# Investigating the Impact of Approach Channel Sediment Removal on Spillway Performance

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## Abstract

Garrison Dam near Riverdale, North Dakota on the Missouri River is the largest dam in the US Army Corps of Engineers (USACE) inventory, impounding over 23 million acre-feet of water at the top of exclusive flood control zone. The spillway is designed to pass over 800,000 cfs during the Spillway Design Flood. Over the past several decades, continued erosion of the left bank of the spillway approach channel has resulted in a significant deposition of material in the spillway approach channel, averaging 9 feet, reducing approach depth from 15 feet to 6 feet. According to research published by the US Bureau of Reclamation (USBR), the reduced approach depth would reduce the efficiency of the spillway crest by nearly 7% at the design head with gates fully open. The same research suggests that spillway efficiency would be reduced by roughly 20% if the approach were to fill with sediment to the height of the ogee weir. The research applies only to flows at the design head; it does not address flow at lesser heads, nor does it discuss the impact on flow with gates controlling the flow. Hydraulic model studies done during design demonstrated that less than ideal approach conditions resulted in overtopping of the downstream chute walls and poor energy dissipation in the stilling basin. Funding has been obtained to procure riprap to stabilize the approach channel left bank as well as dredge material from the spillway approach channel. A 2D HEC-RAS model and a sectional CFD OpenFOAM model are being developed to assess the impact that varying degrees of sediment removal may have on spillway efficiency and performance. Pressures along the ogee crest of the spillway from physical model testing from 1956 were compared to the OpenFOAM results to verify the ogee crest weir pressure profile closely matched the physical modeling. Preliminary results from the 2D model suggest up to a 34% increase in flow if all the sediment were removed from the spillway approach channel, assuming sediment had increased to the level of the spillway crest. We will investigate the impacts that varying degrees of sediment removal may have on spillway efficiency and performance with both the 2D and 3D model, ensuring that the limited funding available for dredging provides the greatest increase in efficiency and performance that can be attained.

# Introduction

## Hydraulic Modeling

Aggradation of sediment in the approach channel has decreased both the capacity of the approach channel and the efficiency of the ogee weir that is derived from the approach depth. Ogee weir manual calculations and 2D model runs indicate that the approach channel existing conditions have reduced the spillway capacity to 85-93% of the design discharge. The initial objective of building a 2D model of the spillway approach channel in a study in 2017, was to determine how far back dredging and/or excavation needs to go to return ogee weir crest efficiency to the design conditions; however, results from the 2D model did not yield any definitive answers on the distance required to restore the ogee crest efficiency. The study is now being re-examined with CFD to better understand the approach depth impacts on the ogee weir crest. 2D HEC-RAS Shallow Water Equations (SWE) will be utilized to supplement the findings from the CFD modeling.

Described below are the modeling efforts utilized to ensure optimal dredging that can maximize the capacity of the spillway.

