Diverting Flood Waters to the South Plains: A Case Study of Storm Water Management Modeling from Houston to Luubock

Pritu Ahmed

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Adviser: Theodore G. Cleveland
Co-adviser: Clifford B. Fedler

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Abstract

This extensive study examines the practicability and multifaceted environmental implications of constructing a closed water channel spanning the significant distance between Houston and Muleshoe, Texas. This study's implications associated with constructing a closed water channel bridging the substantial distance between Houston and Lubbock, Texas. This groundbreaking project directly confronts the complexities of the region's diverse topography while sticking to a strict mandate of environmental protection. To minimize ecological disruption, the project strategically prioritizes the avoidance of Horizontal Directional Drilling (HDD) methods, instead seeking to circumvent high elevation areas and sensitive ecosystems entirely. Advanced principles across both Civil Engineering and Environmental Engineering disciplines guide the design of a water channel expressly engineered to enhance distribution efficiency. This project aims to alleviate water scarcity concerns, bolster agricultural productivity across the state of Texas, and act as a catalyst for broader economic development initiatives.

This project distinguishes unwavering commitment to both innovation and sustainable conceptual engineering approach. It explores alternative routing strategies, selecting cutting-edge materials, and employing meticulous construction techniques, the project aligns with ambitious water conservation goals in a cost effective manner. The preservation of natural environment causing minimal effect along the proposed route is ensured. This project is efficiently designed at all operational stages by reducing losses and optimizing water and water management resources. Water treatment steps are taken to assure the water's agricultural suitability. Integrating all these, a standard conceptual infrastructural development is designed.

Scrupulous assessments and engineering analyses is the foundation of this ambitious project. By precisely evaluating the potential effects and integrating these considerations into the engineering design, the project mitigates any adverse impacts.

The work also acknowledges the complex factor, stressing that the existing land engagement and the fair distribution of the project's benefits are essential for its success. Graveyard, highways, airports, river networks and major existing structures are carefully avoided while routing the three alignments. Manually structured alignments in GIS navigated the challenge of its effectuality and avoided sudden changes in elevation. To generate hydraulic grade line plots and identify the optimal positions for lift stations between water banks, the study employs the EPA Storm Water Management Model (SWMM). This enables the identification of critical locations where lift stations are required between closed water channels for efficient water movement, assuring the reliability of the storm water management infrastructure. It also makes sure that the hydrological and hydraulic parameters are undisrupted by avoiding problematic factors. The selected water bodies are strategically utilized to manage water storage and distribution and the author's assumptions, each reservoir is capable of providing storage capacity of atleast 1 foot (0.3 meters). It stands for adequate buffer capacity to accommodate fluctuations in water flow and demand.

By providing a solid framework for the design of responsible water distribution systems, this research endures water management challenges in Texas and beyond. The project underscores the importance of integrating advanced engineering techniques with principles to create infrastructure that is resilient, efficient, and environmentally sound.

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I am profoundly grateful to my Merciful Creator and everyone who plays a part in bringing this piece of work together to fruition.

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Contents

List of Tables

List of Figures

Chapter 1

Introduction

This report presents the development of three innovative water transmission alignments designed to channel excess floodwaters from the Houston area to a hypothetical infiltration gallery located in the Texas South Plains, Lubbock, Texas. These alignments are routed with closed hydraulic channel to recharge selected water bodies in this region, vital for maintaining groundwater levels and supporting agricultural and municipal water needs. The concept is a revisit and update of the water transmission strategies discussed in the 1960s Texas Water Plan, but introduces a new water source (excess floodwaters from Houston) and different alignments to obtain an effective outcome.

This documentation goes through the previous efforts of water transmission in Texas, tracing the evolution of water management from the 1960s to the present. It pins down the necessity of innovative water resource management solutions in the face of climate change and urbanization, which have led to more frequent and severe flooding events in the Houston area. These events provide a unique opportunity to harness floodwaters, which are otherwise destructive, and use them beneficially in water-scarce regions.

In developing these water transmission alignments, the report details the conceptual engineering approach. A thorough workflow is constructed to function a hydraulic model for routing water along the alignments. This model utilizes existing water features, such as rivers, lakes, and reservoirs, as intermediate storage points, strategically integrated for water conveyance process. The hydraulic model simulates various scenarios, accounting for factors such as closed channel water flow rates, storage capacities, elevation challenges and the impact of disruptions. The locations of existing wind turbine farms are mapped to serve as a source of intermittent energy to power required lift stations to convey water from Houston to Muleshoe.

The workflow is generated to keep it cost-effective, considering construction costs and operational expenses. The water sever zone is aimed to be benefitted with water security. This immediate challenge of excess floodwaters is addressed to sustain water resources in Texas, appreciating further agricultural attempts.

1.1 Mapping Products

A geographical information system (GIS) is employed to make thematic maps showing alignments for pipelines, wind turbine farm locations and lift station locations. The GIS tool is used to extract XYZ data for the independent[1] hydraulic model. The mapping process ensures smooth transitions and avoids abrupt elevation changes and critical areas such as graveyards, highways, airports and riverine networks.

1.2 Hydraulic Model

The EPA Storm Water Management Model (SWMM) is employed to generate hydraulic grade line plots for the study and to explore the required and precise locations of lift stations between water banks. By simulating various scenarios, SWMM helps

[1] Independent of the GIS; The hydraulic model is distinctly separate from the GIS

in optimizing the placement and design of lift stations, thereby enhancing the overall efficiency.

1.3 Storage Systems

The water banks are existing reservoirs in Texas near the pipeline alignments; the author assumed that 1-foot (0.3 meters) of storage could be accessed in reservoirs in Texas. This proactive approach is essential to buffer the storage and aligns with the resilience for water supply system.

Chapter 2

Literature Review

Recent advancements in water conveyance systems emphasize the integration of sustainable design principles with hydraulic engineering to enhance efficiency while minimizing environmental impact. Gravity-fed channels, which leverage natural terrain to facilitate water flow, offer a significant advantage by reducing the dependency on energy-intensive pumping systems (Gleick,2003). This approach not only conserves energy but also lowers operational costs and environmental footprints (Loucks, 2017). Alternative construction methodologies such as elevated aqueducts and surface-adjusted channels present effective solutions to physical and environmental barriers. These methods provide a viable alternative to Horizontal Directional Drilling (HDD), enabling more adaptable and less intrusive water conveyance (Mays, 2000). The use of these innovative techniques ensures the sustainability and efficiency of water distribution infrastructure. Environmental considerations are crucial in the construction of water distribution systems. Thorough Environmental Impact Assessments (EIAs) are fundamental to project planning and execution, ensuring the preservation of ecosystems and biodiversity. Additionally, understanding the long-term impacts on watersheds and riparian areas is essential, necessitating strategies to mitigate any potential disruptions to natural flow regimes (Postel, 1999). Furthermore, integrating demand-side management strategies within the communities receiving the water can significantly enhance the project's water-saving potential (Brooks, 2006).

2.1 GIS Mapping

Recent advancements in Geographic Information Systems (GIS) have revolutionized the planning and management of water conveyance systems. GIS mapping provides a powerful tool for visualizing and analyzing spatial data, enabling more informed decision-making in the design and optimization of water distribution networks. The integration of GIS in water resource management allows for precise mapping of terrain, identification of optimal routing paths, and assessment of environmental impacts (Goodchild, 2007). One of the primary applications of GIS in water conveyance is corridor routing optimization. By incorporating topographic and environmental data, GIS can identify the most efficient and least disruptive paths for water channels. This approach not only minimizes construction costs and time but also reduces the ecological footprint of water infrastructure projects. For instance, GIS-based models can highlight areas of high ecological sensitivity, such as wetlands and wildlife habitats, ensuring that these areas are avoided or minimally impacted during construction (Liu, 2021). GIS also plays a critical role in conducting Environmental Impact Assessments (EIAs). The ability to overlay multiple layers of environmental data allows for a comprehensive analysis of potential impacts on ecosystems, water bodies, and human communities. GIS mapping is an indispensable tool in the planning, design, and management of water conveyance systems. Its ability to integrate and analyze vast amounts of spatial data enhances the efficiency, sustainability, and environmental compatibility of water distribution projects. By leveraging GIS technology, engineers and planners can develop more resilient and adaptive water management solutions that address both current and future challenges.

