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

(Synthesis of Current State of Knowledge and Practice)

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16. Abstract

Playa lakes, arid regions, and karst terrains constitute important geographic and hydrological features across Texas, each presenting unique challenges due to their complex and varied hydrology. Currently, there are no uniform guidelines or standards for the hydrological and hydraulic design of transportation infrastructure in these landscapes, leading designers to rely heavily on project-specific judgment to determine suitable hydrological parameters.

This report provides a comprehensive synthesis of current knowledge and best practices related to hydrological studies within three distinct landscapes: playa lakes, arid regions, and karst terrains. The research findings were obtained through an extensive literature review, surveys, and follow-up interviews. Based on existing knowledge, the following conclusions were reached regarding the current hydrology approaches in playa lakes, arid regions, and karst terrains:

Playa Lakes: There is no method specific to the hydrology of playa lakes. Traditional hydrological methods, including the Rational Method and the NRCS Curve Number method, often prove inadequate because they fail to fully account for the complexities of playa lake systems, specifically the influence of infiltration, evaporation, sediment mobilization, and the dynamic interplay between surface and subsurface water flows.

Karst Regions: The FHWA recommends various standard and empirical hydrologic methods for estimating runoff in karst regions. However, these methods are site-specific and often fail to capture the full complexity of subterranean interactions, leading to inaccurate predictions of peak flows and flood extents.

Arid Zones: Traditional hydrological methods, such as NRCS Curve Number method, which often rely on data and parameters from more humid climates, frequently underperform in arid environments, resulting in inaccurate flood predictions and potentially inadequate infrastructure design.

The research reveals significant challenges in accurately predicting rainfall-runoff and effectively managing flood risks in these diverse environments, underscoring the need for region-specific approaches and further investigation. The inherent complexities of the hydrological processes within each region demand a refined understanding that extends beyond traditional methodologies.

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(Synthesis of Current State of Knowledge and Practice)

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Table of Contents

List of Tables

EXECUTIVE SUMMARY

Playa lakes, arid regions, and karst terrains are significant geographic and hydrological features across Texas, each presenting unique challenges due to their complex and highly variable hydrology. Currently, no standardized guidelines or methods exist for the hydrological and hydraulic design of transportation infrastructure in these areas. As a result, designers often rely on project-specific judgment to determine appropriate hydrological parameters, which can lead to inconsistencies and inefficiencies.

To address this need, a comprehensive review was conducted to assess current hydrological approaches for playa lakes, arid regions, and karst terrains. The objective was to identify best practices for improving flood estimation and water management in these challenging environments. This study aimed to synthesize existing knowledge, evaluate current methods, and provide recommendations for developing guidelines and standards to optimize transportation infrastructure design in these regions. The findings were derived from an extensive literature review, surveys, and follow-up interviews.

A thorough literature review was undertaken to provide an overview of the state of knowledge regarding hydrological practices in playa lakes, arid zones, and karst terrains. This involved reviewing a wide range of sources, including drainage design manuals from state departments of transportation, publications from the Federal Highway Administration (FHWA), stormwater design guidelines from various states, cities, and international sources, as well as over 300 research studies published in scientific journals and presented at conferences. The review revealed that while many studies have focused on these regions, few address the specific hydrological challenges these environments pose to infrastructure design.

To further evaluate current practices, a survey was conducted with 76 experts from 30 state Departments of Transportation (DOTs), 13 university faculty members, 12 consultants, and 21 other agencies (federal, state, city, and local). The survey received 24 responses, providing valuable insights into the effectiveness of existing guidelines and hydrological modeling approaches. Additionally, follow-up interviews with selected participants, including representatives from DOTs in Kansas, Minnesota, New Mexico, and Virginia, as well as other experts, provided deeper insights into current practices.

Based on the results of the literature review, survey, and interviews, this report synthesizes the current understanding of hydrological approaches for transportation infrastructure in playa lakes, arid regions, and karst terrains. Key challenges identified include difficulties in predicting rainfall-runoff, estimating flood peak and timing, and accounting for the dynamic and complex interactions within these environments.

Key Findings:

Playa Lakes: Playa lakes are characterized by highly variable and unpredictable hydrology, including flash flooding, erosion, sedimentation, and complex interactions between infiltration, evaporation, and sediment dynamics. The lack of data further complicates accurate hydrological

modeling in these areas. Existing methods, such as the Rational Method and the NRCS Curve Number method, fail to capture the complexities of playa lake systems, particularly the interactions between surface and subsurface water flows, sediment mobilization, and rapid changes in hydrological conditions.

Karst Regions: Karst terrains present challenges due to their unpredictable subsurface water flow, rapid infiltration, and the potential for sinkhole formation. These factors render traditional hydrological methods inadequate, necessitating the use of more advanced techniques. Data acquisition in karst regions is particularly difficult, complicating accurate hydrological analysis. While FHWA recommends several standard and empirical methods for estimating runoff in karst areas, these methods are site-specific and often fail to account for the complex subterranean interactions, leading to inaccurate predictions of peak flows and flood extents.

Arid Zones: Arid regions face challenges due to limited rainfall, high evaporation rates, and scarce water resources, which contribute to flash floods and soil erosion. Traditional hydrological models, such as NRSC Curve Number method, which are often designed for more humid climates, fail to accurately represent the conditions in arid zones. Without modifications, these models lead to inaccurate flood predictions and potentially inadequate infrastructure design. Tailored approaches that account for the specific hydrological dynamics of arid zones are essential for improving the reliability and resilience of infrastructure.

This study emphasizes the need for advanced, customized approaches to water resource management and infrastructure design in complex environments such as playa lakes, arid regions, and karst landscapes. The findings highlight significant challenges in predicting rainfall-runoff and managing flood risks in these diverse regions, stressing the importance of region-specific solutions and further research. The intricate hydrological processes unique to each environment require a more refined understanding that goes beyond traditional methodologies.

The report also advocates for the refinement of the current design standards to account for the unique characteristics of these environments. Such improvements are essential for enhancing infrastructure design and building more resilient transportation networks capable of withstanding the challenges posed by Texas' complex and dynamic landscapes.

CHAPTER 1: INTRODUCTION

1.1. Project Background

Karst terrains, playa lakes, and arid regions are key features of Texas's diverse landscape, each found in distinct areas of the state. The hydrology of these regions is complex, shaped by factors such as climate, soil properties, and land use, which pose significant challenges for the hydrologic design of transportation infrastructure managed by the Texas Department of Transportation (TxDOT). With Texas experiencing rapid population growth, the demand for resilient and reliable transportation infrastructure continues to rise. TxDOT is tasked with developing and maintaining this infrastructure in accordance with rigorous guidance and best practices. Therefore, a comprehensive understanding of the unique hydrological processes in these regions is essential for sustainable infrastructure planning and development. Although some existing design guidelines and standards address flood estimation and management in these environments, significant knowledge gaps remain in understanding the hydrologic behavior of playa lakes, karstic areas, and arid regions. Addressing these gaps is essential for advancing infrastructure design and strengthening the resilience of transportation networks statewide.

1.2. Objective and Scope

The project aimed to compile and synthesize the current knowledge and practices on hydrologic approaches for playa lakes, karst terrains, and arid regions. Using a comprehensive methodology, the research team sought to enhance the understanding of hydrological behavior in these unique environments, supporting more informed decision-making in the development of hydrological design guidance and standards of practice.

The project scope involved an extensive literature review using both national and international sources, complemented by surveys and interviews to gather insights on current knowledge and practices from state Departments of Transportation (DOTs) and international transportation agencies. A GIS dashboard was developed to compile reference materials, foster knowledge sharing, and facilitate collaboration with other agencies and researchers. To access the dashboard, use the following links: Playa Lakes, Karst Region, Arid Zones.

Findings from the literature review, surveys, and interviews were synthesized to provide a comprehensive understanding of the topic. Finally, recommendations were developed for future research to support the creation of more effective and sustainable transportation infrastructure.

1.3. Research Plan

The following four major tasks were performed to accomplish the objectives of this research study.

Task 1: Project Management

This task involved documenting the project's findings, submitting monthly progress reports, participating in project progress meetings organized by TxDOT, and assessing the project’s Value of Research (VoR). The VoR and areas in which the state and TxDOT benefit from the results of this study are discussed in **Appendix A**. These benefits include enhanced knowledge, improved management and policy development, environmental sustainability, system reliability, increased productivity and work efficiency, reduced traffic and congestion, lower construction, operation, and maintenance costs, improved freight movement and economic vitality, and enhanced safety.

Task 2: Literature Review

The research team conducted a comprehensive review of the current knowledge and practices related to hydrological approaches for playa lakes, arid regions, and karst terrains. The findings from this review are presented in **TM #2** and included in **Appendix B**.

Task 3: Conduct Survey and Interviews

A survey was conducted to evaluate current hydrological practices for playa lakes, arid areas, and karstic zones. The survey engaged a diverse group of experts, including professionals from state Departments of Transportation (DOTs), university faculty members, consultants, and representatives from federal, state, city, and local agencies. To gain deeper insights into these practices, the research team conducted follow-up interviews with selected participants from the initial survey. The results of the survey and interviews are presented in **TM #3** and included in **Appendix C**.

Task 4: Synthesis of Current State of Knowledge and Practice

Based on the findings from the literature review, survey, and interviews, a report was prepared to synthesize the current knowledge and best practices for hydrological approaches in playa lakes, arid regions, and karst terrains, highlighting the unique challenges these diverse environments pose for transportation infrastructure. The report emphasizes the difficulties in accurately predicting rainfall-runoff and managing flood risk in these areas. The synthesis is provided in **TM #4** and is also included in **Chapters 4** to **6** of this report.

1.4. Report Structure

This report is organized as follows: **Chapter 1** provides an overview of the project background and objectives. **Chapters 2** and **3** highlight the findings from the literature review (Task 2) and the survey and interviews (Task 3). **Chapters 4 through 6** summarize the synthesis of the current state of knowledge and practices related to hydrological approaches for playa lakes, arid regions, and karstic terrains, respectively (Task 4). **Chapter 7** presents the key findings of this project and offers recommendations for future work in developing guidance and standards. The Value of Research (VoR) is detailed in **Appendix A**. Finally, the findings from the literature review and the survey and interviews are included in **Appendices B** and **C**, respectively.

CHAPTER 2: LITERATURE REVIEW

Playa lakes, arid regions, and karst terrains constitute important geographic and hydrological features across Texas, each presenting unique challenges due to their complex and varied hydrology. Currently, there are no uniform guidelines or standards for the hydrological and hydraulic design of transportation infrastructures in these landscapes, leading designers to heavily rely on project-specific judgment to determine suitable hydrological parameters. The primary objective of this review was to provide a comprehensive overview of the current state of knowledge and practices regarding hydrological approaches to playa lakes, arid regions, and karst terrains.

The methodology employed to achieve the project's objective involves a systematic review of design guidance, standards, and recommendations relevant to hydrology and hydraulic design of transportation infrastructure such as drainage and stormwater systems. This involved reviewing various sources, including state departments of transportation drainage design manuals, publications from the Federal Highway Administration (FHWA), and stormwater design manuals from various states, cities, and communities, as well as international drainage design guidance and manuals. Additionally, a review of research studies and technical reports was conducted. This review aimed to identify new approaches to hydrology and hydraulic studies tailored to regions characterized by playa lakes, karst terrains, and arid conditions.

The literature review was completed as part of Task 2, with the full report provided in **Appendix B**. Below is a summary of the key findings from the report.

2.1. Review State and Federal Design Guidance and Recommendations on Hydrologic Approaches to Playa Lakes, Karst Areas, and Arid Regions

In our review of design guidance and standards, we focused on two key aspects: identifying acceptable methods for hydrological analysis by the DOTs and other relevant agencies; and determining if their manuals offer approaches to hydrology of playa lakes, karst terrains, and arid areas. The Rational Method, NRCS (SCS) Method, and Regional Regression Equations (or similar methods developed outside of the U.S.) are widely adopted by national and international transportation agencies, states, cities, and communities. These methods are recommended for estimating peak flow and developing flow hydrographs. Moreover, certain manuals have incorporated specific approaches and methods to address the hydrologic characteristics unique to these environments. These approaches are listed here:

Playa Lakes:

- Excluding non-contributing areas such as playas and dry lakebeds from the watershed area.

- Assigning different runoff coefficient (C) values in Rational Method for isolated and non-isolated playas.

Arid Areas:

- Employing Rational Method runoff coefficient (C) values recommended for desert regions.
- Utilizing NRCS curve numbers (CN) recommended for arid and semi-arid areas.
- Applying regional regression equations and methods for flood frequency developed specifically for arid regions.
- Employing SCS Type II cumulative type curve for hydraulic modeling.

Karst Terrains:

- Excluding non-contributing areas (due to karst topography features) such sinkholes and depressions from the watershed area.
- Applying empirical reduction factors to peak runoff.
- Adjusting the Rational Method runoff coefficient (C).
- Using an NRCS Type I rainfall distribution (low-intensity, longer-duration rainfall) within a Type II area (characterized by intense, shorter-duration rainfall events).
- Modifying curve number values or peak rate factors using the TR-20 method.
- Employing regression equations tailored for karst terrain.

2.2. Review Literature on Hydrologic Approaches to Playa Lakes, Arid Areas, and Karst Terrains

Over 300 research studies and technical reports were reviewed. This review aimed to uncover new approaches to the hydrology of playa lakes, karst terrains, and arid areas. The regions covered in these studies include not only the United States but also other parts of the world facing similar hydrology challenges. A summary of the review for each region is as follows:

Playa Lakes

While playa lakes can contribute significantly to flooding and flood mitigation, the primary focus of research studies on these features centers around various aspects such as their distribution, inundation characteristics, estimation of depth, storage volume, duration, and infiltration rates. Nonetheless, some research efforts have targeted flood forecasting and management in these vital components of arid and semi-arid regions. These efforts encompass developing models to simulate playa lake behavior under different rainfall scenarios, analyzing hydrologic connectivity within watersheds, and examining the correlation between rainfall and playa lake response. Despite these efforts, there is still much to learn about playa lake hydrology, as no study has exclusively addressed the effect of these features on rainfall-runoff relationships, time of concentration, and peak flow estimates.

Arid Areas

The hydrology of arid and semi-arid regions is characterized by low and highly variable precipitation, high evapotranspiration, and limited surface water resources. Research in this area, therefore, has focused on developing hydrologic models to simulate watershed responses to rainfall events, analyzing precipitation variability, and studying the impacts of land use and climate change on flood risk. Challenges arise in accurately estimating parameters such as initial abstraction and time of concentration (T_c) due to limited data availability.