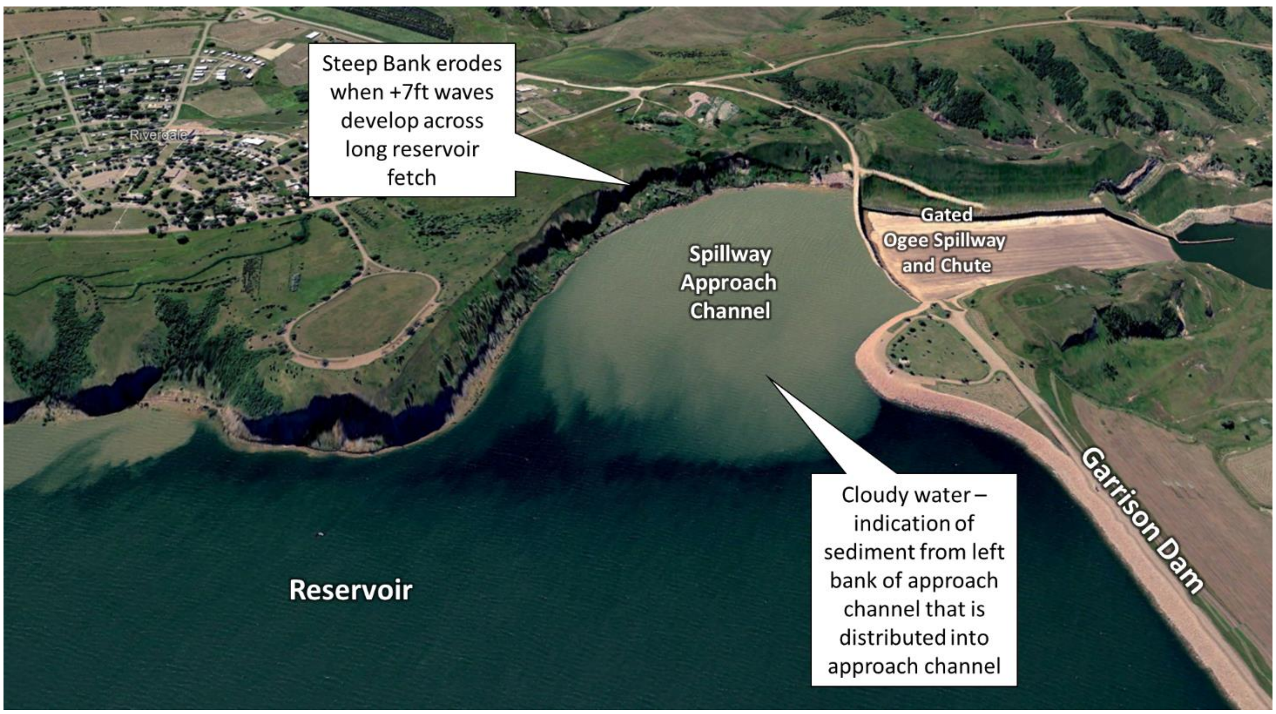


**Figure 1.** Overview of Spillway Approach Channel Condition

## Physical Model Analysis

A physical model of scale 1:41.6 of one bay and half of 2 adjacent bays, and a 1:100 scale of the full spillway approach were both commissioned and studied in the Waterways Experiment Station (currently Engineering Research and Development Center [ERDC]) in March 1956. The physical model discharges, water surface profiles and pressures were utilized to evaluate the accuracy of the CFD modeling.

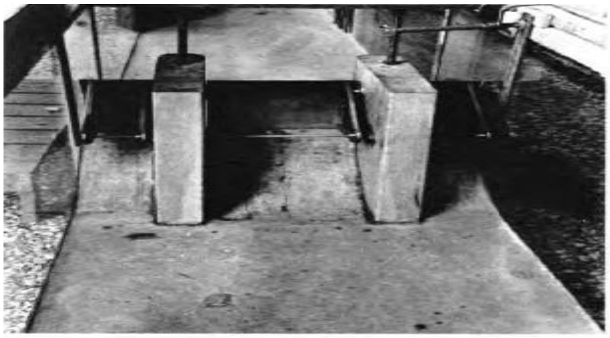

**Figure 2.** 1:46.1 Scale Physical Model of Crest

## Empirical Analysis

The method presented within the Design of Small Dams (Bureau, 1987) for computing ogee weir efficiency as effected by approach depth was utilized to evaluate discharge coefficients used in the 2D modeling:

$$Q = CL_eH_e^{\frac{3}{2}} \qquad \text{(eq. 1)}$$
$$V_a = Q(H_e + P) \qquad \text{(eq. 2)}$$
$$d = H_e - V_a/2g \qquad \text{(eq. 3)}$$

Where:

$Q$ = flow (cfs)
$C$ = Ogee weir discharge coefficient
$L_e$ = Effective length of ogee crest
$H_e$ = Specific energy head above crest
$V_a$ = Velocity of Approach (ft/sec)
$P$ = Depth upstream channel invert below crest (ft)
$d$ = Flow depth for energy head $H_e$ and approach velocity $V_a$

In these series of equations, the effect on ogee weir efficiency can be evaluated by adjusting the value P (upstream depth of channel invert below crest). As can be seen in **Figure 3**, the approach depth (P) for a given design head is crucial to maintaining spillway design discharge capacity.