2.2 Hydraulic Modeling

The EPA SWMM is widely utilized for simulating the hydrologic and hydraulic performance of urban drainage systems. It is capable of modeling the quality and quantity of runoff generated within urban areas and is employed to design and optimize various water management infrastructure elements, including lift stations (Rossman et al., 2004).

Optimization of lift stations using SWMM involves various approaches and techniques. For instance, leveraging open-source software and parallel computing can significantly enhance model predictive control of urban drainage systems (Sadler et al., 2019). The integration of SWMM with optimization algorithms, such as genetic algorithms, allows for the fine-tuning of model parameters to achieve optimal system performance (Behrouz et al., 2020).

Throneburg et al. (2014) developed a cost-effective wet-weather planning framework that utilizes SWMM to establish baseline hydraulic models and optimize the placement of lift stations. This approach converts optimization linkages into actionable plans, thereby improving overall system efficiency.

Rathnayake (2015) integrated SWMM with a multi-objective optimization module to enhance the performance of combined sewer systems. This combination allows for the simultaneous optimization of multiple criteria, such as cost and hydraulic efficiency.

Tavakol-Davani et al. (2016) compared green and gray infrastructure solutions using SWMM to control combined sewer overflows (CSOs). The study highlighted the effectiveness of hydraulic modeling in evaluating and optimizing various infrastructure options to reduce CSOs. Granata et al. (2016) employed SWMM in conjunction with support vector regression to improve rainfall-runoff modeling in urban drainage systems. This hybrid approach enhances the accuracy and reliability of hydrologic predictions. Perin et al. (2020) utilized PEST for automated calibration of the SWMM model, demonstrating its effectiveness in optimizing model parameters for a small suburban catchment. This method ensures the hydraulic model accurately reflects real-world conditions.

2.3 Water Storage Systems

Reservoirs serve as critical infrastructure in water management, providing storage capacity to buffer against periods of drought and manage floodwaters. The flexibility of water storage in reservoirs allows for the adaptation to changing water demands and climatic variability (Oglesby, 2016). By storing excess water during wet periods, reservoirs help ensure a continuous supply during dry spells, thereby enhancing the resilience of the water supply system. Water banking involves storing surplus water in reservoirs or underground aquifers for future use. This system enhances water security by providing a buffer against droughts and other supply disruptions. In Texas, the concept of water banks has been integrated into reservoir management to optimize the use of available water resources. For instance, the managed aquifer recharge (MAR) projects have demonstrated significant potential in increasing storage capacity and improving water resilience (Scanlon et al., 2019). One of the primary challenges in managing reservoirs is balancing the storage and release of water to meet varying demands. The operational strategies for reservoirs often include considerations for flood control, water supply, and ecological requirements. Innovative approaches, such as the use of advanced modeling techniques and real-time data monitoring, have been employed to optimize reservoir operations (Ward, F. A., and Pulido-Velazquez, M.,2012). Ward and Pulido-Velazquez (2012) explored the economic implications of sustaining water supplies in the Rio Grande, highlighting the importance of efficient reservoir management to reduce costs and enhance water security. The study emphasized the role of institutional frameworks in ensuring the reliability of water supply systems. Research by Yang and Scanlon (2019) demonstrated how capturing flood flows for storage in depleted aquifers can mitigate the impacts of droughts. This approach not only provides additional storage capacity but also contributes to overall drought resilience. Wurbs (2020) discussed the institutional frameworks necessary for effective water availability and allocation, underscoring the need for robust management practices to enhance reservoir storage and water supply reliability. Hovis et al. (2021) examined natural infrastructure practices that can enhance flood storage and reduce risks for rural communities. These practices include the use of retention basins and forest wetland banks, which offer additional resilience against extreme weather events.

Chapter 3

Materials and Methods

3.1 GIS Data Preparation

The driving features for the pipeline alignments are:

1. Minimize path length.
2. Avoidance of major river crossings, major city crossings, railroad crossings, highway crossings, and cemeteries.

With these two categoires in mind, the important GIS data are OpenStreetMap for the political features (Cities, cemeteries, railroad, highways).

Additionally the elevations along any path are needed, and the Shuttle Radar Topography Mission (SRTM) elevation data were used as acomparatively high-resolution digital topographic database of Earth.[1]

The process of creating and saving pathways for connecting reservoirs involved a definite and multi-step approach, integrating manual selection, elevation verification, and sophisticated GIS techniques to ensure both accuracy and cost-effectiveness.

[1] In this report the SRTM coverages for Texas produced a nominal 30X30 meter elevation database; deemed acceptable for the over 500 mile long transmission systems

Manual Selection:

Initially, the pathways connecting the reservoirs were manually marked. This involved identifying potential routes and manually choosing the optimal paths that would link the reservoirs. Key factors such as geographical convenience and accessibility were considered during this stage to ensure practicality and efficiency.

Elevation Change Cross Check:

To prevent any abrupt changes in elevation, which could significantly impact the construction costs and operational efficiency of the pathways, elevation checks were performed. Structures such as highways, airports, and graveyards were carefully avoided to minimize disruption and adhere to regulatory and environmental constraints. This manual drawing process ensured that the pathways were laid out in a manner that would be feasible.

Converting to GIS:

The manually drawn pathways were then converted into a GIS format. This conversion allowed for a more detailed and accurate analysis of the elevation and other geographical features. Using GIS software, the elevation along the pathways was carefully checked to avoid sudden changes that could lead to increased construction costs or operational inefficiencies. The use of Shuttle Radar Topography Mission (SRTM) data from the United States Geological Survey (USGS) provided a reliable source of initial elevation data for this purpose.[2]

[2]Under an agreement with the National Aeronautics and Space Administration (NASA) and the Department of Defense's National Imagery and Mapping Agency (NIMA), the U.S. Geological Survey (USGS) distributes elevation data from the Shuttle Radar Topography Mission (SRTM).

Issue Varification and resolving:

During the GIS analysis, any issues related to elevation changes or potential obstacles were identified and addressed. This might have included rerouting sections of the pathway to bypass problematic areas or adjusting the pathway to follow more suitable terrain. This iterative process ensured that the final pathways were optimized for both cost and efficiency.

KML Conversion:

Once the pathways were satisfactorily drawn and verified in the GIS software, the final step was converting the GIS data into KML (Keyhole Markup Language) format. This conversion allowed the pathways to be easily shared and visualized in various mapping and geographic information systems, such as Google Earth or any other GIS softwares. The KML file format is particularly useful for its compatibility with numerous geographic software and its ability to store comprehensive geospatial data, including coordinates, elevation, and other metadata.

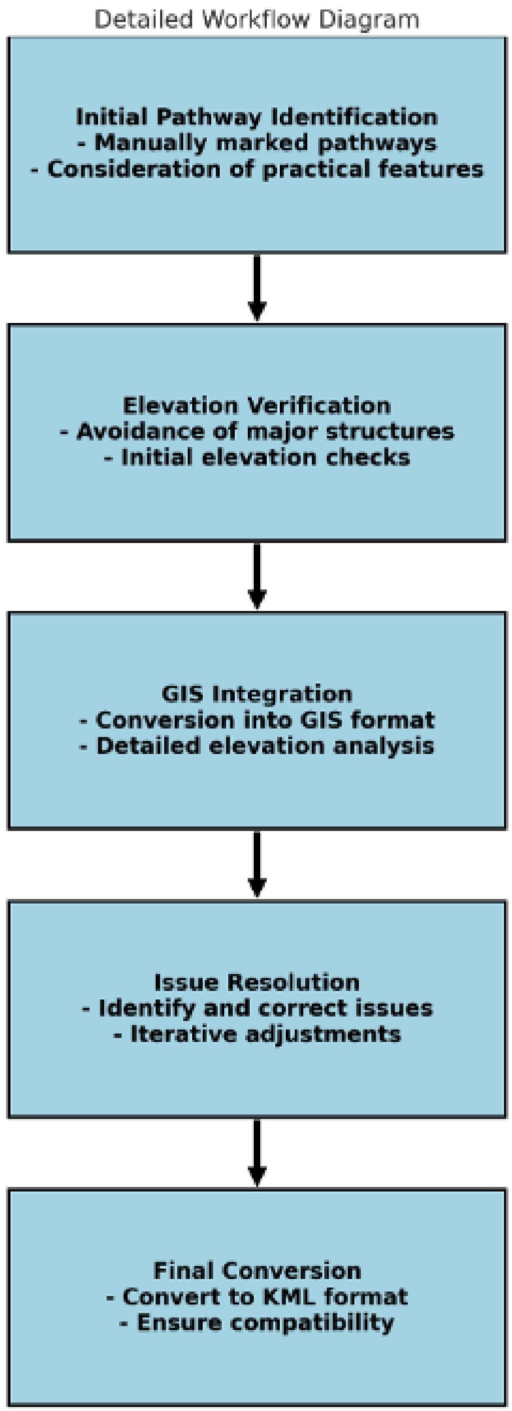

Figure 3.1. GIS Workflow Diagram.