Since conventional methodologies for estimating peak flow rate and flood hydrographs are tailored for non-arid regions, several studies have attempted to modify these methods for arid areas. These modifications include adjusting the curve number in the NRCS method and proposing equations to calculate CN for dry and wet conditions based on antecedent moisture condition (AMC) and antecedent runoff condition (ARC). While these methods have shown promising results in various arid regions, their applicability in other areas requires further investigation.

The time of concentration (T_c) in arid regions can be estimated using various methods, but studies evaluating these methods show wide variability in their performance. Despite challenges, recent research has shown promise in refining empirical equations through graphical analyses, leading to more accurate estimations of T_c in arid environments.

Karts Terrains

The literature review revealed that past and current research in karst regions primarily focuses on geotechnical and structural issues related to karstic features, groundwater movement and quality, water availability, and interactions between groundwater flow, erosion, and subsurface processes. Few studies concentrate on hydrologic challenges for flood forecasting in karst landscapes, at both national and international levels.

Unlike modeling drainage areas with soil pores, which have limited infiltration rates, karstic fissures and shafts allow for rapid and substantial flow discharge, contributing to shorter response times and higher peak flooding magnitudes. Additionally, water retention in voids and aquifers within karst formations can delay movement and reduce peak flood levels. Therefore, research on karst hydrology has focused on developing methods for estimating infiltration or loss through sinkholes and fissures within karst zones. One approach is modifying the NRCS curve number (CN) for karstic regions based on factors such as permeability, land use, and watershed drainage capacity. The modified NRCS-CN method has been extensively applied in Mediterranean karst regions for estimating surface runoff, peak discharge, and flash flooding, showing promising performance in assessing flood risks.

Researchers have also proposed modifications to soil moisture calculation to better account for the unique characteristics of karstic watersheds. In conventional methods, peak runoff estimation heavily relies on soil moisture conditions, determining infiltration rates and surface runoff generation. However, in karstic environments, where water rapidly infiltrates into subsurface conduits, soil moisture loss rates can differ significantly from non-karstic areas. To address these challenges, it is suggested to adopt soil moisture calculation methods to reflect the rapid drainage and subsurface flow processes characteristic of karstic watersheds. This may involve incorporating additional parameters or refining existing models to account for the complexities of flow pathways in these environments.

The findings from the literature review (Task 2), along with survey responses and interviews (Task 3), were synthesized to provide a comprehensive analysis of the hydrologic design challenges and current methodologies applied in playa lakes, karst terrains, and arid regions. This synthesis is presented in **Chapters 4** to **6**.

CHAPTER 3: CONDUCT SURVEY AND INTERVIEWS

Playa lakes, arid regions, and karst terrains are significant geographic and hydrological features throughout Texas, each posing unique challenges due to their complex and varied hydrology. Currently, there are no standardized guidelines or criteria for the hydrological and hydraulic design of transportation infrastructure in these landscapes, which forces designers to rely heavily on project-specific judgment to determine appropriate hydrological parameters. The primary objective of this task was to conduct surveys and interviews to gather information on the current state of knowledge and practices regarding the hydrology of playa lakes, karst terrains, and arid regions.

The survey engaged a diverse cohort of 76 experts, including representatives from 30 state Departments of Transportation (DOTs), 13 university faculty members, 12 consultants, and 21 other entities encompassing federal, state, city, and local agencies. Ultimately, 24 responses were collected, providing valuable insights into the effectiveness of existing guidelines and modeling approaches related to the hydrology of these critical ecosystems. The survey comprised 37 questions covering various topics, including location, infrastructure design and damages, studies and standards, modeling practices, hydrology and hydraulic models, hydrologic and hydraulic parameters, and recommendations for improvement. Each question was analyzed using pie charts, and specific participant comments were included where relevant.

To gain deeper insights into hydrological practices, the research team conducted follow-up interviews with select participants from the initial survey. This qualitative phase included seven experts from DOTs in Kansas, Minnesota, New Mexico, and Virginia, alongside two researchers, and a consultant. These interviews provided a more nuanced understanding of the challenges and successes encountered in managing hydrological resources in these areas. The interview results are summarized according to the three main areas of questions and are further organized by their relevance to the three focus areas: playa lakes, arid regions, and karst zones.

The survey and interviews were conducted as part of Task 3, with the full report provided in **Appendix C**. A summary of the key findings from this report is presented below.

3.1. Survey on Hydrologic Approaches to Playa Lakes, Karst Geology, and Arid Regions

The key insights from the survey, reflecting the perspectives of field experts, are summarized in the following section. This summary highlights the main findings on the effectiveness of current hydrological practices related to playa lakes, arid areas, and karstic zones, identifies gaps in knowledge, and suggests areas for further research and improvement.

Study Area Focus and Engagement

The survey revealed varying levels of engagement in studies across different geographic areas. Karstic zones garnered the most attention, with 42.4% of respondents involved in research. Arid regions followed with 27.3% engagement, while Playa Lakes received the least attention at 21.2%. These findings highlight a strong interest in understanding karstic zones and arid regions, while Playa Lakes remain a less explored area.

Information Sharing and Collaboration

Approximately 40% of respondents expressed a willingness to share documentation or resources related to identifying playa lakes, karstic zones, or arid regions. However, conditions like official requests or confidentiality restrictions may limit information sharing. This suggests a potential for collaboration and knowledge exchange, but strategies like direct contact and institutional requests may be necessary to access relevant resources.

Infrastructure Assets and Environmental Challenges

Infrastructure assets are prevalent in karstic zones (32.4%), followed by arid regions (29.7%) and playa lakes (21.6%). These findings highlight the importance of infrastructure resilience and risk management in these regions due to environmental challenges such as drought, flooding, and geological instability.

Hydrology and Hydraulic Studies

A significant portion of respondents (52%) have conducted hydrology and hydraulic studies in these areas, indicating a moderate level of expertise and documentation. Many expressed a willingness to share their reports, facilitating knowledge transfer. However, confidentiality restrictions and the absence of reports in some cases limit accessibility.

Expert Knowledge and Experience

A substantial majority of respondents (71.4%) have personal experience in hydrology and hydraulic studies, highlighting a strong foundation of expertise. However, a lack of expert referrals among those without personal experience indicates potential knowledge gaps and limited connections within the field.

Guidelines and Standards

Federal or state guidelines are used by a portion of respondents for hydrology and hydraulic studies in these regions. However, a significant number (34.4%) find them not applicable, suggesting the need for more tailored guidance. Many respondents believe that current guidelines are inadequate for infrastructure design, emphasizing the need for updates and revisions to address specific challenges.

Hydrology Studies and Modeling

The focus of hydrology studies varies, with a notable emphasis on arid regions and a more specialized interest in karstic zones and playa lakes. The validation of hydrological models primarily relies on hydrograph comparisons but also includes other techniques. However, a significant portion of respondents use "*Other*" methods or find the question not applicable, highlighting the need for tailored validation strategies.

Runoff Calculation Methodologies

The Rational Method, SCS Curve Number Method, and TR-55 Method are the most commonly used methodologies for calculating runoff. However, other techniques like HEC-HMS and the SCS Unit Hydrograph Method are also employed, reflecting the diversity of approaches used in these complex environments. The choice of methodology is influenced by factors such as accuracy, data availability, and specific study area characteristics.

3.2. Follow-up Interviews

The key insights from the interviews, reflecting the perspectives of field experts, are summarized in the following section. This summary highlights the main findings on the effectiveness of current hydrological practices related to playa lakes, arid areas, and karstic zones. It identifies gaps in knowledge, reveals best practices, and suggests areas for further research and improvement.

Playa Lakes and Arid Regions

- General Tools and Guidelines: USGS StreamStats and regression equations are used for estimating runoff in playa lakes and arid regions, but these tools are generalized and not specifically tailored for these unique environments.
- Inadequate Hydrological Models: Current methods, such as SCS (NRCS) Curve Number Method, often assume high initial abstractions, which do not reflect actual hydrological behavior, particularly in arid regions and playa lakes.
- Soil Absorption: There is limited data on soil absorption rates, particularly in arid regions. General models like SCS often inaccurately estimate runoff, leading to skewed results.
- DEM Data: The 30m USGS DEM data used for identifying and modeling playa lakes is too coarse necessitating better data like Lidar to accurately map and model these regions.
- Rainfall Data: The lack of comprehensive rainfall data in arid zones impacts hydrological modeling and makes model calibration difficult.
- Retention Capacity: Playa lakes possess retention capacity, making overflow events rare. However, past projects have inadvertently caused issues such as groundwater infiltration, highlighting the need for specific guidelines.
- Urban Development: In urban areas, such as Lubbock and Amarillo, overflow between playa lakes due to urban development poses challenges, leading to drainage solutions.
- Flash Flooding: Arid regions often experience flashier hydrological events, but current tools overestimate runoff, which leads to overbuilt infrastructure.

- Need for Research: Further research and funding are essential for improving models in arid regions, particularly to refine the understanding of sediment transport and rainfall clustering patterns.

Karst Regions

- Lack of Standardization: There are no comprehensive guidelines addressing karst regions. Engineers rely on geotechnical teams to assess hydrological risks like sinkholes and unpredictable water flow.
- Avoidance Strategy: Some DOTs, such as Virginia DOT, adopt an avoidance strategy due to the complexity of karst regions. When construction is unavoidable, mitigation measures are implemented. A principle in karst regions is to avoid development due to the unpredictability of water movement underground.
- Data Gaps: Hydrological models for karst systems are particularly weak due to the unpredictable nature of water flow through springs and sinkholes. Insufficient data makes accurate modeling difficult, and reliance on local knowledge.
- Limited Guidelines and Models: There is a lack of detailed, actionable guidelines and comprehensive hydrological models for karst regions. Most hydrological tools fail to account for the underground water movement typical of karst landscapes.
- Unpredictable Hydrology: Karst areas present a hydrological challenge because water flows unpredictably through underground systems, making traditional watershed models inadequate.

The findings from the survey responses and interviews (Task 3), along with the literature review (Task 2) were synthesized to provide a comprehensive analysis of the hydrologic design challenges and current methodologies applied in playa lakes, karst terrains, and arid regions. This synthesis is presented in **Chapters 4** to **6**.

CHAPTER 4: SYNTHESIS OF CURRENT STATE OF KNOWLEDGE AND PRACTICE OF HYDROLOGIC APPROACHES TO PLAYA LAKES

4.1. Introduction

Playa lakes, also known as playas, pans, or ephemeral lakes, are shallow, seasonally flooded depressions commonly found in arid and semi-arid regions. Playa lakes are unique and important features of the hydrological landscape. These lakes, primarily play a vital role in the local habitats for wildlife and as significant recharge areas for groundwater resources. Playas have evolved over time due to various factors, with their water evaporating and leaving behind vast areas rich in sediment and minerals. The formation of playa lakes is heavily influenced by climate and geographical location. These lakes act as local discharge sites, typically receiving water from precipitation and runoff within their watersheds. Additionally, they can also receive groundwater inflows from both their local watershed and regional aquifers (Haukos and Smith 1992; 2003).

Playa and playa lake systems are widespread and vary in size from small, less than 250 acres (1 km²), to very large, up to 2,400,000 acres (9700 km²), exemplified by Lake Eyre in Australia (Briere, 2000). The distribution of playa lakes in the United States varies across different regions, with notable concentrations found in areas such as the Great Plains, the southwestern states, and parts of the western United States. Playa lakes are particularly prevalent in states such as Texas, Kansas, Oklahoma, New Mexico, and Colorado. The High Plains Aquifer, also known as the Ogallala Aquifer, spans over 174,000 square miles across eight U.S. states, including Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (Gurdak and Roe, 2009). High Plains region features several crucial playa lakes essential for floodwater storage, irrigation, livestock support, and wildlife habitats, potentially aiding aquifer recharge into its northern, central, and Southern High Plains (SHP) (Steiert and Meinzer, 1994; Luo et al., 1997; Smith, 2003). There are approximately 20,000-24,000 playa lakes throughout the Texas Panhandle and western North Texas covering 3.0-4.5 million acres of land, i.e., 0.4-2.56% of the total land in Texas (TPWD, n.d.; Playa Lakes Joint Venture (PLJV), 2009; Fish et al., 1998).

Playas exhibit a complex interplay between geological and hydrological factors, defined by distinct zones: the hydric soil-lined floor, the sloped annulus, and the surrounding interplaya region (Hovorka, 1995). The interplaya includes upland drainage areas and spaces between playas, while the floor and annulus, made of interbedded clay and loam, reflect historical lake size fluctuations. Soil texture significantly influences playa characteristics, with fine-textured soils hosting larger, higher-volume playas than medium-textured regions (Grubb and Parks, 1968). Interplaya areas feature silty clay loam and evaporative caliche layers, further illustrating geological-hydrological interactions (Hovorka, 1995). Fish et al. (1998) and Gurdak and Roe (2010) have mapped over 20,000 playas in the SHPs, enhancing insights into their morphology, soil composition, and hydrology. These findings highlight the critical role of soil texture and geomorphology in shaping the distribution and characteristics of playa lakes.

Understanding the hydrology of playa lakes is vital for developing sustainable infrastructure design and management practices, conserving biodiversity, and addressing climate-related challenges that impact water availability and quality in these regions.

This chapter addresses the challenges associated with playa lake hydrology and synthesizes current knowledge on key hydrologic processes and modeling approaches reviewed in **Appendix B** (Task 2). It also incorporates findings from surveys and interviews conducted as part of **Appendix C** (Task 3). This effort was conducted under Task 4, titled "*Synthesis of Current State of Knowledge and Practice*".

4.2. Hydrology of Playa Lakes and Challenges for Transportation Infrastructure

Playa lakes, typically found in arid and semi-arid regions, may present challenges for transportation infrastructure due to their unique hydrological and environmental characteristics. These flat depressions, which intermittently collect and store water during rainfall, are prone to flash flooding that can severely disrupt transportation systems. Roads and highways near playas are often closed during heavy storms, causing traffic delays and forcing detours. Erosion and water damage to roadways, especially those constructed on unstable or erosion-prone soils, further compound the issue. Additionally, floodwaters pose safety risks for drivers, particularly when water levels obscure the road surface or create traction issues. The NMDOT Environment Group reported several serious vehicular accidents due to dust from playas (**Appendix C**).