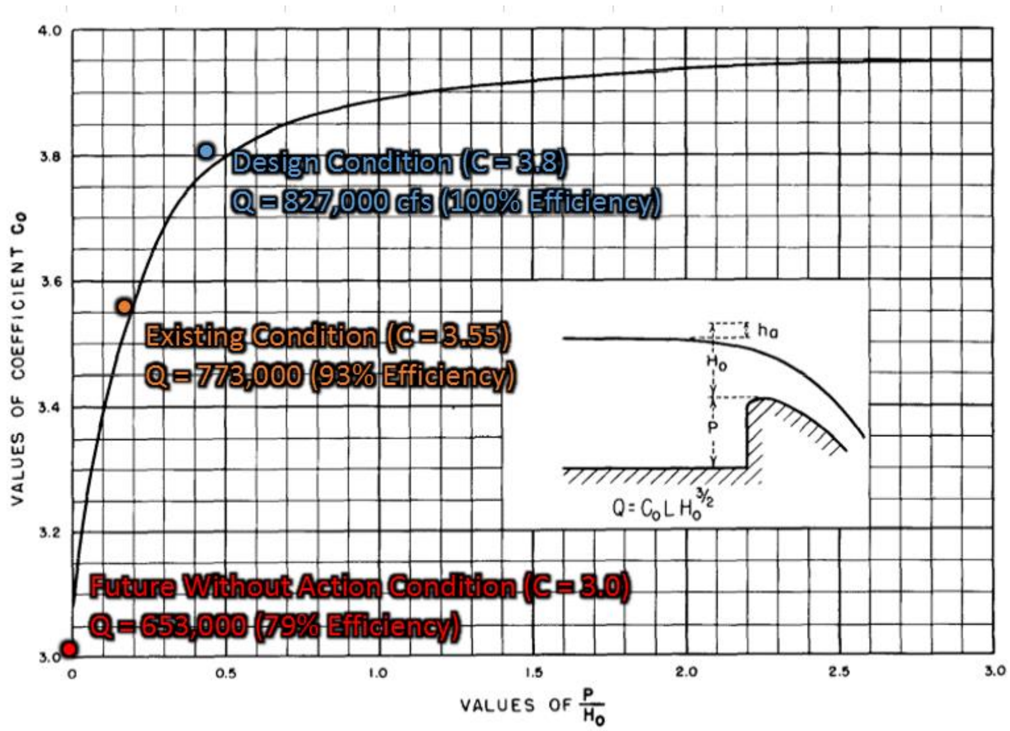


**Figure 3.** Ogee Weir Coefficient Chart from Design of Small Dams (Bureau, 1987).

## 2D Hydraulic Model (HEC-RAS and AdH)

A HEC-RAS 2D model and a 2D Adaptive Hydraulics (AdH) were utilized to estimate the approach channel losses due to sedimentation. The depth averaged solution compiled from 2D modeling does not account for the vertical accelerations in the approach depth leading up to the ogee weir. However, the 2D modeling shallow water equations (SWEs) may approximate the impact of the approach channel without being overly computationally intensive. And this modeling can supplement the 3D flow modeling described below.

## CFD Modeling (OpenFOAM)

An OpenFOAM Reynolds Averaged Navier Stokes (RANS) k-Epsilon turbulence model was utilized as a Computational Fluid Dynamics (CFD) or 3D Flow model to evaluate the impact of sedimentation in the approach channel and the corresponding impact on the ogee weir efficiencies due to loss of approach depth. As can be seen below in **Figure *4***, the physical model data was utilized to validate the results of the design conditions in the CFD modeling, prior to beginning the alternative analysis for dredging out the approach depth. The CFD demonstrated good agreement with the physical model water surface elevations and crest pressures along the ogee.

