Site-Specific and Generalized Weir Design for the Mississippi Delta*

Mallory R. Poff, Maggie E. Cox, Carleigh M. Wood, Jackson T. Abele, and W.T. Pluer

Abstract – **The Mississippi Delta encompasses 3.0 million acres, of which 2.2 million are irrigated for staple crops such as corn, soybeans, rice, and catfish. The Mississippi River Valley Alluvial Aquifer (MRVAA) is used to irrigate this area; over the past 30 years, it has decreased 20 feet in depth, requiring efforts to increase aquifer recharge and surface water availability for agriculture demands. A weir constructed in a river pools water upstream, promoting aquifer recharge through infiltration and increasing the availability of surface water withdrawals. Weir placement is important to the success of aquifer recharge. In partnership with the Yazoo Mississippi Delta Joint Water Management District (YMD), we created a scalable weir design guide that will allow for broad implementation and increased water availability across the Delta region. The site for the first weir was selected as an area characteristic of the Delta region and will serve as an example for subsequent designs. The supplemental design guide will allow for further weir implementation in the Delta region by providing the necessary steps for a weir design process. Inputs will be easily accessible for non-engineers and the outputs will be designs for Professional Engineer approval. By providing YMD with this weir guide, they will be able to design and install weirs more quickly and cheaply than before, supporting agriculture and groundwater resources in the Mississippi Delta.**

I. Introduction

The Mississippi Delta is a region of alluvial floodplain that stretches from the Mississippi River to the Yazoo River, lying in northwest Mississippi with portions in Arkansas and Louisiana, shown in Figure 1 [1]. The Mississippi River Valley Alluvial Aquifer (MRVAA) is the main groundwater source in the region, providing for irrigation, aquaculture, and wildlife management needs [2]. Additionally, large scale water management projects to reduce flooding have altered hydrology to generally move water more quickly from the landscape. Water demands from the MRVAA have exceeded the recharge rates, leading to a significant drop in the level of the aquifer [1]. This has impacted agricultural and municipal wells increasing the need for agricultural water management practices and engineered designs to increase infiltration could mitigate this issue.

The Yazoo Mississippi Delta Joint Water Management District (YMD) was created in 1989 to develop local, non-regulatory solutions to the Delta's growing water resource challenges with emphasis on increasing its water supply [3]. While local farmers have been encouraged to conserve and reduce their water usage, the withdrawal in the region is greater than the aquifer recharge rate. [3]. To support YMD's non-regulatory mission, engineering solutions could increase aquifer recharge to meet agricultural demands. However, due to limited mission scope and resources, engineering solutions are difficult for YMD and other localized water management districts to design and implement.

