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ERASMUS MUNDUS JOINT MASTER DEGREE

MASTER DEGREE IN SUSTAINABLE DESIGN, CONSTRUCTION AND MANAGEMENT OF THE BUILT ENVIRONMENT

MBUILD

Climate-Resilient Road Infrastructure in Developing Countries: Assessing the Applicability of International Best Practices in Panama through Case Studies

LEYLA CRISTEL CORONEL MORENO

Supervision: Pablo Pascual, UC

Santander, September 2025

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Dedicated to all Panamanians who not only dream of a better country
but wake up every day and work fervently to make it happen.

Climate-Resilient Road Infrastructure in Developing Countries: Assessing the Applicability of International Best Practices in Panama through Case Studies.

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ABSTRACT

Road infrastructure is a critical part of any society, not only for economic development but also as a lifeline for mobility and connectivity. However, the increasing frequency and intensity of climate-related hazards, such as floods, extreme temperatures, and sea level rise, pose growing challenges to the durability and functionality of road systems. These challenges are particularly difficult for developing countries, which often require more time and resources to implement effective recovery and adaptation measures. This is the case of Panama, a small yet rapidly emerging country in Central America that is highly vulnerable to the impacts of climate change due to its geographic location and weather conditions. The aim of this thesis is to study road resilient infrastructure methodologies used in other countries and define how these strategies can be implemented in Panama. Specifically, this research explores four international case studies: the use of permeable pavements in the United States of America, geosynthetics for landslide prevention in Brazil, the Room for the River program in the Netherlands, and heat-resilient asphalt mixtures in the United Arab Emirates. These strategies were selected for their relevance to challenges that Panama currently faces, such as intense rainfall, flooding, landslides, and extreme heat. The thesis analyzes the applicability of each strategy to Panama, considering the country's social, political, and economic context. By comparing these international practices with Panama's existing infrastructure standards and climate vulnerabilities, the study aims to evaluate opportunities for integration, adaptation, and long-term resilience building in the national road network.

Keywords: resilience, road infrastructure, comparative study, sustainable development.

RESUMEN

La infraestructura vial es una parte fundamental de cualquier sociedad, no solo para el desarrollo económico, sino también como un elemento vital para la movilidad y la conectividad. Sin embargo, el aumento en la frecuencia e intensidad de los fenómenos climáticos, como las inundaciones, las temperaturas extremas y el aumento del nivel del mar, plantea desafíos crecientes para la durabilidad y funcionalidad de los sistemas viales. Estos desafíos son particularmente difíciles de afrontar para los países en desarrollo, que a menudo requieren más tiempo y recursos para implementar medidas eficaces de recuperación y adaptación. Este es el caso de Panamá, un país pequeño, pero con un rápido crecimiento en Centroamérica, es altamente vulnerable a los impactos del cambio climático. El objetivo de esta tesis es estudiar metodologías de infraestructura vial resiliente utilizadas en otros países y definir cómo estas estrategias pueden ser implementadas en Panamá. Específicamente, esta investigación explora cuatro estudios de caso internacionales: el uso de pavimentos permeables en los Estados Unidos de América, geosintéticos para la prevención de deslizamientos en Brasil, el programa Room for the River en los Países Bajos y mezclas de asfalto resistentes al calor en los Emiratos Árabes Unidos. Estas estrategias fueron seleccionadas por su relevancia frente a los desafíos que actualmente enfrenta Panamá, tales como lluvias intensas, inundaciones, deslizamientos de tierra y calor extremo. Esta tesis analiza la aplicabilidad de cada estrategia en el contexto panameño, considerando sus condiciones sociales, políticas y económicas. Al comparar estas prácticas internacionales con los estándares de infraestructura existentes en Panamá y sus vulnerabilidades climáticas, el estudio busca evaluar oportunidades de integración, adaptación y fortalecimiento de la resiliencia a largo plazo en la red vial nacional.

Palabras clave: resiliencia, infraestructura vial, estudio comparativo, desarrollo sostenible.

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

IMPHPA - The Panama institute of Meteorology and Hydrology

GCMs - Global Climate Models

SHRP - Strategic Highway Research Program, Washington, DC

MPM - Material Point Method; numerical simulation technique

I / Ks - rainfall intensity / saturated hydraulic conductivity of the soil

HMA - Hot Mix Asphalt

UNDRR - United Nations Office for Disaster Risk Reduction

SDG – Sustainable Development Goals

PCR - Peru’s Rural Roads Program

GIB - Global Infrastructure Basel Foundation

FHWA - US Federal Highway Administration

ADCIRC - Advanced Circulation Model

STWAVE - Steady State Spectral Wave model

NAVD88 - North American Vertical Datum of 1988

RCC - Roller Compacted Concrete

ICBP - Interlocking Concrete Block Pavements

SuDS - Sustainable Urban Drainage Systems

USGS - United States Geological Survey

SBS - Styrene Butadiene Styrene

PMB – Polymerer Modified Bitumen

DVR–LDPE - devulcanized rubber combined with low-density polyethylene

DVR–PP - devulcanized rubber combined with polypropylene

NB - neat bitumen

LAS - Linear Amplitude Sweep

MOP - Ministry of Public Works of Panama

NDC - Nationally Determined Contribution Report

IDAAN - National Institute of Aqueducts and Sewage Systems

IHCantabria - Instituto de Hidraulica Ambiental

IDB - Inter-American Development Bank

SENACYT - National Secretariat for Science and Technology in Panama

MiAMBIENTE - Ministry of Environment of Panama

GCF - Green Climate Fund

SINAPROC - National Civil Protection System

UTP - Universidad Tecnologica de Panama

Fig – Figure

1

INTRODUCTION

1.1. BACKGROUND

Road infrastructure is an essential component of any society, not only for economic development but also as a foundation for sustainable mobility and connectivity. Poorly planned or ineffective designs can undermine long-term environmental sustainability by increasing vulnerability to climate-related hazards, reducing adaptability, and weakening the lasting life of road infrastructure. In the last decades, natural hazardous events have been happening more often, and this is having a huge impact in road infrastructure. To mention an example, by mid-century, the Greater Vancouver area is projected to experience significantly more annual rainfall days, increasing climate-related stress on road infrastructure infrastructure [1]. These changes suggest a challenge for infrastructure resilience, relying on a greater need for resources in the long run.

The most vulnerable communities regarding climate hazard related problems in road infrastructure are those situated in coastal and flood-prone regions, especially those where rapid urbanization is taking place. In addition, impoverished communities in high-risk zones face a greater challenge due to limited adaptive capacity [2]. In this context, Panama emerges as a relevant country to study due to its geographical location, exposure to climate-related hazards such as heavy rainfall and flooding, to mention some. In 2024, Panama registered such strong rainfall that caused the complete collapse of a road that provides access to several communities in the province of Chiriqui. The Panama institute of Meteorology and Hydrology (IMPHPA) reported that the rainfall intensity was a result of the intertropical convergence zone and low-pressure systems, that could be more severe that year due to climate change conditions [3]. This is not the first time a rainfall event has caused terrible damage to communities in the area, and the most affected infrastructure is roads. This situation leaves residents in difficult conditions during the time required for road repairs. In addition to this, Panama is rapidly growing its urbanization development in the last years. Overall, Panama has an approximate road network of 15.137 km, of which 6.351 km are paved, and the government has said that in the next coming years, this network will be improved and expanded. This funding could overcome 3 billion USD [4]. However, as a developing country, with significant infrastructure demands, but limited adaptive capacity, Panama faces considerable challenges in ensuring the resilience of its road networks against current and future climate risks. Therefore, examining Panama's vulnerabilities and exploring how resilience strategies from developed countries can be applied, can offer valuable insights for improving road infrastructure planning and long-term sustainability.

1.2. PROBLEM STATEMENT

Road infrastructure is undeniably a critical component of national development, providing connectivity, ensuring access to essential services, and supporting economic activities. Nevertheless, in many developing countries, road infrastructure systems are increasingly threatened by the impacts of climate change, including more frequent and intense precipitation. These changes lead to flooding and landslides, which directly affect road networks. In addition, the rise in mean temperatures is another factor that can compromise road durability, and this issue will be explored later in the study.

To mention some examples of developing countries that are facing challenging consequences regarding climate change and the resilience of their road infrastructure, Bangladesh's roads have suffered damage due to seasonal flooding and waterlogging, isolating communities and disrupting communication and supply chains. Kenya also suffers consequences from rising temperatures and irregular rainfall, which have been linked to pavement deformation and culvert collapse, specifically in remote areas. Another example occurs in Nepal, where landslides triggered by the monsoon rains often destroy road embankments, particularly in areas with mountainous terrain and weak soil composition. These are just a few examples that illustrate the important need for climate-resilient design and planning across countries that already face difficult climate conditions affecting the integrity of road infrastructure [5].

Panama is one such case. A country with diverse topography and tropical weather, the impacts on climate related hazards such as flooding, heavy rainfall, and landsides have become more severe and frequent. According to the World Bank [6], Panama is ranked as the 14th most hazard-prone country in the world in terms of the percentage of its land area exposed to multiple natural hazards.

Despite the visible vulnerabilities, Panama's current road infrastructure planning and design often lack the integration of strategies that have been applied in developed countries with success. Panama continues to rely on traditional construction practices that are not sufficient to face the challenges that changing climate poses today. Deficient infrastructure, especially poor road infrastructure and maintenance are the main challenges in Panama that hold the country back [4]. This whole situation is an example of a critical gap in the country's infrastructure policy, which is the absence of a comprehensive approach to climate resilience. Without adopting new strategies to acquire resilient road infrastructure, Panama's roads will continue to suffer increasing damage, leading to higher maintenance costs, prolonged disrupted connectivity, and a threat to user's safety.

Climate change threatens road infrastructures in several ways, some of these impacts are related to heavy precipitation. This is because road design specifications are determined by factors such as frequency, intensity and duration of extreme precipitation events. In this sense, the duration ranges or recurrence intervals that have been used for civil engineers for road culverts, pavement design, subgrade layers, and storm water drainage systems are outdated due to the projected increases in the intensity of the precipitation. This situation puts all the values mentioned in a need for greater capacity and shorter recurrence intervals, raising the costs for the systems [7].

As these intense precipitation events become more frequent and prolonged, the risk of flooding in urban areas increases, while river floods in rural regions can lead to bridge collapses and landslides. Urban flood hazard levels in Panama are high, and the future design projects in the country need to be solid to prevent river flood hazards in the future [8]. On the other hand, rural roads have already been a blank for extreme weather-related events. In November of 2020, the region of Cerro Punta in the province of Chiriqui, Panama, experienced heavy and prolonged that triggered landslides, resulting in death of 17 people and leaving dozens missing. In addition, river floods caused the collapse of a bridge, cutting off the community from the city [9].

Developing countries whose cities are rapidly emerging, such as is the case of Panama City should consider resilient strategies that adapt to the new challenges that climate change brings road infrastructures. However, the applicability of these strategies should be adapted to the country's resources and challenges that exist.

1.3. RESEARCH OBJECTIVES

This thesis aims to explore climate-resilient strategies for road infrastructure in developed countries and analyse how these strategies can be adapted to developing nations. While the broader focus is on transferable climate adaptation practices, Panama is used as a representative case study of a developing country facing increasing climate-related risks to its road infrastructure.

This research seeks to contribute to the advancement of sustainable and resilient practices for road networks, which are experiencing growing challenges in durability and functionality due to climate change-related hazards.

1.3.1. Specific research objective list

a) To explore how climate-resilient strategies have been implemented in developed countries to address emerging climate change challenges in road infrastructure.

b) To analyse the current state and climate vulnerability of road infrastructure in a developing country context.

c) To assess the applicability of international resilience strategies to the context of developing countries.

d) To propose practical recommendations for enhancing road infrastructure resilience to climate-related hazards in developing countries.

1.4. SCOPE OF THE STUDY

This study focuses on the analysis of climate-resilient road infrastructure strategies in selected countries and evaluates their applicability to Developing countries. Specifically, it examines international practices from the United States, Netherlands, Brazil, and the United Arab Emirates, representing a diversity of climatic conditions and institutional capacities in both developed and developing settings.

Panama is used as the primary case study for assessing the applicability of these strategies in the context of a developing country. The application of this research centers on the country's most climate-vulnerable areas, including both urban and rural regions. In urban areas, the study considers adaptation strategies in the context of rapid population growth, which increases exposure to climate risks such as flooding and heat. In rural areas, particularly in mountainous zones with high precipitation, road functionality is frequently compromised due to landslides and erosion during extreme weather events.

The methodology employed includes a literature review and comparative analysis of case studies to identify key strategies and evaluate their relevance to Panama. While the study reviews aspects of the institutional and policy framework related to climate adaptation, it does not include detailed legal or financial feasibility analysis.

This thesis focuses exclusively on climate-related hazards, including flooding, heavy rainfall, and landslides. It does not address risks associated with seismic activity or other natural hazards beyond the scope of climate change.

2

STATE OF THE ART

2.1. CLIMATE CHANGE AND ROAD INFRASTRUCTURE

Road infrastructure has traditionally been designed using engineering standards that rely on historical data. However, this approach is increasingly inadequate in the context of climate change, which has introduced variability and greater intensity in weather patterns. The frequency of extreme events such as intense rainfall, and the increase in temperatures has increased greatly in recent decade, challenging the assumptions built into conventional design practices. Historical climate data can no longer serve as a reliable guide for predicting future weather conditions, especially after 2050, when uncertainty in climate projections is expected to increase even further [10].

If road infrastructure continues to be developed following outdated standards that fail to incorporate evolving climate risks, these systems will remain to extreme damage, disruption, and early deterioration during extreme weather events. This highlights the current need to integrate climate models that follow adaptive design principles into transportation infrastructure planning and engineering.

When the vulnerabilities of road infrastructure to climate change are not addressed or assessed properly, the resulting damage and service disruptions during hazardous weather events can compromise public safety, affect mobility, and thus, negatively impact a country's economy. That is another reason why road infrastructure resilience needs to be prioritized as a strategic goal. A 2016 study on Mexico's transport infrastructure assessed the vulnerability of different region roads from 2015 to 2050, using and low and high impact model climate scenarios. The study projected fiscal damages and estimated opportunity cost percentages, and it was divided into two timeframes: from 2015 to 2030 and from 2031 to 2050. To assess the vulnerability of road infrastructure to climate change, the study employed a combined modelling approach that incorporated climate projections based on several Global Climate Models (GCMs), considering the uncertainty that is associated with future climate conditions. This research selected two main scenarios: "the 5th percentile" to represent a low-impact projection, and "the 95th percentile" to reflect a high impact scenario. This approach allowed them to evaluate the potential outcomes and understand better the magnitude of risks for road infrastructure under different climate futures. The results are presented in Table 1, showing that while the opportunity cost remained low in the first studied period, it increased drastically in the second studied period, up to 14% under high severity climate projections. This suggests that more serious climate-related damage to road infrastructure is expected beyond 2030, reinforcing the importance of incorporating climate risk into long-term infrastructure planning [11].

Table 1. Primary roads vulnerability by region for the periods 2015 – 2030 and 2031 – 2050. 5th and 95th percentile model represents low and high severity climate change damages, respectively.

Region	**Cost (USD M)**				**Opportunity cost**			
	2015–2030		**2031–2050**		**2015–2030**		**2031–2050**	
	5th	95th	5th	95th	5th	95th	5th	95th
North East	192	637	424	1134	5%	16%	11%	29%
North West	25	208	75	462	1%	4%	2%	9%
Central	49	199	146	485	1%	3%	2%	8%
Peninsula	51	370	132	654	2%	12%	4%	22%
South West	72	212	147	500	2%	5%	3%	11%
TOTAL	**389**	**1626**	**923**	**3235**	**2%**	**7%**	**4%**	**14%**

This vulnerability study is not unique to Mexico. Worldwide, road infrastructure is increasingly threatened by climate variability and the growing frequency of extreme weather events. As these challenges intensify over time, there is an urgent need for international guided adaptation efforts. In response to this problem, various global institutions and agreements have developed frameworks to support countries in building climate resilient infrastructure. These initiatives, besides providing scientific guidance, contribute to the creation of policy tools, funding mechanisms and collaborative platforms that help nations incorporate infrastructure planning and long-term investment strategies. Some of these frameworks will be explored in the next subchapter.

It is also important to understand how climate related hazards directly impact the durability of road infrastructure. Intense rainfall, leading to flooding and landslides, and heatwaves, to mention some accelerate the degradation of road materials and sub-grade. The climate action plan from the U.S. Department of Transportation recognizes some of the most notable potential impacts that extreme climate conditions can have on road duration. Among the most pressing climate-related challenges, which are also affecting road infrastructure in the country under study, are rising sea levels, increased rainfall intensity, and the increase of heatwaves and global temperatures. These climate change related situations contribute to the deterioration of paved surfaces, shortening service life, and leading to higher maintenance and repair costs, specifically for those areas located in coastal areas [12].

One of the most critical manifestations of climate change for coastal road infrastructure is sea level rise, which especially poses great risks to road networks near shorelines. In an intermediate high scenario study, global sea level rise is projected to increase by

1.20 m minimum and 2.00 m maximum, from 2014 to 2100. These projections are based on statistical links that have been observed in air temperatures and global sea level changes, including contribution from ice sheet loss [13]. As sea level continues to rise, vulnerable zones in low lying coastal areas face increasing risk of flooding, erosion and permanent submersion, creating more challenges to road infrastructure. In certain areas, groundwater levels will be elevated by sea level rise to the point where they can reach the unbound layers of coastal roads, compromising the stability and strength of pavement structures [14]. Indeed, the combination of inland systems threats such as intense rainfall events and sea level rise, put coastal transport infrastructure in greater risk of all [15].

Another serious climate related hazard threat that could affect road infrastructure are intense rainfall and flooding. Water infiltration into pavement layers decreases their strength and stiffness, reducing its load bearing capacity of the saturated roadway. When traffic passes over this weakened section, it can result in rutting, cracking, reduced pavement lifespan, and localized structural failures, as illustrated in Fig. 1.

Fig. 1 - Colorado, USA; flooding damage [16].

In addition, heavy rainfall can lead to overwhelming drainage systems, which can lead to surface water accumulation on pavement. This persistent moisture can infiltrate the pavement layers and reduce the adhesion between the binder and the aggregate, causing structural damage, which is typically referred to as stripping [17]. Moisture damage in asphalt pavement can be manifested in two primary types of failures: adhesive failure, where the bond between the binder and the aggregate breaks down, and cohesive failure, where the binder itself loses internal strength. These forms of failure are shown on Fig. 2 and have been the subject of extensive research for decades.