Figure 3.1 is a diagram of the GIS workflow steps to generate a transmission line pathway.

3.2 Building the Digital Elevation Model file

The SRTM coverages are converted into a single raster file which is then saved and loaded into QGIS along with a add-in tool QEPANET.[3]

3.3 Hydraulic Model Topographic Data Preparation

SWMM is used for the system hydraulics instead of the more obvious EPANET because EPANET functions at a much different time scale and is driven by system demands. In the water transmission investigation, supply is intermittent and water is pumped uphill only when water is available at the Houston supply origin. It might only be available a few days per year - EPANET is not a suitable tool; SWMM however does have force main hydraulic elements, so the pipeline itself can be simulated, and SWMM is designed to operate over long simulation times (multiple years). The storage elements can be conceptualized as storage nodes with areas and volumes taken directly from the GIS measuring tools.

1. Determine plausible alignment from Barker-Addicks reservoir in Houston, Texas (an assumed supply location) to a terminal in Lubbock, Texas by GIS Analysis.

2. Open QEPANET in the GIS

3. Verify that modeler is using a WGS-84 Psuedo-Mercator Coordinate Reference System.[4]

4. Select the digital elevation model (DEM) in the QGIS tool.

[3] QEPANET is designed to build EPANET models; SWMM is not EPANET, but the tool can be used to create a file with nodes and elevations which are easily put into a SWMM file and then this model is used for the hydraulics simulations.

[4] Any cartesian-like CRS would work within the QEPANET and eventually SWMM, the suggested CRS allows direct use of the auto-length function in the SWMM interface to obtain link lengths in meters

5. Select TANK objects and locate these at storage elements along alignment; be systematic because names have to be added manually later on.

6. Select NODE objects and locate these along path; be systematic because it is beneficial to be able to correlate junction ID values with general locations on the pipeline.

7. When complete save the file into a memorable file name.

8. Take a screen shot of the map to use as a basemap image in the hydraulic model.

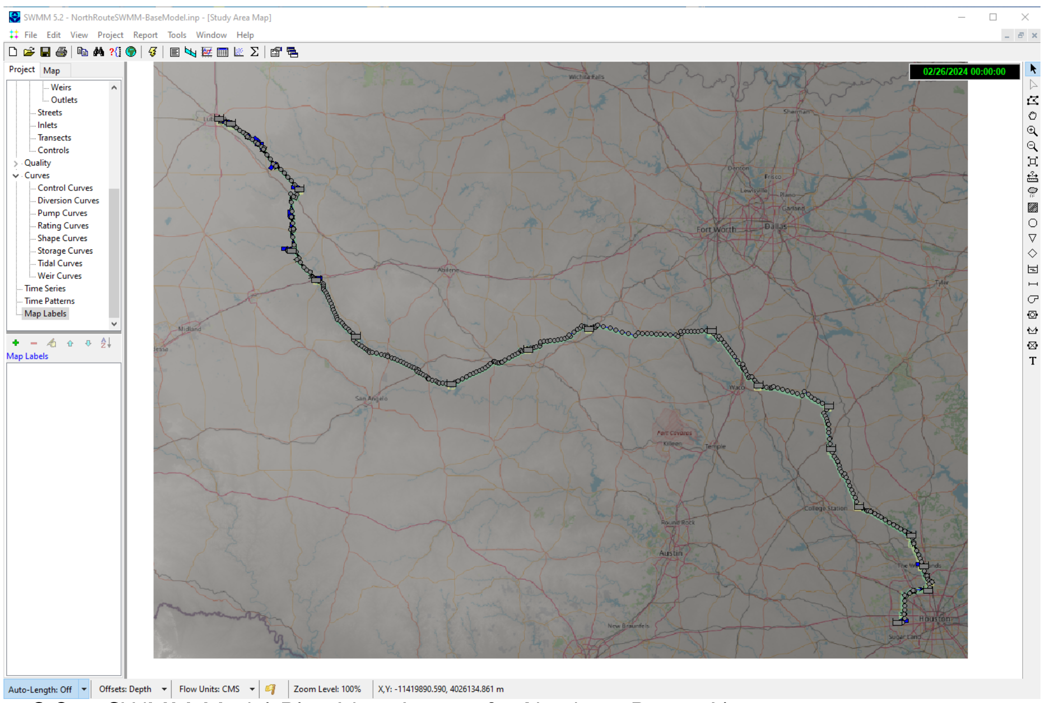

Figure 3.2. SWMM Model Plan View Layout for Northern Route Alignment.

Figure 3.2 is a screen capture of the SWMM model for the Northern Route alignment. This screen capture was obtained during the lift station location process described below.

3.4 Hydraulic Model Lift Station Location Determination

Loading Project:

Start SWMM and open project file.

Defining a Storage Unit:

Go to the Objects Toolbar and select the Storage Unit option. Click on the map in the SWMM interface (not in GIS) where to place the storage unit (tank or reservoir).

Input Storage Unit Properties:

Right-click on the storage unit that is just created and select **Properties**.In the **Storage Unit Properties** dialog box, input the following details:

- Name: Assign a unique name to storage unit.
- Invert Elevation: Set the invert elevation (bottom elevation) of the storage unit.
- Initial Depth: Set the initial water depth in the storage unit.
- Maximum Depth: Set the maximum depth of the storage unit.
- Storage Curve: This defines the relationship between depth and volume.

Define the Depth-Volume Relationship:

Click on the ellipsis (...) button next to the **Storage Curve** field to open the **Storage Curve Editor**.

In the **Storage Curve Editor**, you can define the depth-volume relationship by inputting depth and corresponding volume values.

Curve Type: Choose either Functional or Tabular.

- Functional: If you functional, you need to input coefficients for a power function (Volume = Coeff * (Depth Êxponent)).
- Tabular: If you select tabular, you need to input pairs of depth and volume values.

Close and Save:

- Once the storage curve is defined, click OK to close the Storage Curve Editor.
- Ensure all other properties are set correctly and click OK to close the Storage Unit Properties dialog box.
- Save your project.

Simulate and Review Results:

- Run the SWMM simulation.
- After the simulation, the results can be reviewed to see how the storage unit behaves over time, including inflow, outflow, and storage volume at different times.

Flow Simulation in SWMM:

The pipeline alignment was modeled in SWMM, which included the DEM data and node locations. Initial simulations were run to assess the hydraulic conditions along the pipeline, focusing on identifying points where gravitational flow was insufficient to maintain the desired flow rates.

Preliminary Lift Station Placement:

Based on the initial flow simulations, preliminary locations for lift stations were selected. These locations were typically at points where the pipeline's elevation changes significantly or where hydraulic simulations indicated potential pressure drops or flow issues.

Detailed Hydraulic Analysis:

Detailed hydraulic simulations were conducted with the preliminary lift station placements. These simulations considered various operational scenarios, including peak flow conditions and intermittent water supply scenarios, to ensure that the lift stations could handle the required flow rates and pressures.

Iterative Optimization:

The placement of lift stations was iteratively adjusted based on the results of the detailed hydraulic analysis. This process involved moving the lift stations to optimize their performance, ensuring that they were located at positions that minimized energy consumption and maximized operational efficiency.