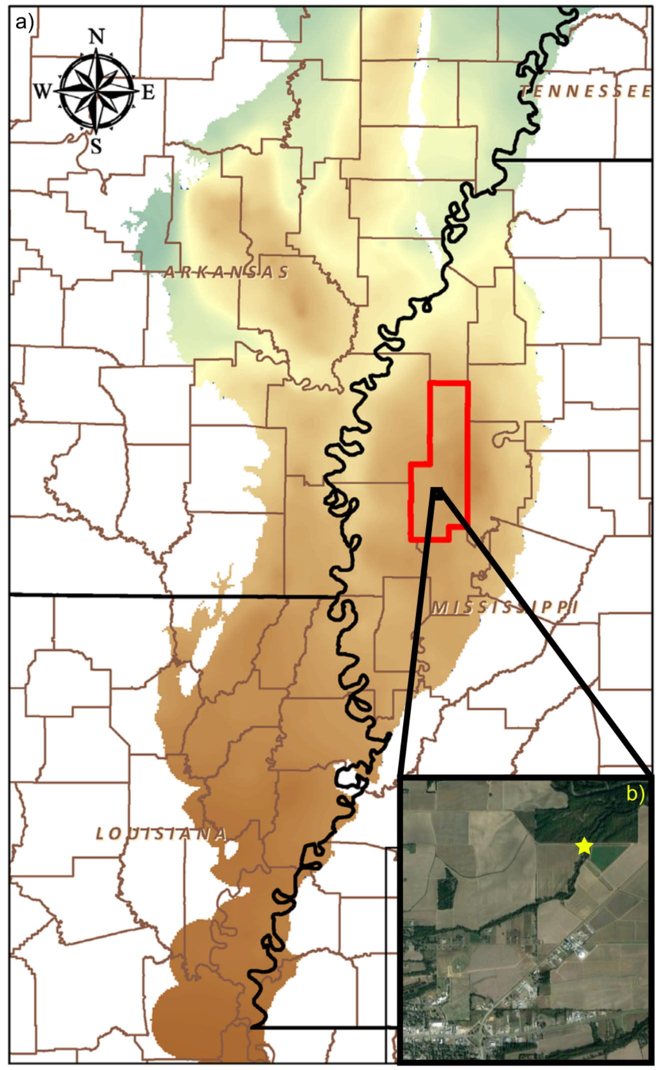

Figure 1: (a) Mississippi River Valley Alluvial Aquifer and (b) specific weir site. The alluvial aquifer extends across five states [1]. Colors indicate the water table elevation within the aquifer ranging from high (green) to low (brown) based on U.S. Geological Survey data from 2016. Sunflower County, where this study was conducted, is outlined in red and the weir site is indicated with a star in the aerial inset.

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Mallory R. Poff, Maggie E. Cox, Carleigh M. Wood, and Jackson T. Abele in the Department of Engineering at Elon University, Elon, NC 27244 USA

W. T. Pluer is an Assistant Professor in the Department of Engineering at Elon University, Elon, NC 27244 USA, (corresponding author; phone: 336-278-6310; e-mail: wpluer@elon.edu).

Most of the world's rivers are impacted by either dams or weirs, or both [4]. A weir is a barrier that alters flow of a river for attenuation or control, flow measurement, and/or water sample collection (Figure 2). Weirs can help improve the environment for certain fish colonies as well as stabilize the water flow of a river [5]. The upstream pool maintains water during low flow that could potentially infiltrate through the streambed.

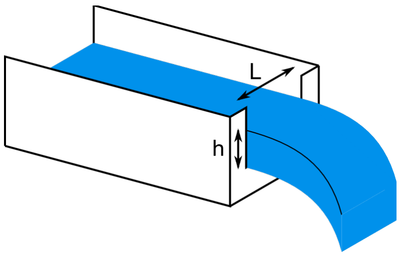

Figure 2: General weir function. Flow of water is proportional to the length of the weir, L, and the height of water above it, h. Empirical formulas have been developed for different weir shapes. Our design is based on a modification of the contracted rectangular weir shown here.

Weirs can be altered for different applications, landscapes, or flow rates. While there are a wide range of shapes to select from, most large weirs aim to maximize weir length to reduce flow velocity [6]. Modifications to the contracted rectangular weir can increase the weir's length to greater than the width of the channel while also focusing the energy from the drop into a contained plunge pool [6]. For larger weirs, the plunge pool and resulting hydraulic jump at the exit need to be contained within a reinforced area to avoid erosion and undercutting of the weir.

Maintaining an upstream pool could facilitate surface withdrawals for agricultural use during low flows. Additionally, in some locations with high hydraulic conductivity, increased pressure head could lead to increased infiltration and recharge rates. Both drivers would improve the aquifer water level in the immediate area. However, it is likely that multiple weirs would be needed to significantly impact the large area covered by the MRVAA. Thus, with this project, we had two goals: 1) design a site-specific weir to address water quantity in a single location, and 2) design a weir design guide to enable non-engineers to conduct an initial design for more widespread application of low-level weirs throughout the region. Together, these could improve water quantity and availability in the Mississippi Delta without altering agricultural practices or ecosystems.

II. Design Process

A. Site Description

Two initial visits to the Mississippi Delta were conducted to better understand the water needs and management practices as well as identify potential sites. Originally, the weir was to be placed in an area of the Delta with high connectivity with the MRVAA to facilitate greater aquifer recharge. However, results from a large USGS project to map the substrates and aquifers of the Delta was not completed in time. Therefore, a site was selected based on hydrology characteristics, accessibility for surveying and construction, and adjacent landowner approval.

The selected site was on the Beaver Dam Bayou in Sunflower County, just upstream of its confluence with the Sunflower River. In Figure 1b, Beaver Dam Bayou is flowing north and the weir site was just south of its intersection with Gwin-Lipnick Road, where the stream then enters a conservation easement. The Beaver Dam Bayou watershed is 23 square miles of mixed agriculture that also includes some of the city of Indianola, MS.

On a following trip, this area was surveyed using a TopCon GPS system. This included a longitudinal length of 250 feet upstream and seven cross-sections totaling over 300 survey points. This survey was coupled with Lidar data updated in 2019 [7] for a more robust evaluation of topography and weir impacts on flooding.

