, and parts of Sub-Saharan Africa face similar challenges with seasonal monsoon flooding affecting rural infrastructure. The use of GIS-based flood mapping and the Rational Method for peak discharge estimation can be applied in these contexts to enhance climate resilience in rural transportation networks. Moreover, the identified mitigation strategies—such as improved drainage, road elevation, and the use of permeable materials—are universally applicable and can be adapted to local conditions to strengthen infrastructure resilience globally (Intergovernmental Panel On Climate Change (Ipcc), 2023).

5.5 Recommendations

Four targeted infrastructure solutions are proposed to mitigate flood risks. First, improved drainage systems are necessary to accommodate rising runoff volumes, especially in vulnerable areas like Siem Reap Road 04, where peak discharges are projected to exceed 30 m^3/s by 2034. Second, road elevation in high-risk areas, such as Siem Reap Road 03, can prevent floodwaters from overtopping and damaging road surfaces. Third, using permeable materials in low-traffic areas, particularly on Siem Reap Road 01, can help manage surface runoff effectively. Finally, slope protection along critical catchment areas is recommended to prevent erosion and protect road foundations from runoff during extreme rainfall. These measures are vital to improving road resilience and ensuring the continued functionality of rural transportation networks.

5.6 Limitations

This study faced limitations related to data quality and methodology. The reliance on historical rainfall data and 30-meter resolution raster data for GIS analysis limited the precision of identifying flood-prone road segments, particularly in areas with fine-scale topographical variations. Inconsistencies in rainfall records and data gaps further impacted the accuracy of Rational Method predictions. Methodologically, while effective for small, homogenous catchments, the Rational Method introduced uncertainties when applied to larger, complex watersheds with diverse land uses. Uniform runoff coefficients and time of concentration (Tc) values did not account for slope, vegetation, or soil permeability variations. Additionally, IDF curves based on historical data may not fully capture future climate variability, leading to potential overestimations or underestimations of peak discharge. Future research should address these limitations by integrating higher-resolution datasets, real-time monitoring systems, and advanced hydrological models to improve accuracy and account for climate change projections and localized environmental factors.

References

ADB (2016). Cambodia: Addressing Climate Change Impacts on Rural

Infrastructure. *Asian Development Bank*.

Bollinger, L. A., Bogmans, C. W. J., Chappin, E. J. L., Dijkema, G. P. J.,

Huibregtse, J. N., Maas, N., Schenk, T., Snelder, M., Van Thienen, P., De Wit, S., Wols, B., & Tavasszy, L. A. (2013). Climate adaptation of interconnected infrastructures: A framework for supporting governance. *Regional Environmental Change*.

https://doi.org/10.1007/s10113-013-0428-4

Chinowsky, P., Schweikert, A., Strzepek, N., Manahan, K., Strzepek, K., & Schlosser, C. A. (2013). Climate change adaptation advantage for African road infrastructure. *Climatic Change*, *117*(1–2), 345–361. https://doi.org/10.1007/s10584-012-0536-z

D'Agostino, A. L., & Sovacool, B. K. (2011). Sewing climate-resilient seeds: Implementing climate change adaptation best practices in rural Cambodia. *Mitigation and Adaptation Strategies for Global Change*, *16*(6), 699–720. https://doi.org/10.1007/s11027-011-9289-7

Intergovernmental Panel On Climate Change (Ipcc). (2023). *Climate*

Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009325844

IPCC (2021). Climate Change 2021: The Physical Science Basis. *Intergovernmental Panel on Climate Change*.

Jacobson, C. (2020). Community climate resilience in Cambodia. *Environmental Research*, *186*, 109512. https://doi.org/10.1016/j.envres.2020.109512

Lebel, L., Käkönen, M., Dany, V., Lebel, P., Thuon, T., & Voladet, S. (2018). The framing and governance of climate change adaptation projects in Lao PDR and Cambodia. *International Environmental Agreements: Politics, Law and Economics*, *18*(3), 429–446. https://doi.org/10.1007/s10784-018-9397-x

Natarajan, N., Brickell, K., & Parsons, L. (2019). Climate change adaptation and precarity across the rural–urban divide in Cambodia: Towards a 'climate precarity' approach. *Environment and Planning E: Nature and Space*, *2*(4), 899–921. https://doi.org/10.1177/2514848619858155

Odemerho, F. O. (2015). Building climate change resilience through bottom-up adaptation to flood risk in Warri, Nigeria. *Environment and Urbanization*, *27*(1), 139–160. https://doi.org/10.1177/0956247814558194

Ogunbode, C. A., Böhm, G., Capstick, S. B., Demski, C., Spence, A., &

Tausch, N. (2019). The resilience paradox: Flooding experience, coping and climate change mitigation intentions. *Climate Policy*, *19*(6), 703–715. https://doi.org/10.1080/14693062.2018.1560242

Phy, S. R., Sok, T., Try, S., Chan, R., Uk, S., Hen, C., & Oeurng, C. (2022). Flood Hazard and Management in Cambodia: A Review of Activities, Knowledge Gaps, and Research Direction. *Climate*, *10*(11), 162. https://doi.org/10.3390/cli10110162

Regmi, M. B., & Hanaoka, S. (2011). A survey on impacts of climate change on road transport infrastructure and adaptation strategies in Asia. *Environmental Economics and Policy Studies*, *13*(1), 21–41. https://doi.org/10.1007/s10018-010-0002-y

UNDP Cambodia (2021). Strengthening Climate Resilience in Cambodia's Rural Communities. *United Nation Development Programme*.

Wilby, R. L., & Keenan, R. (2012). Adapting to flood risk under climate change. *Progress in Physical Geography: Earth and Environment*, *36*(3), 348–378. https://doi.org/10.1177/0309133312438908

World Bank (2020). Cambodia: Strengthening Resilience to Floods. *World Bank Group*.

Authors

Monirath Ly rath.dawson@gmail.com

Chunho Yeom *(corresponding author)* chunhoy7@uos.ac.kr

International School of Urban Sciences, University of Seoul, 02504 Seoul, Korea.

Funds

This study was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (grant #NRF-2020S1A5C2A01092978).

Competing Interests

The authors hereby state that there are no financial and non-financial competing interests.

Citation

Ly, M. & Yeom, C. (2025). Climate resilience to floods on rural roads in Cambodia *Visions for Sustainability*, 24, 11406, 1-25. http://dx.doi.org/10.13135/2384-8677/11406