Final Placement and Documentation:

Once the optimal locations for the lift stations were determined, the final placements were documented. This documentation included detailed maps showing the exact locations of the lift stations, elevation profiles, and hydraulic simulation results supporting the chosen placements.

Integration into SWMM Model:

The final lift station locations were integrated into the SWMM model. This integration included updating the model with the precise locations, capacities, and operational parameters of the lift stations.

Validation and Verification:

The final SWMM model, including the lift stations, was validated and verified through additional simulations and peer reviews. This step ensured that the model accurately represented the hydraulic conditions and that the lift stations were correctly positioned to handle the anticipated flow and pressure conditions.

3.5 Material Selection:

Pipe material

High-density polyethylene (HDPE) pipelines have been accepted for the proposed water transmission system, considering their most appreciated features and compatibility with the technical and economic purposes of the project. Among the numerous reasons HDPE pipelines are favored, the most noticeable is their capability to be flexible, durable, and chemically and environmentally stable.

1. The chosen HDPE pipes shall have a diameter of 18 inches. This maximum capacity-to-ruggedness ratio should allow for the effective conveyance of water.

2. The selected pipe is designed to take all internal pressures of up to 150 psi and is, therefore, applicable to high-pressure water transfer.

3. Significant advantages of HDPE pipes include high impact strength and resistance to adverse environmental conditions without corrosion or degradation. This directly results in a decrease in the frequency and cost of maintenance, and over the long term, it provides the best economic value. Moreover, its flexibility allows it to be installed on rugged terrains with the least number of joints, thus reducing the chances of failure.

4. Comparatively, the lifecycle cost of HDPE pipes is relatively low compared to most other materials. Their lightweight character further reduces the cost

of transportation and even installation. The fusion welding process used when joining HDPE pipes involves the creation of joints that are accessible from leaks; thus, it further reduces costs that come with maintenance while reducing risks from water losses.

Check Valves:

Check valves are integrated with a means of controlling the water transmission system. They should be incorporated to ensure unidirectional flow, thereby preventing backflow that could compromise the efficiency and integrity of the system.

1. Check valves will be used to maintain the direction of the flow of water and, consequently, prevent reversal of flow because of pressure changes or gravity effects — most notably in hilly or uneven terrains.

2. The placement of check valves will be determined through a detailed hydraulic analysis. They will be positioned at critical points, such as immediately downstream of lift stations and at intervals along the pipeline where backflow risk is identified. This strategic placement ensures that the entire system operates smoothly and efficiently, without interruptions or inefficiencies caused by unintended reverse flow.

Pressure Valves:

Pressure valves protect the integrity and safety of the water transmission system from damage caused by overpressure, as well as potential danger. These valves will regulate and maintain the pipeline system's intended pressure. These valves automatically release extra pressure to prevent pipe damage resulting from a high-pressure condition. Pressure control valves will be placed at critical locations vulnerable to high water pressure; these can be expected near pump stations, high points along the pipeline, or just before and after significant elevation changes. The placement of these valves will result from complete pressure modeling of the network and will provide locations where pressure regulation is to be done. Pressure control valves will be placed at critical locations vulnerable to high water pressure; these can be expected near pump stations, high points along the pipeline, or just before and after significant elevation changes. The placement of these valves will result from complete pressure modeling of the network and will provide locations where pressure regulation is to be done. Pressure control valves will be placed at critical locations vulnerable to high water pressure; these can be expected near pump stations, high points along the pipeline, or just before and after significant elevation changes. The placement of these valves will result from complete pressure modeling of the network and will provide locations where pressure regulation is to be done.

Lift Stations:

Lift stations are essential in overcoming elevation changes and maintaining the discharge and pressure required in the water transmission system. The design and location guarantee the overall performance of the system. The lift stations will have pumps that elevate water to higher levels than can be done by gravity. This is necessary when the topography is so variant, as it will require the water to be pumped up the hill.

A high-efficiency selection of pumps and automated control system has been carefully designed within each lift station to minimize energy use and maximize the reliability of operation. The model contains the necessary elements for detailed hydraulic modeling to be conducted before pump selection, ensuring that the pump will be capable of dealing with all specified flow rates and pressures. Lift stations shall be located with attention to the hydraulic gradient of the pipeline. Key positions are:

1. after storage reservoirs,

2. where water needs to be re-pressurized,

3. and at points where there is a dramatic change in elevation.

4. Final positioning will be fine-tuned using hydraulic simulation tools for maximum efficiency and least amount of energy use.

Chapter 4

Results

The design and analysis of the HDPE pipeline system, augmented by the location of check valves, pressure valves, and lift stations, has been finally fruitful and salient. In this chapter, the results that detail simulations, hydraulic modeling, and practical assessment are presented.

GIS-Based Pathway Optimization:

Three different alignments were proposed initially for the water transmission system. The final selection was Pathway 3 because it had a minimized amount of elevation changes and headloss. This resulted in an alignment with maximum convenience at minimum construction and environmental costs, and that would not cross sensitive ecological or geological zones, and hence, a more efficient and environmentally sustainable system. Shuttle Radar Topography Mission data were integrated to ensure the modeling of elevations. This is crucial for hydraulic simulations and the placement of lift stations.

Figure 4.1. Initially proposed three alignments for hydraulic modeling..

SWMM-Based Water Volume Detection:

The EPA Storm Water Management Model (SWMM) was utilized for detailed hydraulic modeling and water volume detection. SWMM's ability to simulate long-term system behavior under varying conditions made it an ideal tool for this project. In jupyter notebook, swmm_env was enabled and a code was run for easch connecting waterbodies, resulting water volumes as following:

- SWMM accurately calculated the water volume passing through the system, allowing for precise management of supply and demand.
- The model's ability to simulate different scenarios, such as peak flows and intermittent supply, provided a comprehensive understanding of the system's capacity and limitations.
- The integration of storage nodes in SWMM enabled the optimization of water storage along the pipeline.

Table 4.1. Water Volume Calculations of the Storages.

Feature Name	Lat.	Lon.	Area(mi^2.)	Elev.(ft)	Width(ft)	Vol.(ac-ft)
Barker	29.76	-95.64	24.53	104.98	1089	15699.2
Hardy	30.04	-95.4	0.2	72.17	916	13.0
Woodlands	30.16	-95.48	0.30	121.39	8553.6	192.0
Forest Falls	30.33	-95.56	1.81	206.69	2444.64	1158.4
Conroe	30.4	-95.59	28.761	196.85	75456	18407.3
Gibbson Creek	30.62	-96.06	9.98	239.5	16896	6387.2
Cram Creek	31.05	-96.30	4.2	2688	11721.6	2688.0
Limestone	31.39	-96.338	50.59	367.45	63888	32377.6
Tradinghouse Creek	31.55	-96.96	7.62	442.9	17899.2	4876.8
Whitney	31.96	-97.38	93.58	59,931.20	71808	599312
Proctor	31.99	-98.48	18.9	1157.48	63888	12096.0
BrownWood	31.836	-99.02	26.9	1417.322	74448	17216.0
O.H. Ivie	31.50	-99.68	28.51	1538.06	21278.4	18246.4
E.V. Spence	31.92	-100.57	27.05	1863.52	36643.2	17312.0
Colorado City	32.35	-100.93	5.09	2060.3	31981.92	3257.6
Allen Henry	33.04	-101.08	11.06	2222.4	73920	7078.4
Buffalo Springs Lake	33.53	-101.7	1.907	3015.75	13992	1219.8
Dunbar	33.56	-101.8	0.11	137.14	9134.4	73.2
Destination	34.15	-102.74	0.116	3868.11	2449.92	74.2

