TxDOT Report 0-7201-R1 Appendix A

HYDROLOGIC APPROACHES TO PLAYA LAKES, AREAS OF SIGNIFICANT KARST GEOLOGY, AND ARID REGIONS: Appendix A

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APPENDIX A: VALUE OF RESEARCH

The primary objective of this project was to compile and synthesize current knowledge and practices related to hydrological approaches for playa lakes, karst terrains, and arid regions. To achieve this, the project began with a comprehensive evaluation of existing research, design guidance, standards, and practices for hydrological studies in these areas, identifying key knowledge gaps and opportunities for improvement. The project also gathered and analyzed data through surveys and interviews with transportation agencies and other stockholders to assess the current state of knowledge, practices, and challenges in hydrology of these complex environments. Insights from the literature review, surveys, and interviews were then synthesized to develop recommendations for future research. These recommendations focus on improving hydrological approaches, methods, and models, addressing design challenges, and supporting the development of sustainable and reliable transportation infrastructure. Detailed recommendations are outlined in **Chapter 7**.

Table A.1 highlights the value of research and benefit areas identified by the research team. These benefits, both qualitative and quantitative, include level of knowledge; management and policy; environmental sustainability; system reliability; improved productivity and work efficiency; traffic and congestion reduction; reduced construction, operation, and maintenance cost; freight movement and economic vitality; and safety.

In cases where documented cost-benefit data were unavailable, the average cost of infrastructure damage in these regions was used to estimate the value of research.

Table A.1 The Project Value of Research (VoR)

Benefit Area	**Qual**	**Econ**	**Both**	**TxDOT**	**State**	**Both**
Level of Knowledge	x					x
Management and Policy	x					x
Environmental Sustainability	x					x
System Reliability	x		x			x
Improved Productivity and Work Efficiency	x					x
Traffic and Congestion Reduction	x		x			x
Reduced Construction, Operation, and Maintenance Cost			x			x
Freight Movement and Economic Vitality	x					x
Safety	x					x

A.1 Economic Value

Transportation infrastructure in regions characterized by playa lakes, karst terrains, and arid climates faces significant hydrologic challenges that can lead to structural instability, reduced reliability, and costly failures. In karst regions, the presence of sinkholes and underground drainage systems can cause sudden subsurface flow, undermining road stability (Scuderi et al., 2010). Playas contribute to extreme ponding and flooding events due to their limited infiltration (Rodríguez-Rodríguez et al., 2007), while arid regions exhibit intense, localized rainfall events that can cause flash flooding and surface erosion (Rodríguez-Rodríguez & Malte, 2014).

Failures of critical infrastructure, such as transportation systems, can lead to significant economic losses and widespread social disruptions (Strelcová et al., 2015; Koks et al., 2019). These failures impose both direct and indirect costs. Direct costs encompass the economic losses associated with physical damage to roadways, bridges, and related infrastructure, requiring expensive repairs or replacements. Indirect costs, on the other hand, reflect the broader societal impacts, such as disruptions to supply chains, reduced access to essential services, increased travel times, and lost productivity (Singh et al., 2017).

Flooding, as a leading cause of infrastructure failure, imposes an especially high economic burden. The total annual cost of flooding in the United States is estimated to range between $179.8 billion and $496.0 billion (Joint Economic Committee, 2024). In Texas alone, flooding events have incurred damages amounting to $10–20 billion from 1980 to 2024 (NOAA, n.d.), highlighting the state's vulnerability to extreme hydrological events.

Despite the severe financial and societal impacts, there is a notable gap in documentation and analysis of flooding in specific hydrologically vulnerable regions, such as karst terrains, playa lakes, and arid zones. These regions face unique challenges, such as sinkhole formation, rapid water level changes, and flash flooding, yet there is no comprehensive national database capturing the frequency, extent, or economic costs of flooding in these areas. As a result, this study relies on limited sources and incorporates certain assumptions to develop the Value of Research (VoR) for the project.