Notably, the Strategic Highway Research Program (SHRP) in Washington, DC, conducted a detailed study on moisture sensitivity in asphalt mixtures as early as 1994 [18]. These moisture related issues not only shorten the pavement’s lifecycle but also increase maintenance costs and could even compromise road safety due to accelerated formation of potholes and rutting.

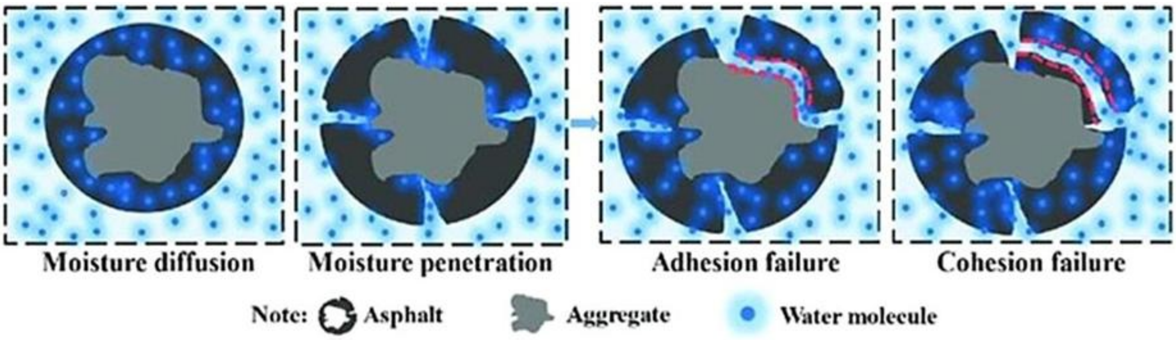

Fig. 2 - Damage progress of asphalt pavement leading to either adhesion and cohesion failure due to moisture [17].

In addition to understanding the types of failure in asphalt, it is crucial to identify the key mechanisms that cause moisture damage in pavement. Fig. 3 illustrates two of the most critical mechanisms: pore pressure and hydraulic scouring. Pore pressure occurs when water becomes trapped within the asphalt mixture and builds up pressure under traffic loads. This internal pressure weakens the bond between the bitumen and the aggregate, leading to stripping. The likelihood of this phenomenon depends heavily on the air void content. When the air void content is below 8%, the voids are generally sealed off, making it difficult for water to enter. However, when the air void content falls between 8% and 10%, the voids begin to interconnect and let water enter, but draining it becomes difficult. This creates a critical zone in which moisture becomes trapped, and under repeated loading, builds pressure that stresses the binder–aggregate interface, initiating microcracks and ultimately causing stripping. The second major mechanism is hydraulic scouring, which involves the removal of asphalt binder by pressurized water that is forced into the pavement surface by the rolling action of vehicle tires. As traffic applies repeated compression and tension cycles to the trapped water, the bond between the binder and aggregate weakens. Over time, this deterioration leads to pavement degradation. The presence of fine particles such as clay and silt suspended in the water can also worsen the damage, as they act like abrasives that accelerate the erosion of the binder film.

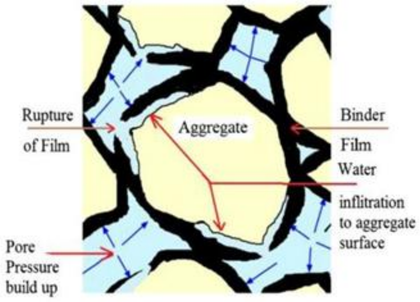	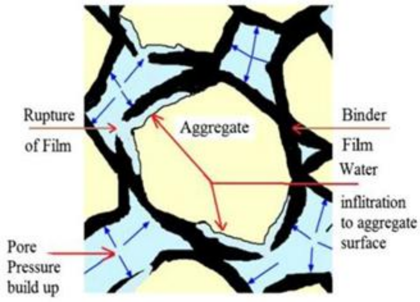
(a)	(b)

Fig. 3 - (a) Moisture damage due to pore pressure; (b) Moisture damage by hydraulic scouring [17].

Moisture damage is already a persistent challenge that has increased with the rise of extreme weather events related to heavy rainfall and flooding. Therefore, enhancing pavement designs to address moisture susceptibility has become an urgent priority in road infrastructure planning and development [2].

While moisture related damage is a major threat to the performance of road infrastructure, severe geotechnical hazards can occur during periods of intense rainfall, particularly landslides. In mountainous or steep terrain with poor drainage, saturated soil conditions lead to structural instability, which often result in road failure. These events pose significant risks not only to road users but residents nearby. A study by McAdoo [19] showed that in Nepal more landslides occur near roads due to heavy rain than earthquakes. To explain better, the roads specially built near slopes are even more vulnerable when it rains heavily, than when they are exposed to earthquakes. This could locate roads constructed along or cut into slopes on vulnerability when climate change intensifies rainfall patterns. Furthermore, heavy rainfall elevates pore water pressure within sloped soils causing shallow landslides [20]. A numerical simulation technique known as the Material Point Method (MPM) was employed to explore the mechanisms by which heavy rainfall triggers landslides in saturated slopes [21]. This method is particularly effective for modeling large deformations in geo- materials under dynamic loading conditions, such as those caused by rainfall infiltration. In the analysis, the authors introduced a dimensionless ratio I / Ks, where I represents rainfall intensity and Ks denotes the saturated hydraulic conductivity of the soil. Their simulations demonstrated that when this ratio exceeds 0.5, the infiltration rate surpasses the soil's capacity to drain water, resulting in a rapid increase in pore water pressure within the soil matrix. This pressure buildup reduces the effective stress acting on the soil, thereby diminishing shear strength and significantly increasing the likelihood of slope failure. Fig. 4 illustrates how rainfall intensity is relative to soil permeability (expressed as the I/k_s ratio) influences the development of pore water pressure in slopes. When the ratio is low ($I/k_s < 0.5$), water slowly infiltrates the soil, forming an unsaturated wetting front that moves downward gradually. In this case, groundwater rises slowly, and pressure builds up first at the bottom of the slope. In contrast, when the ratio is high ($I/k_s > 0.5$), heavy rainfall saturates the soil rapidly, causing pore water pressure to increase more quickly and uniformly throughout the slope. This difference in saturation behavior directly affects the timing and nature of slope failure, making the I/k_s ratio a key indicator in predicting rainfall-induced landslides.

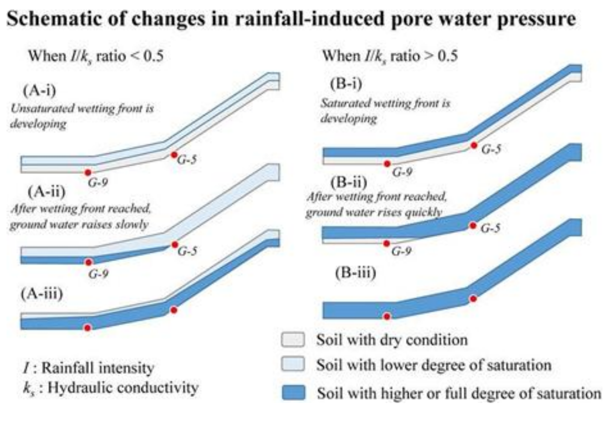

Fig. 4 - Representation of changes in pore pressure water caused by rainfall [21].

The study further showed that this process typically initiates with surface saturation, leading to the onset of shallow landslides. However, if rainfall persists or intensifies, the zone of saturation can migrate deeper into the slope profile, potentially transitioning into more destructive failures. These findings further highlight the importance of integrating hydrological and geotechnical parameters into early warning systems and risk assessments, especially in regions with steep topography and high rainfall variability, while also accounting for the increasing weather extremes driven by climate change.

Just as extreme rainfall threatens infrastructure through landslides and moisture damage, another growing concern for road durability is the rise in temperatures and extreme heat events. Global climate change is also driving a significant rise in extreme heat events, including more frequent and intense heatwaves. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, human activities, particularly the emission of greenhouse gases, have already increased global temperatures by approximately 1.1°C since the late 19th century, and the projections indicate that the global average temperature will likely reach or surpass 1.5°C in the coming decades, with impacts expected across all regions of the world [22]. As pictured in Fig. 5, global surface temperatures have sharply increased since the late 20th century. The most concerning part is that recent decades are showing the most pronounced warming. The alarming situation supports the allegation that historical climate records are no longer acceptable for road infrastructure design [23].

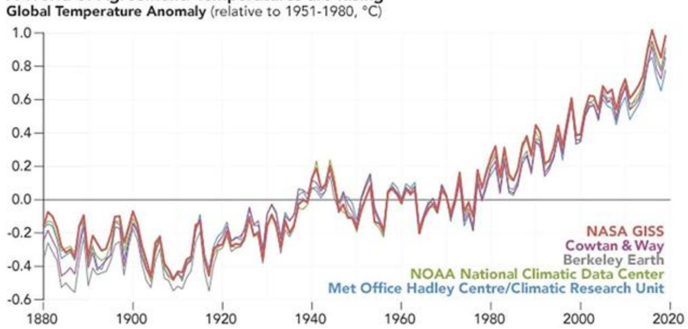

Fig. 5 - Global surface temperature anomalies, 1880–present, relative to the 1951–1980 average [23].

This trend in global temperatures shows not only a climatic shift to continue, but an increase in the severity, duration and frequency of extreme heat events. These changes have direct implications on the performance of road infrastructure, especially asphalt pavement, which are highly sensible to thermal stress. High temperatures during prolonged times can cause asphalt to soften, expand, and deform, to mention some consequences, resulting in serious pavement distress such as rutting, cracking and bleeding. The structural performance of pavements under extreme heatwave events were evaluated through case studies and determined that these extreme temperatures, in the form of heatwaves, the increase of mean annual temperatures, and the changes in the annual extreme temperatures, in general, lead to a faster deterioration in the pavement structure [24]. These forms of deterioration lead to various types of pavement distress, including surface ruptures (blow-ups), loss of binder-aggregate adhesion (stripping), excess bitumen on the surface (bleeding), and permanent shape changes like rutting or deformation [25]. In his article of 2024, Vamos explains how in hot climates and during peak summer conditions, the rise in temperature significantly reduces the viscosity and stiffness of the asphalt binders, making hot mix asphalt (HMA) more prone to rutting [26]. It has also been noted that heavy traffic load transmits greater vertical stress to the subgrade as the binder softens. Thus, as climate change causes more frequent and extended period of hot temperatures, pavements are every time more exposed to conditions beyond their designed limits. It is essential that pavement design standards and material evolve to be more resilient against climate change and pavement durability.

2.2. RESILIENCE CONCEPTS AND FRAMEWORKS

When it comes to road infrastructure, resilience plays a critical role in supporting the continuous development of nations by minimizing disruptions caused by road damage or closures and by enabling communities to recover faster after hazardous events. In recent decades, climate change has created increasingly severe weather conditions that pose significant challenges to road infrastructure. These hazards not only reduce the service life of roads but also pose serious risks to public safety and economic stability. Disaster-resilient infrastructure is designed to better withstand and recover from natural hazards than conventional systems [27]. However, before effective resilience policies can be developed, it is essential to have a clear and shared understanding of what resilience means. As defined by the National Infrastructure Advisory Council in 2009, infrastructure resilience consists of three core attributes: robustness, the ability to maintain critical operations during a crisis; resourcefulness, the capacity to effectively plan for, respond to, and manage disruptions; and rapid recovery, the ability to restore normal operations quickly and efficiently after a disruptive event [28]. In developing countries, building resilient infrastructure is especially urgent. Limited institutional capacity and resource constraints often lead to delayed repair efforts, meaning that disruptions to the road network can persist for extended periods, hindering mobility, disrupting economic activity, and affecting daily life.

In 2015, the World Road Association created the International Climate Change Adaptation Framework for Road Infrastructure, to increase the resilience of road by identifying and revising the current construction and design standards [10]. This framework established four stages to assign new standards for the design of road infrastructure, and these go from identifying and gathering all existing data to integrating each of their findings in the decision-making process that put the assessment of risks on the cusp of this work. In addition to this, the flexibility that characterizes this framework allows it to be applied across numerous ranges of settings, including regions with different economic capacities and government strengths. It is designed to support high- income nations as well as developing countries making efforts to enhance climate resilience over their existent and future road infrastructure [11].

The United Nations Office for Disaster Risk Reduction (UNDRR), in collaboration with University College London, has developed the Sendai Framework with a group of principles and actions aimed at strengthening national resilience and ensuring the continuity of critical infrastructure systems. Although the framework is cross-sectoral, it aligns closely with SDG 9 and is particularly relevant to road infrastructure networks. It sets out six core principles for achieving resilient infrastructure, the first of which emphasizes continuous learning. This principle exhorts stakeholders to engage in ongoing knowledge acquisition and capacity building; without such commitment, operators are less able to prevent outages and to recover quickly when failures occur. The framework therefore underscores rapid anomaly detection and evidence-based decision-making as prerequisites for optimizing resilience through timely recovery and disaster mitigation. A further objective involves analysing current conditions and formulating improvements. The absence of reliable data and the limited understanding of transport systems' vulnerabilities to climate related hazards prevent planners from designing robust networks that can accommodate rising demand and future risks [29]. For instance, Sierra Leone offers a practical illustration by collecting data on both formal and informal mobility and using mobile applications such as RoadLabPro to map flood prone culverts, drains, and other critical locations. By doing this, the government gained clearer insight into road-network vulnerabilities to floods and landslides. Combining this data with climate projections produced the first climate risk informed transport map for Freetown; thus, guiding infrastructure policy and planning for better outcomes [30].

Fig. 6 illustrates the interconnection among UNDRR's six resilience principles. Once the commitment to continuous learning is in place, the next imperative is to proactively protect. This principle emphasizes anticipating the known and unknown emerging hazards and accordingly to them, establishing a higher safety baseline. It also promotes the incorporation of multiple proactive layers, which translates to redundancies that ensure essential functions are maintained during disruptive events. A practical example is the Pakistan Shelter Design Guide, developed by the International Organization for Mitigation, in collaboration with Arup. Drawing on empirical research and full-scale structural testing, the guide elevates structural safety standards for flood prone regions and provides planners, designers, and builders with clear criteria for resilient construction [31].

Fig. 6 - The interconnection of the six principles of resilient infrastructure by the United Nations Office for Disaster Risk Reduction [29].

The third principle, environmentally integrated, emphasises the importance of the natural environment as the center of resilient strategies, and this must be true in all stages of resilient infrastructure. It calls for harmonising green and blue solutions with grey infrastructure, that way ecosystem services complement any engineered defence, so decision makers base their choices on ecological data and seek to align infrastructure interventions with natural processes instead of intersecting them. For example, planting trees can slow floodwater velocities and thereby protect critical infrastructure, while permeable pavements and other green-infrastructure measures foster a more balanced coexistence between built and natural systems. Infrastructure will always be necessary, but this principle emphasises integrating it into the environment to minimise ecological damage [29].

The fourth and fifth principles, socially engaged and shared responsibility, respectively, emphasize the importance of inclusive participation from all stakeholders. "Socially engaged" has the main goal of building community participation. In regions where awareness of disaster resilient practices is limited, engaging residents in preparedness and response activities builds local capacity and resilience literacy. Community involvement also eases the adoption of transition plans or technical interventions and gives a sense of ownership over shared assets. By raising public understanding of risks and response mechanisms, this principle enhances both the legitimacy and the effectiveness of resilience initiatives. A clear example of how this principle can advance transport is Peru's Rural Roads Program (PCR). The program initially targeted the rehabilitation of rural roads in the country's twelve poorest regions; by 2008, the initiative had expanded nationwide with the support of residents and elected representatives. Stakeholders selected and ranked road segments for rehabilitation and maintenance, placing emphasis on the routes that mattered most to residents. Such participatory planning provides a sense of ownership and helps ensure the long-term maintenance and continued accessibility of rural roads. Moreover, this system can be applied to any road-infrastructure resilience initiative: users are the most affected by non-resilient infrastructure, and consequently they can exert the strongest pressure for better outcomes [32].

The fifth principle, on the other hand, focuses on "shared responsibility." This principle encourages stakeholders, particularly those with access to vital information, to share that information and their expert knowledge to support decision-making in infrastructure design, planning, and construction. This resilience framework emphasizes that when a collaborative approach with clear accountabilities and established responsibilities is in place, it helps identify major threats at early stages, enabling a rapid response to disruptions. This also leads to increased diversity of stakeholder engagement, which in turn fosters the development of more robust solutions. In addition, one of the most important components of this principle is the presence of effective platforms that facilitate the sharing of knowledge and information in a clear and understandable manner [29].

Finally, UNDRR presents the sixth principle of resilient infrastructure, titled “adaptively transforming.” In summary, this principle calls for constant learning and adaptation based on current evidence. It builds upon continuous learning, which provides the necessary insights to identify the areas of resilience that need to be strengthened. Other key actions under this principle enhance the ability to respond to unforeseen events, extend beyond traditional system boundaries when required, and enable infrastructure systems to recover and improve following disruptions. Flexibility in the design and operation of infrastructure systems is essential, as disaster and climate risks cannot be fully eliminated. Decisions should be guided by the latest scientific data and should anticipate future changes in supply or demand. Adaptive strategies must also be integrated into business continuity plans and operational management, including systems such as early warning and evacuation protocols.

To transform effectively the resilience concept into actionable measures, many countries and organizations have developed other climate resilience frameworks. These schemes provide strategies tailored to withstand the impacts of climate change on road infrastructure. In addition, these frameworks integrate scientific climate projections with engineering principles, and other considerations that ensure that planning and maintenance are both, proactive and adaptive. Examples of such frameworks include the Federal Highway Administration (FHWA) Vulnerability

Assessment and Adaptation Framework, the Global Infrastructure Basel Foundation (GIB), and the Climate and Disaster Risk Screening Tools, among others.

The US Federal Highway Administration (FHWA) Assessment and Adaptation Framework, which initially developed in 2012 and updated in 2018, serves as a model for evaluation how climate change and severe weather affect transportation infrastructure while explores possible adaptation strategies, adjusting the decision-making procedures with actual conditions. This framework is structured into six subchapters that explain the key procedures in assessing vulnerabilities and making informed adaptation decisions, and these are divided into: defining objectives and study scope; collecting asset and climate data; assessing vulnerability (exposure, sensitivity, adaptive capacity); evaluating and prioritizing adaptation options using multi-criteria or economic analyses; and integrating results into transportation planning, design, operations, and asset management. By offering a structured, real data driven approach to resilience planning, this framework is critical for strengthening the capacity of road infrastructure systems in the United States of America to resist and adapt to future climate challenges for road networks [33]. Fig. 7 shows a storm surge simulation created by the U.S. Department of Transportation. The model used combines the Advanced CIRCulation (ADCIRC) model and the Steady State Spectral WAVE (STWAVE) model to simulate storm conditions based on historical hurricane data. The image specifically illustrates the expected storm surge depth if a hurricane similar to Katrina were to directly strike Mobile, Alabama, under a sea level rise scenario of 0.75 meters, using the North American Vertical Datum of 1988 (NAVD88). NAVD88 is a standardized elevation reference system used across the United States, Canada, and Mexico to provide a consistent baseline for sea elevation level changes. These measurements allow accurate comparisons in flood modelling, environmental assessments, and infrastructure planning.