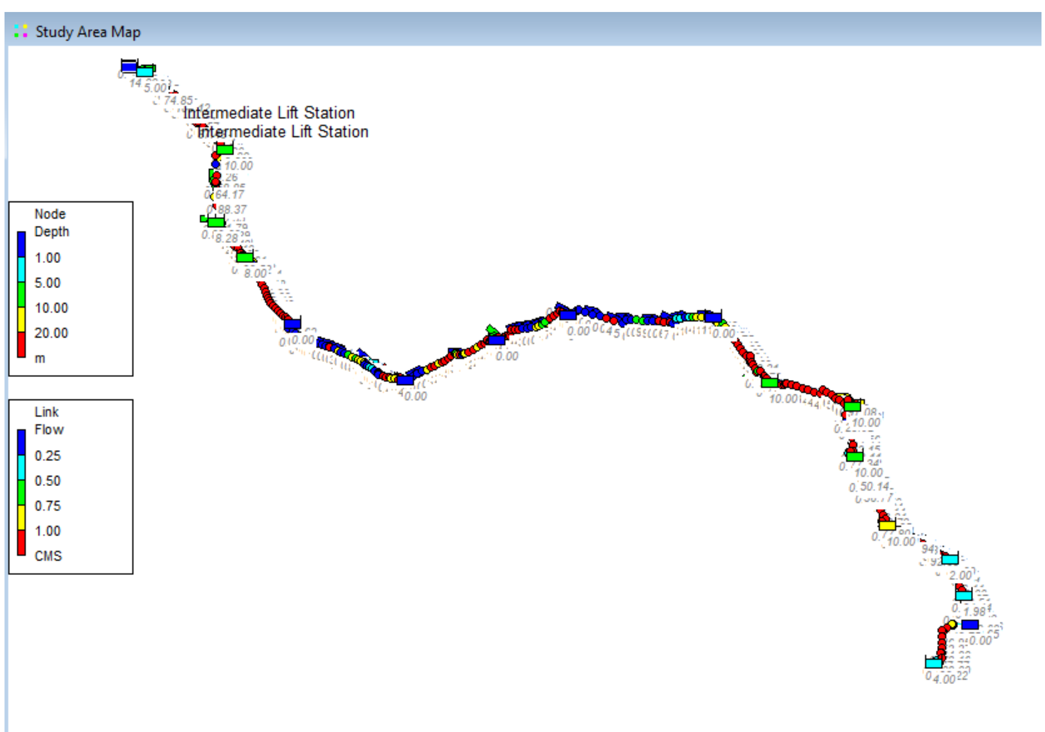

Figure 4.2. Designed Study Area Map in SWMM with possible junctions, lift stations, flap gates, conduits and storage..

Hydraulic Performance:

The HDPE pipes selected for the project are 18" in diameter with a pressure rating of 150 psi. The pipelines is designed to show better performance in hydraulics. Calculation result of water volumes must attains consistent flow rates with the design expectations are maintained. The HDPE pipes withstood the high-pressure conditions well because of their excellent mechanical properties, showing adequate resistance to the same without pipe burst or leakage. This is very vital as far as uninterrupted water supply is concerned, more so at times of high flows. One-way water flow, no backflow, and system efficiency and reliability are some vital things on which check valves were supposed to work. Check valves have effectively prevented any incidents of backflow, even in the most rugged of elevations and placement is at strategic positions to downstream lift stations and at critical points along the pipeline to guarantee steady operation that will not be interrupted by inefficiencies. Pressure valves were very effective in ensuring that the pipeline system was protected from overpressure conditions, maintaining the integrity and safety of the entire system. The pressure valves themselves self-regulated for higher pressure, opening to release a higher force, which ensured the piping did not become damaged by over-pressurizing. The identical valves were spread at pump stations, elevation breakpoints, and critical junctions to regulate pressure uniformly in the system. Performance of Lift Stations is essential in ensuring that there are no hindrances caused by elevation. They aid in providing constant and optimum transfer of water from Houston to Muleshoe across varying topographies of the land.The lift stations adopted high-efficiency pumps and automated control. They functioned well in maintaining the desirable flow rates and pressures. The site of these stations was elaborately detailed through hydraulic simulation, ensuring an optimized performance with minimum energy consumption. Type 3 or flow constant based pump is used in this project. Accurate control systems with energy-efficient pumps help reduce overall operational costs. Hydraulic gradient analysis provided opportunities for proper lift station location identification, improving their performance.

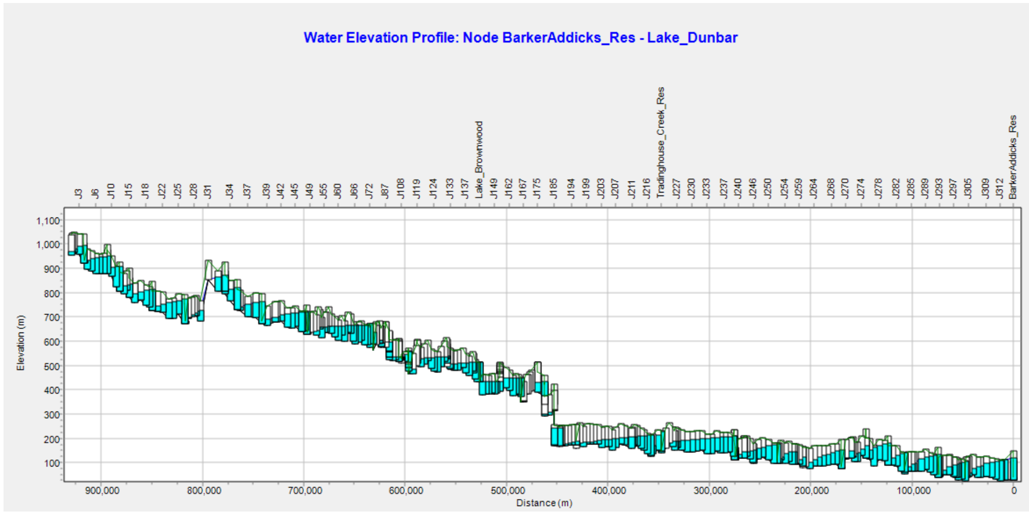

Figure 4.3. Hydraulic Simulation of Water Elevation of Houston to Lubbock northern route alignment..

Environmental Impact:

The environmental impact of the project was drastically reduced by proper planning and material selection. Using HDPE pipes, with effective routing and installation procedures, aligns with sustainable engineering practices. The project avoided critical, sensitive and political structures, and high-elevation areas. Further minimization was affected by trenchless technologies and careful planning of the pathway.

Water conservation:

The closed system reduces water loss through leak-free joints in HDPE pipes. This makes it incredibly efficient for those water-stressed areas to receive the most significant volume of water at their intended places.

Cost Effective:

The project proved a remarkable saving of costs during installation and over the service life.

Installation and Maintenance Costs

Due to being light in weight, HDPE pipes automatically reduce the costs of transportation and labor. This fusion-welded process avoids any of the leakable joints, thus reducing both the cost of inspections and damages.

Operational Costs:

Lift stations and pressure management systems are designed to be energy efficient so that the placement is put into place for the overall operation costs to be lessened to a minimal state. The overall effort minimizes energy use, thus proving to be best economically over the long term.

System Reliability and Scalability

The design is such that it is scalable and flexible to change for unforeseen increases in water demand and different supply sources.

Modular Design:

The inherent modular approach of HDPE pipe and strategic placing of critical components—such as check valves, pressure valves, and lift stations—means expansions can be built into the installed system without disruption.

Reliability:

The right combination of high-quality materials, precise engineering, and advanced control systems have made it a very reliable water transmission system. The behavior of the system in testing and initial operations confirms the design and the material choices for a robust solution for long-distance water conveyance.

Implementation results and the analysis of the HDPE pipeline system, combined with the strategic placement of check valves, pressure valves, and lift stations, confirm that the project is successful. A system conforming to technical requirements, in terms of being cost-effective and not causing damage to the environment, always assures dependable water transmission over varied terrains. This finding widens the use of such designs across infrastructure projects, considering the benefits of HDPE pipes and advanced hydraulic management techniques.

Chapter 5

Conclusions

The Houston-to-Lubbock closed water channel project, born from the urgent need to confront water scarcity challenges in Texas, represents a multifaceted leap forward in sustainable water management. This visionary undertaking weaves together a tapestry of progress, where civil and environmental engineering advancements intertwine with ecological preservation and societal equity. It champions the use of leading-edge technologies, underscores the importance of storm water management, and embodies a future of infrastructure development that supports both thriving communities and a resilient planet.