Hydrological challenges in playa lake regions complicate the design and management of transportation infrastructure. Estimating rainfall-runoff is difficult due to the variability in hydrological behavior, lack of detailed data for model calibration, and the complex topography and drainage systems characteristic of these areas. Rapid response times of water levels during rainfall events, coupled with sediment mobilization, add uncertainty to peak flow calculations. The intricate drainage patterns and depression storage further challenge calculations of time of concentration, as does the heterogeneity of soil and vegetation affecting infiltration rates. Depression storage dynamics, influenced by sedimentation, vegetation growth, and human activity, alter the hydrological behavior over time, complicating long-term planning and flood mitigation. Infiltration modeling in playa lakes is similarly complicated with difficulty due to the variability of soil properties and the influence of vegetation on soil moisture and hydraulic conductivity. Losses to evapotranspiration and groundwater interactions require detailed investigations to understand the interplay between surface and subsurface processes. Developing accurate hydrological models is particularly challenging in these regions due to the complex interconnections between surface water, groundwater, and sediment transport. The lack of comprehensive data in these environments further complicates the parameterization of models, making reliable predictions essential but elusive. Together, these hydrological and infrastructural challenges necessitate detailed, site-specific guidelines to ensure sustainable development and maintenance of transportation systems in playa lake regions.

The results of the survey conducted for this project showed that 8% of survey participants reported experiencing transportation infrastructure damage in their jurisdictions. Nonetheless, they attributed these damages to inadequate design guidelines, uncertainties in hydrological and hydraulic modeling, and a lack of reliable data. Key data-related issues include insufficient geological investigations, challenges in data collection, and limited or low-quality datasets. Additional contributing factors include uncertainties in hydrological and hydraulic methodologies, models that fail to account for the physical properties of playa lakes, and inadequate consideration of the spatial and temporal variability of effective parameters in modeling playa lakes (**Appendix C**).

4.3. Hydrologic Processes of Playa Lakes

Hydrology of playa lakes is influenced by climate, geology, land use, and human activities, with soil type, subsurface geology, and vegetation cover significantly affecting water balance and recharge rates (Bexfield, 1995; Ganesan et al., 2016; Sallenave and Ganguli, 2021). These ephemeral waterbodies exhibit fluctuating hydrological dynamics, alternating between flooding and drying periods due to precipitation and evapotranspiration (Smith, 2003; Hovorka, 1997). While heavy rainfall contributes to water accumulation, high evaporation rates in arid and semi-arid areas pose challenges for water retention (Dugan and Zelt, 2000; Gustavson et al., 1995). These hydrological complexities, including runoff dynamics, water loss, and evaporation, underscore the importance of understanding playa lake inundation characteristics such as flow depth, duration, and infiltration rates for effective water management and flood mitigation (Hauser and Lotspeich, 1968; James, 1998).

The following sections provide an overview of the key parameters and processes influencing the hydrology of playa lakes, including precipitation, runoff, evaporation infiltration, groundwater, storage, as well as inundation and sedimentation.

4.3.1. Precipitation and Runoff

Precipitation serves as the primary water source for playa lakes, especially in arid and semi-arid regions where these lakes predominantly exist. Relying on direct rainfall and local runoff, playa lakes typically lack consistent inflow from rivers or streams. During wet seasons, precipitation fills these lakes, while dry periods cause them to evaporate, making precipitation patterns essential in determining the frequency and duration of inundation. Heavy rains contribute to water accumulation, but high evaporation rates in these regions make water retention challenging (Dugan and Zelt, 2000; Gustavson et al., 1995).

The variable hydrological behavior of playa lakes presents unique challenges in hydrological studies, particularly precipitation. Estimating rainfall-runoff for these lakes is complicated due to the scarcity of comprehensive hydrological data for model calibration and the complex topography and drainage networks (Elfeki and Bahrawi, 2017; Kamis et al., 2018; Marko et al., 2019). The rapid response times of water level and flow during rainfall events add to the difficulty in estimating peak flows in playa lake regions. Sediment mobilization during storm events may alter flow patterns, leading to increased uncertainties in peak flow calculations.

Evapotranspiration rates, combined with precipitation patterns, contribute to the fluctuating hydrology of playa lakes, resulting in alternating periods of flooding and drying (Smith, 2003; Hovorka, 1997). Climate change and variability are expected to impact playa hydrology and regional water resources significantly. Changes in precipitation patterns could affect playas in the High Plains. Reduced snowfall during winter, particularly, may increase winter recharge beneath playas due to lower evapotranspiration losses, while decreased annual precipitation in areas such as New Mexico and Texas could reduce playa recharge. Meanwhile, an increase in summer precipitation, while seemingly beneficial, could lead to higher erosion and sedimentation, ultimately reducing recharge. High variability in precipitation, including potential local droughts and regional flooding, poses complex challenges to playa hydrology (Gurdak and Roe, 2009).

Variations in precipitation directly influence groundwater recharge rates beneath playa lakes. During high rainfall periods, infiltration often increases due to desiccation cracks in the clay-lined playa floors, enabling more significant water movement into underlying aquifers. Although high evaporation can limit recharge, heavy rainfall following dry spells often drives substantial infiltration. This relationship underscores the need for precipitation-based infiltration models that account for fluctuating rainfall conditions to accurately estimate recharge rates.

Technological advancements, including satellite-based precipitation monitoring, are increasingly aiding the study of playa hydrology. Remote sensing data enables continuous tracking of rainfall and surface water extent, providing insights into precipitation impacts on playa lake systems. For instance, Landsat and MODIS satellite imagery allow researchers to observe temporal changes in inundation areas and correlate specific rainfall events with surface water levels in playa basins (French and Miller, 2012; French et al., 2006). These technologies enhance our understanding of playa lake dynamics, supporting more accurate predictions of their hydrological responses to varying precipitation events.

4.3.2. Evaporation

Evaporation plays a major role in the hydrological cycle of playa lakes, especially in arid climates where high temperatures drive significant water loss. The hydrology of playa lakes is highly variable, characterized by alternating cycles of flooding and drying, which are largely influenced by precipitation patterns and evapotranspiration rates (Smith, 2003; Hovorka, 1997). High evaporation rates in arid and semi-arid regions challenge water retention efforts, even when heavy rains contribute to temporary water accumulation (Dugan and Zelt, 2000; Gustavson et al., 1995).

Evaporation from playa surfaces is further affected by seasonal variations and soil composition, disrupting the hydrological balance. For instance, evaporation rates in SHPs range between 13 and 24 inches, compared to potential evapotranspiration rates of 65 to 69 inches (Brown et al., 1976).

In spring and summer, high temperatures and wind in arid and semi-arid regions can further accelerate evaporation and reduce the water volume on the lakebed (French et al., 2006).

The impact of climate change and variability on water resources is an increasing concern. Changes in precipitation patterns, especially during winter, could influence playa hydrology. Increased winter precipitation may enhance groundwater recharge beneath playas due to reduced evapotranspiration losses during cooler months (Gurdak and Roe, 2009)

4.3.3. Infiltration and Groundwater Recharge

Infiltration within playa lakes is strongly influenced by soil composition. Playa floors are typically lined with clay-rich hydric soils that affect water penetration, and the dynamics of infiltration vary, impacting both groundwater recharge and chemical transport (Claborn et al., 1985; Knowles et al., 1984). The infiltration process in playas is closely related to recharge, although these are distinct processes. Infiltration refers to water entering the soil from precipitation, irrigation, or surface sources, while recharge describes the rate or volume of water that enters and interacts with the groundwater system (Gurdak and Roe, 2009). In the SHPs, playa lakes play a key role in concentrating runoff and various chemical constituents, with infiltration rates ranging from 0 to 116 inches per hour, generally higher at the center due to desiccation cracks that enhance water movement through the clay floor (Gurdak and Roe, 2009). However, infiltration rates decrease as the clays swell and seal these cracks, as observed in studies by Evans (1990), James (1998), and Parker et al. (1998).

Early studies attributed water level changes in playas to evaporation (Theis, 1937), but research by Wood and Sanford (1994) and Wood et al. (1997) emphasized groundwater infiltration as a key process, contributing significantly to groundwater recharge. Zartman et al. (1994) also noted a positive correlation between clay content and infiltration beneath a single playa, challenging the view that high clay content restricts infiltration. Scanlon and Goldsmith (1997) further showed that recharge is strongly influenced by the surface water volume and infiltration depth. Factors such as vegetation cover, soil permeability, and evaporation rates further influence aquifer recharge potential (Brown et al., 1976; James, 1998).

Estimating infiltration rates in heterogeneous soil and land cover conditions presents challenges, as complex drainage patterns, depression storage, and limited hydrological data introduce uncertainties in calculating the time of concentration for playa lake regions. Estimating recharge is also challenging due to soil variability and precipitation patterns (Hauser and Lotspeich, 1968), with infiltration rates in playa floors generally higher than in surrounding interplaya areas (Scanlon and Goldsmith, 1997). Direct measurement techniques, such as groundwater level monitoring and soil moisture assessments, are often used to determine recharge rates. However, water-budget calculations, essential for estimating infiltration, introduce uncertainties due to potential errors in surveying playa geometry and subsurface water movement (McMahon et al., 2006; Gurdak et al., 2007; Gurdak and Roe, 2009). Despite the importance of these methods, the lack of monitoring wells at study sites limits direct observations of aquifer response to playa flooding, constraining definitive recharge estimates (Weinberg et al., 2021).

Tracer-based techniques, including using tritium (3H) and chloride (Cl-) as environmental tracers, have been applied in groundwater studies to estimate recharge over broader spatial scales. Unlike point-specific unsaturated-zone studies, these methods provide averaged recharge estimates, beneficial for regional assessments but potentially lacking fine spatial resolution for individual playas (Scanlon et al., 2002, 2003). Using tritium, Nativ and Smith (1987) estimated playa recharge rates between 0.5 and 3.24 inches per year, indicating that the High Plains aquifer primarily receives recharge through focused infiltration from playas rather than diffuse recharge sources, which range between 0.01 and 0.57 inches per year (Barnes et al., 1949; Stone and McGurk, 1985; Stone, 1990). Wood and Sanford (1995) used a chloride-mass balance approach to estimate a regional recharge rate of 0.43 inches per year for the northern SHPs, highlighting the significance of focused recharge processes in supporting aquifer sustainability. These findings underscore the complexity of groundwater recharge in playa lakes.

Factors influencing playa hydrology are often overlooked. For instance, channel transmission losses, where water seeps or evaporates as it flows toward the lake, can significantly affect water volume (French et al., 2006). Additionally, Claborn et al. (1985) conducted a water-budget analysis on 22 SHP playas, revealing that 30–50% of the runoff entering playas could infiltrate through the playa annulus, contributing to groundwater recharge.

4.3.4. Storage and Inundation

Estimating the peak flow is directly related to the storage capability of the watershed and the amount of rainfall loss in the region. However, characterizing storage in playa lakes is challenging due to variability in depression features such as size, shape, and depth, which require precise quantification to accurately reflect storage capacities (Elfeki and Bahrawi, 2017; Kamis et al., 2018; Marko et al., 2019). Temporal changes in storage capacity caused by sedimentation, vegetation growth, and human activities also complicate long-term hydrological studies (French and Miller, 2012; Weinberg et al. 2015). Additionally, the limited surface water storage capacity in playa lakes, which often lack outlets, can lead to flooding during heavy rains and drought during dry periods, as they cannot easily drain excess water.

Inundation depth and duration are critical to understanding playa lake storage. The depth of inundation affects the storage capacity of playas, influencing groundwater recharge rates and sediment transport patterns, while the duration of inundation dictates the availability of water for vegetation and wildlife habitats. Inundation dynamics also play a role in managing flood risk, as they can regulate peak flow events in nearby areas (French and Miller, 2012; Weinberg et al. 2015).

Estimation of inundation depth and storage volume in playa lakes lacks standardized guidelines. French and Miller (2012) adapted a methodology using the NRCS Curve Number method to analyze a 100-year flood event at Rogers Lake, Mojave Desert, calculating rainfall-runoff relationships based on soil, land use, and vegetation. Weinberg et al. (2015) applied a similar method to Texas playas, incorporating field surveys, remote sensing, and regression modeling to explain over 70% of annual water volume variance. Their findings, validated through Landsat imagery, were extrapolated to 374,587 acres of playas in the Ogallala Aquifer, highlighting significant annual detention volume fluctuations.

Predicting the duration of inundation in playa lakes involves a complex interplay of factors, including precipitation characteristics, watershed attributes, and the unique hydrological and geological properties of each playa. Several studies (e.g., Bryant and Rainey, 2002; French et al., 2006; Doña et al., 2016; Solvik et al., 2021) have combined field measurements with remote sensing techniques to estimate inundation duration.

Remote sensing, using satellites or aircraft, has proven to be an effective tool for studying playa inundation dynamics. French et al. (2006) utilized remote sensing to investigate the relationship between precipitation and water surface area changes at Rosamond Lake, California. They estimated runoff volume using the NRCS-CN method and applied temporal remote sensing to track the lake's inundation footprint over time. By correlating precipitation data with surface water changes, the study determined the precipitation threshold required to generate runoff. Treating the lakebed as a fully impervious surface simplified calculations for direct precipitation effects, but this approach neglected key factors such as channel transmission losses, lakebed evaporation, and infiltration (French and Miller, 2012). By identifying specific precipitation events that produce surface runoff and accounting for losses through infiltration and evaporation, the methodology enables a more accurate estimation of water inflow into playas. Moreover, integrating these estimates with evaporation rate calculations facilitates predictions of how long water will persist on the lakebed. This combined approach is a valuable tool for estimating both the frequency and duration of flooding events in playa lakes.

The survey results for this project revealed a variety of methods have been used by participants to identify playa lake locations. The largest group (36%) reported relying on traditional techniques, including topographic maps (14.9%), field surveys or ground-truthing soil (14.9%), and soil or ground depression surveys (6.4%). A smaller proportion (23.5%) employed advanced technologies such as LIDAR (8.5%), drones and UAVs (6.4%), remote sensing (4.3%), and geophysical methods (4.3%). Historical hydrological analysis has been used by 6.4% of respondents, while 4.3% reported using other techniques.

Participants also highlighted methods used by their institutions to track the evolution of playas. These included remote sensing, LIDAR, drones, or UAVs (10.7%); hydrological monitoring, such as water surface elevation and gauge monitoring at inflow and outflow boundaries (14.3%); bathymetric surveys (3.6%); and ground-penetrating radar (3.6%). Other approaches (21.4%) encompassed boreholes, soil sampling, historical aerial photography, field inspections, and the use of GIS layers for identifying playa boundaries and extents, terrain data, topographic maps, and tools like USGS StreamStats for estimating non-contributing drainage areas.