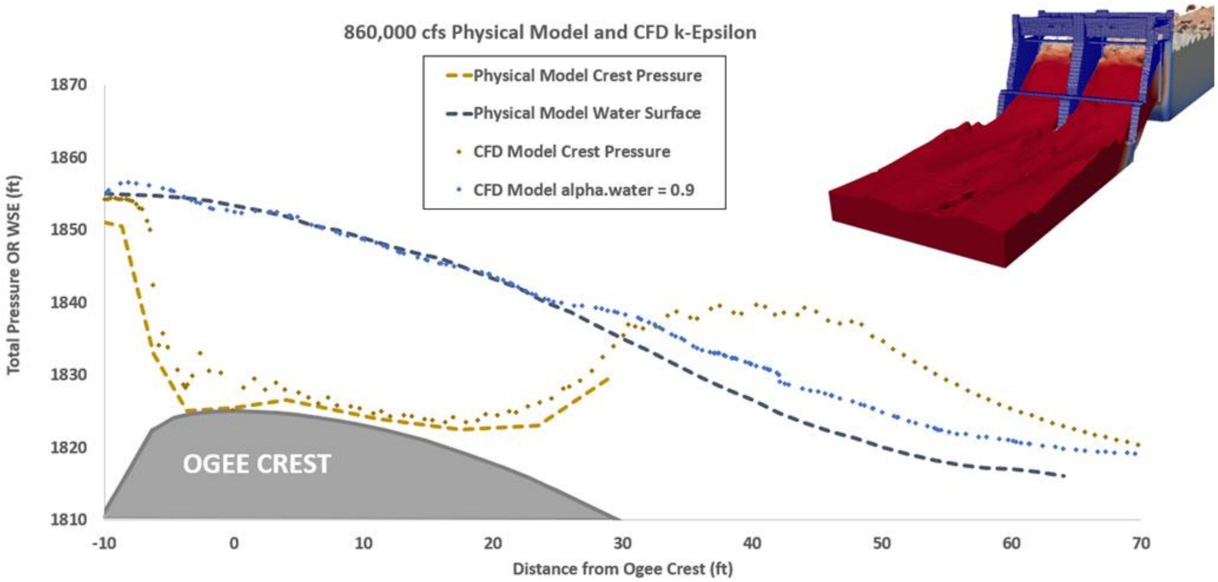


**Figure 4.** Verification of CFD model accuracy for estimating crest pressures and water surface profile

# Alternative Analysis

## Dredging and Excavation Extents

In 2017, dredging was proposed for distances ranging between 200 and 2000ft (see **Figure 5** below) and the entire approach channel. A full comprehensive CFD model that is meshed to the appropriate size and also captures each proposed alternative was considered too computationally intensive, and too expensive to run the alternatives on the High Performance Computers at ERDC. Instead, a pseudo-2D model that only utilized a 1-meter slice of the spillway and a smaller spillway domain was used in the preliminary analysis. A 2-Bay sectional model will be run on the HPC after the preliminary results have been evaluated.