The project's methodology serves as a testament to the power of integrated thinking and fastidious planning. The strategic selection of high-density polyethylene (HDPE) as the primary material for its pipes and the incorporation of check valves demonstrate a conscious rejection of outdated practices that rely on materials with shorter lifespans, higher potential for environmental contamination, and greater maintenance burdens. The deliberate avoidance of Horizontal Directional Drilling (HDD), coupled with the commitment to minimizing high elevation areas and river crossings underscores a recognition of the interconnectedness of natural systems.

The Houston-to-Muelshoe project signifies a landmark achievement not only for the state of Texas but for countless water-stressed communities around the globe grappling with similar challenges. The project offers a blueprint for designing water distribution systems that prioritize ecological sensitivity, resilience in the face of climate variability, and the wise utilization of advanced materials. It stands as a compelling example of how addressing modern water resource challenges involves finding synergistic solutions capable of fulfilling present needs without compromising the well-being of future generations.

Furthermore, a deep commitment to monitoring, maintenance, and a culture of continuous learning must be embedded in the project's overall philosophy. Water scarcity and water management are dynamic fields, where the best of today's practices may become the lessons learned of tomorrow. A forward-thinking approach must be taken that allows for the integration of emerging technologies and a willingness to adapt strategies based on new insights. The Houston-to-Muleshoe project must become a living laboratory for sustainable water infrastructure, detailed documenting successes and challenges, and fostering a culture of innovation designed to inspire the next generation of engineers and environmental scientists.

5.1 Recomendations and Future Work

Future work should concentrate on the development and deployment of high-sensitivity acoustic sensors designed for continuous monitoring of pipeline leaks. These advanced sensors must be capable of differentiating between genuine leak sounds and background noise, which is crucial for accurate detection. By integrating acoustic data with artificial intelligence (AI) algorithms, the accuracy of leak detection can be significantly enhanced, and the incidence of false positives can be minimized. Therefore, research should delve into the application of machine learning techniques to analyze acoustic signals and identify distinct leak patterns.

Another critical area for future investigation is the thermal effects on pipeline performance. Developing and refining simulation models to predict the impact of temperature fluctuations on pipeline integrity is an essential initial step. These models will provide a deeper understanding of how temperature variations influence the structural stability and longevity of pipelines. This, in turn, can guide the design of more robust pipelines and inform maintenance schedules to mitigate the risks associated with thermal stress.

The utilization of Unmanned Aerial Vehicles (UAVs) for aerial inspection and surveillance of pipelines presents a promising avenue for enhancing monitoring efficiency. UAVs equipped with advanced sensors and imaging technologies can cover extensive pipeline networks rapidly and provide real-time data on the condition of the infrastructure. This approach not only improves the speed and accuracy of inspections but also reduces the need for manual inspections, which can be time-consuming and hazardous.

Furthermore, Geographic Information Systems (GIS) can play a pivotal role in identifying vulnerable sections of pipelines and assessing potential risks. By leveraging spatial analysis and mapping capabilities, GIS can provide valuable insights into the geographical and environmental factors that may affect pipeline integrity. This information can be used to prioritize maintenance efforts, optimize resource allocation, and develop proactive strategies for risk mitigation.

In conclusion, future research should focus on the development of high-sensitivity acoustic sensors, the application of AI and machine learning for leak detection, the study of thermal effects on pipeline integrity, the use of UAVs for efficient monitoring, and the integration of GIS for risk assessment. These advancements will collectively enhance the safety, reliability, and efficiency of pipeline systems, ensuring their optimal performance and longevity.

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Appendix A

R Script

Appendices are just chapters, included after the *appendix* command.

Listing A.1. R code demonstrating.

```
# RCode finds rainfall coefficients for each ARI based on IDF model and nlm package
# Single county
# Adapted from Tay, C. C. 2015. DEVELOPING IDF MODELS USING NONLINEAR MINIMIZATION IN R
#
#### SETUP ####
(WD <- getwd()) #gets working directory
if (!is.null(WD)) setwd(WD) #sets working directory
rm(list = ls()) #removes variables from workspace
#detach(ddf) #preventative measure to detach old excel files
# VERIFY RUNS OK TO HERE 5-SEP-17 TGC
# Assumes THIS script is in same direcory as the input source and target output

#########################
## PROTOTYPE FUNCTIONS ##
#########################
depthfunc <- function(tc,eee,bee,dee) #Depth model - tc is time of concentration in minutes
{
dep <- (tc/60)*(bee/((dee+tc)^eee))
return(dep)
}
#########################
intensityfunc <- function(tc,eee,bee,dee) #Intensity model - tc is ti   me of concentration
     in minutes
{
int <- bee/((dee+tc)^eee) #in/hr
return(int)
}
#########################
sse <- function(x,duration,ddfdepth) #Sum of Errors Squared Function (SSE) used in NLM
    process
{
# x[1] == eee; x[2] == bee; x[3] == dee
sum((ddfdepth - depthfunc(duration,x[1],x[2],x[3]))^2)
}
#########################


#### USER DEFINE DATA #####
# 1. Define "text in quotations.csv" to match source.csv title = Case sensitive
### future version make this interactive so user can enter the filename from console
#ddf <- read.csv("PF_Depth_English_AMS.csv", header = FALSE,na.strings = "")
ddf <- file("PF_Depth_English_AMS.csv", "r") #make connection to input file
metadata <- (readLines(ddf, n=14, ok = TRUE, warn = TRUE,encoding = "unknown", skipNul =
    FALSE))
durfreq <- (readLines(ddf, n=10, ok = TRUE, warn = TRUE,encoding = "unknown", skipNul =
    FALSE))
close(ddf)
# split the string
durfreq <- unlist(strsplit(durfreq,split=","))
# durfreq should be first 10 rows of data
durat <- character(0)
depth2 <- numeric(0)
depth5 <- numeric(0)
```

```
depth10 <- numeric(0)
depth25 <- numeric(0)
depth50 <- numeric(0)
depth100 <- numeric(0)
depth200 <- numeric(0)
depth500 <- numeric(0)
depth1000 <- numeric(0)
irow <- -9
for(i in 1:10){
irow <- irow+10
durat[i] <- durfreq[irow] # this is a string array
depth2[i] <- as.numeric(durfreq[irow+1])   # convert to numeric
depth5[i] <- as.numeric(durfreq[irow+2])   # convert to numeric
depth10[i] <- as.numeric(durfreq[irow+3])   # convert to numeric
depth25[i] <- as.numeric(durfreq[irow+4])   # convert to numeric
depth50[i] <- as.numeric(durfreq[irow+5])   # convert to numeric
depth100[i] <- as.numeric(durfreq[irow+6])   # convert to numeric
depth200[i] <- as.numeric(durfreq[irow+7])   # convert to numeric
depth500[i]  <- as.numeric(durfreq[irow+8])  # convert to numeric
depth1000[i]  <- as.numeric(durfreq[irow+9])  # convert to numeric
}
# Force 10min = 5min values
# first save the 5 min for later plotting
d2temp <-     depth2[1]
d5temp <-     depth5[1]
d10temp <-   depth10[1]
d25temp <-   depth25[1]
d50temp <-   depth50[1]
d100temp <- depth100[1]
#   depth2[1]<-  depth2[2]
#   depth5[1]<-  depth5[2]
#  depth10[1]<- depth10[2]
#  depth25[1]<- depth25[2]
#  depth50[1]<- depth50[2]
# depth100[1]<-depth100[2]
# Minimization Process
duration <- c(5/60,10/60,15/60,30/60,1,2,3,6,12,24)  # durations, numeric in hours
duration <- 60*duration # convert into minutes to work with the prototype functions

# nlm starting guess vector
x <- vector()
x[1] <- 0.004 #eee
x[2] <- 0.004 #bee
x[3] <- 0.004 #dee
NEW <- nlm(sse,c(x[1],x[2],x[3]),duration,depth2,steptol=1e-16, gradtol=1e-6)
ebd2 <- NEW$estimate
depthmodel2 <- depthfunc(duration,ebd2[1],ebd2[2],ebd2[3])
x <- NEW$estimate  #use these values for next ARI
#
NEW <- nlm(sse,c(x[1],x[2],x[3]),duration,depth5,steptol=1e-16, gradtol=1e-6)
ebd5 <- NEW$estimate
depthmodel5 <- depthfunc(duration,ebd5[1],ebd5[2],ebd5[3])
x <- NEW$estimate  #use these values for next ARI
#
NEW <- nlm(sse,c(x[1],x[2],x[3]),duration,depth10,steptol=1e-16, gradtol=1e-6)
ebd10 <- NEW$estimate
depthmodel10 <- depthfunc(duration,ebd10[1],ebd10[2],ebd10[3])
x <- NEW$estimate  #use these values for next ARI
#
NEW <- nlm(sse,c(x[1],x[2],x[3]),duration,depth25,steptol=1e-16, gradtol=1e-6)
ebd25 <- NEW$estimate
depthmodel25 <- depthfunc(duration,ebd25[1],ebd25[2],ebd25[3])
x <- NEW$estimate  #use these values for next ARI
#
NEW <- nlm(sse,c(x[1],x[2],x[3]),duration,depth50,steptol=1e-16, gradtol=1e-6)
ebd50 <- NEW$estimate
depthmodel50 <- depthfunc(duration,ebd50[1],ebd50[2],ebd50[3])
x <- NEW$estimate  #use these values for next ARI
#
NEW <- nlm(sse,c(x[1],x[2],x[3]),duration,depth100,steptol=1e-16, gradtol=1e-6)
ebd100 <- NEW$estimate
depthmodel100 <- depthfunc(duration,ebd100[1],ebd100[2],ebd100[3])

outfile <- file("output.txt","w")
write(c(ebd2[1],ebd2[2],ebd2[3]),outfile,sep=",")
write(c(ebd5[1],ebd5[2],ebd5[3]),outfile,sep=",")
write(c(ebd10[1],ebd10[2],ebd10[3]),outfile,sep=",")
write(c(ebd25[1],ebd25[2],ebd25[3]),outfile,sep=",")
write(c(ebd50[1],ebd50[2],ebd50[3]),outfile,sep=",")
write(c(ebd100[1],ebd100[2],ebd100[3]),outfile,sep=",")
```

```
close(outfile)
# plotting for QA/QC checks

# now put the 5 minute values back onto the vectors for plotting
depth2[1] <- d2temp
depth5[1] <- d5temp
depth10[1] <- d10temp
depth25[1] <- d25temp
depth50[1] <- d50temp
depth100[1] <- d100temp

plot(duration,depth100,log="xy",ylim=c(0.1,10),xlab="Duration (min)",ylab="Depth (mm)")
lines(duration,depthmodel100,col="royalblue4", lwd=2)

lines(duration,depth50,type="p")
lines(duration,depthmodel50,col="skyblue4", lwd=2)

lines(duration,depth25,type="p")
lines(duration,depthmodel25,col="skyblue3", lwd=2)

lines(duration,depth10,type="p")
lines(duration,depthmodel10,col="skyblue2", lwd=2)

lines(duration,depth5,type="p")
lines(duration,depthmodel5,col="skyblue1", lwd=2)

lines(duration,depth2,type="p")
lines(duration,depthmodel2,col="skyblue", lwd=2)

leg <- c("2 Year", "5 Year","10 Year","25 Year","50 Year","100 Year")
legend("bottomright", leg , col=c("skyblue","skyblue1","skyblue2","skyblue3","skyblue4","
    royalblue4"), lwd=2, bty="n")
```