The economic value of the project is calculated based on the following assumptions:

1) The recommended approaches by this project will lead to follow-up project(s) aimed at developing hydrological study guidelines tailored to karst regions, playa lakes, and arid zones. The follow-up project(s) would cost $500,000 in the next 3 years in addition to the total budget of the current project (i.e. $53,323).
2) The cost of flooding in karst regions, playa lakes, and arid zones, totaling $91 million per year ($40 million + $24 million + $27 million). The utilization of these guidelines is expected to reduce flood-related damages to transportation infrastructure by at least 50%

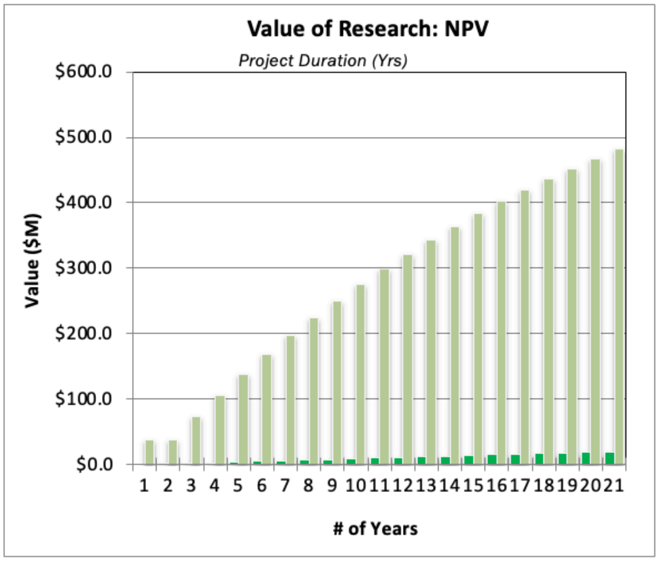
(or $40.5 million per year) over the next 20 years. The annual cost of flooding in these regions is calculated based on the following assumptions:

- **Karst Regions**: Flood-related damages in karst regions of the U.S. were estimated to exceed $300 million annually (Weary, 2015), with 70% attributed to roads and bridges. Texas accounts for 9.1% of U.S. bridges and 7.8% of U.S. road length (FHWA, 2009). Assuming damage costs are proportional, the annual damage to Texas transportation infrastructure is estimated at $25.8 million. Adjusting for construction inflation rates from 2015 to 2024 (Inflation Indexing, n.d.), the inflation-adjusted estimate for 2024 is $37.7 million per year. Rounding to the nearest million, this is approximately $40 million per year.
- **Playa Lakes**: The 1990 Martin County, Texas Flood Protection Study estimated annual spending of $155,000 to repair flood-damaged roads in the playa lake regions of the county (HDR, 1990). Adjusted for inflation, this cost in 2024 would be $377,000 (Amortization.org, n.d.). With playa lakes in Martin County accounting for 1.52% of the total surface area of all playa lakes in Texas (**Appendix B**, **Table ABSM.1**), the annual cost of flooding across all Texas playa lake areas is estimated at approximately $24 million per year.
- **Arid Zones**: Texas is highly susceptible to flash flooding, particularly in the arid and semi-arid regions of Central and West Texas. Flash floods account for 70% of flood damage costs nationwide (National Weather Service, n.d.). Approximately 39% of Texas' total land area is classified as arid or semi-arid (**Appendix B**). From 1980 to 2024, flooding events in Texas have caused damages totaling between $10 billion and $20 billion (NOAA, n.d.). Assuming that 30% of flood damage is related to transportation infrastructure (Rhodes and Trent,1992), the estimated annual cost of flooding in Texas' arid areas ranges from $18 million to $36 million, with an average of $27 million per year.

Assuming a 5% discount rate and a 50% reduction in flood-related damages to transportation infrastructure, the net present value of improving hydrological design approaches for transportation infrastructure in karst areas, arid zones, and playa lakes over a 20-year horizon is projected to exceed $299 million (**Figure A.1**). The cost-benefit ratio is 542 which shows the overall value of TxDOT investment on the project.

	Project #	0-7201		
	Project Name:	Hydrologic Approaches to Playa Lakes, Areas of Significant Karst Geology, and Arid Regions		
	Agency:	UTA	**Project Budget**	$ 553,323
	Project Duration (Yrs)	4.5	**Exp. Value (per Yr)**	$ 40,500,000
	Expected Value Duration (Yrs	20	**Discount Rate**	5%
Economic Value				
Total Savings:	$ 363,946,677		**Net Present Value (NPV)**	$ 299,148,108
Payback Period (Yrs)	0.013662		**Cost Benefit Ratio (CBR, $1 : $___):**	$ 541

Years	Expected Value
0	$39,946,677
1	$0
2	$40,500,000
3	$40,500,000
4	$40,500,000
5	$40,500,000
6	$40,500,000
7	$40,500,000
8	$40,500,000
9	$40,500,000
10	$40,500,000
11	$40,500,000
12	$40,500,000
13	$40,500,000
14	$40,500,000
15	$40,500,000
16	$40,500,000
17	$40,500,000
18	$40,500,000
19	$40,500,000
20	$40,500,000



* The project duration and cost are consideered based on the assumptioon that follow-up projec(s) to develop guidlined recoomned in this study will be initiated by TxD