B. Site Hydrology

Several methods were considered for determining the flow necessary for the weir design. While the weir will improve conditions for low flow, it cannot increase the chances of flooding infrastructure or adjacent fields. Technical Report 55 [8] and the Cypress Creek Equation [9] would be generalized and broadly applicable for subsequent weir designs. However, their limitations and assumptions make them poor fits for this region. Gage stations on the Sunflower River would allow for statistical evaluation of recurrence intervals for the selected site, but this would not be available for future designs. Ultimately, generalized regression equations for the Mississippi Delta region were selected [10]. The simple inputs and regional fit make it a suitable method.

Generalized ordinary least squares regression procedures based on gaged stations in the MS Delta have produced the following equations for recurrence intervals:

$$Q_2 = 171\, A^{0.87}\, S^{0.25}\, L^{-0.52} \quad (1)$$

$$Q_{100} = 236\, A^{1.00}\, S^{0.57}\, L^{-0.55} \quad (2)$$

where Q_T is the estimated peak discharge for a recurrence interval of T years in cubic feet per second, A is the contributing drainage area in square miles, S is the channel slope in feet per mile, and L is the main-channel length in miles [10]. Inputs for these equations were calculated using ArcMap 10.4.

C. Weir Design

The site-specific weir was designed to accommodate the 2-year peak flow event. The minimum pool elevation was calculated to meet the requirements for common redraw pumps used in the area because the upstream pool will be used for irrigation withdrawals. This calculation provided the maximum height that the pumps could draw water up without cavitating; subtracting this height from the bankfull elevation provided the elevation for the weir. Thus, any flow height above the weir would reduce pump power requirements and pumps would be stopped if the water level fell below the weir invert as this would impact low flow in the stream.

Next, an initial weir length was calculated to pass the flow while not exceeding a 2.4 ft rise in water levels. The intention is that flow in excess of the 2-year event will be passed through an adjacent spillway. For the initial calculation, a simple contracted rectangular weir equation was used:

$$Q_{weir} = 3.33\ (L - 0.2H)\ H^{1.5} \tag{3}$$

where Q_{weir} is flow over the weir in cubic feet per second, L is the weir length in feet, and H is the height of water above the weir at maximum flow in feet. As expected, the necessary length was greater than the stream width so a semicircular shape will be necessary to accommodate the flow (Figure 3).

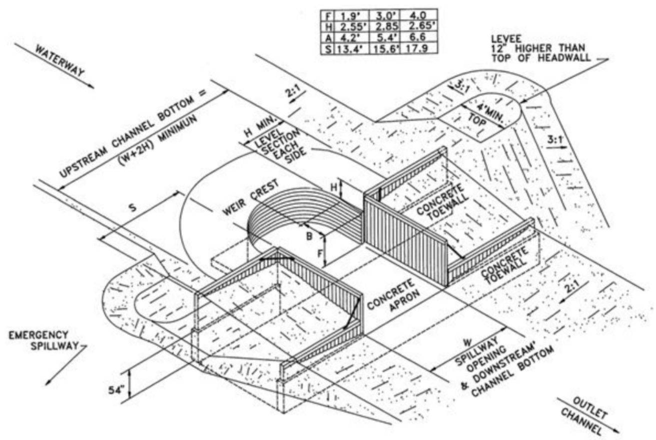

Figure 3: Semicircular contracted rectangular sharp-edged weir selected for designs [11]. This shape is effective for the widest range of channel and flow conditions while containing energy to minimize erosion. The apron length shown further insures stability of the weir.

The magnitude and length of the resulting hydraulic jump were calculated to provide the necessary apron beyond the weir. Given the prevalence of alluvial sediments in the Delta, erosion is a critical concern, and the apron serves as a solution to mitigate its impact. Downstream of the weir site is a bridge and flow must be restored to stable conditions before the bridge pilings. Thus, the final stream height after the hydraulic jump must be equal to the current stream depth. The following equation for hydraulic jump was used:

$$\frac{h_2}{h_1} = \sqrt{\frac{1}{4} + 2\,Fr_1^2} - \frac{1}{2} \tag{4}$$

where h_1 and h_2 are water depths upstream and downstream of the hydraulic jump, and Fr_1 is the Froude number of the upstream flow. Solving this for h_1 gives the height of the water exiting the plunge pool. This was then multiplied by 7 for a conservative estimate of hydraulic jump length. The designed apron should be at least this long, and the weir should be placed at least three times this far upstream of the bridge.