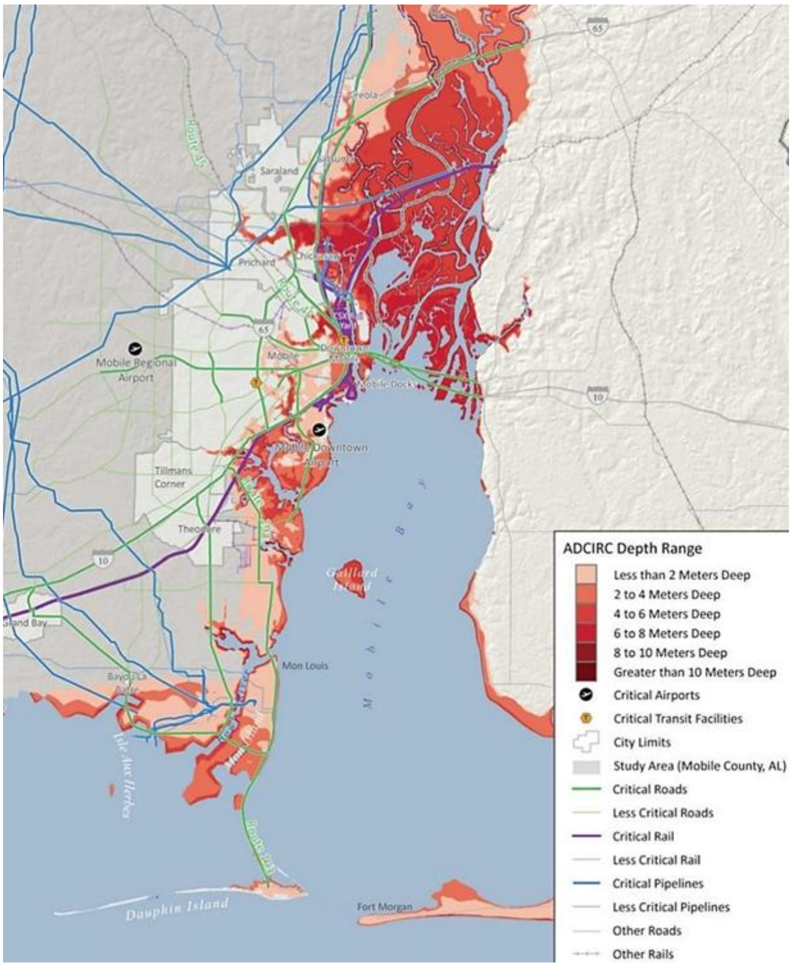

Fig. 7 - Projected storm surge depth in Mobile, Alabama, under a 2.5 ft sea level rise scenario, modeled using ADCIRC and STWAVE with NAVD88 as the vertical reference [33].

Expanding more on the GIB, mentioned above, this foundation is a Swiss-based non-profit organization dedicated to promoting and providing services that help advance sustainable and resilient infrastructure development worldwide. Since GIB was established in 2008, it has actively engaged a broad range of stakeholders from municipal authorities to project developers, emphasizing the support to developing countries. GIB contributes to resilience of infrastructure projects through developing internationally recognized standards for infrastructure design using an approach grounded in multi stakeholder collaboration. Furthermore, GIB is committed to building institutional a professional capacity by giving their users the tools they need to think green, and everyone is able to access these tools. This foundation invests in research that explores the relation between infrastructure sustainability and financial performance. Thus, it contributes to evidence-based policy development. In addition to these efforts, GIB provides an accessible online platform rich with resources aimed at promoting green infrastructure and climate resilience. This platform offers informative webinars, seminars, analytical tools, and educational materials designed to empower practitioners, policymakers, and the public. Fig. 8, an image of the platform's knowledge section is shown, which includes a variety of tools available for public use. The platform currently features 714 case studies from around the world and 238 courses related to green infrastructure, sustainability, and resilient infrastructure. Publications can be explored by country or geographic region, offering insights into areas such as socioeconomic context, natural asset base, environmental and resource productivity, quality of life, policy frameworks, economic opportunities, and wealth changes. Additionally, relevant documents linked to the selected countries or regions can be accessed through the portal. This tool serves as an example of how the "shared responsibility" principle, dis- cussed earlier, can be applied across various sectors involved in sustainability and resilient infrastructure. Such knowledge dissemination is vital for raising awareness, strengthening institutional capacities, and fostering the broader societal engagement necessary for the transition to a more resilient and environmentally sustainable infra- structure sector [34].

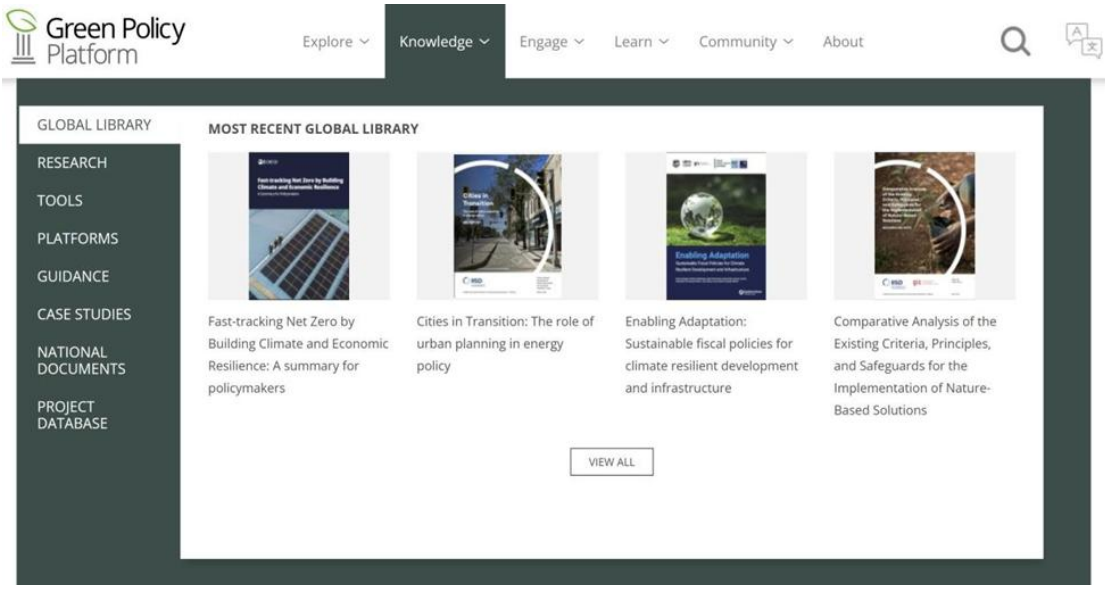

Fig. 8 - Screenshot from the Green Policy Platform's publicly accessible tools for sustainability knowledge [34].

Finally, the Climate and Disaster Risk Screening Tools from The World Bank provide essential methodologies for assessing and managing risks that are associated with climate change and natural hazards. The World Bank recognizes that climate change is bringing new challenges to road infrastructure and to address these growing challenges, climate and disaster risk screening tools are prioritized to embed resilience into infrastructure planning. By using these tools, potential climate related threats are early identified, allowing decision-makers to design more adaptable and durable road infrastructure projects that can endure changing environmental conditions. This approach is particularly valuable in the road sector, where frequent repairs, interruptions in service, and a reduction in road safety, can have significant costs for the population. Programs such as these strengthen technical decision making and promote long term investment efficiency and sustainability, which makes them indispensable to resilient road infrastructure development [35].

Building on this framework, the World Bank has developed a structured methodology to operationalize climate and disaster risk screening in infrastructure planning. The Four Steps for Climate and Disaster Risk Screening provide a systematic process for evaluating the vulnerability of infrastructure projects to climate and disaster risks. These steps are illustrated in Fig. 9, which outlines the sequential process from hazard identification to final risk assessment.

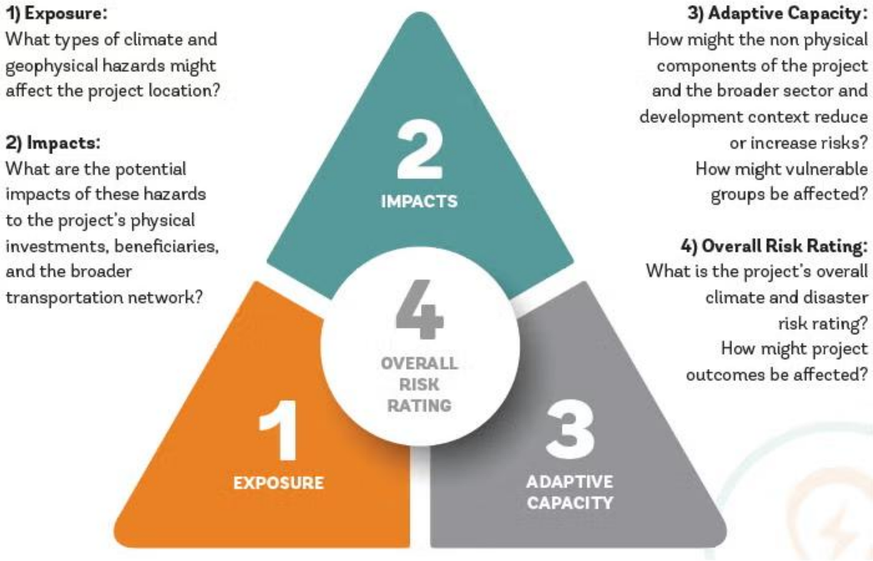

Fig. 9 - Sequential process from hazard identification to final risk assessment [35] .

The first step, Exposure, identifies the types of climate and geophysical hazards, such as flooding, landslides, or extreme heat that could affect the project. The second step, Impacts, evaluates the potential consequences of these hazards on the infrastructure itself, as well as on surrounding systems and communities. The third step, Adaptive Capacity, considers how well institutions, policies, and communities can manage and respond to those risks, including their ability to adapt and recover. Finally, the Overall Risk Rating synthesizes information from the previous steps to determine the project's overall level of climate and disaster risk. This rating helps guide decisions on where and how to implement adaptation measures to improve long term resilience [35].

In conclusion, the creation and implementation of climate resilience frameworks are essential for transforming theoretical resilience into practical and scalable solutions, specifically in the context of road infrastructure. By integrating existent scientific data and taking into consideration engineering principles and early stage risk assessments, these to not only guide the decision-making entities but also empower institutions to plan for road network that can endure and adapt to evolving climate change threats. As climate change continues to bring new challenges, the refinement of these tools and the implementation of new ones will remain a cornerstone of sustainable infrastructure development.

Besides these frameworks, other physical strategies have been adopted to enhance the resilience of road infrastructure to climate related hazards, particularly flooding. These strategies fall into three main categories: design based, material based, and drainage focused interventions. From a design perspective, measures such as elevating road alignments, sealing surfaces, and incorporating longitudinal drainage systems have proven effective in reducing flood-related damage. In regions with weak or highly erodible subgrades, techniques like cement-stabilized base construction have been shown to significantly increase structural performance under saturated conditions [36]. Material based strategies also play a critical role in building resilient road infrastructure. In the Climate Adaptation review [36], Bituminous concrete with reduced air voids and rigid pavement types, such as roller compacted concrete (RCC) and interlocking concrete block pavements (ICBP), offer greater resistance to prolonged water exposure and heavy loads. In zones that are subject to frequent inundation and heavy traffic volume, these materials have been prioritized. The implementation of Sustainable Urban Drainage Systems (SuDS) is also an alternative that has been studied and applied in recent years. Some of the most common examples of this type of infrastructure are vegetated swales, bioretention systems, filter drains and strips, detention basins, ponds and wetlands, permeable pavements, within others. Each alternative aims at reducing moisture accumulation on the pavement surfaces, which as discussed earlier, has great negative impacts on the performance and endurance of road infrastructure [36].

A comprehensive overview of the impacts that infrastructure systems face following hazardous events, along with commonly implemented mitigation measures, has been presented in [38]. Table 2 provides a summary of these impacts and corresponding mitigation strategies, specifically in the context of flooding and water-related hazards. However, a major limitation is that many of these measures have not been regularly updated or adapted across all regions. This problem highlights the urgent need for continued development and innovation to ensure that infrastructure systems are genuinely resilient in the face of increasingly complex and evolving climate and disaster risks.

Table 2 - Flooding effects on road infrastructure and typical mitigation measures applied [36], [37].

Hazard	Impact	Typical Mitigation Measure
Fluvial and river flood due to extreme precipitation	Inundation that leads to washouts and road deterioration	Improve/maintain drainage (increase culvert capacity)
Pluvial and surface flood due to extreme precipitation	Inundation leading to washout and pavement failures	Improve and maintain drainage
Landslides caused by extreme rainfall events	Closure by debris flows, mud- flows and road failure	Some protection measures such as barriers, fences, ditches, tunnels

Countries with advanced economies, in their majority, have increasingly integrated resilient infrastructure into their road planning and management. Some of them focus on proactive measures such as incorporating climate risk assessments in the early stages of any project design, designating funding for adaptation, and creating institutional collaboration across institutions. Examples that reflect a broad understanding of the importance of resilient infrastructure are: the prioritization of maintenance of critical routes, upgrading material and design and construction Countries with advanced economies, in their majority, have increasingly integrated resilient infrastructure into their road planning and management. Some of them focus on proactive measures such as incorporating climate risk assessments in the early stages of any project design, designating funding for adaptation, and creating

institutional collaboration across institutions. Examples that reflect a broad understanding of the importance of resilient infrastructure are: the prioritization of maintenance of critical routes, upgrading material and design and construction.

2.3. GAPS IN THE LITERATURE

Despite the growing interest in climate resilient road infrastructure, several gaps remain in the literature, those which addressing them, could significantly support the planning, design, and implementation of adaptation strategies in road infrastructure, particularly in developing countries such as Panama. One notable gap is the limitation in the performance evaluation of materials under extreme climate conditions. In this sense, technologies such as polymer-modified asphalt (used to enhance heat resistance) and permeable pavements, which help support better drainage and reduce water accumulation, have successfully been applied in various countries for a long time. However, there is limited literature examining their performance in tropical environments, under high intensity precipitation and resource-constrained setting such as Panama [38].

Throughout the examination of the literature on the techniques used to adapt to flooding on road infrastructure, it has been noted that there are a few studies directly address the reduction of flood impacts through material selection and construction methods, in general, there have been several studies that review strategies to reduce the damages by flood to pavement, but they focus more on what these damages are, and instead of focusing more on engineering solutions. Instead of advancing the technical implementation of resilient materials and construction strategies, many studies repeatedly return to the use of conceptual models and framework approaches [16].

3

METHODOLOGY

This thesis was developed through a qualitative and comparative approach, focusing on the identification and evaluation of international strategies for resilient road infrastructure in the context of climate change adaptation. The strategies analysed were selected with the objective of assessing their potential adaptation to the Panamanian context. The methodology followed five main stages.

First, the problem framing was established, recognizing the challenges that developing countries face with vulnerable road infrastructure unable to withstand current climate conditions. Panama was examined as a representative case to understand why, despite being one of the most prosperous countries in Central America, it struggles to overcome these challenges. This stage also identified what would be required for Panama to withstand climate-related hazards and advance toward becoming a resilient country. The central research question guiding this study was therefore: What strategies for road resilience used internationally can be identified, and how can they be adapted to Panama's climatic and social context?

Second, the selection of case studies was carried out using criteria related to climatic relevance, evidence of successful implementation, and the potential for transferability to Panama's conditions. Climatic relevance was particularly important, since Panama is affected by intense rainfall, flooding, landslides, and extreme heat, and it was essential to focus on cases from countries facing similar hazards. The case studies also needed to demonstrate clear results in strengthening road resilience, and they had to offer lessons that could be realistically adapted to the socio-economic and institutional context of a developing country. Based on these considerations, four case studies were selected: permeable pavements in Chicago (USA), the Room for the River flood management program in the Netherlands, geosynthetics for landslide prevention in Brazil, and heat-resilient asphalt mixtures in Abu Dhabi (UAE). Their selection was guided by climatic similarities to those observed in Panama, which include intense rainfall and landslides in mountainous regions, urban flooding due to inadequate drainage, and prolonged exposure to extreme heat. Chicago's case was chosen as a reference for urban flooding mitigation through permeable pavements. The Netherlands was selected for its large-scale floodplain management program, which integrates road resilience into river adaptation. Brazil was included to highlight a developing-country perspective through the cost-effective use of geosynthetics for landslide prevention. Abu Dhabi's case was chosen for its advances in developing heat-resistant asphalt mixtures to withstand extreme temperatures, and the ability of providing ideal environment for evaluating the durability of asphalt under prolonged high temperature stress.

The inclusion of the Brazilian case was particularly relevant because, as a developing country, Brazil has successfully implemented low-cost and technically sound strategies such as geosynthetics for slope stabilization in high-rainfall areas. This case illustrates that innovative infrastructure adaptation is not exclusive to high-income nations and provides a realistic reference point for Panama. Moreover, the use of geosynthetics in projects like São Paulo's Rodoanel reflects Brazil's longstanding domestic experience with these materials. Geosynthetic engineering in Brazil dates back to the early 1970s, supported by a substantial body of experimental studies in real life and lab tests that have shaped design practices that suit tropical conditions. Rather than adopting this technique from international models, Brazil's engineers have been in the long-term study and usage of geosynthetics, making Rodoanel a product of homemade innovation in climate resilient road infrastructure.

Third, data collection was conducted through desk research, which involved reviewing peer-reviewed journal articles, technical manuals and engineering guidelines, government and policy documents, international agency reports such as those from the World Bank and the UNDRR, and journalistic sources for recent information. Some documents lacked methodological detail or completeness but were nonetheless valuable in demonstrating the frequent gap between policy design and implementation in developing countries, including Panama.

Throughout the research process, attention was given to both institutional and climatic dimensions of each strategy. Funding mechanisms were acknowledged as a critical factor for implementation, but they were not analysed in depth because financing is more directly linked to governance, political will, and fiscal policy, which extend beyond the scope of this thesis. Instead, the study emphasized technical viability, climatic relevance, and institutional adaptability. Each case study was analysed in terms of its objectives, implementation process, outcomes, and the main challenges encountered.