4.3.5. Sedimentation

Sediment transport is a key process affecting the morphology and longevity of playa lakes. Over time, sediment accumulation can reduce the depth and water-holding capacity of playas, impacting their ability to store water. Sedimentation rates are influenced by land use, erosion processes in the watershed, and agricultural practices that contribute to increased soil runoff into playas. Managing sedimentation is critical for maintaining the hydrologic function and ecological integrity of playa lakes.

Peak flows in playa lakes are affected by sediment mobilization during rainfall events, altering flow patterns and increasing uncertainties in hydrological modeling. These rapid hydrological responses complicate predictions and water management strategies. Furthermore, the variability in depression storage- governed by playa size, shape, and depth- along with temporal changes caused by sediment accumulation, vegetation growth, and human activities, poses challenges to quantifying long-term hydrological impacts.

Sedimentation also influences groundwater recharge rates. While excessive sediment can reduce infiltration and storage, coarser sediments may enhance recharge by filling desiccation cracks, creating more permeable pathways for water movement. This dual effect underlines the importance of managing sediment composition and flow to maintain the delicate balance of playa lake ecosystems (**Appendix C**: Interview with the University Researcher #2).

Climate change adds complexity to these dynamics. For instance, increased summer precipitation could exacerbate erosion and sedimentation, further reducing playas' recharge potential and water retention capabilities (Gurdak and Roe, 2009).

4.4. Hydrological Approaches for Estimating Stormwater Runoff in Play Lakes

The design of roads, highways, and associated structures, such as bridges, culverts, and stormwater drainage systems, in playa lake regions requires accurate runoff estimation. Methodologies for characterizing stormwater runoff must consider all relevant hydrological processes specific to playa lakes, as outlined in **Section 4.3**. These processes include rainfall-runoff relationships, infiltration, evaporation, storage, and sedimentation.

This section highlights commonly employed methods for rainfall-runoff estimation in playa lake regions, with a particular focus on peak flow calculations, runoff hydrograph analysis, and timing parameters such as time of concentration. The findings are based on the literature review (**Appendix B**) and insights gathered through surveys and interviews conducted during this project (**Appendix C**).

4.4.1. Stormwater Peak Flow and Hydrograph Estimation in Playa Lakes

In the absence of hydrological methods specifically tailored for playa lakes, practitioners often rely on approaches developed for the hydrology of arid regions. These methods are adapted due to the similarities between playa lakes and other arid landscapes, such as low annual precipitation, high evaporation rates, and sporadic, intense rainfall events. However, playa lakes pose additional complexities, such as their unique geomorphology, intermittent flooding patterns, absence of consistent drainage outlets, and significant variability in soil infiltration and storage capacity.

Appendix B provides an overview of the common methods employed by state departments of transportation (DOTs), cities, and international transportation agencies for hydrological modeling in playa lake regions. The NRCS Curve Number (CN) method, Rational Method, and statistical methods based on gauge data are commonly employed to estimate runoff and flood peak discharge in playa lake regions. The results of the survey, conducted for this study, also indicated that the NRCS Curve Number (CN) methods are being used by 33% of respondents, the Rational Method by 11%, and statistical methods based on gauge data by 6.7%. These methods account for factors such as soil type, land use, rainfall intensity, and watershed characteristics but often require adjustments to address the distinctive features of playa lakes. For instance, infiltration and evaporation, which play a dominant role in playa hydrology, may necessitate additional considerations that go beyond typical arid-region methodologies. While these general approaches provide a starting point, their application to playa lakes can lead to inaccuracies if the unique hydrological dynamics of playas, such as sedimentation, localized ponding, and prolonged water retention, are not adequately addressed. As a result, there is a growing need for more tailored methods that integrate the specific processes governing playa lake hydrology to improve accuracy in runoff estimation, flood management, and ecological assessments.

The applicability of the NRCS Curve Number (CN) method, Rational method, and statistical methods in playa lake regions, and suggested modifications to each of these methods are discussed below.

Rational Method

The Rational Method is a commonly used approach for calculating peak discharge in small drainage areas, particularly in urban environments. It estimates peak flow using **Equation 4.1**:

$$Q = C\ i\ A \tag{4.1}$$

where Q represents the peak discharge (cfs), C is the runoff coefficient indicating the fraction of rainfall that contributes to runoff, i is the rainfall intensity (in/hr) obtained from Intensity-Duration-Frequency (IDF) curves for a specified return period and storm duration, and A is the watershed area (acres).

The surface of playas is often treated as impervious due to minimal infiltration; therefore, assigning a runoff coefficient of C =1 is recommended. For projects adjacent to playas, runoff coefficients should be adjusted to reflect the unique hydrological characteristics of these regions (City of Lubbock Manual, 2019). If a playa lacks an outlet, precipitation falling directly on its surface does not contribute to downstream flow, and in such cases, a runoff coefficient of $C = 0.06$ is recommended. Conversely, if the playa has an outlet and is considered part of the *connected areas*, a runoff coefficient of $C = 0.85$ is advised (Abu Dhabi Manual, 2022).

The total area (A) contributing to runoff requires careful consideration in playa regions, where adjustments must be made to account for unique hydrological characteristics. Non-contributing areas, such as playas with internal drainage, should be excluded from the contributing area (A) (ODOT Manual, 2014). Additionally, the storage capacities of playas should be incorporated into runoff calculations if they are significant, typically exceeding 10%. The Rational Method is particularly effective for small watersheds under 200 acres and is commonly used for detention basin design in urban settings. For even smaller watersheds, typically 20 acres or less, the Modified Rational Method is preferred, as recommended by the City of Amarillo (2008). However, applying these methods in playa regions comes with limitations, including the difficulty of accurately accounting for depression storage, infiltration, evaporation, and backwater effects caused by the playas.

The Rational Method is a simple and widely understood approach that requires minimal data, making it well-suited for preliminary designs or regions with limited hydrological data. However, its application to playa lakes presents several challenges. The method does not inherently account for the retention or detention characteristics of playas, nor does it accommodate the non-linear runoff behavior typical of semi-arid regions. Additionally, the careful selection of runoff coefficient (C) values is critical to accurately reflect the unique hydrological characteristics of playa lakes, such as variable infiltration, evaporation, and storage dynamics.

NRCS Method

The NRCS Curve Number (CN) and Unit Hydrograph (UH) methods are widely recognized for modeling rainfall-runoff relationships and have been applied in hydrological studies of playa lakes. These methods are particularly recommended for larger basins exceeding 200 acres, where runoff hydrographs with a standard peaking factor of 484 are required (City of Lubbock, 2019). The NRCS methods are also recommended for designing detention and retention basins in playa regions, especially when hydrographs are required for detailed hydrological analysis (City of Amarillo Manual, 2008). In these methodologies, runoff depth is calculated using **Equation 4.2**:

$$Q = \frac{(P-I_a)^2}{(P-I_a+S)} \tag{4.2}$$

where Q is the runoff depth (inches), P is the rainfall depth (inches), I_a is the initial abstraction (inches) often approximated as $0.2S$, and S is the potential maximum retention after runoff begins, calculated as $S = \frac{1000}{CN} - 10$.

The curve number (CN) ranging from 0 to 100, reflects runoff potential. It is influenced by soil type, land use, hydrologic conditions, and antecedent moisture. In playa lakes, CN is often assigned a high value (e.g., $CN = 98$), representing near-total runoff due to the impervious nature of lakebeds (City of Lubbock, 2019). The initial abstraction I_a in playa lakes is minimal due to the low infiltration capacity of the lakebed.

The application of NRCS methods in playa lakes is particularly valuable for developing detailed hydrographs, especially in urbanized regions adjacent to playas, and for modeling peak flow and runoff volumes, often in conjunction with tools such as HEC-HMS. These methods rely on parameters specific to playa lakes, including Hydrologic Soil Group (HSG), Antecedent Moisture Condition (AMC), and time of concentration (T_c). Soils in playa lakes are typically categorized as Group D, indicating very low infiltration rates, while CN values are adjusted for pre-storm soil moisture conditions, with AMC-II representing average conditions and AMC-III for wetter conditions. The advantages of NRCS methods include their simplicity in parameterization, adaptability to diverse environments, including playas, and suitability for event-based modeling of peak flow and runoff hydrographs. However, they face challenges in capturing complex hydrological processes such as depression storage, evaporation, and infiltration in playas, and require calibration to account for unique characteristics like sedimentation and variable soil permeability.

Statistical Methods

Statistical methods analyze historical streamflow or rainfall data from gauges to estimate stormwater parameters such as peak discharge for specific return periods, flood frequency distributions, and runoff volume and characteristics. These methods are particularly applicable when sufficient gauge data is available, though their relevance in data-scarce regions, such as playa lakes, can be limited. Statistical methods are referenced in several hydraulic design guidelines but are less commonly applied directly in playa lakes regions due to the scarcity of long-term, localized streamflow data. Instead, they are often used in conjunction with regional regression equations or distribution models such as Log-Pearson Type III, which are standard in hydrological studies.

The statistical method provides accurate peak flow estimates when reliable, long-term gauge data is available and allows for direct calculation of flood frequencies without relying on assumptions about watershed characteristics. However, its application to playa lakes faces challenges. Gauge data are often unavailable due to the ephemeral nature and remote locations of these features. Additionally, statistical relationships developed in gauged areas may not be directly applicable to ungauged playa lakes. Limited data records further reduce confidence in flood frequency estimates, particularly for extreme events such as the 100-year flood.

4.4.2. Time of Concentration

The time of concentration (T_c) is a critical parameter for accurate hydrograph modeling, as it represents the time it takes for runoff to travel from the most distant point in a watershed to the outlet. Several methods have been developed to estimate T_c, including empirical equations, kinematic wave theory, and approaches that consider watershed characteristics such as slope, land cover, and flow path. Common methods include the Kerby- Kirpich method for overland flow, the Kirpich equation for small watersheds with well-defined channels, and the NRCS method, which incorporates factors like surface roughness and hydraulic length.

The survey results from this project revealed that respondents commonly used the Kerby-Kirpich method (23.8%), NRCS method (23.8%), and the Kinematic Wave Equation (19%) to calculate the time of concentration (T_c) in playa lakes (**Appendix C**). While these methods have been applied in hydrological analyses of playa lakes, they often encounter challenges in accurately capturing the unique characteristics of these systems. Playa lakes display complex hydrological behaviors, including significant depression storage, high variability in infiltration rates, and ephemeral surface flow patterns. Consequently, standard T_c estimation methods may require modifications or calibration to adequately reflect the distinct physical and hydrological properties of playa lake environments.

4.5. Hydrological Models to Estimate Stormwater Runoff in Playa Lakes

Hydrological models are vital for simulating stormwater runoff, particularly in regions with unique landforms like playa lakes. These areas present significant challenges for runoff estimation due to distinctive hydrological features such as intermittent flooding, low infiltration rates, internal drainage, and substantial depression storage. While various hydrological models have been developed and adapted to address complex conditions, none are specifically tailored to playa lakes. The applicability, complexity, and effectiveness of these models depend on factors such as data availability, watershed scale, and the required level of detail.

Despite the variety of models available, estimating stormwater runoff in playa lake regions remains challenging. The key issues include:

- *Data Scarcity and the Challenge of Accurate Runoff Predictions:* A major challenge to accurately simulating playa lake behavior in hydrological models is the limited rainfall-runoff data, particularly in regions like the Texas High Plains. Also, effective simulation of playa lakes requires detailed information on soil permeability, infiltration rates, and precipitation variability, data that is often unavailable. This scarcity of critical input data can lead to discrepancies in runoff predictions, especially under scenarios involving variable rainfall. The lack of such detailed data hinders the ability of most hydrological models to accurately represent the hydrologic behavior of playa lakes, as these systems are highly sensitive to even minor changes in precipitation and soil moisture.
- *Hydrological Complexity:* Playa lakes exhibit non-linear runoff behavior, significant depression storage, and variable soil permeability, which are difficult to model using standard methods.
- *Model Calibration:* Many models require site-specific calibration to account for the unique hydrological and geomorphological characteristics of playa lakes.
- *Integration of Playa-Specific Features:* Most conventional models do not inherently account for playa lake processes such as sedimentation, evaporation, and internal drainage, necessitating additional customization.

The survey results from this showed that HEC-HMS is the most commonly used model, employed by 24% of respondents, while SWAT is utilized by only 4%. None of the respondents reported using other models such as VIC, MODFLOW, MIKE SHE, PRMS, RHESSys, or PRC. Additionally, 28% of respondents reported using other models such as ICPR, StreamStats, 2D modeling that includes distributed rainfall (e.g., FLO-2D, HEC-RAS 2D), and PC-Hydro.

To improve the accuracy of stormwater runoff estimation in playa lake regions, it is recommended to combine traditional hydrological models with advanced techniques such as remote sensing, GIS-based analysis, and field surveys. Additionally, incorporating playa-specific parameters such as depression storage, infiltration variability, and evaporation into model frameworks can enhance their applicability.

CHAPTER 5: SYNTHESIS OF CURRENT STATE OF KNOWLEDGE AND PRACTICE OF HYDROLOGIC APPROACHES TO ARID REGIONS

5.1. Introduction

Arid regions, characterized by low and irregular rainfall, high evaporation rates, and limited surface water resources, cover nearly one-third of the Earth's land surface (Herczeg and Leaney, 2011) and are home to over 2.5 billion people (Qader et al., 2021). These areas face unique challenges, with fragile ecosystems and complex hydrologic processes shaped by both natural variability and human activities.

Arid areas are commonly classified based on annual precipitation, which shapes their environmental characteristics and hydrology. Deserts receive less than 2.7 inches (30 mm) of rain per year and typically support little to no vegetation. Arid regions, with rainfall between 2.7 and 7.8 inches (70 to 200 mm) annually, have sparse vegetation and experience high evaporation rates, often exceeding precipitation. Semi-arid regions receive between 7.8 and 17.7 inches (200 to 450 mm) of rainfall per year, allowing for more vegetation but remaining susceptible to drought (Soliman, 2010).

In the United States, arid and semi-arid regions are distributed unevenly across the landscape, shaped by climate patterns, geography, and elevation. Notable arid regions include the Southwest, which encompasses parts of Arizona, New Mexico, Nevada, and Southern California, home to deserts like the Sonoran and Mojave (Seager et al., 2007). The western Great Plains also experience semi-arid conditions, marked by limited rainfall and frequent droughts (Rosenberg, 1987). The Intermountain West, including Utah, Idaho, and parts of Colorado, is characterized by arid conditions due to rain shadows from surrounding mountain ranges (Comer and Schulz, 2007). Additionally, sections of the Pacific Coast, particularly southern coastal California, feature semi-arid climates with seasonal rainfall and high evaporation rates (Baldocchi et al., 2004).