D. Design Guide

To aid in future designs, a Design Guide was built using site specific inputs as previously mentioned for the design discussed above. The goal was for the guide to be adaptable for a wide range of implementation locations while limiting the number of variable inputs for the simplest calculations. This was initially written in MS Excel as this is a widely available program used by YMD. The initial draft had more than 15 input variables, including event precipitation for a given recurrence interval, longest flow path length in the watershed, and surveyed channel cross-sectional areas.

Using the Design Guide this way would require knowledge of watershed hydrology, site surveying, and weir characteristics. Instructions on a README page walked through the design process but this was deemed too complicated, even with individual training on the guide. Alternate versions and simplifications were considered to increase accessibility of the Design Guide.

III. Design Modifications

A. Prefabricated Weir Selection

With the breadth of possible designs, it would be easy for non-engineering users to become overwhelmed with the number of options available to them. Alternatively, they may develop a design that is not feasible; this would result in the engineering firm contracted to confirm the plans having to redo the design at a much higher cost. In an effort to increase the accessibility, the hydrologic inputs were decreased, and a single weir shape was selected. However, this still resulted in too many inputs for the guide. After discussions about weirs previously installed in the region, we decided to develop designs in collaboration with a specific company.

This company provides prefabricated aluminum weirs and their plans based on a small number of inputs [11]. This company will provide the construction plans for our site-specific weir and then will be able to assist future weir designs, taking the outputs from the Design Guide and generating engineering drawings, a bill of materials, and ultimately the prefabricated pieces for construction. These designs will not include site-specific considerations, such as nearby infrastructure and accessibility for machinery. This also does not include a review of design and energy calculations beyond the maximum weir elevation. Thus, the Design Guide will need to consider larger flows in a secondary design phase. In general, selecting the largest weir provided by the company will make the design process simpler, with the majority of design decisions centered on the flood spillway.

B. Addition of Spillway

As mentioned above, the limitations on weir sizing requires more emphasis on the spillway. A spillway is necessary when the flow is too great to pass all of the water through the weir in a controlled way. The spillway will accommodate flows greater than the 2-year recurrence interval used for designing the weir and ensure that the weir will not fail. The spillway was designed based on a 100-year recurrence interval using Equation 2 and the Manning Equation 5:

$$q_{spillway} = \frac{1.49}{n} R_h^{2/3} A \sqrt{s} \tag{5}$$

where q is flow rate in the spillway in cubic feet per second, n is the dimensionless Manning roughness coefficient, R_h is the hydraulic radius in feet, A is the spillway cross-sectional area in square feet and s is the slope in ft/ft. Designs were developed both for a hydraulicly efficient trapezoidal concrete channel and a wider rock swale. This will allow adjacent farmers and financing groups to select the best fit for each site.

C. Changes to the Guide

Initially, the Design Guide was built in MS Excel for its calculation and data input functionalities. However, after undergoing testing, a shift was made to a Google Sheets platform. Google Sheets allows for collaboration within design teams, is not tied with a particular Excel version, and makes use of the team's adeptness with JavaScript, the programming language used by Google Sheets, as opposed to VBA, which is utilized by Excel. Additionally, Google Sheets offers the ability to run a website, using Sheets as the backend. This will allow for improved user experience because it will hide all of the calculations, providing a more streamlined interface. Finally, Google Sheets offers enhanced user collaboration, a crucial factor both during the creation phase to ensure efficient teamwork and throughout the user experience, given that multiple individuals may be involved.

D. Design Guide Training

To bridge the divide between the technical expertise and the stakeholders' engineering knowledge, a training session will be conducted. The purpose of this meeting is to educate the YMD team on using the Design Guide, walking them through the site-specific weir design so they will be able to replicate this on their own. This will feature a comprehensive walkthrough of the process utilizing the survey data collected from the Beaver Dam Bayou. Additionally, the session will provide an opportunity for stakeholders to inquire and solicit feedback, thereby fostering effective communication. While the Design Guide will incorporate a README page for user convenience, the training session will serve to clarify any lingering ambiguities.

IV. Conclusion

Due to dropping water levels in the MRVAA, moving farmers to surface water for irrigation will benefit both agriculture and hydrology in the MS Delta Region. A weir is a simple and cost-effective engineered solution. In this project, both a site-specific weir design and a Design Guide were developed to allow non-engineers to create plans for future weirs. To date, the designs have not been approved nor has the Design Guide been used for subsequent plans so it remains to be seen how impactful this project will be. Additionally, due to costs and interest of YMD, the client, water tables below the weir pool will not be monitored to determine ultimately how effective weirs are for aquifer protection and recharge. Further study is necessary before deeming this a solution for the region; however, water conservation in the MS Delta will require a number of strategies and weirs are likely a strong component of that.

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