Appendix B

Printing and Binding

Listing B.1. PHP code as configuration.php file to connect to MySQL data Server.

```
<?Php
/// Update database login details here ///
$dbhost_name = "host_name";        // host name
$database = "database_name";       // database name
$username = "username";            // login userid
$password = "password";            // password
/// End of database details of the server ///

/// Database connection function - no need to edit below ///
try {
$dbo = new PDO('mysql:host='.$dbhost_name.';dbname='.$database, $username, $password);
} catch (PDOException $e) {
print "Error!: " . $e->getMessage() . "<br/>";
die();
}
?>
```

Listing B.2. Web application HTML and PHP code as index.php file.

```
<?php
//// Database connection
require 'config.php';
//// End of connecting to database
?>

<!DOCTYPE html>
<html>
<head>
<title>EBD Look Up</title>
<!-- Bootstrap core CSS -->
<link rel="stylesheet" href="https://maxcdn.bootstrapcdn.com/bootstrap/4.0.0-beta.3/css/
    bootstrap.min.css" integrity="sha384-Zug+QiDoJOrZ5t4lssLdxGhVrurbmBWopoEl+
    M6BdEfwnCJZtKxi1KgxUyJq13dy" crossorigin="anonymous">
<!-- Custom styles -->
<link href="custom.css" rel="stylesheet">

<SCRIPT language=JavaScript>
function reload(form){
var val=form.cat.options[form.cat.options.selectedIndex].value;
self.location='index.php?cat=' + val ;
}
</script>
</head>

<body>
<nav class="navbar navbar-expand-lg navbar-dark bg-dark">
<!-- <a class="navbar-brand" href="#">Navbar</a> -->
<button class="navbar-toggler" type="button" data-toggle="collapse" data-target="#
    navbarSupportedContent" aria-controls="navbarSupportedContent" aria-expanded="false"
    aria-label="Toggle navigation">
<span class="navbar-toggler-icon"></span>
</button>
```

```
<div class="collapse navbar-collapse" id="navbarSupportedContent">
<ul class="navbar-nav mr-auto">
<li class="nav-item active">
<a class="nav-link" href="index.php">Home <span class="sr-only">(current)</span></a>
</li>
</ul>
<ul class="navbar-nav ml-auto">
<li class="nav-item">
<a class="nav-link" href="contact.php">Contact Info <span class="sr-only">(current)</span
    ></a>
</li>
</ul>
</div>
</nav>
<!-- Main jumbotron for call to action -->
<div class="jumbotron">
<h2 class="display-6">Rainfall Intensity-Duration-Frequency Coefficients</h2>
<p>County-level rainfall intensity estimation for the United States </p>
</div>


<!-- PHP code to construct the drop-down list -->
<?Php

@$cat=$_GET['cat']; // Use this line or below line if register_global is off
if(strlen($cat) < 0 ){ // to check if $cat is numeric data or not.
echo "Data Error";
exit;
}

//// Getting the data from Mysql table for first list box; States
$quer2="SELECT DISTINCT State FROM ebdval";
//// End of query for first list box

//// for second drop down list, Counties, check if $cat is selected else display all the
    $subcat
//// $cat --> Category --> States
//// $subcat --> subcategory --> Counties
if(isset($cat) and strlen($cat) > 0){
$quer="SELECT DISTINCT County FROM ebdval where State='".$cat."'";
}else{$quer="SELECT DISTINCT County FROM ebdval"; }
//// end of query for second subcategory drop down list box

echo "<div class='container-fluid'>";
echo "<div class='row pad-32'>";
//// First Column - the input forms
echo "<div class='col-md-3 col-sm-12 alert alert-primary'>";
echo "<form method=post name=f1 action='index.php'>";

//// Starting of first drop downlist
echo " <div class='form-group'><label class='lead' for='cat'>State:</label>";
echo "<select class='form-control' name='cat' onchange=\"reload(this.form)\" required><
    option value=''>Select State...</option>";
foreach ($dbo->query($quer2) as $i) {
if($i['State']==@$cat){echo "<option selected value='$i[State]'>$i[State]</option>"."<BR
    >";}
else {echo  "<option value='$i[State]'>$i[State]</option>";
}
}
echo "</select></div>";
//// end of the first drop down list

//// Starting of second drop downlist
echo "<div class='form-group'><label class='lead' for='subcat'>County:</label>";
echo "<select class='form-control' name='subcat' required><option value=''>Select County
    ...</option>";
foreach ($dbo->query($quer) as $j) {
echo  "<option value='$j[County]'>$j[County]</option>";
}
echo "</select></div>";
//// end of the second drop down list

//// Time of Concentration input box
echo "<p class='lead'>Time of Concentration:<br>";
echo "<input type='radio' name='T' value='min' checked> Minute  ";
echo "<input type='radio' name='T' value='hr'> Hour";
echo "<input type='text' name='toc' class='form-control' id='toc' pattern='[+-]?([0-9]*[.])
    ?[0-9]+' title='input a number' required></p>  ";
//// end of Time of Concentration input box
```

```
//// Unit radio check box
echo "<p class='lead'>Select English or SI Units:<br>";
echo "<input type='radio' name='unit' value='eng' checked> English  ";
echo "<input type='radio' name='unit' value='si'> SI</p>";
//// end of Unit radio check box

//// submit button
echo "<input type=submit class='btn btn-primary' value=Submit>";
//// end of submit button

echo "</form>";
echo "</div>";

if ( isset($_POST['cat']) && isset($_POST['subcat']) && isset($_POST['toc'])) {
//// Second Column - the table of ebd values
echo "<div class='col-md-5 col-sm-12'>";
echo "<p class='lead text-center'>".$_POST['cat'].", ".$_POST['subcat']."<br>";
$state="'".$_POST['cat']."'";
$county="'".$_POST['subcat']."'";
if ($_POST['T']==='min') {
$time = $_POST['toc'];
echo "Time of Concentration = ".$_POST['toc']." min</p>";
} else {