In Texas, arid conditions are found in the western part of the state, with more humid subtropical climates in the east. According to the Köppen classification, approximately 39% of Texas is arid or semi-arid. The USDA estimates that 61% of the state receives less than 20 inches (500 mm) of annual precipitation, with regions such as West Texas, the Big Bend, and the Panhandle experiencing desert and semi-desert ecosystems, such as the Chihuahuan Desert and Great Plains grasslands (Texas Parks and Wildlife, 2022; USDA, 2023).

With growing concerns about rapid urbanization, climate change, water scarcity, and sustainable development, understanding the hydrology of arid regions is crucial for effective water resource management, ecosystem preservation, and the support of socio-economic activities. Furthermore, it is essential for developing sustainable infrastructure design and management practices.

This chapter presents the challenges of arid regions hydrology and synthesizes current knowledge on key hydrologic processes and modeling approaches reviewed in **Appendix B** (Task 2). Additionally, it integrates findings from surveys and interviews conducted as part of **Appendix C** (Task 3) of this report. This effort was conducted under Task 4, titled "*Synthesis of Current State of Knowledge and Practice*".

5.2. Hydrology of Arid Regions and Challenges for Transportation Infrastructure

Arid regions present unique challenges for transportation infrastructure due to extreme weather events, soil characteristics, and limited water resources. Flash floods, which are common in these areas, can quickly erode and undermine roadways, bridges, and other structures, making them unsafe or impassable. The high rates of evaporation and low precipitation lead to the accumulation of salts and minerals on road surfaces, degrading pavement and reducing its lifespan. Wind-blown sediment, eroded from dry soils, can accumulate on roads, reducing visibility and creating hazardous driving conditions. Other infrastructure challenges in arid areas include extreme temperatures, which accelerate the deterioration of roads and bridges, and frequent sand and dust storms that damage roads, railways, and airports while reducing visibility. The scarcity of water resources impacts the construction and maintenance of transportation systems, and soil erosion, particularly during intense rainfall events, can destabilize transportation infrastructure. Many arid regions are also in remote locations, making access and infrastructure maintenance difficult, and desertification, which alters soil properties, increases the risk of landslides and further erosion.

Hydrological challenges in arid regions are similarly complex. Traditional hydrological models, designed for more temperate, humid climates, often struggle to accurately predict rainfall-runoff relationships in arid areas due to sparse data and different climate patterns. Factors such as time of concentration, rainfall intensity, soil type, and land cover significantly influence flow intensity and direction but vary widely across arid regions. The frequent occurrence of flash floods, often caused by intense, short-duration rainfall events, further complicates hydrological predictions, particularly for peak flows and time of concentration. Climate variability, including extreme weather events like droughts and intense rainfall, poses additional challenges, and climate change is expected to worsen these conditions by altering precipitation patterns. Furthermore, vegetation cover in arid regions is sparse, which leads to high evapotranspiration rates and depletion of soil moisture and surface water. Many arid regions also feature ephemeral or intermittent streams with limited channel storage capacity, causing rapid runoff response to rainfall events. Finally, hydrological models used in arid regions often lack essential components necessary for accurate predictions, as they are typically adapted from models designed for more humid regions with unsuitable parameters for arid conditions.

These challenges have led to a lack of comprehensive federal or state guidelines for hydrological studies in arid regions that can effectively support design engineers. The survey conducted for this project reveals that, although current federal or state guidelines provide some direction for infrastructure design in arid regions, more than half of the participants believe these standards require modification or revision. Additionally, the lack of appropriate design standards for arid regions has been linked to transportation infrastructure damage. Specifically, 16.7% of respondents reported damage linked to the lack of such guidelines. Participants also identified several reasons for infrastructure damage in arid regions: 15% cited uncertain hydrology and hydraulic methodologies, while another 15% pointed to limited or low-quality data, including topography and groundwater monitoring. Five percent noted that models often fail to account for arid region characteristics, such as evaporation and seasonal variability. Neglect of future considerations, including climate change, was identified by 10%, and 15% emphasized the absence of dynamic modeling for transient conditions. Additional factors included ignoring spatial and temporal variability in parameters (10%) and insufficient model validation and calibration (5%). These findings underscore significant technical and data-related challenges in addressing infrastructure resilience in arid regions (**Appendix C**).

5.3. Hydrologic Processes in Arid Regions

The hydrology of arid regions is characterized by unique processes that differ greatly from those in temperate climates. While arid areas experience similar hydrological functions, such as surface runoff, infiltration, evaporation, and transpiration, their hydrology cannot easily be predicted using data from wetter regions due to different environmental conditions (Goodrich, 2017). Furthermore, flooding is a major natural disaster in these areas, often resulting from intense rainfall. However, forecasting floods in arid regions remains difficult due to the complex hydrological processes and limited availability of data in these dry environments.

The following sections briefly discuss the key parameters and processes that shape the hydrology of arid regions, including precipitation, runoff, evaporation, infiltration, transmission losses, as well as sedimentation, erosion, and stream geomorphic characteristics.

5.3.1. Precipitation and Runoff

In arid regions, precipitation is sparse, highly variable, and often occurs in short, intense bursts. This pattern creates unique challenges, as short rainfall events can result in significant surface runoff due to the low permeability of dry soils, which are often compacted or crusted. Flash floods are common in these environments, despite the general scarcity of rain. In addition, the topography can play a significant role in the rainfall-runoff relationship in arid areas. Understanding the frequency, intensity, and spatial distribution of precipitation events is critical for flood prediction and managing surface water and groundwater resources effectively.

Rainfall-Runoff Relationship

In arid regions, the relationship between rainfall and runoff is highly variable and influenced by factors such as soil type, land cover, topography, and rainfall patterns. Rainfall in these areas is typically intense but brief, leading to limited runoff, as a substantial portion is either absorbed by dry soils or quickly lost through evaporation. However, during periods of prolonged heavy rainfall, significant runoff can occur, contributing to rivers, streams, and groundwater recharge. Land cover also plays a crucial role; areas with sparse vegetation, such as deserts, produce higher runoff rates as there is little vegetation to intercept and absorb rainfall, whereas areas with denser vegetation can slow down runoff by capturing and storing more water. Additionally, topography significantly affects the rainfall-runoff relationship in arid areas. The steep terrain found in regions such as West Texas, with its canyons and arroyos, can funnel water and greatly increase the risk of flash flooding and erosion (Jiang et al., 2015). Approaches for estimating runoff in arid regions are detailed in **Section 5.4**.

Rainfall Pattern

Floods in arid and semi-arid regions have distinct characteristics, primarily due to low annual precipitation, which results in low annual runoff rates and greater interannual variability as precipitation decreases (McMahon, 1979; Rodier, 1985). In North American arid lands, the variability in mean annual runoff is nearly double the continental average, underscoring the challenges in predicting runoff in these areas (McMahon, 1979). Additionally, highly variable precipitation patterns lead to a wide range of annual runoff totals for watersheds of similar sizes, making watershed areas an unreliable indicator of runoff in arid and semi-arid regions (Reid and Frostick, 1997).

Streamflow Variability

Streamflow calculation in arid and semi-arid regions is complex due to limited data availability, and the essential role of riparian ecosystems, which, though occupying small areas, significantly influence hydrological, geomorphic, and ecological processes (Shaw and Cooper, 2008). These regions contain two main types of streams: *ephemeral streams*, which flow briefly after rainfall, and *intermittent streams*, which flow seasonally. With low and variable rainfall, these areas rely heavily on streams to support both hydrological and ecological functions, especially in contrast to surrounding dry upland areas. Desert stream ecosystems involve interactions among various zones, including surface, riparian, hyporheic, and parafluvial areas, which are vital to the ecosystem's integrity (Levick et al., 2008). However, transmission losses and partial storm coverage complicate rainfall-runoff modeling, especially in larger watersheds (Goodrich et al., 1997). Since rivers in these areas experience prolonged dry periods, studies often focus on infrequent flood events, which vary in magnitude depending on storm types (Graf, 1988). The variability and unique flow dynamics in desert streams highlight the need for advanced monitoring to improve classification and understanding of these systems.

Flood Characteristics and Flash Flood

Floods in arid and semi-arid regions vary widely, from fully channeled events to unchanneled sheet floods in foothill areas, depending on landscape and rainfall intensity (Olsen, 1987; Graf, 1988). Channeled floods, including flash floods, single-peak, and multiple-peak events, are common in ephemeral and intermittent streams, occurring suddenly after intense, short-duration precipitation (Graf, 1988). Flash floods, triggered by convective storms, exhibit steep rising and receding limbs on hydrographs, while larger floods from tropical storms or snowmelt show broader hydrograph patterns (Reid, 1994; Dick et al., 1997; Knighton and Nanson, 1997). Identifying flash flood-prone areas relies on geomorphology-based, frequency-based, and flash flood guidance approaches (Gaume et al., 2009; Marchi et al., 2009; Reed et al., 2007; Georgakakos, 2006). Saharia et al. (2017) proposed a geospatial method for detecting flash flood-prone basins using USGS streamflow data, geomorphology, and climatology, introducing a *flashiness* metric that measures a basin's rapid runoff potential. The study revealed high flashiness in central Texas and other U.S. regions prone to flash flooding, influenced by unique geomorphological and climatic conditions.

5.3.2. Evaporation

In arid and semi-arid regions, evaporation significantly influences stormwater runoff estimates, affecting both the volume and timing of runoff events. Intense solar radiation, high temperatures, and low humidity create conditions for rapid evaporation, which reduces the water available for surface flow by causing substantial portions of rainfall to evaporate before contributing to streamflow. Water retained in surface depressions or soil in these landscapes is also prone to quick evaporation, further limiting runoff accumulation.

Evaporation also affects runoff duration and peak flow, especially during the brief, intense rain events typical of arid regions. A large portion of rainfall is either absorbed by the dry soil or evaporates soon after precipitation ends, often resulting in flash floods with steep hydrographs that quickly reach peak discharge and then recede rapidly. This leads to short-lived runoff events with minimal water retention, reducing potential contributions to groundwater recharge or continuous surface flows. Although longer-duration storms may generate more runoff, evaporation still limits sustained flow compared to humid regions.

Accurate stormwater runoff estimation in these environments requires careful consideration of evaporation losses. Models must account for the variability in evaporation rates alongside factors like soil permeability and sparse vegetation. Ignoring evaporation can lead to overestimated runoff predictions, which impacts water resource management, flood risk assessments, and infrastructure planning in arid and semi-arid areas. For example, a critical parameter in the NRCS rainfall-runoff relationship is the initial abstraction, which includes all losses before runoff primarily from evaporation and surface depression storage (Rammal and Berthier, 2020).

5.3.3. Infiltration and Transmission Loss

Infiltration and transmission losses significantly affect stormwater runoff estimates in arid and semi-arid regions, reducing both runoff volume and flow duration. Due to the dry and highly absorbent nature of soils in these areas, a substantial portion of rainfall infiltrates directly into the ground, limiting surface runoff. Transmission losses occur when water flowing over dry streambeds infiltrates permeable soils, especially in intermittent streams that remain dry most of the year. These losses are particularly pronounced in larger watersheds, where extended dry channels can absorb substantial amounts of water, diminishing downstream flow. Therefore, in arid rivers, streamflow is distinct in its spatial and temporal variations. Downstream flow volumes often decrease in arid regions- a phenomenon known as influent flow- where water infiltrates into the unconsolidated alluvium forming the channel boundaries, leading to transmission losses that reduce flow and provide a critical source of groundwater recharge (Babcock and Cushing, 1942; Keppel and Renard, 1962; Sharp and Saxton, 1962; Lane, 1983; Goodrich et al., 1997; Cataldo et al., 2004). This effect is especially noticeable along larger alluvial channels, where many flows fail to traverse the entire channel length, resulting in dry regions in the lower watershed (Keppel and Renard, 1962; Aldridge, 1970). Additionally, rainfall patterns influence these downstream reductions: widespread precipitation events can offset transmission losses as tributary inflows boost downstream flow, while localized rainfall, combined with limited tributary contributions and hydrograph attenuation, can cause substantial downstream reductions in flow volume, flood peak, and flow frequency (Keppel and Renard, 1962; Lane, 1983; Goodrich et al., 1997; Knighton and Nanson, 1997).

5.3.4. Sedimentation, Erosion, and Stream Geomorphic Characteristics

Unlike perennial streams, which have a steady capacity for sediment movement, ephemeral and intermittent streams in arid regions mobilize sediment primarily in response to brief, intense thunderstorms that trigger flash floods. These flash floods, with their rapidly rising hydrographs, carry heavy sediment loads, including coarse materials from uplands and hillslopes. Channels in these regions often contain deep layers of unconsolidated sands and gravels interspersed with resilient shrubs capable of withstanding strong floodwaters. However, these sediments are more easily mobilized than the armored or clay-bedded channels typical of humid regions, resulting in considerable transmission losses as streamflow infiltrates through the deep sediments. This infiltration reduces downstream flow volume and velocity, leading to the deposition of bed load and coarse sediment along the channel.

As mentioned in **Section 5.3.3**, in arid regions, runoff often dissipates within the channel network before reaching the outlet, while transmission losses create a pulsing sediment transport pattern in which material is gradually deposited and stored within the watershed until mobilized by subsequent flows. Ephemeral and intermittent streams can accommodate various sediment sizes, with larger material remaining stationary but available for transport during high flows. These sediment dynamics are essential for biotic communities, influencing moisture availability, root structures, and overall habitat. Changes in sediment deposition patterns can significantly impact vegetation and stream biota, shaping community structure and productivity (Jacobson et al., 2000). Consequently, disturbances such as the removal of headwater channels for development can disrupt these flow and sediment processes, increase downstream erosion rates, alter ecosystem stability, and pose risks to infrastructure.

Rivers in arid and semi-arid regions exhibit significant spatial and temporal variability in fluvial processes, influencing desert landscapes in ways often underappreciated (Tooth, 2000). Compared to perennial streams in humid areas, ephemeral and intermittent streams have unique geomorphic traits, such as high drainage density, braided patterns, low sinuosity, and wide, shallow channels (Graf, 1988; Thornes, 1994; Reid and Frostick, 1997). Their channels tend to widen downstream due to rapid discharge-related depth increases, although transmission losses may limit width in channels without substantial tributary flow (Wolman and Gerson, 1978; Dunkerley, 1992). Stream channels also exhibit an alternating pattern of narrow, incised sections and wide, shallow sections with low-relief channel bars and flat beds, which are often reshaped by receding flows (Reid and Frostick, 1997). These geomorphic patterns underscore the need to understand fluvial processes in these regions for effective water resource management and landscape mitigation strategies.