Finally, the insights gained from the selected case studies were applied to Panama's context, with particular focus on Panamá Province and Chiriquí. These two provinces were chosen for their complementary climate-related challenges. Panamá Province, which includes the capital city, faces frequent urban flooding, infrastructure strain, and rapid unplanned growth, making it a critical site for evaluating adaptation strategies in dense metropolitan settings. Chiriquí, by contrast, features rural mountainous terrain and is a major hub for agricultural production, particularly in the Tierras Altas region, where landslides, river overflows, and road disruptions regularly affect livelihoods and mobility. While these two provinces served as the primary focus, other regions of the country were also considered due to their exposure to heat-related deterioration and rainfall-induced landslides. These include Veraguas, Herrera, Los Santos, Coclé, Bocas del Toro, Darién, Eastern Panama, and the indigenous Comarca of Ngäbe-Buglé. These areas not only present critical geoclimatic challenges similar to those in the case studies but also underscore the importance of region-specific adaptation measures.

By applying international strategies to these varied contexts, the study aims to generate practical, scalable, and context-sensitive recommendations that respond to Panama's diverse climatic, geographic, and socio-economic conditions.

4

SELECTED RESILIENCE STRATEGIES

To contextualize the international strategies explored in this thesis, see Fig. 10 to geographically locate the four case studies analysed: Chicago in the United States, São Paulo in Brazil, Nijmegen in Netherlands, and Abu Dhabi in the United Arab Emirates. These cities were selected based on their approaches to road infrastructure resilience in the face of climate change. Each represents a different climatic, institutional, and geographic context, providing a diverse foundation for evaluating the transferability of their strategies to developing countries.

Fig. 10 - World map illustrating the locations of the four case studies for road infrastructure resilience selected.

4.1. PERMEABLE PAVEMENTS: CASE STUDY – CHICAGO GREEN ALLEY PROGRAM (USA)

Due to the struggle that flooding and moisture poses for pavement durability, and the recognition that climate change has been intensifying these hazardous conditions to the city's road network, the Chicago Department of Transportation decided to start moving towards "greener" pavement materials and designs to prevent flooding and improve stormwater management. Since 2006, the Chicago Green Alley Program was launched primarily to mitigate and adapt to the challenges that climate change brought. As part of the state's Climate Action Plan, program managers were tasked with identifying the effects that climate change had on each of their projects and taking action to adapt to the anticipated impacts [39].

According to David Leopold, project manager for the Streetscape and Sustainable Design Program of the Chicago Department of Transportation, Chicago accounts for one of the most extensive alley networks of any city in the world. Introducing green alternatives within this network presents a great opportunity to relieve the pressure on the city's transportation and sewer infrastructure, especially considering that many older alleys were built without connections to the sewer and stormwater systems. The program began with five initial pilot projects and gradually evolved into a regular practice, enabling the installation of over 100 redesigned alleys across the city by 2009. The main goal of this project is to convert traditional alleys into permeable surfaces that slow stormwater runoff. This promotes natural infiltration and contributes to the replenishment of groundwater reserves [39].

Before implementing the system, a suitability study is carried out, and only in locations where the soil is appropriate for infiltration, green alleys are applied. The applicability of this system depends on the type of soil, ensuring proper water infiltration. Alongside soil suitability, other considerations are made to align with broader city sustainability goals. For example, these alleys are designed with high albedo materials, which reflect heat energy and help maintain cooler temperatures during heatwaves, reducing the urban heat island effect. The project also promotes the use of recycled materials to minimize construction waste. In Fig. 11, there is an illustration of an alley section in Chicago before (with traditional impermeable pavement) and after the Green Alley project introduced a permeable alternative.

Fig. 11 - Road before and after alley incorporation was applied to a street in Chicago [39].

There are several techniques proposed in this approach. The first involves proper pitching and grading so that water drains into the center of the alley and, when necessary, into the sewer system. While this may seem like an obvious strategy, it is crucial to ensure that even when the first portion of water infiltrates through the pavement, any excess runoff is still effectively directed into the city's drainage network. The second technique includes the use of three types of permeable pavement: permeable asphalt, permeable concrete, and permeable pavers. In areas where the soil does not easily drain, a combination of permeable pavement and subsurface drainage systems, such as underdrain pipes or gravel trenches, can be applied to slow runoff and reduce the load on the sewer system. This design is considered to offer multiple benefits, such as relieving pressure on the stormwater system and preventing flooding, which can severely damage pavement infrastructure [40].

A study conducted by the United States Geological Survey (USGS) [40] evaluated three types of permeable pavement: permeable interlocking pavers, permeable concrete, and permeable asphalt, at the Madison Streets Division East Office in Wisconsin. Over two years, the runoff behaviour of these pavements was analysed, and it was found that all were capable of draining water at rates ten times higher than what standard drainage systems require. These surfaces also helped filter debris, which was monitored through a collection system. However, one disadvantage of this type of pavement is the maintenance requirement. Thus, it is important to target to surface maintenance solutions so that the drainage properties can be sustained and clogging is avoided to ensure that drainage capacity is preserved. Fig. 12 illustrates the three permeable pavement types used in the study.

Fig. 12 - Three permeable pavement studied by USGS [41].

The third technique applied in this green alley program is the use of high albedo pavement. This light-coloured surface material reflects sunlight, reducing heat absorption by the pavement and contributing to lower urban temperatures. As mentioned before, the Green Alley Project also looks for improving sustainability quality.

Another sustainability focused strategy in the program is the use of recycled construction materials whenever possible. For instance, slag (a steel byproduct) is incorporated into concrete mixes, and ground tire rubber is used in porous asphalt. These practices reduce the use of virgin natural resources and minimize construction waste sent to landfills [39].

This program also promotes one of the key principles of resilient infrastructure discussed earlier in this thesis: community engagement. The project's handbook outlines various actions that community members can take, along with estimated costs per residential strategy. Some of these include: recycling, using compost bins, planting trees, installing native landscaping, or building rain gardens. These small-scale actions indirectly help protect and support the city's road infrastructure [39].

Regarding the future of the program, a 2024 article discussed some of the challenges it faces [42] Some of these problems started with the fact that most of the places that were going to acquire green alleys were not connected to the sewer systems and the landscaping and coordination sewer works were making each unit more expensive than predicted. In addition, the dissolution of the city's Department of Environment in 2012 further complicated funding availability, limiting the infrastructure budget. Despite these challenges, the Chicago Works Capital Plan reactivated the program in 2021, allowing each city council member to propose one green alley per year. This revived the program, increasing the number of alley installations to around 30 per year from 2021 to 2023. Although this is still below citywide needs, the program continues to expand as resources allow. Each green alley has the capacity to di- vert thousands of gallons of stormwater per hour, making it a highly effective tool for urban flood control [41]. In flood prone cities like Panama City and Colón, integrating permeable pavements in urban roads, parking lots, and public spaces can reduce sur- face water, alleviate stress on drainage systems, and decrease flash flood risk.

The Chicago Green Alley Program is a valuable example of how permeable pavements solutions can be of help for urban flooding, enhancing stormwater management, and even contributing to broader climate resilience goals. Seeing the integration of suitability studies, the use of diverse permeable pavement technologies, and the community involvement shows that there is an adaptive approach that aligns with the principles of resilient infrastructure. Even though the program has faced challenges in the cost and construction coordination, it remains a successful urban model for mitigating the impacts of climate change by the use of nature-based solutions.

4.2. USE OF GEOSYNTHETICS: CASE STUDY – SÃO PAULO RING ROAD (BRAZIL)

São Paulo's famous ring road, most known in Brazil as "Rodoanel" encircles the metropolitan and connects at least 12 major highways and 16 municipalities [42]. This road network crosses a range of different soils and topographies, including flood plains, marshes and slopes that are prone to landslides. In response to this challenge, the project's engineers developed a comprehensive plan aimed at minimizing environmental impact and enhancing the road's resilience, particularly during periods of heavy rainfall when infrastructure is most vulnerable to damage and closure. The Rodoanel spans 177 kilometers and is divided into four segments: West, South, East, and North. The West section was inaugurated in 2002, followed by the South in 2010, the East in 2014, and the final North section is scheduled for completion in 2026 [42].

An important aspect to highlight is the commitment to preserving natural ecosystems. For instance, along the Northern section there is Cerra de Cantarera, an Atlantic Forest preservation that will be addressed with the construction of 7 tunnels. This is a demonstration of the capacity for innovation and sustainable design [43]. Fig. 13 illustrates the four stages of the Rodoanel construction with the extension of each section.

Fig. 13 - Rodoanel Stages *[43]*.

One of the most significant challenges encountered during the construction of the Rodoanel was soil stability. In the southern section of the beltway, it was necessary to treat low bearing capacity soil layers due to the presence of soft soils, and to protect the side slopes from erosion. To address these geotechnical concerns, Bidim geotextile was implemented to serve several functions. First, it provided a separation layer between the drainage mattress and the compacted backfill placed on soft soil. Second, geotextile was used to separate the concrete covering from the base soil. Third, a sediment barrier was installed using a vertical curtain formed by geotextile blankets affixed to wooden posts. Lastly, filtration and separation were applied along the banks, where the geotextile created a boundary between the granular dike materials and the adjacent soil from excavation zones. In all four techniques, the geotextile acted as a critical separator that maintained the structural integrity of distinct soil and drainage layers, thus preserving the mechanical properties of each material.

Geotextiles are permeable textiles used in contact with soil, rock, or foundation layers to provide functions such as separation, filtration, reinforcement, and drainage [44]. Specifically, the use of Bidim geotextile allowed for the retention of fine particles while permitting water flow, effectively preventing bank erosion and lagoon silting, these are particularly crucial during periods of intense rainfall. These characteristics directly contribute to increased road resilience, helping to reduce the risk of landslides and infrastructure deterioration in the face of climate-induced extreme weather events [43]. An example of the application of geosynthetics for slope stabilization and drainage control can be seen in Fig. 14, which shows the installation of a Bidim geotextile acting as a separation layer between the drainage mattress and the backfill material. The backfill material can be seen positioned directly on top of the Bidim geotextile.

Fig. 14 - Installation of Bidim geotextile served as a separation layer between the drainage mattress and the backfill to be applied [46].

Fig. 15 - Bidim geotextile installation on slopes prior concrete coating [45].

Fig. 16 - Aerial view of the Southern section of Rodoanel Beltway finished [47].

The advantages of geosynthetic reinforcement in slope embankments have been demonstrated through the Almere Test Embankment [46]. This experiment specifically investigated the behaviour of geosynthetic-reinforced embankments over very soft soils, revealing a notable difference in failure height. The reinforced section exhibited a ductile failure at a height of 2.75 m, whereas the unreinforced section failed at just 1.75 m. Beyond enhancing structural performance, the use of geosynthetics contributed to cost savings and, in some cases, reduced the number of construction stages required. The study presents a compilation of eight case studies, each highlighting how geotextile application improves embankment performance. These benefits, including improved durability, reduced construction complexity, and increased structural stability, are fundamental to sustainable infrastructure and closely align with road resilience strategies designed to address the impacts of climate change. These improvements can directly translate into extended service life and a reduction in repairs and maintenance interventions. For instance, in areas prone to heavy rainfall, a geotextile-stabilized slope may prevent collapses, whereas unreinforced roads often require more than one repair during a single rainy season. Thus, in addition to enhancing road safety, maintenance costs can be significantly lowered.

It is also important to emphasize that the application of geosynthetics is particularly relevant for developing countries such as Brazil, as it offers a cost-effective alternative to more complex structural solutions in areas with weak or sloped soils. As previously mentioned, geosynthetics can be installed with relatively simple equipment, without requiring extensive excavation or highly specialized labour. This makes the technique especially valuable in remote or economically constrained regions, often the case for roads located in difficult-to-access areas. Finally, the modularity offered by geosynthetics makes them a scalable and adaptable tool for increasing the resilience of road infrastructure.

4.3. ROOM FOR THE RIVER PROGRAM, NIJMEGE, NETHERLANDS

Due to the geographic composition and climatic conditions of the Netherlands, flooding has long been a persistent threat for its residents. In recent decades, rainfall has become more intense, and weather patterns have shifted unfavourably for the country. During the 1990s, the Netherlands experienced severe flood damage due to the limited capacity of its floodplains and rivers to manage excess water [47]. In fact, in 1995, river levels rose to such extremes that several dikes were breached, forcing the evacuation of 250,000 people and 1 million cattle [48]. This alarming event heightened the concerns of stakeholders and prompted the search for long-term solutions.

What makes the Netherlands stand out is that, rather than relying solely on traditional flood defences, authorities embraced a nature-based solution. This approach included lowering the levels of floodplains, creating water buffers, deepening side channels, relocating levees, and constructing flood bypasses. This comprehensive initiative became known as the Room for the River Programme, which was launched in 2007 and encompassed over 30 projects aimed for completion by 2022 [47]. Fig. 17 illustrates the planned modifications to floodplain areas designed to enhance the resilience of infrastructure located near rivers in the face of extreme rainfall events.

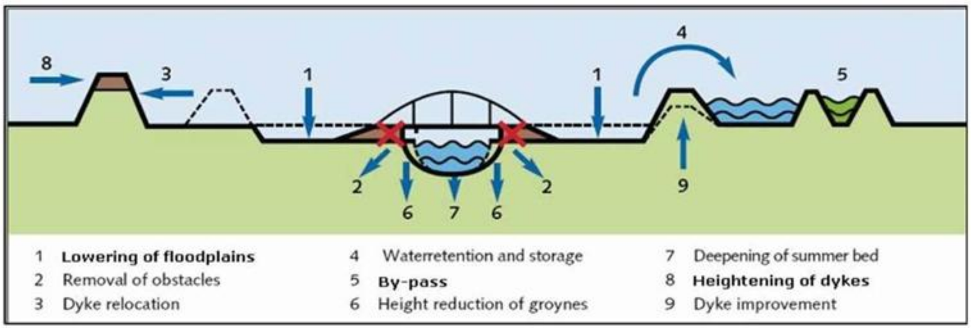

Fig. 17 - Main measures applied in the Room for the River Program [49].

One of the selected areas to implement the Room for the River Programme was the city of Nijmegen, in the Dutch province of Gelderland. This project even received an award in 2011 from the Waterfront Center, based in Washington, D.C., for successfully combining flood protection with the creation of a riverside park that actively engaged the local community. Rather than solely focusing on raising or reinforcing the river dikes in Nijmegen, the project involved relocating the northern branch of the river to create a wider floodplain, which now serves as a safety buffer against future floodwaters [50] This intervention significantly reduces flood-related hazards to the city, thereby contributing to the protection of nearby road infrastructure. Fig. 18 illustrate a before-and-after comparison of the river's transformation through the Room for the River program in Nijmegen. It can be noted on the images that A width of 350 m on land was removed on the north area as well as a channel to connect the island and the riverfront neighborhoods.

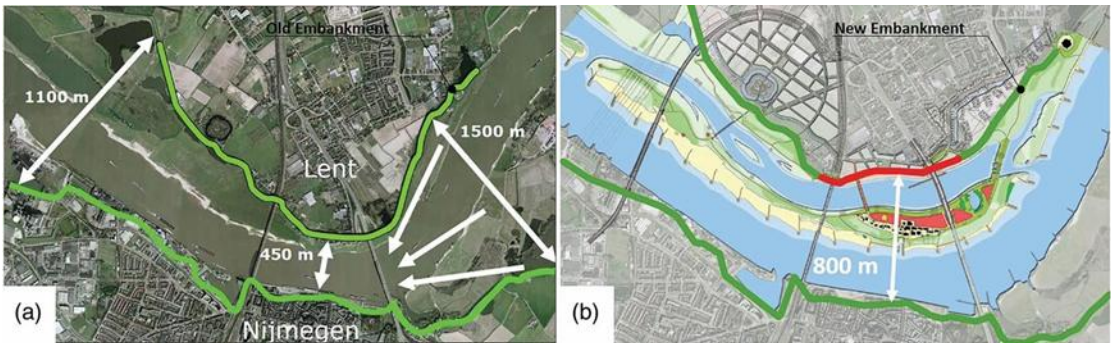

Fig. 18 - (a) Riverfront aerial imagen before program implementation; (b) River Nijmeges after Room for the Program implementation [51].

Another important factor that makes this program a strong example of resilient infrastructure for other nations is not only what was done, but how it was done. In this regard, the program adopted a multi-level, interdisciplinary approach that brought together a wide range of expertise. For instance, it was not only water safety and planning agencies that were involved, but also all other relevant organizations operating

in the affected areas [52]. This strategy enabled decentralized governments to link local development projects, such as recreational and natural areas with the broader water safety agenda [53]. These two elements reflect one of the key principles of resilient infrastructure discussed earlier in this thesis: shared responsibility among stakeholders. By encouraging inclusive participation, the program ensured that all actors had a role in shaping the outcomes of the project.

The success of the Room for the River project in Nijmegen highlights the value of interdisciplinary coordination in climate-resilient infrastructure planning. Fig. 19 presents an aerial view taken after the project's completion, illustrating how collaborative design reshaped the river landscape to improve flood resilience.

Fig. 19 - Aerial picture taken in 2016 after the completion of Room for the River plan in Nijmegen [54].

Several key characteristics of how this project was managed throughout its phases contributed to its overall success. These included learning from past experiences, continuous adaptation to change, and strong public engagement. First, having worked on other water management initiatives, such as the Overdiepse Polder, a project that reintegrated farmland with the river through controlled flooding while protecting residences on elevated mounds; the depoldering of the Noordwaard, which allowed a large polder to flood naturally during high water events to reduce river levels; and the floodplain excavation in Schellener, aimed at restoring natural overflow areas to reduce downstream flood risk, provided the Netherlands with an opportunity to refine project coordination between teams and program officials. These earlier experiences strengthened technical planning, improved team configuration across different disciplines, and enhanced the quality control practices led by the programme office [55].

The Room for the River Programme also demonstrated a strong capacity to adapt to evolving circumstances. This adaptability extended to the internal operations of government agencies, which responded to shifting demands while remaining focused on the project's primary objectives. A key aspect of this flexibility involved recognizing and addressing knowledge gaps within project teams. When technical expertise proved insufficient, the programme office adopted a more facilitative role by providing direct support to local teams. As the projects progressed into the implementation phase, additional gaps emerged in areas such as procurement, logistics, and contract management. In response, the central office assigned senior staff from its knowledge and control departments to work closely with local project leads. This proactive strategy of institutional learning and capacity building helped sustain project momentum, resolve issues in real time, and ensure that long-term climate resilience goals remained on track.