Years	**Expected Value**	**Expected Value**	**Expected Value**	**NPV**
0	$39,946,677	$39,946,677	$39.95	$38.04
1	$0	$39,946,677	$39.95	$38.04
2	$40,500,000	$80,446,677	$80.45	$73.03
3	$40,500,000	$120,946,677	$120.95	$106.35
4	$40,500,000	$161,446,677	$161.45	$138.08
5	$40,500,000	$201,946,677	$201.95	$168.30
6	$40,500,000	$242,446,677	$242.45	$197.09
7	$40,500,000	$282,946,677	$282.95	$224.50
8	$40,500,000	$323,446,677	$323.45	$250.61
9	$40,500,000	$363,946,677	$363.95	$275.47
10	$40,500,000	$404,446,677	$404.45	$299.15
11	$40,500,000	$444,946,677	$444.95	$321.70
12	$40,500,000	$485,446,677	$485.45	$343.18
13	$40,500,000	$525,946,677	$525.95	$363.63
14	$40,500,000	$566,446,677	$566.45	$383.11
15	$40,500,000	$606,946,677	$606.95	$401.67
16	$40,500,000	$647,446,677	$647.45	$419.34
17	$40,500,000	$687,946,677	$687.95	$436.17
18	$40,500,000	$728,446,677	$728.45	$452.19
19	$40,500,000	$768,946,677	$768.95	$467.46
20	$40,500,000	$809,446,677	$809.45	$482.00

Figure A.1 Value of Research

A.2 Level of Knowledge

Designing transportation infrastructure in hydrologically challenging regions such as karst terrains, playa lakes, and arid areas necessitates a nuanced understanding of their unique water movement characteristics. The current state and federal stormwater design guidelines provide general recommendations but often overlook the specific hydrological challenges posed by these environments. This oversight can result in design inefficiencies, economic losses, and safety hazards during extreme hydrological events, such as flash floods or prolonged droughts.

Hydrological Complexities and Challenges

Karst Terrains

Karst terrains are characterized by underground drainage systems, sinkholes, and caves, leading to highly variable flow patterns. The unpredictable nature of flash floods in these regions complicates the prediction of water movement and infiltration rates, which can damage infrastructure and increase maintenance costs (Shafiquzzaman et al., 2022; Liu et al., 2018). The heterogeneous and anisotropic properties of karst formations further complicate modeling efforts, making it challenging to estimate flow paths and design effective mitigation measures. Addressing these issues can yield significant benefits, including improved public safety and reduced maintenance costs, thereby enhancing infrastructure longevity (Alsubeai & Burckhard, 2021).

Playa Lakes

Playa lakes, primarily found in arid regions, are ephemeral bodies of water influenced by precipitation, evaporation, and groundwater interactions. Their dynamic hydrology presents challenges such as variability in water volume, rapid filling during storms, and extensive evaporation under high temperatures (Saber et al., 2021; Tan and Vanapalli, 2021). Infrastructure near these lakes is particularly vulnerable to flash flooding, road submergence, and erosion, necessitating improved hydrological understanding and infrastructure design (Abd-Elhamid, 2023). Enhanced flood forecasting accuracy can mitigate economic losses due to road closures and structural damage while conserving ecosystems reliant on these lakes (Liao, 2012).

Arid Regions

Arid regions are characterized by low precipitation, high evaporation, and intermittent intense storms, leading to flash floods, sediment transport, and soil erosion (Prama et al., 2020; Yodying et al., 2022). The sparse gauging networks and irregular precipitation patterns complicate the prediction of hydrological responses, posing risks of rapid infrastructure degradation and increased repair costs (Baalousha et al., 2023; Bakr et al., 2022). Hydrologic models tailored to these environments can provide quantitative benefits, such as reduced reconstruction costs, and qualitative gains, including improved safety and transportation system reliability (Ding et al., 2015).

Addressing Knowledge Gaps

This project aimed to assess the current state of hydrological approaches for the design of transportation infrastructure in karst terrains, playa lakes, and arid areas. The critical knowledge gap was identified by combining an extensive literature review with surveys and interviews. The key focus areas include: (1) exploring the impact of subsurface features on surface water dynamics in karst terrains, (2) examining the interactions between evaporation, infiltration, and sedimentation in playa lakes, and (3) assessing flood estimation methodologies tailored to arid and semi-arid climates.

By synthesizing insights from the literature review, surveys, and interviews, this project provides a comprehensive evaluation of existing hydrological challenges, and the strategies employed to address them. The findings are presented in an organized report that captures the complexities of hydrological behavior in the specified regions and serves as a foundation for future studies or guideline development.