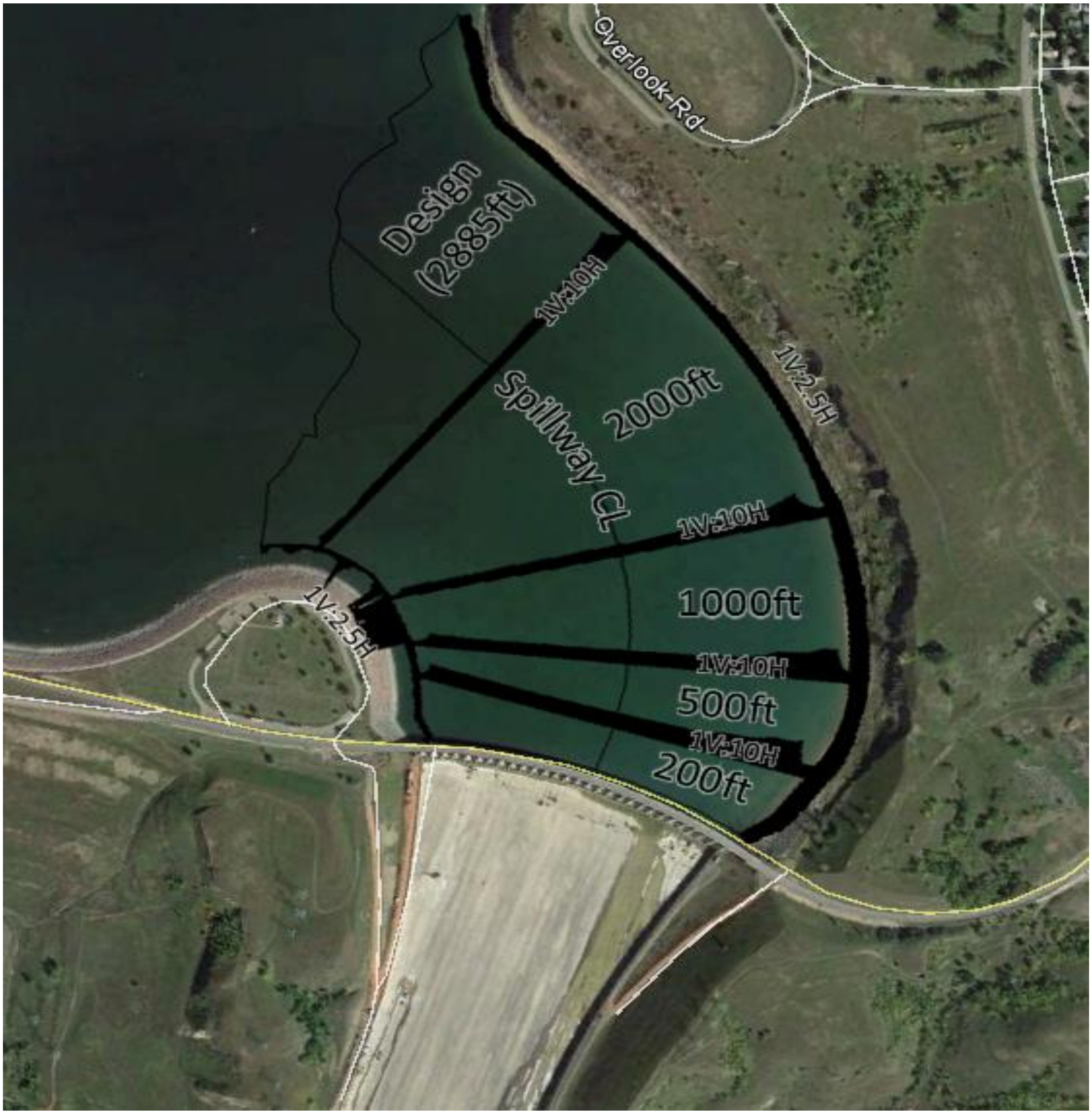


**Figure 5.** Dredging alternatives for CFD analysis

# Conclusions

## Recommended Dredging Distance

A variety of dredging distances (0ft, 10ft, 20ft, 50ft, 100ft, 200ft and 500ft) were meshed with snappyHexMesh and blockMesh, and then extruded as Psuedo-2D slices of the spillway, 1-meter wide cells, and were converged on a 24 core machine with interFoam (a multiphase solver for two isothermal, incompressible, immiscible fluids using Volume of Fluids) to determine the optimal dredging distance from the ogee weir. An upstream total pressure boundary was set at 1860ft Local Project Datum (LPD) (similar to spillway design pool elevations evaluated in the physical model study), and the downstream boundary was set to a zeroGradient inletOutlet condition. Preliminary results are shown below in ***Table 1*** and **Figure 6**. The results of the pseudo-2D slices produced two unexpected anomalies:

(1) For distances between 50-200ft, the trend in efficiency vs approach depth is unclear. This may be due to the location of the expansion of flow. If the proximity of this expansion is close enough the ogee, the velocities remain high until flows pass over the ogee. If the expansion takes place farther than 200ft away from the ogee, there appears to be an increasing trend in efficiency again. However, if the expansion takes between 50-200ft, it appears the higher velocities near the ogee cause a more rapidly varied flow expansion and also a rapidly varied contraction at the ogee. It may be the case that excavation between 50-200ft may be less optimal than 10-20ft. Further 3D flow modeling with OpenFOAM on a 3 million cell 2 Bay model will help confirm the conclusions of the pseudo 2D-slice analysis. Further effort will also be made to quantify the energy loss in the spillway at the expansions and the contraction over the ogee.

(2) There was a larger than expected expansion losses and change in water surface elevation as flow expands into the excavated approach depths; in some cases water surface would change as much as 10ft. As stated above, the location of these expansion losses may be affecting the overall spillway performance, creating unavoidable contraction/expansion losses. It is unlikely that a 10ft or 20ft dredging operation may provide an optimal increase in spillway efficiency for a given cost of dredging. Instead, it is possible that the velocities in the streamlined 2D slice sectional model are over-estimating the headloss and amplifying the expansion losses at the transition from excavated spillway to un-excavated spillway.