Finally, the program office provided tailored training for stakeholders in project management roles. Community organized events targeted specific groups, including project managers, decision-makers, and risk managers. Through these sessions, participants shared experiences, discussed challenges, and explored potential solutions. Ultimately, these actions strengthened collective knowledge and project capacity [56]

The project also emphasized the importance of public involvement. While the community is one of the most critical components of any public works or development initiative [56], it is equally important to determine the appropriate timing for engagement. Involving the community too early can raise expectations and lead to frustration if promised outcomes are not delivered. Conversely, involving the public too late in the development process can significantly limit the value of public input, thereby increasing the risk of legal disputes or opposition in the future.

The Room for the River Program represents a particularly relevant climate-resilient strategy designed to prevent flooding caused by the increasingly frequent extreme precipitation events of recent decades. As previously discussed, flooding can significantly impact road infrastructure, compromising both its performance and durability. This case serves as an example of effective climate adaptation, shifting away from traditional infrastructure solutions toward ecologically attuned planning that reduces the vulnerability of road networks. By creating more space for water and redirecting flow pathways, the program has mitigated risks to homes, ecosystems, and road corridors that had previously been affected by flooding.

4.4. HEAT-RESISTANT ASPHALT MIXES: ABU DHABI, UAE

Given the rapid urban expansion of the United Arab Emirates and its exposure to extreme heat, the country has emerged as a regional leader in pavement innovation, investing in materials and technologies aimed at extending the life cycle of its road networks. As mentioned previously, extremely high temperatures can cause rapid deterioration of conventional asphalt, resulting in damages such as rutting, softening of the binder, which leads to stripping, cracking, among others. All these issues increase of maintenance costs and cause significant disruptions to the population. The United Arab Emirates exemplifies the challenge of providing resilient road infrastructurewhile enduring extreme summer temperatures, with peaks reaching 50 °C. A particular concern is that this region is warming at a rate of 0.45 °C per decade [57], surpassing the global average of 0.27 °C per decade [58]. The development and expansion of Abu Dhabi has led to increased traffic volumes, which combined with extreme heat, pose considerable challenges to the structural integrity of asphalt pavements.

One notable proposal to improve asphalt performance involved the use of polymer modified bitumen, as studied by the University of ALHOSN in Abu Dhabi. In this study, Styrene Butadiene Styrene (SBS) was evaluated against traditional asphalt pavement under the extreme heat conditions characteristic of the UAE. As part of its broader efforts, the UAE also established a local facility for producing polymer modi- fied bitumen (PMB) using Sealoflex technology, a proprietary elastomeric system that enhances asphalt performance in high-temperature environments. This initiative ena- bled the country to reduce its dependency on conventional bitumen and adopt tailored solutions adapted to local climate demands. In this context, SBS has also been examined in multiple studies, most of which conclude that its use, particularly in combination with lime as a mineral filler, leads to improved stiffness, stability, and strength in HMA [59]. Incorporating 4.5% SBS-PMB in place of traditional bitumen resulted in a 7.3% increase in asphalt stiffness, a 19.5% improvement in stability, a 1.8% increase in bulk density, and a 9.7% enhancement in flow [60].

The UAE has been using PMB for several years to produce stronger asphalt mixtures capable of withstanding the extreme heat conditions the country faces annually. Recognizing the limitations of conventional asphalt in enduring prolonged exposure to high temperatures and heavy traffic loads, road authorities have adopted PMB to improve elasticity, rutting resistance, and fatigue life. This long-standing commitment is reflected in the development of formal technical guidelines, most notably the Pavement Design Manual (TR-513) published by the Abu Dhabi Department of Transport. The manual, which reached its second edition in 2021, explicitly incorporates the use of polymer modified bitumen in asphalt mix designs, underscoring its relevance in the UAE’s pavement engineering standards [61].

While the adoption of SBS-PMB has yielded clear performance benefits, it remains reliant on imported SBS polymers from Berlin, introducing logistical and environmental challenges. In response, the UAE has begun exploring locally available polymeric waste materials to reduce greenhouse gas emissions associated with long distance transport and to address the country's growing waste management burden [62]. Converting waste into a potentially high performing and sustainable binder addresses two major concerns simultaneously: the environmental impact of waste accumulation and the need for durable asphalt in extreme climatic conditions.

A study evaluated two types of waste-derived materials for their suitability in pavement applications [62]: devulcanized rubber combined with low-density polyethylene (DVR–LDPE), and devulcanized rubber combined with polypropylene (DVR–PP). The objective of the study was to develop a binder that delivers outstanding asphalt performance by leveraging the elastic properties of DVR and the stiffness contributed by plastics. To evaluate their effectiveness, five distinct binder scenarios were tested: neat bitumen (NB), traditional PMB, DVR, DVR combined with LDPE (DVR–LDPE), and DVR combined with PP (DVR–PP). Fig. 20 illustrates the mechanical behavior of each binder under stress using the Linear Amplitude Sweep (LAS) test, a method designed to assess fatigue performance.

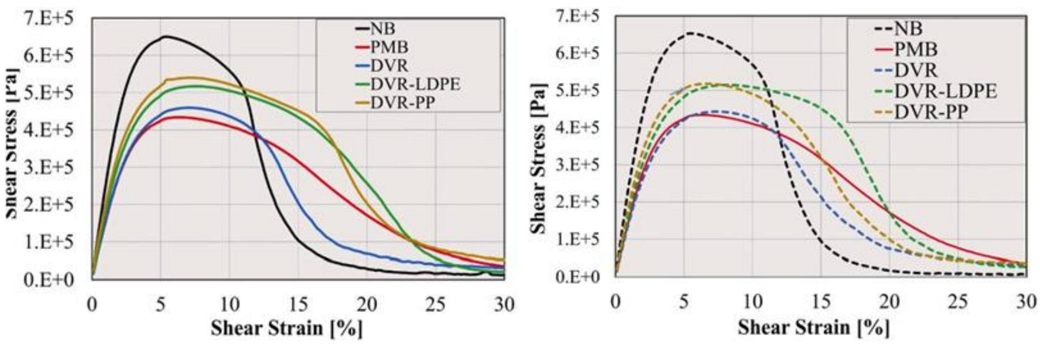

Fig. 20 - LAS-derived shear stress-strain curves [62].

In the initial test (left graph), NB demonstrates the poorest performance, losing strength rapidly after a short strain interval. On the contrary, PMB performs better, exhibiting improved flexibility. However, the binders modified with DVR, especially DVR–LDPE and DVR–PP, show even greater resistance to deformation, with DVR–LDPE achieving the highest strain capacity. This indicates superior flexibility and crack resistance. After simulated aging (right graph), DVR–LDPE continues to outperform the other binders, maintaining both its strength and flexibility. These results suggest that DVR–LDPE is not only the most resilient under stress but also the most durable over time, making it a promising alternative to traditional PMB in high-performance asphalt applications.

This research highlights a significant advancement in sustainable asphalt technology in the UAE, demonstrating that DVR–LDPE composites outperform both conventional PMB and DVR–PP in several key areas. These include improved viscoelastic behavior, greater resistance to aging, and enhanced fatigue performance, especially under heavy traffic loads. The DVR–LDPE blend enhances elasticity and reduces oxidative degradation, positioning it as a viable substitute for PMB in high-performance pavements. Although further optimization is needed to improve elastic recovery, the study supports the integration of upcycled waste materials into asphalt production. This approach aligns with national sustainability goals and contributes to the development of more climate-resilient infrastructure in the UAE [62].

These efforts exemplify how countries facing extreme climatic conditions can serve as living proof of sustainable infrastructure innovation. By integrating advanced material science with waste management strategies, the UAE contributes to a broader model of circular economy practices in road engineering. Its proactive approach, ranging from formal technical guidelines like the Pavement Design Manual (TR-513) to pilot studies using recycled rubber and plastics, positions the country as a regional leader in climate-adaptive transportation infrastructure.

5

PANAMA AS ADAPTATION CASE FOR RESILIENT ROAD INFRASTRUCTURE IN DEVELOPING COUNTRIES

5.1. OVERVIEW OF PANAMA'S CLIMATE CONDITION AND ROAD INFRASTRUCTURE

Panama has a tropical and high humidity weather, with consistent elevated temperatures throughout the year. The country experiences significant rainfall, especially during the rainy season, which extends from May to November. In Some regions, the annual precipitation can exceed 3,000 mm. Between 1971 to 2020, Panama has shown spatially heterogeneous trends in precipitation. In other words, there has been significant declines in rainfall in the easters area, such as the Embera indigenous group region, 109.34 mm and 103.71 mm respectively per decade. In contrast, the westerns and Caribbean provinces, including Bocas del Toro and the Ngäbe Bugle region, recorded significant increases in precipitation of 63.07 mm and 59.63 mm per decade, especially during the wet season [63].

See Fig. 21 and Fig. 22 for topographic and political reference. As illustrated in the topographic map, Panama's most mountainous region is in the western part of the country. Administratively, Panama is divided into ten provinces and six Indigenous comarcas, four of which hold provincial-level status.

Fig. 21 - Topographic map of the Republic of Panama.

Fig. 22 - Political map of the Republic of Panama.

These geographic and administrative characteristics are directly linked to the country's climate vulnerability. In particular, the combination of mountainous terrain in the west and densely populated urban areas elsewhere makes road infrastructure highly sensitive to extreme weather events. The intensification of precipitation patterns poses notable challenges for road infrastructure, including flooding, landslides, and accelerated pavement deterioration. Moreover, the expansion of urbanized areas across the country emphasizes the importance of integrating climate considerations into infrastructure planning, design, and maintenance strategies to enhance long-term resilience and durability.

Complementing these precipitation trends, Panama also experiences a dry season from December to April, that has brought intense summers over the last years. The World Bank Group agrees that the country has undergone a steady rise in mean temperature, averaging an increase of 0.23 °C per decade between 1971 and 2020. The eastern provinces, particularly Darién and Emberá, recorded the most pronounced warming trends, reaching up to 0.37 °C per decade. The most intense temperature increases occurred during the summer months, with nearly all provinces registering mean temperature rises above 0.20 °C per decade. Notably, Darién reported maximum summer temperatures rising by as much as 0.35 °C per decade [64]. To illustrate national temperature variations, Fig. 23 presents a heatmap of historically observed monthly average mean temperatures, highlighting seasonal trends and long-term thermal patterns across the country.

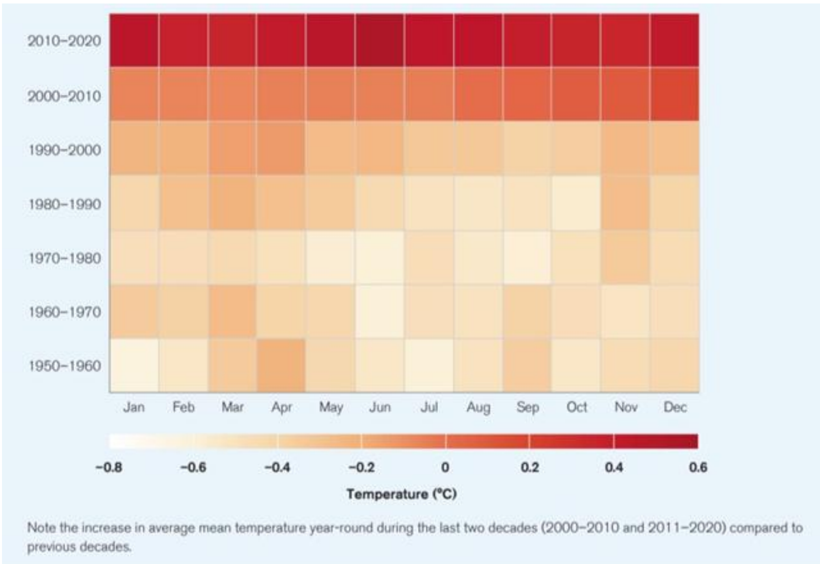

Fig. 23 - Heatplot of Historically Observed Average Mean Temperature Trends per Mont Nationally (1951–2020) *[64]*.

This consistent rise in temperature, particularly the increase in maximum and summer temperatures, has direct implications for infrastructure performance, especially roads. Asphalt is highly sensitive to heat, and prolonged exposure to elevated temperatures can soften the binder, reduce structural stiffness, and accelerate surface deformations such as rutting, bleeding, and cracking. In places with hot and humid climates such as Panama, these effects are intensified, shortening the service life of pavements and increasing maintenance demands.

Given the increasing climatic variability and rising temperatures, it is essential to assess the current state of Panama's road infrastructure, which serves as a critical backbone for national connectivity and economic development. The country's road network not only links major urban centers with rural communities but also plays a key role in facilitating regional trade and integration. However, the resilience of this network is increasingly tested by climatic stressors such as intense rainfall, heat, and extreme weather events. Understanding the structure, condition, and investment trends in Panama's road system provides the necessary context for evaluating its vulnerability and adaptive capacity in the face of ongoing climate change. According to the Análisis de Inversiones en el Sector Transporte Terrestre Interurbano Latinoamericano A 2040, from the Banco de Desarrollo de América Latina, Panama had a total road network of 16.366 km up to 2016. From this total, 43% is paved, 28% is "surfaced", meaning it has gravel and possibly a bituminous treatment, and 30% is unpaved or "earth road". The report highlights that the primary issue is not the total length but rather the poor condition on many of existing roads, which represents a significant challenge in terms of resilience. Some of these deteriorated roads are located in high traffic urban areas, while others are found in mountainous rural zones, where poor road conditions can pose serious safety risks during hazardous weather events [65].

Although other sources [66] describe Panama's highways as "well-maintained", recent official statistics on the quality and extension of the road network remain limited. However, government plans have emphasized continued investment in infrastructure development. According to the 2020 report, while Panama's investment in road infrastructure has not reached the global average, it still exceeds the regional average for Latin America, which is a promising indicator for future improvements in road performance and resilience. To contextualize Panama's investment capacity in comparison to other regions, Fig. 24 illustrates public spending in thousands of U.S. dollars per capita, comparing Panama with the regional average and high-income countries.

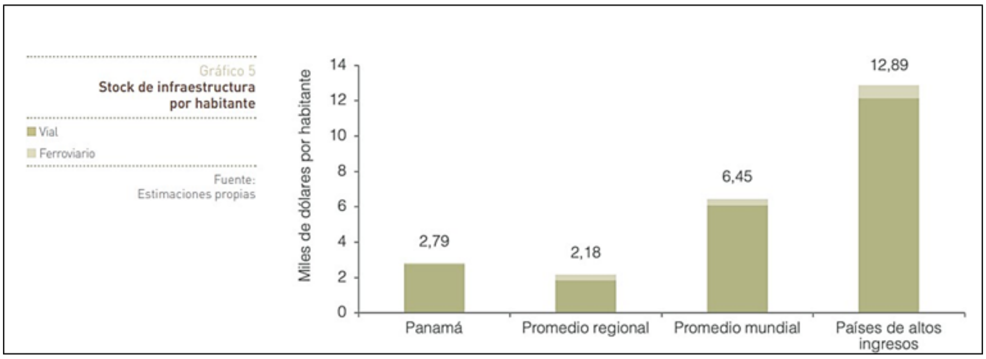

Fig. 24 - Thousands of U.S. Dollars for Habitant for Panama, Regional Average, and High-income Countries [65].

The Panamanian government has acknowledged the urgent need to invest in more resilient road infrastructure in response to the increasing deterioration of roads caused by climate-related hazards. In 2025, the Ministry of Public Works (MOP) [67] announced a budget allocation of USD 453 million for upcoming road projects, along with an additional USD 136 million in bids expected before the end of the year 2025 [67]. The report also emphasized immediate responses to environmental damage caused by the extreme rainfall events that occurred throughout the whole country, from October to November 2024, which led to landslides, road collapses, and pavement cracking, leaving several regions temporarily disconnected. In response, the government designated USD 120 million specifically for emergency repairs. These investment efforts reflect a growing recognition of the need for more climate-resilient infrastructure. However, disparities remain. While funding has focused primarily on national and regional roads, remote and vulnerable communities, particularly indigenous populations in rural areas, continue to face exclusion from infrastructure improvements. This gap highlights the importance of ensuring that resilience strategies address not only technical challenges but also promote equitable and inclusive road infrastructure planning. Evaluating Panama's current investment patterns considering international best practices can help identify more effective, climate-responsive approaches.

5.2. INSTITUTIONAL FRAMEWORK AND PANAMA'S COMMITMENTS TO CLIMATE RESILIENT INFRASTRUCTURE

Panama is a country attempting to develop in every possible way. In this context, climate resilience, climate change mitigation and adaptation are key priorities that Panama aims to achieve in order to sustain its development and improve the quality of life of its residents. For instance, in 2020, Panama updated its first Nationally Determined Contribution (NDC1), which outlines a national commitment to fostering climate resilience across all sectors of society [68]. In this document, the importance of understanding Panama's unique climate and geography is emphasized. For instance, due to the country's position between two oceans, humidity presents a significant challenge, and climatic patterns are further influenced by the North Atlantic, which generates trade winds that affect national weather conditions [69]. This document implies that it takes this part seriously for the development of strategies that can adapt better to this cli- mate condition. However, although the NDC1 frequently emphasizes the need to build resilient infrastructure throughout the country, particularly in areas, both urban and rural, that are already facing the consequences of climate change on a regular basis, the plan does not provide any concrete or detailed strategies for resilient infrastructure implementation. This absence of concrete measures is especially concerning given Panama's geographic vulnerability. As a narrow isthmus bordered by both the Pacific Ocean and the Atlantic Sea, the country, and particularly Panama City, face high exposure to sea-level rise, coastal flooding, and tropical storms. Fig. 25 illustrates the capital's proximity to the coastline, underscoring the urgent need for spatial planning and resilient infrastructure in low-lying urban zones.

(a) (b)

Fig. 25 - (a) and (b) illustrating sea proximity to the capital of Panama.

To strengthen institutional capacity, Panama's Ministry of Environment, together with governmental authorities, enacted Law No. 8 of 2015, which provides a framework aimed at improving oversight of infrastructure related institutions. Among its objectives is the promotion of public access to data, particularly to enhance transparency in the financial management of infrastructure projects [68]. However, this remains one of the country's major institutional challenges. In many cases, the platforms designed to ensure transparency are either incomplete or not accessible for public consultation, making it difficult for citizens to track how public funds are being allocated. One example is the platform called Gestión Transparente Panamá, which is intended to display all ongoing public projects, with data organized by province. However, in practice, accessing detailed information about specific projects through this portal is not possible. Users are unable to open individual project pages, and there is no functional mechanism to contact responsible entities for clarification or additional data. As shown in Fig. 26, the platform illustrates the process of locating a project, but it fails to provide sufficient information regarding project costs or financial breakdowns. The platform also provides a contact message receiver, but when intended to send the message requesting information of a specific project, there marks to be an error. This lack of transparency poses a serious obstacle to the development of resilient cities, particularly given that many of the resilience strategies employed by developed countries rely on substantial financial investment and accountability.