5.4. Hydrological Approaches for Estimating Stormwater Runoff in Arid Regions

The design of bridges, culverts, stormwater drainage systems, and other hydraulic structures requires accurate runoff estimation. Scientists and practitioners employ a range of methodologies and models to characterize stormwater runoff in arid regions. All hydrological parameters and processes highlighted in **Section 5.3** for the hydrology of arid regions must be considered when selecting the appropriate methodology to calculate hydrological parameters such as peak flow rate, storage, curve number, rainfall losses, runoff coefficient, etc.

The quantity and timing of stormwater runoff are influenced by rainfall characteristics, such as pattern, intensity, and duration, and by the physical features of the drainage basin, including shape, size, slope, and soil type. Various methods exist for estimating rainfall-runoff characteristics. Some methods estimate only peak stormwater runoff (e.g., the Rational Method), while others, such as the NRCS Unit Hydrograph Method, provide complete stormwater hydrographs. The time of concentration (T_c) is a critical parameter in peak flood estimation and flood hydrograph development, indicating how quickly water flows through a watershed in response to rainfall. Inaccuracies in estimating T_c contribute significantly to errors in predicting peak discharge in arid regions (Bondelid et al.,1982), where limited data availability further complicates T_c estimation (Bondelid et al., 1982; Zahraei et al., 2021). Numerous empirical and semi-empirical methods have been developed to estimate T_c for ungauged watersheds. Detailed discussions on methods for estimating peak stormwater runoff, stormwater hydrographs, and T_c are available in the **Appendix B**.

This section summarizes the most widely used methods for estimating peak stormwater runoff, stormwater hydrographs, and time of concentration (T_c) in arid regions. Additionally, it covers approaches for assessing transmission losses in streams within arid regions. The summary is based on findings from the literature review (**Appendix B**) and insights gathered through surveys and follow-up interviews conducted for this project (**Appendix C**).

5.4.1. Stormwater Peak Flow and Hydrograph Estimation in Arid Regions

Common methodologies for estimating stormwater peak flow and hydrographs in arid and semi-arid regions include the infiltration method, overland flow hydrograph, Rational Method, NRCS (SCS) method, and unit hydrograph method. A key aspect of these methods is calculating rainfall loss, which accounts for precipitation lost through evaporation, infiltration, and other processes (Soliman, 2010). The NRCS (SCS) method has been widely used by scientists and practitioners to estimate runoff in arid and semi-arid regions. Its advantage lies in its ability to incorporate soil characteristics, land use, and land cover through the use of curve number (*CN*) values. These values are typically determined using tables provided by USDA-SCS (1985), with runoff depth calculated by assuming an initial abstraction of 20%. However, studies have indicated that for arid regions, with annual rainfall of less than 20 inches, assuming a 20% initial abstraction can lead to an underestimation of stormwater peak flow and volume (Niyazi et al., 2022). To address this, methods such as the Least Squares Method (LSM) and the Asymptotic Fitting Method (AFM) have been utilized to calculate *CN* values for gauged areas in arid and semi-arid regions. Farran and Elfeki (2020a, b) applied the LSM to optimize the initial abstraction value for several arid areas in Saudi Arabia, finding that the most accurate initial abstraction for these regions is 0.01, in contrast to the typical 20% suggested by USDA-SCS (1985). Additionally, *CN* values, which are traditionally derived under normal (humid/semi-humid) conditions, may need adjustment to better reflect the hydro-climatic conditions of arid and semi-arid regions (Alsubeai, 2021).

A review of hydraulic and drainage manuals from five state Departments of Transportation (DOTs) in the arid and semi-arid regions of the U.S. – Arizona, California, New Mexico, Texas, Nevada, and Utah – indicates that the Rational Method, regional regression equations, NRCS (SCS) method, and unit hydrograph method are the most commonly used approaches for estimating peak flow and stormwater hydrographs. This finding aligns with the results of a survey conducted for this project. The survey, distributed to sixteen state DOTs in the arid and semi-arid U.S., revealed that the most frequently employed methods included the NRCS (SCS) Unit Hydrograph, and the Rational Method. A smaller subset of respondents utilized methods such as Statistical Analysis of Stream Gauge Data, Clark Unit Hydrograph, and others.

Among the DOT hydraulic and drainage manuals reviewed, only those from Arizona, California, New Mexico, and Texas include specific provisions for hydrological studies in arid areas. These provisions include:

- *Selection of Runoff Coefficient (C) for the Rational Method:* The Arizona, California, and New Mexico DOTs recommend using the Rational Method to calculate runoff coefficients (C) for desert areas, with guidelines specifically tailored for arid regions smaller than 160 acres.
- *Selection of Runoff Curve Number (CN) for the NRCS (SCS) Method:* The Texas and New Mexico DOTs provide CN values for arid and semi-arid rangelands for use with the NRCS Method.
- *Regional Regression Methods:* Caltrans recommends using newly developed regional regression equations specifically designed for California's desert regions. While these equations for the Northern Basin and Range region yield more accurate results than earlier USGS-developed equations, some uncertainty remains. For ungauged watersheds in this area, developing a rainfall-runoff model may be a preferable approach.
- *Green-Ampt method:* If the HEC-HMS model is used to develop a flow hydrograph, the Arizona DOT recommends specific surface retention loss values for the Green-Ampt

method in desert areas. Additionally, the initial soil moisture should be set to "dry" for such regions.

Additionally, Chapter 11 of the *FHWA Hydraulic Design Series No. 2: Highway Hydrology* (FHWA, 2024) addresses hydrologic analyses specific to arid and semi-arid environments. These analyses cover gaged flow analysis of records with zero flows, the use of regression equations for arid regions, and methods for estimating transmission losses, assessing alluvial fans, and estimating bulked flow. In arid regions, stream records often include years with minimal, infrequent, or no rainfall, resulting in limited or no significant flooding. In contrast, some years experience intense, short-duration rainfalls that produce high peak flows relative to the overall runoff volume. These factors complicate flood magnitude and probability estimation. Therefore, the manual recommends that for arid regions with *existing gauges*, a flow analysis specific to records with zero flows should be conducted. At *ungauged sites*, the manual also recommends using regression equations developed by the USGS for the southwestern United States, which are particularly suitable for arid areas in this region. These equations apply to Arizona, Nevada, Utah, and parts of California, Colorado, Idaho, New Mexico, Oregon, Texas, and Wyoming. These equations are specifically designed for basins smaller than approximately 200 square miles (500 km²). The general form of the equations is typical for the desert southwest, where flow is a function of drainage area and mean annual precipitation (Equation 3.1). These equations are developed for estimating 2-, 5-, 10-, 15-, 50-, and 100-year peak discharges. The values of a_T, b_{1T}, and b_{2T} in **Equation 5.1** corresponding to these return periods are included in **Table 5.1**.

$$Q_T = a_T A^{b_{1T}} P^{b_{2T}} \tag{5.1}$$

where:

Q_T = Peak flow for return period T, ft^3/s (m^3/s)

A = Drainage area, mi^2 (km^2)

P = Mean annual precipitation, inches (mm)

a_T = Constant summarized in **Table 5.1**

b_{1T}, b_{2T} = Exponents summarized in **Table 5.1**

Table 5.1 Regression Equations for Estimating Regional Flood-frequency Relations for Arid and Semi-arid Regions in the Southwestern United States (FHWA, 2024)

Return Period, T (years)	a_T	b_{1T}	b_{2T}	Average Standard Error (%)	Equivalent Record Length (years)
2	0.124	0.845	1.44	59	0.16
5	0.629	0.807	1.12	52	0.62
10	1.43	0.786	0.958	48	1.34
25	3.08	0.768	0.811	46	2.50
50	4.75	0.758	0.732	46	3.37
100	6.78	0.750	0.668	46	4.19

5.4.2. Time of Concentration

The time of concentration (T_c) is crucial for developing accurate flood hydrographs. Errors in T_c estimation can significantly affect peak discharge predictions, particularly in arid regions where limited data complicates accurate calculations. Two major gaps exist in T_c estimation research, especially for arid and semi-arid regions. First, most studies focus on temperate and tropical areas, neglecting the distinct characteristics of arid watersheds, such as unique rainfall patterns, soil moisture, and vegetation. Second, although hydrograph and hyetograph data could provide more accurate T_c estimates, few studies have used actual rainfall-runoff data, mainly due to its scarcity in arid regions.

T_c can be estimated using various methods, including empirical, semi-empirical, and graphical approaches. While empirical and semi-empirical methods are commonly used in ungauged watersheds, relying on characteristics like area, slope, channel length, and roughness, graphical methods, which utilize hyetograph and hydrograph data, are less frequently applied.

Recent studies have evaluated the accuracy of commonly used empirical and semi-empirical methods for estimating T_c in arid and semi-arid regions. These studies compared observed T_c values with estimates from methods such as Kirpich (1940), California Division of Highways (1960), Arizona DOT (1993), Kinematic Wave Formula (Kibler and Aron, 1982), USGS (2000), and Chow (1962). The findings revealed significant variability in T_c estimates (Alamari et al., 2023; Zahraei et al., 2021; Fang et al., 2008). Despite challenges, recent research has shown promise in refining empirical equations through graphical analyses, leading to more accurate estimations of T_c in arid environments.

Graphical methods have been used to evaluate empirical equations for estimating T_c by calculating the time difference between the end of rainfall excess and the inflection point on the hydrograph. Recent studies have employed rainfall-runoff analysis through graphical methods to refine these equations for arid regions, showing improved accuracy (e.g., Zahraei et al., 2021). A study on four small sub-watersheds in Texas, USA, demonstrated that modified methods enhance T_c estimates and improve the NRCS method by selecting the most hydraulically distant watershed point and appropriate channel discharge values. A key finding highlights T_c's sensitivity to DEM resolution when using the NRCS velocity method, emphasizing the need to account for terrain characteristics in 2D flood modeling, particularly in arid regions prone to flash floods (Grimaldi et al., 2012).

The survey, distributed to sixteen state DOTs in the arid and semi-arid U.S., revealed that the most frequently methods employed by DOTs included the Kerby-Kirpich, NRCS, and kinematic wave. It was noted that there are two NRCS methods: watershed lag method and velocity method. Both methods tend to underpredict time of concentration, leading to increased peak design discharges (NRCS, 2010). It was also highlighted that TxDOT-funded research (reflected in the TxDOT Hydraulic Design Manual) demonstrated that Kerby-Kirpich gives the best estimates of time of concentration of several methods evaluated.

For desert regions, the Arizona DOT Highway Drainage Design Manual recommends using the equation proposed by Papadakis and Kazan (1987) to calculate T_c for the Rational Method and the Clark Unit Hydrograph equation for T_c to develop storm hydrographs.

The New Mexico DOT uses the Lag Time equation to calculate T_c instead of the traditionally used Kirpich equation, as it provides more accurate discharge estimates in arid regions. In ongoing projects, the Lag Time equation aligns flow estimates more closely with observed storm events and local flooding history (**Appendix C**).

5.4.3. Transmission Loss

As the initial portion of a stormwater hydrograph enters and moves through a dry stream channel, significant water infiltration into the bed and banks occurs, known as *transmission loss*. These losses vary during a flood event and across regions, influencing hydrograph shape and reducing downstream flow. Key factors affecting transmission loss include channel material, bed and bank surface area, groundwater table position, antecedent moisture, and vegetation. While vegetation and moisture are often overlooked in designs, they may warrant consideration during data analysis. For cases with observed inflow and outflow data, Chapter 19 of the *National Engineering Handbook* (NRCS, 2007) provides a methodology for estimating transmission losses, while Appendix C addresses estimation without observed data. Detailed assumptions and limitations are provided in the chapter.

The Arizona DOT Highway Drainage Manual (ADOT, 2014) notes that transmission loss can significantly reduce runoff volume, particularly in ephemeral watercourses that are initially dry. However, incorporating such losses into a watershed rainfall-runoff model requires ADOT approval, as reliable procedures and data are generally unavailable.

The Austroads Guide to Road Design (Austroads, 2023) highlights that most studies on transmission losses have focused on long-term impacts for water resource planning, with limited applicability to flood estimation. In large arid catchments, transmission losses may be significant, but for most flood design applications, they are typically negligible and covered within lumped models. In urban catchments, transmission losses are less pronounced but can still occur along drainage systems. For extreme floods in arid rural areas, no initial loss should be deducted for Probable Maximum Precipitation (PMP) floods. For design storms, slightly higher loss rates (up to 3 mm/hr) may be appropriate compared to humid regions.

The New Mexico DOT Drainage Design Manual (NMDOT, 2018) states that channel losses generally do not significantly impact peak discharge rates for larger, infrequent flood events but can have measurable effects on floods up to the 5-year event. Transmission losses should not be included in modeling floods of the 10-year event or greater.

5.5. Hydrological Models to Estimate Stormwater Runoff in Arid Regions

Simulating rainfall-runoff in arid and semi-arid regions is challenging due to their unique climatic conditions. Many models used in these areas lack the necessary components for accurate and reliable results because they were originally developed for humid regions with parameters that do not fit arid environments. This issue is evident in widely used models such as Mike 11 Nam, which was designed in Denmark for temperate climates but has been applied in countries such as Turkey (Keskin et al., 2007), Iraq (Kamel, 2008), and Iran (Hafezparast et al., 2013), where climates differ greatly. Similarly, models like Sacramento, Pitman, and IHACRES have been used in the Middle East with minimal adjustments to their parameters.

The survey conducted for this project revealed that, for simulating arid region hydrology, 4.8% of respondents used SWAT, while 19.1% relied on HEC-HMS. Other models mentioned included ICPR, StreamStats, and rain-on-grid modeling with tools like FLO-2D or HEC-RAS 2D. To validate their hydrological models, participants used various methods, with 31% reporting the comparison of hydrographs with field observations or gauge data as the most common approach. This emphasizes the critical role of data in evaluating model accuracy and ensuring reliable predictions in arid regions. However, interviews conducted for this project highlighted that the lack of comprehensive data, such as rainfall measurements, significantly affects hydrological modeling and complicates model calibration in arid zones (**Appendix C**).