The project's scope was not to develop new methodologies or standards but to create a robust repository of knowledge. This repository is intended to serve as a valuable reference for TxDOT, other state departments of transportation (DOTs), international agencies, and stakeholders involved in designing and managing infrastructure in areas characterized by karst geology, playa lakes, or arid conditions. The project's findings aim to guide ongoing and future efforts toward developing more informed hydrological design standards, enabling more sustainable and resilient infrastructure solutions in these challenging environments.

A.3 Management and Policy

Effective management and policy development are essential for addressing the hydrological challenges associated with playa lakes, karst terrains, and arid regions. These regions present unique hydrological behaviors, such as unpredictable flash flooding in karst systems, high evaporation rates in playa lakes, and erratic rainfall patterns in arid zones. Current hydrological design practices often rely on regional expertise and ad-hoc methodologies, resulting in inconsistent standards. By synthesizing existing knowledge and conducting structured surveys, this project aimed to provide a comprehensive foundation for informed policy-making and management strategies. These strategies will help standardize design practices, enhance infrastructure resilience, and mitigate risks related to hydrological events.

A.4 Environmental Sustainability

Environmental sustainability is a critical consideration in the development and maintenance of transportation infrastructure, particularly in regions characterized by playa lakes, karst terrains, and arid conditions. These unique environments are often ecologically sensitive, with features such as groundwater recharge zones in playa lakes, intricate karst drainage systems, and fragile ecosystems in arid areas. Poorly designed infrastructure in these regions can disrupt natural hydrological processes, deplete vital water resources, and cause long-term environmental degradation. This research emphasizes the importance of understanding the hydrological dynamics of these areas to design infrastructure that minimizes environmental impact and supports sustainable development. The insights from this study will guide policies and design standards that promote environmentally friendly practices, such as integrating green infrastructure solutions and prioritizing hydrological modeling that accounts for environmental variables. Furthermore, the recommendations from this research can serve as a framework for collaboration between environmental agencies and transportation departments, ensuring that infrastructure development aligns with broader sustainability goals.

A.5 System Reliability

Transportation infrastructure in regions characterized by playa lakes, karst terrains, and arid conditions faces distinctive hydrological challenges that can substantially affect its service life and reliability. In Texas, bridges and roadway systems are often exposed to complex hydrological forces, including flash flooding in karst regions, episodic flooding in playa lakes, and extreme rainfall-runoff variability in arid areas. Addressing these challenges requires a tailored hydrological understanding and design approach to enhance the resilience and longevity of infrastructure. The findings of this study will contribute to the development of hydrological guidelines that enhance the reliability of transportation systems in these regions. By incorporating region-specific hydrological insights, such as the unpredictable underground drainage in karst terrains or the rapid water level changes in playa lakes, the project aims to reduce the risk of failures due to hydrological events. While not directly prescribing hydrological models and methods specific to these areas, the research provides a foundation for future studies to develop and implement practices that extend the service life of infrastructure in hydrologically complex regions.

A.6 Improved Productivity and Work Efficiency

Transportation infrastructure in regions with complex hydrological characteristics, such as playa lakes, karst terrains, and arid zones, often requires significant planning and maintenance efforts to ensure reliability. Hydrological uncertainties in these areas, ranging from unpredictable sinkhole formations in karst regions to rapid flooding in playa lakes, can lead to inefficiencies in infrastructure management. This project addresses these inefficiencies by providing a consolidated knowledge base derived from literature reviews, professional surveys, and interviews, enabling transportation agencies to adopt evidence-based practices that enhance productivity and streamline operations. The study's recommendations, aimed at developing design guidelines specific to these regions, will improve work efficiency and pave the way for infrastructure systems that meet the needs of growing populations while ensuring operational efficiency and long-term cost-effectiveness.

A.7 Traffic and Congestion Reduction

Transportation infrastructure in regions characterized by playa lakes, karst terrains, and arid environments is critical for maintaining smooth traffic flow and minimizing congestion. Failures or disruptions in these areas due to hydrological challenges can lead to significant traffic detours, delays, and increased fuel consumption. These impacts are further exacerbated by the unique hydrological characteristics of these regions, such as flash flooding in karst terrains, rapid water level changes in playa lakes, and unpredictable rainfall-runoff patterns in arid areas. For example, extreme hydrological events in karst regions may cause sudden sinkhole formation or waterway blockages, leading to infrastructure damage or closure. Similarly, in arid zones, flash floods can result in significant damage to roads and bridges, while playa lake flooding can temporarily inundate transportation routes, causing extended detours. Such events not only disrupt daily commutes but also affect the regional economy by delaying the movement of goods and services.