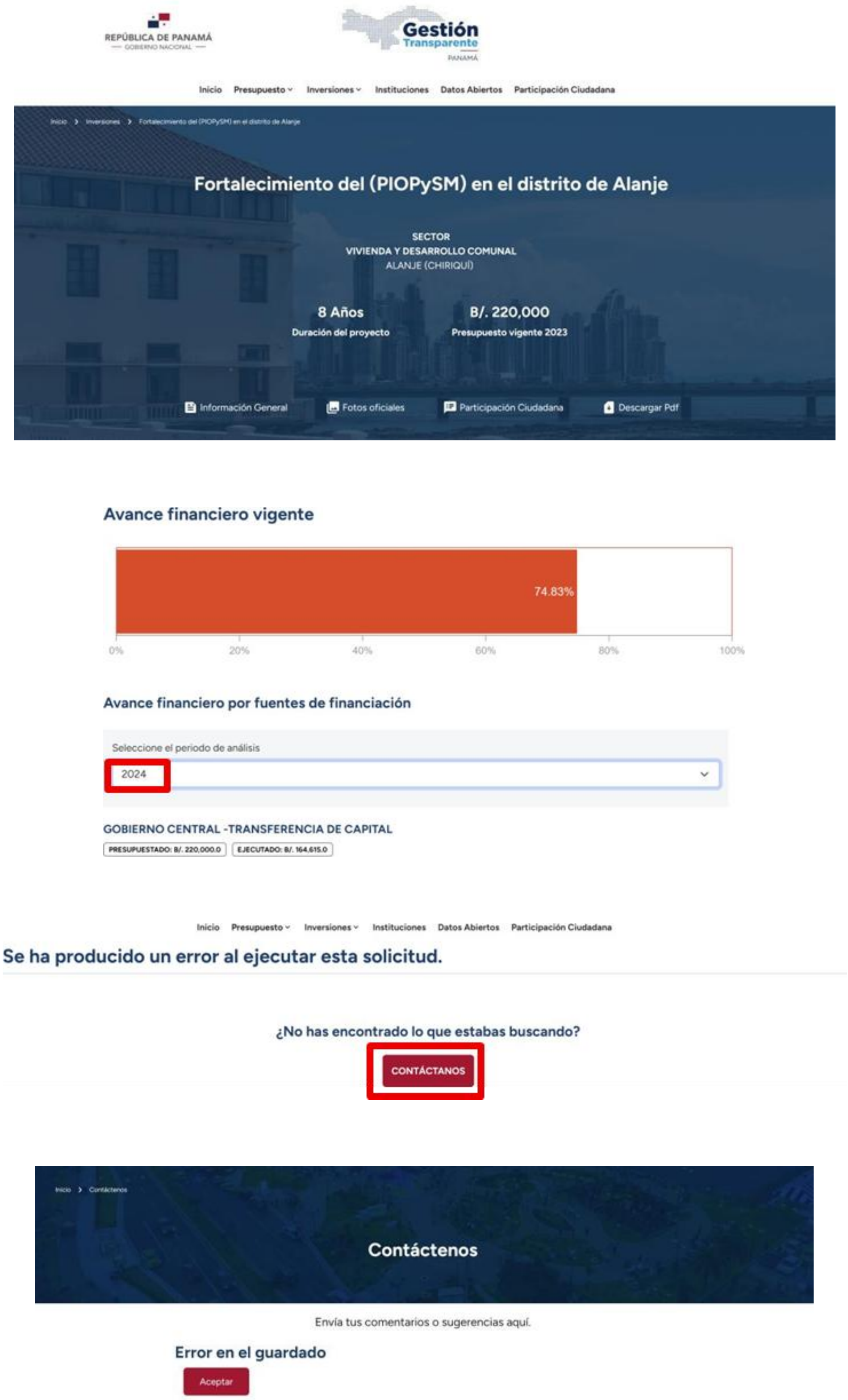

Fig. 26 - Platform Gestión Transparente Panamá. Process of requesting information about specific public work project *[70]*.

In 2021, Panama released its Second Biennial Update Report (2IBA) [71]. This report emphasizes the urgent need to create climate resilient infrastructure, identifying transport and road infrastructure as among the most vulnerable sectors. The fact that Panama continues to communicate its national intentions and institutional efforts through such reports reflects a sustained commitment to environmental responsibility and signals a focus on building a more sustainable future. However, it is time that greater action is required to transform these commitments into tangible outcomes and advance toward a more climate resilient nation.

In 2016, Panama became part of the 100 Resilient Cities program. The following year, the country published Panamá Resiliente, a strategic document outlining objectives related to various sectors, including infrastructure, water, and mobility, with a long-term vision extending to 2030 [72]. The document recognizes the need for a fundamental shift in infrastructure development to better withstand the increasing risks associated with climate change. Given that one of Panama's primary challenges in road infrastructure is the occurrence of intense rainfall during the wet season, one of the most prominent initiatives featured in the strategy is the Green-Blue Micro-Infrastructure Program. The goal of this program is to reduce flooding through the integration of bioretention elements into parks, traffic islands, roundabouts, and other available open spaces. The strategy also outlines the implementation of complementary pilot projects, including permeable pavements and green roofs. These initiatives were projected to follow a timeline of 12 months for construction and an additional 24 months for maintenance and monitoring. The program envisioned close coordination between Panama's two main institutions responsible for road construction and stormwater management, the MOP and the National Institute of Aqueducts and Sew- age Systems (IDAAN), under the leadership of the central government [72]. Despite its early launch in 2017, there is no public record confirming the field implementation or monitoring of the Green-Blue Micro-Infrastructure Program as of 2025. This lack of follow-through suggests that, despite institutional commitment, the program has not advanced beyond the planning stage. Furthermore, the strategy references other international cases as sources of inspiration. Notably, it cites the Northern Park project in Santa Fe, Argentina, a proposal attributed to architect Lucas Henquin. However, this example appears to remain conceptual in Argentina as well, with no public record of implementation or follow up. This reflects a broader pattern of relying on aspirational models that, while innovative, may not provide tested or scalable solutions. Fig. 27 illustrates Henquin's proposal for a park designed with natural water retention strategies. However, publicly available evidence suggests that the Santa Fe example remains a conceptual design rather than a fully implemented and monitored program. This reflects both the ambition and the limitations of precedent-based planning, where the use of aspirational references does not necessarily correspond to proven technical implementation or operational maturity.

Fig. 27 - Render from Lucas Henquin's Arquitectual Portfolio [73].

In 2023, Panama collaborated with the Instituto de Hidraulica Ambiental (IHCantabria) of the University of Cantabria, along with the MOP and the Inter-American Development Bank (IDB), in a study aimed at identifying climate vulnerabilities in Panama City's urban transport system. The study focused on the impacts of flooding and extreme heat, particularly in the context of Panama’s long-term goal of transitioning toward a decarbonized public transport fleet through the adoption of electric vehicles. Although the study centers on urban transport, road infrastructure plays a critical role, as the identified climate risks directly hinder the provision and maintenance of reliable, safe, and accessible road networks [74].

The main objective of the project was to update Panama’s climate forecasts in order to anticipate and better plan the actions necessary to address climate change. The study included a quantitative analysis of disaster and climate risk based on projected scenarios extending to 2050. It identified areas that are most susceptible to flooding and heat related disruptions and emphasized the need to integrate nature-based solutions into infrastructure planning. Moreover, the study incorporated an economic pre-feasibility analysis of two infrastructure projects already awarded by the MOP, which had not yet begun implementation at the time. This provided a timely opportunity to introduce climate adaptation measures into their design from the outset [74].

Fig. 28 - Technical staff from Panama’s Ministry of Environment pose in the photo alongside the Ministry’s National Director of Climate Change, Ligia Castro de Doens (center, front row), and the researchers from IHCantabria who conducted the training workshop [75].

This project highlights the strategic value of international collaboration in supporting Panama’s resilience objectives. Through the combination of specialized academic expertise, institutional coordination, and international financial assistance, the initiative shows how assessments based on global expertise but adapted to local conditions can lay the groundwork for effective policy changes and smart infrastructure investments. In a context where many resilience strategies remain at the conceptual stage, this project represents a significant step toward the operationalization of cli- mate adaptation in the transport sector. Although the study is primarily focused on urban public transportation and not directly on road infrastructure resilience, it constitutes meaningful progress toward climate adaptive planning in Panama. By addressing vulnerabilities in the transport network, particularly those related to flooding and extreme heat, it contributes to the broader objective of sustainable infrastructure development and reflects growing institutional awareness of the need to integrate climate risk into infrastructure decision making processes.

Despite notable progress in climate policy development, strategic planning, and international cooperation, Panama continues to face significant challenges in executing its resilience strategies, especially in the road infrastructure sector. The absence of publicly available updates on the Green-Blue Micro-Infrastructure Program, combined with the reliance on aspirational but unverified international models, reflects a wider institutional pattern: ambitions for resilience are often not matched by implementation capacity. However, the country's growing collaboration with technical and financial partners, such as IHCantabria and the IDB, indicates a commitment to data- driven planning and to embedding climate considerations into infrastructure design. With these institutional and analytical resources now in place, Panama stands at an important point to move from conceptual frameworks to the practical application of resilient infrastructure strategies.

6

ADAPTATION AND DISCUSSION OF INTERNATIONAL BEST PRACTICES FOR ROAD RESILIENCE IN PANAMA

6.1. PERMEABLE PAVEMENTS FROM CHICAGO, IL, USA

Two of the most densely urbanized cities in Panama are Panama City and David. See Fig. 29 for refence. Both cities frequently experience surface runoff and localized flooding during periods of heavy rainfall, especially in narrow street areas. To address these recurring issues, it is essential to identify the most vulnerable zones and prioritize the reconstruction and improvement of their storm drainage systems. Rapid urban expansion in both cities has often outpaced the capacity of existing infrastructure, further intensifying flood risks. In this context, the implementation of permeable pavements presents a viable solution to manage stormwater more sustainably and mitigate the impacts of intense rainfall events.

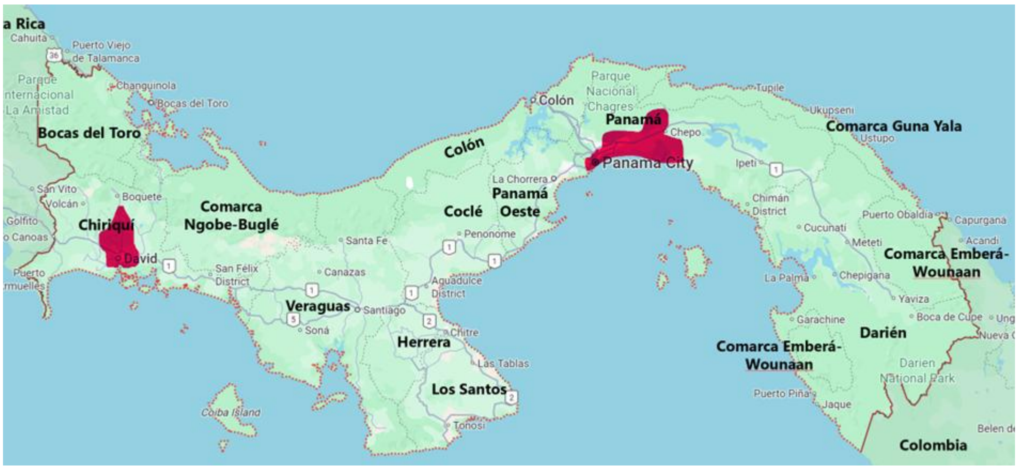

Fig. 29 - David, Chiriqui and Panama City highligthed in red on the national map.

Although interlocking permeable concrete pavers are not yet widely adopted as a central strategy for urban climate resilience, they are not unfamiliar in Panama. In cities like Panama City and David, this type of pavement has been incorporated into public spaces such as Casco Antiguo, Cinta Costera, and Parque Miguel de Cervantes Saavedra. How- ever, their application in these areas might mostly been guided by aesthetic and architectural considerations, particularly in historic or touristic zones, rather than by engineering objectives related to urban runoff or flood control. In addition, there are not public plans or details on the subgrade for these permeable pavements. Thus, it is not 100% known if they are fully permeable meant to be systems. The most common form of permeable pavements used in Panama is interlocking permeable concrete pavers. Fig. 30 illustrates their use in Casco Antiguo, the historic quarter and one of the most visited areas of the metropolitan capital.

Fig. 30 - Casco Antiguo Road, Panama City [76].

Another clear example of this application is La Cinta Costera, a major touristic area in the city that offers visitors a 7.6-kilometer trail for walking, exercising, and recreation [77].

Fig. 31 - Cinta Costera Trail, Panama City [78].

As previously mentioned, and shown in Fig. 32, the city of David has incorporated interlocking permeable pavers in its main park, located in the center of the urban area of the city. This park is considered a refreshing public space during hot days, as it is shaded by trees and features a central fountain, creating a comfortable outdoor environment. The park spans an area of approximately 7,000 m^2 [79].

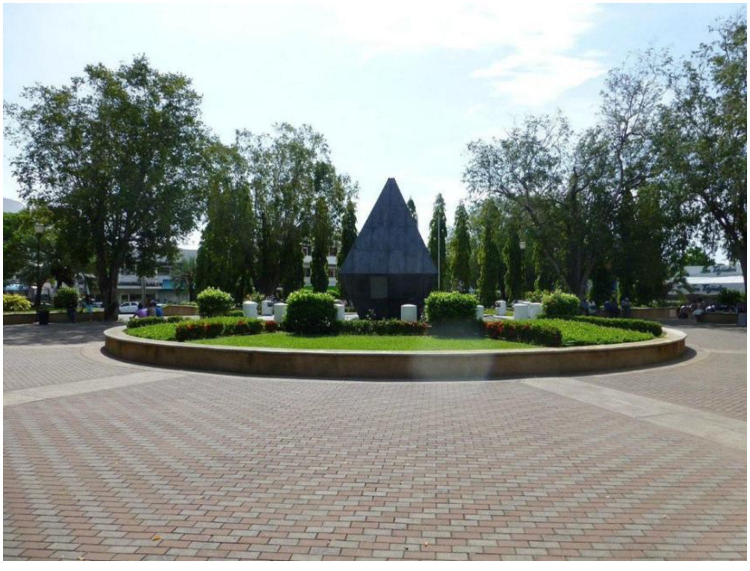

Fig. 32 -Parque Miguel de Cervantes Saavedra in city of David, province of Chiriqui *[80]*.

At the institutional level, permeable pavements have increasingly been recognized as part of Panama's broader climate adaptation efforts. The Panamá Resiliente report specifically highlights them as a potential tool to improve urban water management and mitigate the impacts of heavy rainfall events. Despite this recognition, their application remains limited, and public awareness of their potential as a resilience-oriented solution is still low. This disconnect between institutional planning and public understanding underscores the need for both pilot projects and targeted communication strategies to demonstrate the functional benefits of permeable pavements beyond their aesthetic appeal.

In cities such as Panama City and David, both characterized by extensive impervious surfaces, aging drainage infrastructure, and frequent intense rainfall, there is significant potential to expand the use of permeable pavements. Residential neighborhoods, commercial corridors, and civic spaces affected by recurring runoff could benefit greatly from their integration. These systems could be particularly well suited in Panama for low-traffic urban areas such as sidewalks, pedestrian walkways, parking lots, and bicycle lanes, where their drainage capacity can be optimized without compromising structural durability.

The implementation of permeable pavement systems in Panama can build on the existing, though limited, use of these materials in urban public spaces. Since interlocking permeable pavers are already present in high-profile areas such as Casco Antiguo and the Cinta Costera, there is a baseline of technical familiarity among some municipal authorities, contractors, and suppliers. This existing knowledge provides a practical entry point for expanding the application of permeable pavements into new areas of urban infrastructure, particularly with a focus on climate resilience rather than aesthetics.

To transition from isolated cases to broader integration into urban planning, a coordinated implementation strategy is needed across multiple levels. First, pilot projects should be launched in areas with recurring flooding issues, particularly in Panama City neighborhoods such as Pueblo Nuevo, San Miguelito, and Curundu, as well as in central David, where rapid urban growth has placed increasing pressure on drainage systems [83]. These pilots can demonstrate the hydrological and functional benefits of permeable pavements when properly designed, installed, and maintained. Second, institutional collaboration is essential. The MOP, the National Secretariat for Science and Technology (SENACYT), and municipal governments should coordinate efforts to develop technical guidelines and performance standards tailored to Panama's tropical conditions. These standards should address critical aspects such as infiltration rates, structural performance under heavy rainfall, subgrade preparation, and maintenance protocols. International cooperation with countries and institutions that have success- fully implemented permeable pavement strategies can also support the development of context-specific guidelines.

Third, integration into urban planning and development regulations will be key to ensuring long-term adoption. Urban development codes could be revised to encourage or require the use of permeable pavements in contexts such as parking lots, pedestrian infrastructure, and new residential or commercial projects. Incentive mechanisms, including tax reductions, density bonuses, or expedited permitting, could help motivate private sector participation in the construction of permeable pavement systems.

One of the main challenges to the implementation of these systems, particularly for improving drainage, is securing funding for both the initial investment and long-term maintenance. As seen in the Chicago case, the success of permeable pavement projects depends heavily on access to sufficient upfront capital, as well as dedicated funding for ongoing maintenance to ensure sustained performance. In Panama, financial resources for road infrastructure are not necessarily scarce; in fact, the country consistently allocates a significant portion of its national budget to transport and public works. However, the issue lies not in the volume of funding but in how effectively it is used. Infrastructure investments in Panama have often been hindered by inefficiencies, a lack of transparency, and short-term political priorities. These conditions pose serious obstacles to the implementation of resilient infrastructure strategies, which require long- term vision, technical oversight, and consistent institutional support. Without clear ac- countability and a shift toward performance-based planning, investments in climate-resilient solutions may continue to face institutional and operational barriers, despite their potential to reduce urban flood risks.

Panama continues to direct a substantial share of its public investment toward road and transport infrastructure, with the construction sector accounting for approximately 18% of GDP in the first half of 2024 [81]. Capital expenditures, those which include government investments in long-term infrastructure such as roads and public works, increased by 25% compared to the previous year, reaching nearly US $2.1 billion in the first six months of 2024. Despite these robust funding levels, the effectiveness of public investment remains a persistent concern, particularly in long-term projects that require continuous monitoring and maintenance.