CHAPTER 6: SYNTHESIS OF CURRENT STATE OF KNOWLEDGE AND PRACTICE OF HYDROLOGIC APPROACHES TO KARST REGIONS

6.1. Introduction

Karst regions are characterized by soluble rock formations, such as limestone, which can be dissolved by water (Parise et al., 2018), resulting in unique hydrological systems. Physiographic features of karst landscapes include sinkholes, disappearing streams, caves, and karst springs. Springs are points where groundwater emerges at the surface, while disappearing streams drain into sinkholes, flowing underground. During storm events, surface runoff in karst regions typically drains into sinkholes and caves instead of conventional surface waterbodies, such as streams or lakes. Sinkholes are often directly connected to underlying conduit systems, including underground lakes and rivers (White, 2002), which can transport water rapidly and unpredictably. This dynamic flow can result in hydrological extremes, such as flash floods during heavy rainfall and droughts during dry periods. The unpredictable nature of karst environments poses significant challenges for water management and utilization, with both successes and failures documented worldwide (Milanović, 2000).

The distribution of karst landscapes across the globe is extensive and varied, occurring in many countries on different continents. Regions with notable concentrations of karst formations include Southeast Asia, China, Europe, the United States, Mexico, and Central America. In the United States, karst geology accounts for approximately 20% of the land surface. Prominent areas with significant karstic features include Texas, Florida, Kentucky, Missouri, Pennsylvania, and Tennessee. In Texas, approximately 20% of the land area is underlain by karst formations, although not all of these areas exhibit visible surface karst features. The state's karst regions are primarily located in central, south-central, and southwest Texas, including the Edwards Plateau and the Balcones Escarpment. The Edwards Plateau consists of rugged hills and deep canyons that span much of central Texas, while the Balcones Escarpment is a steep slope running southward from the Dallas-Fort Worth area (**Appendix B**).

Engineering challenges in karst environments are highly variable and include destructive processes such as massive turbulent flows, rapid erosion of unconsolidated deposits, and the propagation of hydraulic pressure over long distances. These dynamics often lead to significant pressure fluctuations, resulting in phenomena such as water-hammer and air-hammer effects (Milanović, 2014). Construction activities in karst regions, such as building dams, reservoirs, housing developments, tunnels, roads, and railways, are inherently complex and delicate. These activities carry significant risks, which can sometimes lead to catastrophic consequences, including the loss of human lives. The unique characteristics of karst environments make them particularly vulnerable to a range of geohazards, including sinkholes, slope movements, and floods. These natural risks are further exacerbated by anthropogenic hazards such as pollution events and land-use changes (De Waele et al., 2010; Parise, 2015). Addressing these challenges requires a nuanced understanding of the hydrological and geological processes at play.

This chapter explores the hydrological challenges of karst regions and synthesizes current knowledge of key hydrologic processes and modeling approaches, as reviewed in **Appendix B** (Task 2). Furthermore, it integrates findings from surveys and interviews conducted as part of **Appendix C** (Task 3) of this report, providing a comprehensive overview of the complexities and risks associated with karst hydrology and engineering interventions. This effort was conducted under Task 4, titled "*Synthesis of Current State of Knowledge and Practice*".

6.2. Hydrology of Karst Regions and Challenges for Transportation Infrastructure

Karst terrains pose unique challenges for transportation infrastructure due to their soluble rock formations, which create underground channels, caverns, and unpredictable water movement. These features lead to hazards such as sinkholes, subsidence, and erosion, threatening roadways and bridges. Sinkholes result from collapsing caverns or dissolved rock, while subsidence occurs as underground water movement destabilizes the ground, especially under heavy traffic. The unpredictable hydrology in karst areas complicates infrastructure design, as factors such as rainfall and land use cause significant variability.

Karst hydrology also complicates rainfall-runoff analysis, as water rapidly enters and exits underground systems, causing sudden flash floods. Predicting peak flows is challenging due to the heterogeneous and interconnected nature of karst aquifers. Water losses are irregular, with streams disappearing and reappearing unpredictably, complicating hydrological modeling. Additionally, data collection in these complex terrains is difficult, hindering accurate modeling and effective flood mitigation planning.

Hydrological processes in karst regions involve internal drainage, the subterranean diversion of surface streams, storage within shallow epikarst zones, rapid conduit flow, and discharge through sizable springs. The unpredictable water connections in these areas vary over time due to the numerous and diverse surface and subsurface karst formations. The hydrology of karst regions is therefore highly complex and dynamic, resulting from interactions between surface and subsurface features. Apart from hydrological complexities, karst regions are particularly susceptible to a range of geohazards, including sinkholes, slope movements, and floods, due to their distinctive characteristics (Stevanović and Milanović, 2015).

Despite these challenges, past and current research in karst regions primarily focuses on geotechnical and structural issues related to karstic features, groundwater movement and quality, water availability, and interactions between groundwater flow, erosion, and subsurface processes. Few studies address the hydrological challenges of flood forecasting in karst landscapes. Moreover, the review of national and international hydraulic design manuals and standards indicates limited guidance on hydrological studies in these areas. Only the Departments of

Transportation in Florida, Kentucky, Pennsylvania, Virginia, and West Virginia provide some guidance on the hydrology of karst regions, each to varying degrees. The Federal Highway Administration's *Highway Hydrology: Evolving Methods, Tools, and Data – HEC-19* (FHWA, 2023) outlines various methods for estimating runoff in karst regions (**Appendix B**).

A survey conducted for this project reveals that, while current federal or state guidelines offer some direction for infrastructure design in karst areas, more than half of the participants believe these standards require modification or revision. The lack of appropriate design standards for karst regions has been linked to transportation infrastructure damage. Specifically, 25% of respondents identified limited or low-quality data collection as a primary cause. Additionally, 16.7% attributed the damage to uncertain hydrology or hydraulic methodologies. Issues with models' ability to account for karst physical properties were noted by 8.3%, while another 8.3% cited insufficient model validation and calibration, and 8.3% mentioned uncertain geological investigations. Furthermore, 33.3% of respondents identified other unspecified reasons for the damage (**Appendix C**).

6.3. Hydrologic Processes in Karst Regions

The hydrology of karst zones is inherently complex, shaped by the interplay of geological, hydrological, and environmental factors. Unlike typical drainage areas with soil pores and limited infiltration rates, karstic fissures and shafts facilitate rapid and substantial water flow, resulting in shorter response times and higher peak flood magnitudes. Conversely, water retention in voids and aquifers within karst formations can delay water movement and help reduce peak flood levels (Dai et al., 2022). Despite advancements in modeling techniques, the complexity of karst hydrology poses significant challenges for accurate flood prediction. These challenges arise from inherent uncertainties and inaccuracies in modeling such dynamic systems (Jiang et al., 2020).

The following sections provide an overview of key parameters and processes influencing karst hydrology, such as precipitation, runoff, contributing drainage areas, drainage mechanisms, and recharge in karst systems.

6.3.1. Precipitation and Runoff

The transformation of rainfall into runoff in karst watersheds differs significantly from non-karst areas due to the unique geomorphology and hydrogeology of karst terrains. Rainfall in karst regions can either flow over the surface or infiltrate through porous rock, cracks, and sinkholes, replenishing underground reservoirs and river networks. These features enable high infiltration rates, which reduce surface runoff and alter peak flow patterns. Unlike watersheds with mineral soils, where river flow is predominantly surface-based, karst systems are dominated by subterranean flow, with spatiotemporal variations influenced by the geological characteristics of the terrain (Wahyullah et al., 2023).

Understanding the rainfall-runoff relationship is crucial for effective water resource management in karst regions and for estimating peak floods when designing engineering projects, such as transportation infrastructure. In karst terrain, initial abstraction and rainfall losses are higher due to the significant storage capacity of karst features, leading to increased runoff effects during smaller, frequent storms compared to larger ones. Urban development in karst regions, including the use of impermeable surfaces and the filling of sinkholes, can reduce rainfall losses but may increase post-development runoff volumes and peak flows.

6.3.2. Karstic Zone and Contributing Drainage Areas

In karst landscapes, the watershed area often differs from the contributing drainage area due to unique karst behaviors, such as redirecting surface flow into groundwater or alternate streams. Estimating the total drainage area requires accounting for regions where surface flow terminates or bypasses outlets due to karst features (WVDOT, 2007). Traditional groundwater basin mapping is less effective for karst aquifers, making the term *karst drainage basin* more appropriate, which encompasses both surface and subsurface drainage contributing to a conduit network. Karst basins are categorized into overflow allogenic basins, underflow allogenic basins, and local autogenic basins, based on conduit capacity and recharge sources (Taylor and Greene, 2008). Dye-tracer tests are the most effective method for estimating karst basin areas, identifying flow connections, and defining basin boundaries by tracing groundwater flow (White, 1993; Ray, 2001; Taylor and Greene, 2008). These tests also help map contributing areas of springs and streams, estimate water fluxes, and assess water budgets, particularly in areas with misbehaved drainage (White and Schmidt, 1966; Ray, 2001).

The survey conducted for this project revealed a variety of methods are employed to identify karstic zones. Field observations are utilized by 16.5% of respondents, while geological mapping is used by 13.9%. Both topographic maps and LIDAR are employed by 10.1% of respondents each. Borehole logging is utilized by 7.6%, and historical hydrological analysis is used by 6.3%. Other methods utilized include geophysical methods, karst inventories and databases, and remote sensing, Drones/UAVs, and hydrochemical analysis (**Appendix C**).

6.3.3. Drainage Mechanisms

Karst terrains are characterized by diverse recharge sources that vary in water residence time and contribute differently to the conduit network (Taylor and Greene, 2008). Recharge can be classified as concentrated or diffuse and as autogenic or allogenic, depending on whether it originates from precipitation on karstic terrain or nonkarstic areas (Gunn, 1983). These distinctions influence the distribution and interconnection of conduits, as well as the variability in spring discharge and water chemistry (Ford and Williams, 1989). Water in karst landscapes follows several pathways, such as overland flow, through flow, subcutaneous flow, shaft flow, vadose flow, and vadose seepage, which highlight the complex interactions between surface and subsurface processes. Sinking or losing streams, originating as gaining streams in nonkarstic regions, provide a significant source of concentrated allogenic recharge (Taylor and Greene, 2008), while surface runoff collected in sinkhole depressions is a major source of concentrated autogenic recharge, draining through swallets or percolating through soil (Gunn, 1983). Diffuse allogenic recharge typically comes from water draining down vadose zone shafts, often where karstic rocks are capped by non-soluble materials like sandstone.

6.3.4. Recharge

A karst aquifer is an open hydrologic system defined by surface and subsurface flows, with boundaries determined by catchment limits and conduit geometry (Ford and Williams, 1989). The aquifer's hydrogeology is influenced by conduit structure, which bypasses surface drainage by providing subsurface pathways with lower hydraulic gradients (White, 1999). Conduits create a distinct form of permeability, interconnected with intergranular pores and fractures, contributing to the heterogeneity of karst aquifers. This heterogeneity leads to scale-dependent, temporally variable hydraulic properties, distinguishing karst aquifers from granular and fractured-rock aquifers (Taylor and Greene, 2008). Recharge assessment challenges arise due to the limited understanding of water flux processes, incomplete characterization of hydrogeological frameworks, and measurement uncertainties, particularly in complex karst settings (Taylor and Greene, 2008). Several methods for estimating recharge, primarily developed for detrital aquifers, include the soil water balance, visual balance, and chloride mass balance methods (Guardiola-Albert et al., 2015), though the understanding of these processes is still incomplete, prompting the development of new modeling techniques (Hughes et al., 2008; Sanford, 2002; Andreo et al., 2008).

6.4. Hydrological Approaches for Estimating Stormwater Runoff in Karst Regions

Estimating stormwater runoff in karstic watersheds presents unique challenges due to the complex interactions between surface and subsurface water flow within karst landscapes. Unlike conventional watersheds, karstic watersheds are characterized by highly permeable bedrock and conduit networks that facilitate the rapid infiltration and transmission of water into the groundwater system. As such, estimating runoff in these areas requires approaches that account for both the surface and subsurface hydrological processes.

Several methods and approaches have been used by scientists and practitioners to estimate stormwater runoff in watersheds with karst landscapes. These methods include traditional hydrological approaches (such as the Rational Method and NRCS Curve Number Method), infiltration-excess and saturation-excess models, dye-tracer techniques, groundwater modeling, integrated surface and subsurface models (e.g., MODFLOW), and remote sensing coupled with GIS-based approaches. Some of these methods are discussed in detail in the **Appendix C**.

This section summarizes the most widely used methods for estimating peak stormwater runoff, stormwater hydrographs, time of concentration (T_c), and soil moisture loss in karst regions. The summary is based on findings from the literature review (**Appendix B**) and insights gathered through surveys and follow-up interviews conducted for this project (**Appendix C**).

6.4.1. Stormwater Peak Flow and Hydrograph Estimation in Karst Regions

Traditional methods for estimating stormwater runoff, such as the Rational Method and the NRSC Curve Number method, are commonly used in non-karstic areas. These methods rely on parameters such as rainfall intensity, land cover, and soil type to estimate surface runoff. However, their application in karstic watersheds can be problematic because these methods assume limited subsurface flow and do not account for the rapid infiltration that is typical in karst systems. Therefore, modifications to these methods are often required to adjust for the high permeability of karst aquifers, which can significantly reduce surface runoff.

A modification to the curve number (*CN*) in the NRCS-CN method is proposed to account for the effect of karstic zone infiltration in peak flow calculations (Savvidou et al., 2018). **Equation 5.1** shows the modified *CN* for karst regions, incorporating factors such as permeability, land use, and watershed drainage capacity:

$$CN = 10 + (9 \times i_{\text{perm}}) + (6 \times i_{\text{veg}}) + (3 \times i_{\text{slope}}) \qquad (5.1)$$

where i_{perm} refers to permeability (soil, geology), i_{veg} represents the land cover and land use (vegetation), and i_{slope} is the drainage capacity (slope, building structure). The modified NRCS-CN method has been widely applied in Mediterranean karst regions for estimating surface runoff, peak discharge, and flash flooding, demonstrating promising performance in peak discharge estimation and flood risk assessment (e.g., Kastridis and Stathis, 2020). The parameters required to estimate modified *CN* values based on permeability, land cover, and drainage capacity of karstic zones (Savvidou et al., 2018) are presented in **Tables B.15** to **B.17** of **Appendix B**.

A review of hydraulic and drainage manuals from thirteen state Departments of Transportation (DOTs) in karst regions across the U.S., including Alabama, Florida, Indiana, Kentucky, Minnesota, Missouri, New Mexico, Pennsylvania, Tennessee, Texas, Utah, Virginia, and West Virginia, reveals that the most commonly used methods for estimating peak flow and stormwater hydrographs are the Rational Method, regional regression equations, NRCS (SCS) method, and the unit hydrograph method (**Appendix B**). This finding aligns with the results of a survey conducted for this project, which was distributed to sixteen state DOTs in karst regions of the U.S. The survey found that the most frequently mentioned methods were the Rational Method (16.7%), NRCS Methods (49.9%, including TR-55, NRCS Curve Number, and NRCS Dimensionless Hydrograph), and statistical analysis of stream gauge data (10.4%) (**Appendix C**).