$time = $_POST['toc']*60;
echo "Time of Concentration = ".$_POST['toc']." hr </p>";
}
$tex = "SELECT * FROM ebdval WHERE State=".$state." AND County=".$county;
$stmt = $dbo->query($tex);

//// $rinput a string variable which will have all the R inputs parameters together
     seperated with comma
$rinput = "";
//// crate table of ebd outputs:
echo "<table class='table table-bordered text-center'>"."\n";
echo "<tr><th scope='col'>";
echo "Frequency";
echo "</th><th scope='col'>";
echo "e";
echo "</th><th scope='col'>";
if ($_POST['unit']==='si') {
echo "b (mm)";
} else {
echo "b (in.)";
}
echo "</th><th scope='col'>";
echo "d (min)";
echo "</th><th scope='col'>";
if ($_POST['unit']==='si') {
echo "Intensity (mm/hr)";
} else {
echo "Intensity (in./hr)";
}
while ( $row = $stmt->fetch(PDO::FETCH_ASSOC) ) {
echo "</th><tr><td>";
echo $row['ARI']." year, ". 100/round($row['ARI']+0,4)."%";
echo "</td><td>";
echo round($row['e']+0,4);
$rinput =$rinput.round($row['e']+0,4).",";
echo "</td><td>";
if ($_POST['unit']==='si') {
$b=$row['b']*25.4;
} else {
$b=$row['b'];
}
echo round($b,2);
$rinput =$rinput.round($b,2).",";
echo "</td><td>";
echo round($row['d']+0,2);
$rinput =$rinput.round($row['d']+0,2).",";
echo "</td><td>";
$inten = ($b+0)/($time+$row['d']+0)**($row['e']+0);
echo round($inten,2);
echo "</td></tr>\n";
}
echo "</table>\n";
//// concatenate the units ro R input $rinput
$rinput = $rinput.$_POST['unit'];
echo "</div>";

//// Third Column - plot ////
```

```
echo "<div class='col-md-4 col-sm-12'><br>";

// execute R script from shell
// this will save a plot at temp.png to the filesystem
$exec_arg='"C:\Program Files\R\R-3.3.2\bin\Rscript" '."my_rscript.R ".$rinput;
exec($exec_arg);

// return image tag
$nocache = rand();
echo "<div>";
echo "<img class='img-fluid' width='100%' src='temp.png'>";
echo "</div>";

echo "</div>";
}

echo "</div>";
echo "</div>";
?>

<br>
<!--Footer-->
<footer class="footer">
<div class="navbar navbar-dark bg-dark justify-content-center">
<p class="text-muted credit">&copy 2018 by <a href="http://www.rtfmps.com" target="_blank">
     Theodore G. Cleveland</a>,
<a href="http://myweb.ttu.edu/vsalahia" target="_blank">Vahid Salahi</a></p>
</div>
</footer>

<!-- Bootstrap core JavaScript
================================================== -->
<!-- Placed at the end of the document so the pages load faster -->
<!-- jquery link -->
<script src="https://code.jquery.com/jquery-3.2.1.slim.min.js" integrity="sha384-
     KJ3o2DKtIkvYIK3UENzmM7KCkRr/rE9/Qpg6aAZGJwFDMVNA/GpGFF93hXpG5KkN" crossorigin="
     anonymous"></script>
<!-- <script>window.jQuery || document.write('<script src="../../../../assets/js/vendor/
     jquery-slim.min.js"><\/script>')</script>
<script src="Boostrap/assets/js/vendor/popper.min.js"></script> -->
<!-- javascript for bootstrap -->
<script src="https://maxcdn.bootstrapcdn.com/bootstrap/4.0.0-beta.3/js/bootstrap.min.js"
     integrity="sha384-a5N7Y/aK3qNeh15eJKGWxsqtnX/wWdSZSKp+81YjTmS15nvnvxKHuzaWwXHDli+4"
     crossorigin="anonymous"></script>
</body>

</html>
```

Listing B.3. R code used in web applicationto generate the log-log plot.

```
args <- commandArgs(TRUE)
ebd <- strsplit(args,",")

n<-1
val <- c()
for (i in 1:18){
        val[n] <- as.numeric(ebd[[1]][n])
        n <- n+1
}
depthfunc <- function(tc,eee,bee,dee) #Depth model - tc is time of concentration in minutes
{
        dep <- (tc/60)*(bee/((dee+tc)^eee))
        return(dep)
}
unit <- ebd[[1]][19]
duration <- c(5/60,10/60,15/60,30/60,1,2,3,6,12,24)  # durations, numeric in hours
duration <- 60*duration # convert into minutes to work with the prototype functions
depthmodel2 <- depthfunc(duration,val[1],val[2],val[3])
depthmodel5 <- depthfunc(duration,val[4],val[5],val[6])
depthmodel10 <- depthfunc(duration,val[7],val[8],val[9])
depthmodel25 <- depthfunc(duration,val[10],val[11],val[12])
depthmodel50 <- depthfunc(duration,val[13],val[14],val[15])
depthmodel100 <- depthfunc(duration,val[16],val[17],val[18])

if (unit=='si'){
        png(filename="temp.png",height = 1600, width = 1600, res=300)
        plot(duration,depthmodel2,log="xy",ylim=c(2.54,254),type='l',col="skyblue", lwd=3,
             xlab="Duration (min)",ylab="Depth (mm)")
        lines(duration,depthmodel5,col="skyblue1", lwd=3)
```

```
        lines(duration,depthmodel10,col="skyblue2", lwd=3)
        lines(duration,depthmodel25,col="skyblue3", lwd=3)
        lines(duration,depthmodel50,col="skyblue4", lwd=3)
        lines(duration,depthmodel100,col="royalblue4", lwd=3)
        leg <- c("2 Year", "5 Year","10 Year","25 Year","50 Year","100 Year")
        legend("bottomright", leg , col=c("skyblue","skyblue1","skyblue2","skyblue3","
             skyblue4","royalblue4"), lwd=3, bty="n")
        dev.off()
} else{
        png(filename="temp.png" ,height = 3200, width = 3200, res=600)
        plot(duration,depthmodel2,log="xy",ylim=c(0.1,10),type='l',col="skyblue", lwd=3,
             xlab="Duration (min)",ylab="Depth (in.)")
        lines(duration,depthmodel5,col="skyblue1", lwd=3)
        lines(duration,depthmodel10,col="skyblue2", lwd=3)
        lines(duration,depthmodel25,col="skyblue3", lwd=3)
        lines(duration,depthmodel50,col="skyblue4", lwd=3)
        lines(duration,depthmodel100,col="royalblue4", lwd=3)
        leg <- c("2 Year", "5 Year","10 Year","25 Year","50 Year","100 Year")
        legend("bottomright", leg , col=c("skyblue","skyblue1","skyblue2","skyblue3","
             skyblue4","royalblue4"), lwd=3, bty="n")
        dev.off()
}
```