In 2015, traffic congestion caused people in the U.S. to travel 6.9 billion extra hours and purchase 3.1 billion additional gallons of fuel, amounting to $160 billion in economic losses (Schrank et al., 2015). During the 2015 Memorial Weekend flood, the collapse of the Fischer Store Road bridge west of Wimberley forced a 50-mile detour, highlighting the significant impacts of such infrastructure failures (Cook, 2014). Similarly, the Texas A&M Transportation Institute's 2021 Urban Mobility Report notes that per-hour commercial value of time in Texas is $55.24, while the average state gasoline cost is $2.05 per gallon (Schrank et al., 2021). These statistics underscore the economic and logistical consequences of infrastructure disruptions, particularly when caused by hydrological events. By improving the understanding of hydrological behaviors such as sinkhole dynamics, episodic flooding, and rainfall-runoff relationships, this project aimed to inform better design and maintenance strategies.

Although this project does not recommend hydrological models and methods specific to these areas, it lays the groundwork for future studies to develop and implement practices that extend the service life of infrastructure in hydrologically complex regions.

A.8 Reduced Construction, Operation, and Maintenance Cost

Texas has one of the largest inventories of roads and bridges in the United States (Texas Department of Transportation, 2020). Maintaining these infrastructures is essential for ensuring a reliable transportation network. Constructing new roads and bridges or repairing those damaged by flooding is highly costly. For instance, building a highway bridge in the U.S. typically costs between $1,000,000 and $5,000,000, depending on its size and complexity (Bundy, 2021).

In regions with unique hydrological challenges, such as flash flooding in karst terrains, rapid water level changes in playa lakes, and intense rainfall in arid zones, addressing infrastructure vulnerabilities is critical for reducing construction, operation, and maintenance costs. This project focused on synthesizing knowledge and evaluating best practices for the hydrological design of transportation infrastructure capable of withstanding these challenges. By identifying effective design approaches, the study aimed to uncover gaps in current hydrological practices within these regions. The insights gained will inform TxDOT and other stakeholders about the necessity of developing design guidelines specific to these areas. These guidelines will ultimately contribute to long-term cost savings in construction, operation, and maintenance by mitigating the risks of hydrology-induced failures.

A.9 Freight Movement and Economic Vitality

Efficient freight movement is a cornerstone of economic vitality, particularly in regions where transportation infrastructure supports critical supply chains. In areas with unique hydrological challenges, disruptions caused by hydrological events can severely impact freight operations. Flash flooding in karst terrains, temporary inundation in playa lakes, and unpredictable rainfall patterns in arid zones can lead to road closures, detours, and increased transit times, all of which hinder the flow of goods and services.

Transportation infrastructure designed to withstand the hydrological complexities of these regions can significantly reduce downtime and enhance freight reliability. By understanding the specific risks associated with playa lake flooding, karst system sinkholes, and extreme precipitation in arid zones, the study provides insights that can inform policies and practices for mitigating disruptions. For instance, resilient roadways and bridges that account for rapid water level changes and erosion can help maintain continuous freight operations, reducing the economic impact of delays and ensuring the timely delivery of goods.

The findings of this research will support the development of strategies that align infrastructure performance with regional economic goals. Improved freight movement not only reduces costs for businesses but also enhances the overall economic competitiveness of the region. Additionally, resilient infrastructure can attract investment by ensuring dependable transportation networks. By focusing on the intersection of hydrology, infrastructure design, and economic priorities, this project offers a pathway to strengthening regional economies and supporting long-term economic vitality.

A.10 Safety

Safety is a paramount concern in transportation infrastructure, particularly in regions with complex hydrological challenges such as playa lakes, karst terrains, and arid zones. These areas face unique risks, including sudden flash floods, sinkhole formations, and extreme weather events, which can compromise the safety of road users. Designing transportation infrastructure to address these risks is critical to protecting lives and reducing the likelihood of accidents.

This project aims to enhance safety by synthesizing knowledge about hydrological dynamics and identifying gaps in current design guidelines and standards. In karst terrains, the unpredictable formation of sinkholes and underground water flows poses significant threats to the stability of roadways and bridges. In playa lakes, rapid water level changes during storms can result in flooding, leading to hazardous driving conditions or road closures. Similarly, in arid regions, intense rainfall over dry, impermeable soils can trigger flash floods that inundate roadways with little warning. The findings from this research will guide the development of policies and standards that prioritize safety in hydrologically complex regions. The study underscores the importance of collaboration between transportation agencies and hydrological experts to comprehensively address these safety challenges.

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