6.2. ROOM FOR THE RIVER PROGRAMME FROM NETHERLANDS, EU

Given Panama's geographic and climatic conditions, the Room for the River case study in Netherlands, is highly relevant, particularly in areas where river overflows and associated flooding regularly impact communities and infrastructure, mainly road net- work. Many of Panama's rural and mountainous regions support significant agricultural activity and serve as home to populations that depend directly on land productivity for their livelihoods. In these areas, flood events and landslides triggered by heavy rainfall not only threaten human safety and property but also cause major disruptions to the national economy.

One clear example is Tierras Altas in the province of Chiriqui, a region known for its fertile volcanic soils and critical role in national food production. This region is frequently affected by overflowing rivers and landslides during extreme weather events. These extreme rainfall events that cause overflow of rivers not only damage crops and disrupt agricultural production, but also lead to road and bridge closures, cutting off access to farming zones and leaving entire communities temporarily isolated from markets and essential services.

Fig. 33 - District of Tierras Altas, province of Chiriqui highlighted in red.

The consequences that these extreme rainfall events leave in the community are critical because Chiriqui contributes approximately 52.6% of all registered agricultural activity in Panama [82] and produces around 80% of the vegetables consumed nationwide [83]. The vulnerability of this region to climate related flooding not only endangers local communities but also compromises national food security and economic stability.

Fig. 34 - Flooding of the stream "La Chacha" in the Tierras Altas district due to heavy rainfall in the region [84].

Despite the environmental sensitivity and economic importance of Tierras Altas, river and watershed management strategies remain largely reactive, focusing on emergency response rather than long-term adaptation. Implementing elements of the Room for the River approach, such as designating buffer zones and expanding floodplains to give rivers more space to accommodate increased volumes during extreme rainfall, could offer a more sustainable way to manage flooding. In the long run, this would help reduce the costs associated with rebuilding infrastructure and alleviate the burden on affected communities. These nature-based solutions can also help restore degraded river ecosystems, improve soil retention, and stabilize slopes, thereby reducing the overall risk of landslides and downstream sediment buildup [85].

Another area where the Room for the River strategy could be applied is the Tocumen River Basin, located in the eastern part of Panama City. This area has experienced

rapid urban growth over recent decades. Between 1960 and 2010, the population increased from 2,088 to 114,425 residents, leading to fast-paced development and significant deterioration of natural areas [86]. Among the most affected ecosystems are coastal wetlands, whose loss has contributed to erosion and reduced the landscape's ability to naturally absorb excess water during periods of heavy rainfall. As a result, the area has become increasingly vulnerable to flooding, an issue expected to intensify with the effects of climate change.

In this context, the priority is not only to "create space for the river," but also to restore ecological function. This could involve actions such as the reforestation of floodplains with native vegetation, which would support both flood regulation and environmental rehabilitation. In 2020, the World Bank, in coordination with the municipal government and other key stakeholders, conducted a study focused on flood risk assessment and the prioritization of nature-based hybrid infrastructure to reduce vulnerability in the Tocumen River Basin. The report provided technical findings, spatial analyses, and practical recommendations to guide future interventions in the area [86].

The environmental degradation observed along Panama City's coastal edge reflects broader challenges associated with urban expansion and weak enforcement of land-use protections. Fig. 35 presents a case of mangrove deforestation in Costa del Este, illustrating the processes and impacts that typify the trend-based development scenario affecting coastal ecosystems in the metropolitan area.

Fig. 35 - Figure X. Mangrove deforestation in Costa del Este, Panama City *[86]*.

To ensure the effective implementation of Room for the River strategies in Panama, it is essential to adopt an integrated, multi-stakeholder governance approach. One key step is the creation of basin-level committees composed of representatives from the MOP, the Ministry of Environment (MiAMBIENTE), municipal governments, and relevant local actors. These committees would coordinate actions related to land use, river restoration, and infrastructure protection, mirroring the collaborative governance structures central to the Dutch program Making Room for the River.

In parallel, the integration of river management principles into territorial planning instruments would help ensure that long-term flood protection is reflected in laws, policies, and development plans. These principles could include the formulation of environmental regulations, to be enforced by both local and national authorities. Finally, meaningful community engagement must be prioritized. This includes participatory flood mapping, public awareness campaigns on the role of rivers in urban and rural resilience, and the creation of local monitoring groups to report early signs of erosion or flood risk. Together, these strategies would build the technical, institutional, and social foundations necessary to restore river corridors while protecting critical infra- structure such as road networks.

The Room for the River programme in the Netherlands has demonstrated that nature-based strategies can provide effective, sustainable solutions to river flooding in urban contexts. However, applying this approach in areas such as Tierras Altas (Chiriqui) and Panama City presents distinct challenges that reflect the country's socio-economic and geographic realities.

In Tierras Altas, one of the primary challenges involves balancing agricultural productivity with ecological restoration. Many of the region's flood-prone zones lie within highly productive farmland. Expanding riparian buffer zones or restoring floodplains in these areas could require the relocation or reduction of crop production, which would pose significant economic implications for farming families. Even where the environmental need is clear, the absence of well-defined zoning regulations and enforcement mechanisms complicates efforts to prevent agricultural activities or construction in areas that should be reserved for natural water flow. As such, restoring space for rivers in this region necessitates a careful, participatory approach, one that reconciles the need for risk reduction with the preservation of rural livelihoods. Achieving this will require close coordination between national agencies and local municipalities, along with support programs for affected producers.

In the Tocumen River Basin, the challenges are primarily urban in nature. Rapid and unregulated urban expansion has significantly reduced the river's natural floodplain, limiting the feasibility of large-scale restoration. Proposals to implement green corridors or flood retention areas often require the relocation of informal settlements or modifications to existing infrastructure, processes that can trigger social resistance and political hesitation. Moreover, despite the availability of technical studies, such as the *Evaluación del riesgo de inundación y priorización* conducted by the World Bank in 2020, there is a persistent lack of operational frameworks and sustainable financing mechanisms to move from planning to implementation.

Across both regions, a broader challenge lies in public perception and political prioritization. River restoration is frequently regarded as an environmental or aesthetic concern, rather than as a strategy for infrastructure protection and climate adaptation. This perception often limits its integration into transport and public works agendas, even though the benefits, such as preserving road connectivity, reducing disaster-related costs, and improving watershed function, are closely aligned with national development goals. Strengthening public understanding of the co-benefits of nature-based solutions is therefore essential to building long-term political and community support.

Although these interventions require both initial investment and continuous maintenance, monitoring, and enforcement, the scale of implementation required in

Panama is significantly smaller than in the Netherlands, where the Room for the River concept originated. In Panama, the most vulnerable areas are geographically concentrated, making targeted, well-coordinated interventions both feasible and impactful. Also, Given the scale and complexity of the challenges that Panama might encounter during the application of a strategy similar to Room for the River, international climate finance mechanisms such as the Green Climate Fund (GCF) and the Adaptation Fund could be applied for. Panama is eligible for both funds and has previously submitted ecosystem-based adaptation proposals, making it well-positioned to frame Room for the River interventions within its broader resilience goals [87]. Using a limited scale at first presents an opportunity for phased implementation, beginning with pilot projects in high-risk basins and gradually expanding efforts based on locally generated data, community engagement, and institutional learning.

6.3. USE OF GEOSYNTHETICS IN THE SÃO PAULO RING ROAD, BRAZIL

The use of geosynthetics in Brazil for constructing more resilient roads provides a valuable reference for other developing countries. In Panama, this construction method- ology is particularly relevant in mountainous regions, where landslides caused by in- tense rainfall pose serious risks to road stability.

Panama contains several areas that are highly susceptible to landslides due to heavy and prolonged rainfall during the wet season. The provinces most affected include Chiriqui, Bocas del Toro, Veraguas, Cocle, Los Santos, Darien, and Eastern Panama, as well as the indigenous region of the Ngäbe-Bugle Comarca. These represent seven out of Panama's ten provinces and one of its five indigenous regions [88]. See Fig. 36 for reference.

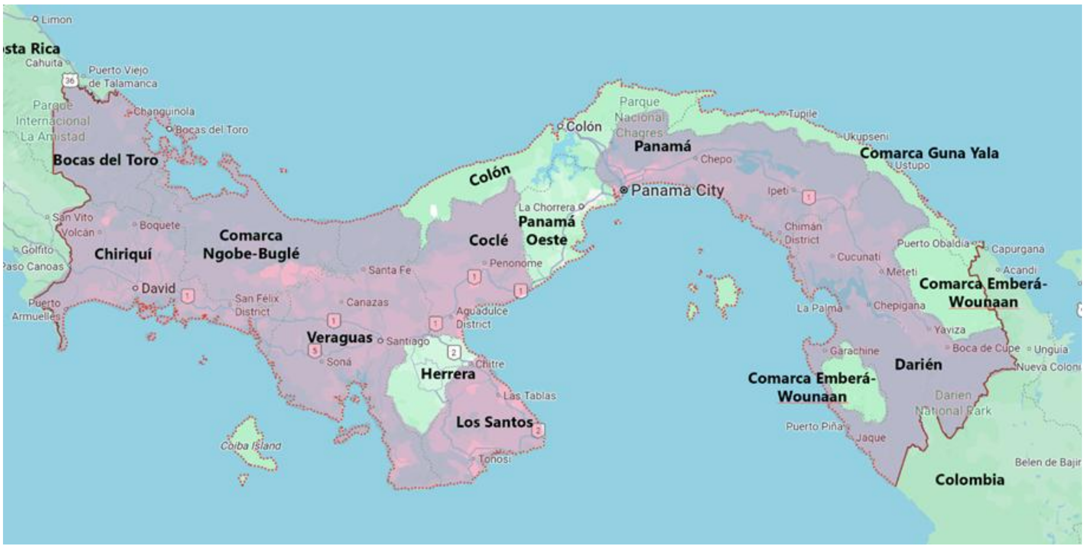

Fig. 36 - Provinces in which the use of geosynthetics for soil stabilizations can be used (highlighted in pink).

Although the use of geosynthetics for road stabilization is not entirely unfamiliar in Panama, its application remains limited. Some private companies supply a range of geosynthetic materials to public and private contractors, including nonwoven geotextiles, geogrids, geocells, and drainage composites, [89]. However, there is a lack of public documentation and government reports verifying the systematic use of these materials in high-risk, landslide-prone areas.

An exception to this limited transparency seemed at first to exist in a 2019 project along a 55-kilometer section of the Pan-American Highway in Chiriqui province. The project aimed to improve pavement durability by incorporating fiberglass geogrids within asphalt layers during resurfacing, instead of fully rebuilding the structure. The objective was to enhance crack resistance and reduce maintenance frequency. While this initiative was presented at a conference on geosynthetics in road construction in Brazil, the accompanying report lacked methodological clarity and revealed discrepancies in cost calculations and design details [90]. This example highlights one more time the need for greater accuracy and transparency in official infrastructure documentation.

To effectively implement geosynthetics in Panama, the process should begin with the prioritization of vulnerable road sections based on historical landslide records, rainfall intensity, and geotechnical profiles. The Ministry of Public Works (MOP), in collaboration with the National Civil Protection System (SINAPROC), should conduct detailed geotechnical assessments to identify critical areas at risk of slope failure and soil erosion. Once high-priority zones are selected, pilot projects should be launched to demonstrate the performance of different geosynthetic applications. These could include geogrids for slope reinforcement, geotextiles for filtration and separation, and geocomposites for subsurface drainage.

The effectiveness of these pilot projects must be assessed through robust monitoring systems, tracking indicators such as slope stability, drainage capacity, and pavement longevity. Road durability presents a practical and measurable indicator of performance, particularly in Panama's mountainous regions where certain road segments require rehabilitation almost every year due to rainfall-induced damage. If a road section stabilized with geosynthetics remains intact for a couple or several years without needing major repairs, this would offer concrete, short-term evidence of the effectiveness of the intervention, demonstrating greater resilience compared to traditional construction methods.

Another essential aspect of implementation is the training of public road engineers, contractors, and field technicians. These programs should focus on the selection, installation, and maintenance of geosynthetics, contextualized within Panama's climatic and geotechnical conditions. The Universidad Tecnologica de Panama (UTP), the country's leading institution in engineering, science, and technology could play a key role in this effort [91]. In addition to theoretical instruction, UTP could lead field demonstrations, develop technical curricula, provide certified trainers, and establish continuing education programs in collaboration with the MOP.

To institutionalize the use of geosynthetics, Panama should also revise its national road construction manuals and tender specifications to formally include these materials for landslide-prone areas. Procurement frameworks should be updated to ease the acquisition of certified geosynthetic products, especially for rural and secondary road networks where accessibility is frequently compromised by landslides.

Despite the advantages of geosynthetics, the effective implementation in Panama faces several challenges. A significant barrier is the limited technical capacity and awareness among public sector engineers and contractors, particularly in remote and indigenous areas such as Tierras Altas and the Ngäbe-Bugle Comarca. Although geosynthetics are available domestically, their practical application remains rare, due in part to the absence of standardized guidelines and structured training programs. Additionally, budgetary constraints present another obstacle. Although geosynthetics offer long-term savings by reducing maintenance needs and enhancing road durability, their higher initial costs are often difficult to accommodate within infrastructure budgets shaped by short-term political agendas. For decision-makers to justify these upfront investments, strong evidence of cost-effectiveness is essential.

Institutional coordination also remains a concern. The successful implementation of geosynthetic strategies requires close collaboration between the MOP, SINAPROC, Mi-AMBIENTE, and municipal governments. Yet, inter-agency efforts are often hampered by bureaucratic inefficiencies and overlapping mandates. This lack of clear institutional roles can slow down implementation efforts.

Land ownership issues may further complicate the stabilization of vulnerable slopes. In many cases, agricultural activities occur close to road infrastructure, and past avoidance of slope treatment may have come from conflicts with private landowners. Addressing this challenge will require stakeholder engagement and negotiation with local communities.

Finally, Panama currently lacks standardized procedures for the long-term monitoring and maintenance of geosynthetic installations. Establishing dedicated teams and clear responsibilities within public institutions is crucial to ensure these materials perform as intended over time and to build trust in their use.

Together, these challenges highlight the need for a comprehensive implementation strategy that integrates technical training, institutional reform, data development, and community engagement to support the widespread and effective use of geosynthetics in Panama's road infrastructure.

6.4. HEAT-RESISTANT ASPHALT MIXES FROM ABU DHABI, UAE

Given Panama's tropical climate, with temperatures frequently exceeding 35 °C throughout the year, the use of heat-resistant asphalt mixtures emerges as a viable strategy to enhance the resilience of the national road network. Densely urbanized provinces, such as Panama, Colón, and David in Chiriqui, are especially susceptible to asphalt deterioration caused by sustained high temperatures. As has been studied in the past chapters, these conditions accelerate the degradation of traditional asphalt surfaces, leading to issues such as rutting, cracking, and binder softening, which ultimately compromise road safety and increase maintenance costs.

Fig. 37 - Provinces in which heat resistant asphalt mixtures could be applied.

Before considering the implementation of heat-resistant asphalt mixtures nationwide, comprehensive local research must be undertaken. In this context, the UTP and SENACYT, two institutions with a history of collaboration in engineering, science, and technology research, could jointly lead studies on the performance of polymer-modified binders under Panama's specific climatic conditions, which include both high heat and high humidity. For instance, considering promising results from the UAE's research, particularly with DVR–LDPE, Panama could conduct parallel laboratory evaluations at UTP's facilities. These efforts would also offer valuable research opportunities for students and serve as an entry point to expand national knowledge on asphalt performance under tropical stressors. This kind of collaboration is possible and comes at a good moment for Panama. To explain better, in April 2023, SENACYT visited UTP installations with the explicit aim of strengthening their institutional relationship and enhancing research initiatives that prepare students to address national development challenges [92]. SENACYT has long funded projects focused on sustain- ability, climate, and infrastructure resilience. Updates on three such projects were publicly presented in late 2023 [93] and by 2025, results were released demonstrating the institutions' capacity to lead research on climate-related vulnerabilities, and this can be potentially extensible to the field of road infrastructure [94].

To ensure the success of this research agenda, some investment may be required to upgrade UTP's laboratory equipment and expand its testing capabilities. While this could pose an initial challenge, it is financially achievable if a portion of the national

road budget is allocated toward climate-resilient innovation. As of 2025, the MOP has committed to investing at least USD 775 million over the next decade in the construction, renovation, and improvement of major highways [98]. Channelling part of these funds toward innovation in heat-resistant materials could yield long-term benefits by reducing the frequency of road rehabilitation and maintenance caused by thermal stress.

Despite the potential of heat-resistant asphalt mixes to improve the lifespan and durability of roads, several challenges must be addressed. First, Panama must develop technical specifications and design guidelines tailored to its climatic conditions to ensure the effective use of modified asphalt mixtures. Second, although UTP and SENACYT possess the institutional capacity for preliminary research, there may be gaps in coordination between academic findings and government implementation. Third, if the country opts to use imported polymers, as was the case of UAE and the usage of SBS in PMB, Panama may encounter logistical and environmental drawbacks. These include cost, carbon footprint, and supply chain reliability. Consequently, this opens an opportunity to explore local alternatives such as recycled rubber or plastics. How- ever, doing so would require the development of reliable systems for collection, processing, and quality control of waste materials, which itself presents technical and logistical challenges.

Finally, another critical obstacle is the higher upfront cost of polymer-modified mixtures compared to conventional asphalt. While long-term economic analyses suggest that reduced maintenance and extended pavement life can offset initial expenses, gaining political and fiscal support for these investments remains a challenge in the current budgetary context.

CONCLUSIONS AND RECOMMENDATIONS

Given the challenges that climate change brings upon road infrastructure, this thesis examined the urgent need for resilient road infrastructure in developing countries such as Panama. Countries like Panama, with fast urbanization and limited resources for public works, face critical risks when hazardous conditions emerge due to climate change. Its vulnerability due to its geographic location has constant challenges to the durability and maintenance of their roadway infrastructure.

This thesis selected and analysed four case studies on road climate resilience strategies: the Green Alley Program in Chicago, USA; geosynthetics in São Paulo’s Rodoanel; the Room for the River program in the Netherlands; and heat-resistant asphalt mixes in Abu Dhabi. During the analysis of each case study, both successes and ongoing challenges were observed, each offering valuable lessons for climate change adaptation.

After examining these case studies, the applicability analysis for Panama revealed that while there are challenges to implementation, these strategies are achievable in the long term. It was noted that Panama is increasingly recognizing the need for climate adaptation; however, this recognition often remains conceptual or unimplemented. In some instances, Panama has begun applying resilient strategies on a smaller scale. For example, permeable pavements have been installed in touristic areas of the country. While their initial use may have been guided by aesthetic or architectural motives, their existence serves as proof that this type of infrastructure can function effectively for urban drainage management.