***Table 1.*** Ogee crest discharge efficiency for given dredging distance upstream of the crest

| Distance of excavation upstream of ogee (ft) | Discharge per 1 meter of ogee crest | | % Efficiency |
|---|---|---|---|
| | (cms) | (cfs) | |
| 0 | 73.6 | 2600 | 90.4% |
| 10 | 74.9 | 2646 | 92.0% |
| 20 | 74.9 | 2644 | 92.0% |
| 50 | 73.3 | 2588 | 90.0% |
| 100 | 74.7 | 2638 | 91.7% |
| 200 | 74.7 | 2640 | 91.8% |

| | | | |
|---|---|---|---|
| 500 | 76.7 | 2708 | 94.2% |
| *Design (>1000) | 81.4 | 2875 | 100.0% |

***2D slice modeling assumed approach channel was maximum 1000ft to reduce the domain size. Actual approach channel center line length is closer to 2,588ft**

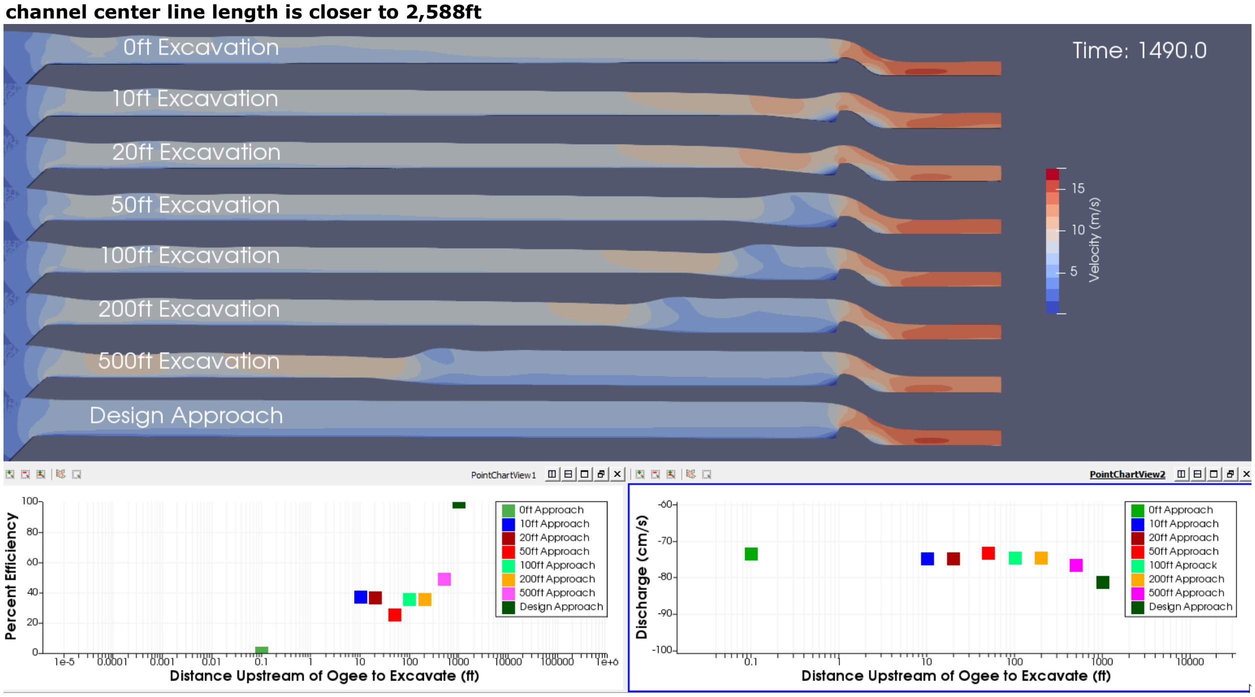


**Figure 6.** Dredging alternatives for CFD analysis

Because the results of the 2D slice modeling are inconclusive for dredging depths between 0 and 200ft, further analysis of the 2D results, and a larger sectional models with 2 bays will be utilized to further inform the above results.

Further analysis that may increase confidence in the results would include:

1. Comprehensive spillway modeling of all 28 bays and the entire approach channel.
2. Computing with 2$^{nd}$ Order numerical schemes to increase accuracy of answer.
3. realizableKE turbulence modeling, which may better predict recirculation and complex flow patterns.

It should also be noted in this conclusion, that the dredged area will likely begin to fill back in with sediment shortly after dredging, unless measures are taken to arrest the wave erosion of the left bank. A project is currently underway to begin armoring on the left bank with riprap to stop wind/wave erosion.

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