Among these DOTs, the Florida, Kentucky, Pennsylvania, Virginia, and West Virginia Departments of Transportation provide varying levels of guidance on karst hydrology, with specific recommendations regarding the inclusion or exclusion of areas containing sinkholes or depressions (non-contributing areas) when determining the total drainage area. Additionally, the Pennsylvania Department of Transportation suggests applying a reduction factor to mitigate runoff in karst topography. This reduction factor, ranging from 0.84 to 0.86, is recommended for estimating peak flow values from $Q_{2.33}$ to Q_{500} (PennDOT, 2010).

Federal Highway Administration - *Highway Hydrology* (FHWA, 2023) recommends various methods for estimating runoff in karst regions including:

- Adjust the runoff coefficient in a rainfall-runoff method,
- Use an NRCS Type I rainfall distribution within a Type II area,
- Adjust the curve number values or peak rate factors using the TR-20 method,
- Apply regression equations developed for karst terrain, and
- Apply empirical reduction factors.

The first three methods employ standard hydrological tools that can be applied across various conditions.

Regression Equations

The U.S. Geological Service (USGS) has developed a regression model (Equation 6.2) applicable to drainage basins primarily underlain by limestone or dolomite bedrock in West Virginia and Pennsylvania:

$$Q = cA^{x} \tag{6.2}$$

where Q is runoff (ft^3/s), c and x are constant values depending on AEP (Annual Exceedance Probability), and A is the drainage area (mi^2). The drainage area in Equation 4.1 refers to the part of the watershed that ultimately flows to the outlet. However, the total drainage area should exclude regions that drain to streams ending or disappearing in karst features, as well as any surface areas where drainage is not directed to the outlet but instead passes through the underlying karst formations (WVDOT, 2007). **Table 6.1** provides *c* and *x* values for different AEPs. It is important to note that the methodology outlined in **Equation 6.2** depends on empirical data specific to each region. Since empirical coefficients can vary significantly by location and hydrologic data in karst regions are often limited, practitioners should consider the evolving technologies and inherent limitations of this method when applying it to their analyses.

Table 6.1 Values of *c* and *x* in the USGS Regression Equation (Adopted from Flippo, 1977)

Annual Exceedance Probability (AEP)	Return Period (yr)	c	x	Standard Error
0.5	2	23.5	0.880	-
0.1	10	39.8	0.933	26
0.04	25	49.1	0.952	27
0.02	50	56.0	0.970	31
0.01	100	64.4	0.979	33

Empirical Reduction Factors

This stormwater runoff estimation approach for karst areas employs a peak flow method multiplied by an empirical reduction factor, referred to as the *karst loss coefficient*. These coefficients, detailed in **Table 6.2**, vary based on the percentage of the watershed area underlain by karst, accounting for abstractions conveyed to the bedrock. It is important to emphasize that designers are encouraged to validate and refine these coefficients through field observations and measurements whenever feasible, ensuring greater accuracy in runoff estimation.

Table 6.2 Karst loss coefficients (Adopted from FHWA, 2023)

Karts Area (%)	Annual Exceedance Probability (Return Period (yr))				
	0.5 (2)	0.1 (10)	0.04 (25)	0.02 (50)	0.01 (100)
100	0.33	0.43	0.44	0.46	0.50
90	0.35	0.46	0.48	0.5	0.56
80	0.38	0.51	0.53	0.56	0.62
70	0.47	0.58	0.60	0.62	0.68
60	0.55	0.66	0.67	0.70	0.74
50	0.64	0.73	0.74	0.76	0.80
40	0.73	0.80	0.81	0.82	0.85
30	0.82	0.86	0.87	0.87	0.89
20	0.91	0.92	0.92	0.92	0.93
10	1.00	0.98	0.98	0.98	0.97
0	1.00	1.00	1.00	1.00	1.00

6.4.2. Time of Concentration

In karst regions, estimating time of concentration (T_c) poses unique challenges due to the complex interplay between surface and subsurface flow paths, variable infiltration rates, and the presence of conduits and sinkholes that alter traditional hydrological assumptions. Errors in T_c estimation can lead to significant inaccuracies in peak discharge predictions and, consequently, flood risk assessments. In karst landscapes, surface flow may rapidly transition into subsurface systems through sinkholes, swallets, or fractures, effectively shortening the flow path and reducing T_c. Conversely, subsurface conduits with longer flow paths or delayed storage effects may increase T_c. These dynamics complicate the application of standard empirical equations or traditional T_c estimation methods, such as those based on slope, land use, and flow path length, which are commonly used in non-karstic regions.

The survey, conducted for this project, revealed that the most frequently cited approaches include the NRCS Method (29.2%), Kerby-Kirpich Method (20.8%), and the Kinematic Wave Equation (16.7%). A smaller percentage (4.2%) reported using the Area-Based Method, while 12.5% of respondents mentioned employing other techniques.

The time of concentration (T_c) calculated using these methods must be adjusted to account for the unique hydrological characteristics of karst landscapes. Alternatively, integrating surface and subsurface flow analyses is highly recommended when determining T_c in karst regions to account for the unique hydrological complexities of these landscapes. This may include:

- *Modified Empirical Formulas:* Adapting T_c estimation equations to account for karst-specific features, such as variable infiltration rates and subsurface connectivity.
- *Field Observations*: Using dye-tracing studies or monitoring flow velocity in karst conduits to better understand the actual travel times.
- *Hydrologic Modeling*: Employing coupled surface-subsurface models, such as MODFLOW or SWAT with karst modules, to simulate flow dynamics and determine Tc more accurately.
- *GIS-Based Approaches:* Analyzing high-resolution topographic and geologic data to identify karst features and refine flow path delineations.

6.4.3. Soil Moisture Loss

In conventional methods, soil moisture conditions significantly influence peak runoff estimation by determining infiltration rates and surface runoff generation. However, in karstic environments, characterized by rapid infiltration into subsurface conduits, soil moisture loss rates differ substantially from those observed in non-karstic areas. To address these differences, adaptations to soil moisture calculation methods have been proposed to better capture the rapid drainage and subsurface flow dynamics unique to karst systems. A comprehensive review of these soil moisture loss adjustment approaches for karst regions is presented in **Section B.5.3.1.1** of **Appendix B**.

The survey conducted as part of this project identified the most commonly used methodologies for calculating loss in karst zones: the NRCS Curve Number Loss Model (23.5%), Green-Ampt Loss Model (17.6%), and the Texas Initial and Constant-Rate Loss Model (11.8%).

While these methods provide valuable insights for estimating runoff loss in karstic watersheds, several challenges persist. The intrinsic heterogeneity of karst aquifers, including variations in permeability and conduit connectivity, continues to pose significant difficulties for accurate loss estimation.

6.5. Hydrological Models to Estimate Stormwater Runoff in Karst Regions

Hydrological modeling in karst regions requires a refined approach to effectively capture the intricate interplay between surface and subsurface water systems. Models suitable for karst hydrology include physically based models, such as the Soil and Water Assessment Tool (SWAT), which simulate water movement based on detailed physical parameters; conceptual models that simplify system dynamics while focusing on key processes; empirical models relying on statistical relationships derived from observed data; and hybrid models, like the Gridded Surface Subsurface

Hydrologic Analysis (GSSHA), which combine elements of multiple modeling approaches to address complex hydrological interactions.

A survey conducted for this project highlighted significant gaps in the application of these models to karst systems. Among the models listed in the questionnaire- SWAT, KarstMod, SUFI-2, MIKE SHE, KINEROS, EPIC, CAVE, and MODKARST- none were reported as having been used by the participants for simulating karst hydrology. Instead, alternative tools such as HydroCAD and EDYS were occasionally mentioned for karst applications, though these are not specifically designed for the unique challenges posed by karst environments.

Despite considerable progress in computational tools and advanced data collection techniques like LiDAR and tracer studies, the adoption of specialized karst models remains limited. Practitioners face several barriers to implementation, including the scarcity of site-specific data critical for model calibration and validation, the high technical expertise required to operate these complex tools, and the inherent challenges in accurately simulating the dynamic and highly variable conditions of karst systems. These factors underscore the need for targeted training, enhanced data availability, and the development of user-friendly modeling platforms tailored to the needs of karst hydrology researchers and practitioners.

CHAPTER 7: SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK TO DEVELOP DESIGN GUIDANCE AND STANDARDS

7.1. Summary

This report provides a comprehensive synthesis of current knowledge and best practices related to hydrological studies within three distinct landscapes: playa lakes, arid regions, and karst terrains. The research reveals significant challenges in accurately predicting rainfall-runoff and effectively managing flood risk in these diverse environments, underscoring the need for region-specific approaches and further investigation. The inherent complexities of the hydrological processes within each region demand a refined understanding that extends beyond traditional methodologies. This synthesis is based on the findings from **Appendix B** (*Literature Review*) and **Appendix C** (*Survey and Interviews*) and is summarized as follows.

7.1.1. Playa Lakes

Playa lakes, while vital components of the regional ecosystem and crucial for groundwater recharge, present considerable challenges for transportation infrastructure. Their shallow, seasonally flooded nature, coupled with highly variable and often unpredictable hydrological patterns, leads to frequent disruptions. Flash flooding, significant erosion, and reduced visibility due to dust and water accumulation on roadways necessitate road closures, resulting in transportation delays and safety risks. Traditional hydrological methods, including the Rational Method and the NRCS Curve Number method, often prove inadequate due to their failure to fully account for the complexities of playa lake systems, specifically the influence of infiltration, evaporation, sediment mobilization, and the dynamic interplay between surface and subsurface water flows. The scarcity of detailed, long-term hydrological data further exacerbates the difficulties in accurate modeling and reliable flood estimation. This necessitates the development of region-specific hydrological models and methodologies that capture these unique characteristics for improved infrastructure design and risk assessment.

7.1.2. Arid Regions

Arid and semi-arid regions face unique challenges stemming from a combination of low and highly variable rainfall, intense evaporation, and limited water resources. These conditions frequently result in extreme hydrological events, with flash floods occurring suddenly and causing significant damage to transportation infrastructure, including road washouts, bridge collapses, and damage to other critical infrastructure. Soil characteristics, such as high salinity and susceptibility to erosion, exacerbate the impact of these events. Traditional hydrological models, such as NRCS Curve Number method, which often rely on data and parameters from more humid climates, frequently underperform in arid environments, leading to inaccurate flood predictions and potentially inadequate infrastructure design. To improve predictive accuracy, it is crucial to develop and employ models that explicitly account for the unique hydrological processes in these regions, particularly the substantial variations in evapotranspiration, infiltration rates, and transmission losses. Furthermore, comprehensive data collection efforts are essential, especially considering the sparse and often unreliable data currently available.

7.1.3. Karst Terrains

Karst terrains present perhaps the most significant hydrological challenges for infrastructure development due to their complex and unpredictable subsurface water flow systems. The highly permeable bedrock and extensive network of underground conduits and caverns result in rapid drainage and highly variable water flow patterns. This unique hydrology leads to sudden flash floods, sinkhole formation, and land subsidence, all of which pose serious threats to transportation infrastructure. Standard hydrological modeling techniques and empirical relationships, such as those outlined in FHWA publications, are often site-specific and fail to account for the full complexity of subterranean interactions. This limitation frequently results in inaccurate predictions of peak flows and flood extents. Improved models must incorporate the intricate connections between surface and subsurface systems, including the dynamics of conduit flow, recharge processes, and the heterogeneous nature of karst aquifers. Similarly, comprehensive investigation, advanced data collection techniques (such as dye tracing studies and LiDAR), and a more complete understanding of the geological controls are essential for enhancing the reliability of hydrological models and, ultimately, for improving infrastructure design in karst regions.

7.2. Recommendations for Future Work to Develop Design Guidance and Standards

This study underscores the critical need for advanced and customized approaches to water resource management and infrastructure design in complex environments such as playa lakes, arid regions, and karstic landscapes. These areas present unique hydrological and geological challenges that necessitate further studies, the refinement of modeling techniques, and improved data collection. Addressing significant gaps in data availability and accuracy is fundamental to enhancing hydrological predictions and promoting sustainable development in these environments. To achieve this, the following recommendations aim to guide the development of standards and practices for hydrologic design in these challenging terrains, facilitating the creation of reliable transportation infrastructure.

- *Form a Multidisciplinary Research Team*

  Assemble a team of experts that includes engineers and scientists from academia, TxDOT, and other state and federal agencies engaged in projects in these environments. This collaboration ensures that diverse expertise is brought together to address the multifaceted challenges associated with hydrologic design in karst, playas, and arid terrains.

- *Disseminate Findings and Identify Gaps*

  Organize workshops, webinars, or in-person meetings to present the findings of this study to the research team and relevant stakeholders. Use these platforms to identify gaps in existing guidance and standards. Collaboratively develop a roadmap for creating comprehensive and practical hydrologic design standards tailored to the needs of karst terrains, playa lakes, and arid regions.

- *Develop a Repository of Previous Studies*

  Compile existing studies, reports, and models from departments of transportation (DOTs), consulting firms, and other sources. This repository will serve as a centralized knowledge base, providing valuable insights into past practices and challenges and facilitating access to critical information for researchers and practitioners.

- *Evaluate the Efficacy of Existing Methods*

  Conduct a systematic review and assessment of current hydrological methods, modeling approaches, and tools. Focus on evaluating their accuracy in predicting flood characteristics and hydrological behaviors specific to karst terrains, playa lakes, and arid regions. This evaluation will identify strengths and limitations in existing approaches.

- *Refine and Select Reliable Models*

  Identify the most reliable methods and models based on their performance in real-world applications. Propose modifications or enhancements to improve their accuracy and applicability in the targeted environments. This step ensures the development of tools that are better suited to the unique challenges of these regions.

- *Prepare Comprehensive Guidelines*

  Develop a summary report that consolidates the findings, evaluations, and recommendations. This document will serve as a guideline for practitioners, offering practical insights into predicting flood characteristics and designing resilient infrastructure in karst terrains, playa lakes, and arid regions.

These actions will lay the groundwork for the development of robust, data-informed guidance and standards, fostering sustainable hydrological practices and infrastructure development in these environmentally sensitive and dynamic regions.

To develop guidelines that practitioners can use for hydrological studies and design in these unique environments, the project team recommends initiating follow-up project(s) by TxDOT to implement these recommendations.

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