It was concluded that permeable pavements can enhance urban drainage in cities like Panama City and David; geosynthetics are highly applicable in mountainous regions prone to landslides; the Room for the River strategy could address flood risks in agricultural zones such as Tierras Altas and rapidly urbanizing basins like Tocumen; and polymer-modified asphalt offers a promising solution for mitigating heat-induced road degradation in high-temperature regions. Yet, a consistent finding throughout this research is the disconnect between Panama's policy ambitions and its operational capacity to deliver resilient infrastructure. Challenges such as limited inter-institutional coordination, insufficient technical training, lack of data transparency, and budget constraints hinder progress. To bridge this gap, Panama must move from reactive responses toward proactive planning and investment in resilience.

To strengthen climate-resilient road infrastructure in Panama, this study recommends beginning with pilot projects in high-risk areas such as the city of David, Tierras Altas, Eastern Panama, and the Ngäbe-Bugle indigenous region. These locations can serve to test and demonstrate the effectiveness of solutions like permeable pavements, geosynthetics, and heat-resistant asphalt under Panama's specific climatic conditions.

Capacity building is also a critical component. Institutions such as the UTP and SENACYT should lead technical training programs and applied research efforts. At the same time, stronger coordination among public agencies, particularly the MOP, MiAMBIENTE, and SINAPROC, will be necessary to align infrastructure planning and implementation across the country.

Revisions to national planning and regulatory frameworks should also be made to integrate resilience principles into road design standards and urban development codes. This will help ensure that long-term adaptation is embedded in infrastructure projects from the outset.

Public investment in infrastructure should be paired with greater transparency and ac-countability. Platforms such as Gestión Transparente Panamá must be improved to provide citizens with better access to project data and performance monitoring tools.

International partnerships and climate finance mechanisms, such as the Green Climate Fund, present valuable opportunities to secure funding and technical expertise. These should be actively pursued, especially for large-scale or nature-based infrastructure projects.

Finally, raising public awareness and involving communities in planning and monitoring efforts is essential. Community participation will help improve project relevance and long-term support, while also ensuring that infrastructure serves both environ- mental and social goals.

REFERENCES

[1] J. A. B. M. a. C. F. D. Hambly, "Projected impacts of climate change on road and rail infrastructure in the province of British Columbia," *Can. K. Civ. Eng.,* vol. 40, pp. 625 - 637, 2013.

[2] P. A. S. A. N. Adger, "Climate Change 2007: Impacts, Adaptation and Vulnerability: Summary for Policy Makers, Working group II Contribution to the Intergovernmental Panel on Climate Change, Fourth Assessment Report," IPCC Secretariat, WHO and UNEP, Geneva, 2007.

[3] J. G. Pinilla, "Colapsa vía en Cerro Punta tras lluvias registradas este fin de semana," *La Prensa,* 28 December 2024.

[4] B. Stiftung, "BTI Transformation Index – Panama Country Report 2024," 2024.

[5] W. Bank, "Lifelines: The Resilient Infrastructure Opportunity," Washington, DC, 2019.

[6] W. Bank, "Panama – Climate vulnerability," Climate Change Knowledge Portal, [Online]. Available: https://climateknowledgeportal.worldbank.org/country/panama/vulnerability. . [Acedido em 1 May 2025].

[7] N. Humphrey, "Potential impacts of climate change on U.S. transportation," *TR News,* pp. 21-24, May 2008.

[8] ThinkHazard, "Global Facility for Disaster Reduction and Recovery (GFDRR)," Panama: Urban Flooding, [Online]. Available: https://www.thinkhazard.org/en/report/191-panama/UF.. [Acedido em 2 May 2025].

[9] O. A. J. a. F. Bocharel, "17 muertos por desastre; declaran estado de emergencia," La Prens, 8 November 2020. [Online]. Available: https://www.prensa.com/impresa/panorama/17-muertos-por-desastre-estado-de- emergencia/.. [Acedido em 2 May 2025].

[10] I. T. Forum, "Adapting Transport to Climate Change and Extreme Weather: Implications for Infrastructure Owners and Network Managers," OECD Publishing, 2016. [Online].

[11] A. S. N. v. d. H. a. P. C. X. Espinet, "Planning resilient roads for the future environment and climate change: Quantifying the vulnerability of the primary transport infrastructure system in Mexico," *Transportation Policy,* vol. 50, pp. 78-86, 2016.

[12] U. D. o. Transportation, "Climate Adaptation Plan, 2021.," USDOT, 2021.

[13] C. W. M. H. K. K. M. S. T. W. P. Kirshen, "Sea-level rise, storm surges, and extreme precipitation in coastal New Hampshire: Analysis of past and projected future trends," 2014.

[14] M. E. J. S. D. J. M. J. a. P. K. J. F. Knott, "Assessing the effects of rising groundwater from sea level rise on the service life of pavements in coastal road infrastructure," *Transp. Res. Rec,* vol. 2639, pp. 1-10, 2017.

[15] E. H. a. L. Chapman, "The impacts of climate change on national road and rail networks," em *Transport and Climate Change*, Bingley, U.K.: Emerald Group, 2012, pp. 105-136.

[16] M. C. a. S. S. M. Mushtaq, "Climate adaptation of roads to flooding hazards—A review," *Construction Materials ,* vol. 4, 2024.

[17] P. N. a. S. Wu, "A comprehensive review of moisture damage in asphalt mixtures: Mechanisms, evaluation methods, and mitigation strategies," *Construction Building Materials ,* vol. 471.

[18] R. T. a. S. Al-Swailmi, "Water Sensitivity of Asphalt–Aggregate Mixes: Test Selection, SHRP Report A-403," *National Research Council,* p. 183, 1994.

[19] M. Q. K. R. G. B. R. A. S. D. P. L. R. a. K. S.-R. B. G. McAdoo, "Roads and landslides in Nepal: How development affects environmental risk," *Nat. Hazards Earth Syst. Sci,* vol. 18, p. 3203–3210, 2018.

[20] G. W. a. K. Sassa, "Pore-pressure generation and movement of rainfall- induced landslides: Effects of grain size and fine-particle content," *Eng. Geol,* vol. 69, p. 109–125, 2003.

[21] M. M. a. C. L. S. W. L. Lee, "An investigation of rainfall-induced landslides from the pre-failure stage to the post-failure stage using the material point method," *Front. Earth Sci,* vol. 9, 2021.

[22] I. P. o. C. Change, "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change," Cambridge University Press, 2021.

[23] N. E. Observatory, "World of change: Global temperatures," 2024. [Online]. Available: https://earthobservatory.nasa.gov/world-of-change/global-. [Acedido em 30 June 2025].

[24] S. G. S. N. Matini, "Evaluation of structural performance of pavements under extreme events: Flooding and heatwave case studies," *Transp. Res. Rec,* vol. 2676, pp. 233-248, 2022.

[25] I. A. a. J. M. D. McEvoy, "The impact of the 2009 heat wave on Melbourne's critical infrastructure," *Local Environ,* vol. 17, pp. 783-796, 2012.

[26] A. Vamos, "Temperature effects on traffic load induced accumulating strains in flexible pavement structures," *Int. J. Pavement Res. Technol,* 2024.

[27] GovPilot, "What is disaster resilient infrastructure & why is it needed?," [Online]. Available: https://www.govpilot.com/blog/what-is-disaster-resilient-infrastructure- why-is-it-needed.. [Acedido em 30 July 2025].

[28] "Critical Infrastructure Resilience, National Infrastructure Advisory Council: Final report and recommendations," 2009.

[29] U. N. O. f. D. R. R. (UNDRR), "Principles for resilient infrastructure," 2022.

[30] J. M. K. H. I. K. a. B. W. T. H. Tun, "Missing mobilities: The popular transport gap in climate adaptation".

[31] A. a. I. O. f. Migration, "Pakistan Shelter Guide: Design for improved flood resilience in Sindh," 2018.

[32] C. M. a. M. Remy, "Building roads to democracy? The contribution of the Peru Rural Roads Program to participation and civic engagement in rural Peru," 2008.

[33] F. H. Administration, "Vulnerability Assessment and Adaptation Framework," 2018.

[34] W. Bank, "What is climate and disaster risk screening and why is it important," Climate Screening Tools, [Online]. Available: https://climatescreeningtools.worldbank.org/what-climate-and-disaster-risk- screening-and-why-it-important. . [Acedido em 30 July 2025].

[35] M. C. a. S. S. M. Mushtaq, "Climate adaptation of roads to flooding hazards—A review," *Construction Materials,* vol. 4, 2024.

[36] S. A. M. M. G. W. a. A. M. K. S. A. Argyroudis, "Fragility of transport assets exposed to multiple hazards: State-of-the-art review toward infrastructure resilience," *Reliab. Eng. Syst.* , vol. 191.

[37] M. K. a. J. E. S. Amirthu, "Pavement materials for adapting climate change," *Int. Res. J. Adv. Eng. Hub (IRJAEH),* vol. 2, pp. 2687-2695.

[38] C. f. E. Excellence, "AASHTO, Chicago's Green Alley Program," 28 May 2024. [Online]. Available: https://environment.transportation.org/case_study/chicagos-green-alley-program/. . [Acedido em 30 July 2025].

[39] W. Selbig, "Evaluating the potential benefits of permeable pavement on the quantity and quality of stormwater runoff," U.S. Geological Survey, 2018.

[40] M. Ernst, "Chicago's green alleys prevent flooding — but vulnerable neighborhoods must wait," 18 April 2024.

[41] MSN, "After 26 years of challenges, Brazil's Rodoanel Norte highway is finally changing São Paulo's future," São Paulo, 2023.

[42] A. R. K. B.-Y. C. J. W. a. B. H. Y. Y.-J. Kim, "Geosynthetic reinforced steep slopes: Current technology in the United States," *Appl. Sci,* vol. 9, 2019.

[43] DIPROTEC, "Utilização de geotêxtil Bidim com função de separação, filtração, proteção e barreira de sedimentos – Trecho Sul Rodoanel-SP," [Online]. Available: https://diprotecgeo.com.br/casos-de-obra/utilizacao-de-geotextil-bidim-com-. [Acedido em 30 July 2025].

[44] S. Hidrobrasileira, "Rodoanel Mário Covas – DERSA," [Online]. Available: https://setechidrobrasileira.com.br/realizacoes/rodoanel-mario-covas-dersa/. [Acedido em 3 July 2025].

[45] R. K. R. a. A. L. Li, "Geosynthetic-reinforced embankments over soft foundations," *Geosynth. Int,* vol. 12, pp. 50-85, 2005.

[46] E. t. H. e. al, "Procesevaluatie Totstandkoming PKB Ruimte voor de Rivier," Utrecht: Berenschot, 2007.

[47] S. v. H. C. Z. a. R. A. J. Rijke, "Room for the River: Delivering integrated river basin management in the Netherlands," *Int. J. River Basin Manag,* vol. 4, pp. 369-382, 2012.

[48] A. D. B. a. P. B. S. Yu, "Making Room for the River," *J. Am. Plann. Assoc,* vol. 86, pp. 417-430, 2020.

[49] "City of Nijmegen, Bestemmingsplan Ruimte voor de Waal," 2013. [Online]. Available: http://ruimtelijkeplannen.nijmegen.nl/plannen/NL.IMRO.0268.BP21000/NL.IMRO.0268. [Acedido em 30 July 2025].

[50] M. v. d. Brink, Rijkswaterstaat on the Horns of a Dilemma, Netherlands: Eburon Uitgeverij BV, 2009.

[51] W. H. e. al, "Evaluatie Ontwerpprocessen Ruimte voor de Rivier," Ecorys, Rotterdam, 2011.

[52] J. Roerink, "Room for the River, Nijmegen," [Online]. Available: https://landezine.com/room-for-the-river- nijmegen-by-hns-landscape-architects/.. [Acedido em 30 July 2025].

[53] S. v. Herk, "Governance of integrated flood risk management to deliver large scale investment programmes: Delivery-focussed social learning in the Netherlands," em *FLOODrisk 2012*, Rotterdam, 2012.

[54] S. v. H. C. Z. a. R. A. J. Rijke, "Room for the River: Delivering integrated river basin management in the Netherlands," *Int. J. River Basin Manag,* vol. 10, pp. 369-382, 2012.

[55] G. Z. e. al, "Climate change and weather extremes in the Eastern Mediterranean and Middle East," *Rev. Geophys,* vol. 60, 2022.

[56] B. D. a. J. M. G. R. T. Sutton, "Land/sea warming ratio in response to climate change: IPCC AR4 model results and comparison with observations," *Geophys. Res. Lett,* vol. 34, 2007.

[57] B. V. K. a. M. Yilmaz, "The effects of using lime and styrene-butadiene-styrene on moisture sensitivity resistance of hot mix asphalt," *Constr. Build. Mater,* vol. 23, 2009.

[58] R. S. a. A. Al-Ghazali, "Polymer modified bitumen asphalt, a proposed solution for UAE pavement deterioration," em *Construction Materials and Structures*, IOS Press, 2014, pp. 620-628.

[59] A. D. D. o. Transport, "Pavement Design Manual (TR-513) Quality and Conformity Council," Abu Dhabi, 2017.

[60] A. Z. A. G. A. a. A. F. H. Ibrahim, "Performance enhancement of asphalt binders using upcycled waste tires and plastics: A UAE-based study on alternatives to SBS-modified binders," *Constr. Build. Mater,* vol. 463, 2025.

[61] W. B. Group, "Washington, DC: World Bank, 2021," Washington, 2021.

[62] W. B. Group, "Climate Change Knowledge Portal," Climate Change Knowledge Portal, 2024.

[63] R. A. J. P. M. J. K. J. E. P. F. B. G. G. e. a. AC&A, "Análisis de inversiones en el sector transporte terrestre interurbano latinoamericano a 2040," 2020.

[64] ReloFirm, "Panama's transportation infrastructure: Navigating the country efficiently," [Online]. Available: https://www.relofirm.com/blog/panamas- transportation-infrastructure-navigating-the-country-efficiently/. [Acedido em 11 June 2025].

[65] P. d. Panamá, "MOP prioriza y reactiva proyectos viales por más de B/.590 millones," [Online]. Available: https://www.presidencia.gob.pa/publicacion/mop-prioriza-y-reactiva-proyectos- viales-por-mas-de-b-590-millones.. [Acedido em 30 July 2025].

[66] M. d. A. d. Panamá, "Contribución Determinada a Nivel Nacional: Actualización 2020 (CDN1), República de Panamá," 2020.

[67] E. (. d. T. E. S.A.), "Descripción general del clima de Panamá," 2009.

[68] M. d. E. y. F. d. Panamá, "Gestión Transparente Panamá," [Online]. Available: https://gestiontransparentepanama.mef.gob.pa/. .

[69] M. d. A. d. Panamá, "Segundo informe bienal de actualización ante la CMNUCC," 2021.

[70] R. C. Network, "Panama City Resilience Strategy, 100 Resilient Cities," 2017.

[71] Coroflot, "Parque Norte - Santa Fe," 2014.

[72] U. d. Cantabria, "IHCantabria colabora con la Ciudad de Panamá para adoptar medidas de adaptación al cambio climático en su transporte público," Noticias Universidad de Cantabria, 7 December 2023. [Online]. Available: https://web.unican.es/noticias/Paginas/2023/12/Panama-ih-trasporte-publico.aspx. . [Acedido em 20 June 2025].

[73] "Comunicacion.IHCantabria," *IHCantabria ha liderado el desarrollo de un proyecto que generó escenarios de cambio climático para Panamá,* 10 June 2024.

[74] Tiqy, "Recorrido histórico a pie por el Casco Antiguo," [Online]. Available: https://www.tiqy.com/es/tour-actividad-info/recorrido-historico-a-pie-por- el-casco-antiguo. . [Acedido em 20 July 2025].

[75] E. porPanorama, "La cinta costera: El 'hub' que une a la ciudad," *Panorama de las Américas,* p. 2024, 3 February 2024.

[76] J. Coley, "How to walk the Cinta Costera to Casco Viejo – Panama," *Coley's Blog,* 2023.

[77] M. d. A. d. Panamá, "Enriquecen flora del Parque Cervantes".*MiAmbiente.*

[78] PanamaGuy, "Skyline of San José de David with new towers under construction," 12 August 2022.

[79] W. International, "Living with water & wetlands: Flood risk reduction in Panama City," Wetlands International, 7 August 2023. [Online]. Available: https://www.wetlands.org/case-study/living-water-wetlands-flood-risk-reduction- panama-city/. . [Acedido em 23 June 2025].

[80] U. S. a. E. C. (SEC), "Republic of Panama investor presentation," 2024.

[81] A. (. d. T. d. Panamá), "Rural & agrotourism in Tierras Altas," [Online]. [Acedido em 30 June 2025].

[82] SINAPROC, "Clima en Panamá: advierten posibles inundaciones, deslizamientos y crecidas," *TVN Noticias.*

[83] A. C. P. B. C. A. G. A. S. a. B. T. N. Seddon, "Understanding the value and limits of nature-based solutions to climate change and other global challenges," *Philos. Trans. R. Soc. B,* vol. 375, 2020.

[84] W. Bank, "Evaluación del riesgo de inundación y priorización de infraestructura híbrida para la reducción del riesgo en la cuenca del río Tocumen, Ciudad de Panamá (Final Report)," 2020.

[85] G. C. Fund, "Panama | Green Climate Fund," [Online].

[86] N. Panama, "Bad weather in Panama causes difficulties for more than 5 thousand people with 5 dead," *Newsroom Panama,* 2024.

[87] J. Abramovich, "Geosynthetics in Panama," PanawebSC43, 17 July 2025. [Online]. Available: https://www.panawebsc.com/geosynthetics-in-panama. [Acedido em 21 June 2025].

[88] A. M. Batista, "Recovering the Pan American road in area of Chiriquí in Panama with geosynthetics, using fiberglass geogrid," Rio de Janeiro, 2020.

[89] G. Admissions, "Universidad Tecnológica de Panamá International Admissions," [Online].

[90] J. Delgado, "La UTP recibe la visita de la Senacyt," *Universidad Tecnologica de Panama,* 24 April 2023.

[91] A. M. Adames, "La UTP lanza y divulga avances de tres proyectos de investigacion financiados por la SENACYT".*Secretaria Nacional de Ciencia, Tecnologia e Innovacion.*

[92] A. H. Guevara, "Presentan resultados de dos proyectos de investigación en materia ambieltal y de los materiales," SENACYT. [Online]. [Acedido em 26 June 2025].

[93] D. Panama, "Panama will invest $775 million in regional road infrastructure," 25 March 2025.

[94] "About us, Green Policy Platform," Global Infrastructure Basel Foundation, 2025. [Online]. [Acedido em 30 July 2025].