Grassy Ridge Flood Reduction Study

Executive Summary

A drainage and hydraulic modeling study has been completed in the Grassy Ridge area of Hyde County. Several water management and drainage canal modifications were investigated to determine the flood reduction benefits of each. Implementing controlled or precision drainage and adopting conservation tillage provide opportunities to reduce surface and shallow ground water drainage by as much as 20%. Research indicates these techniques could improve yields and build resilience for the future. Modification of canals to include a second stage floodplain offers the most direct opportunity to decrease flood magnitude and increase canal capacity.

U.S. FISH & WILDLIFE SERVICE
DEPARTMENT OF THE INTERIOR

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Introduction

Grassy Ridge (GR) is an area of rich farm land located in Hyde County in eastern North Carolina, just north of the Pungo River and south of the Pocosin Lakes National Wildlife Refuge (PLNWR). The area drains southward through a series of canals to the Pungo River. Mucky soils dominate the area, with smaller pockets of sandy or silty loam. The southern portion of GR lies within 5 feet of mean sea level elevation, and nearly the entire area is within 10 feet of mean sea level. PLNWR to the north contributes flow to the area; outflow from the refuge is regulated by a series of water control structures. Intensive lateral ditching is present throughout much of GR to create a lowered water table and allow more productive farming.

Canals and Drainage

There are several major canals in GR. From west to east, these are: Hyde Park, Allen, Boerema, Clayton, De-hoog, Ponzer and Evans. Hyde Park, Boerema and Ponzer are the main drainage pathways out of GR and each of these canals outflow to the Pungo River. The Allen canal drains into Boerema through an east-west flowing cross ditch. Clayton flows westward into Boerema canal. Both De-hoog and Evans canals connect to Ponzer canal before flowing into the Pungo River. This network of canals can be seen in

Appendix 1: Grassy Ridge Modeling Cross-Sections Map.

Modeling Analysis

Hydraulic analysis of GR was performed to understand how changes in land management and changes to the physical canal system would affect flood stage at different locations in the region. Model construction utilized stream cross-section data which was previously collected by KBE staff during past project work in the region and publicly available digital lidar data. Desktop GIS analysis was completed to extract canal cross-section data for use supplementing field collected data where coverage was insufficient. Field collected data were used to extrapolate canal bed elevations to the supplemental cross-sections. Canal crossing inventories were conducted using aerial imagery. Some existing culvert information and experience in the region guided assumptions made about crossing type (bridge or culvert) and size. Model geometry was constructed and run in 1D steady flow analysis using HEC-RAS 5.0.7.

Hydrology

Steady flow rates at various model cross-sections were determined using the canal design discharge equation (Huffman et al., 2013):

$$q = CA^{5/6}$$

where $q =$ the design discharge (m^3/s)

$C =$ coefficient for location and level of

drainage $A =$ drainage area (km^2)

A coefficient for location and level of drainage of 0.59 was used to determine design discharge at model cross-sections. The design discharge equation is an empirically derived equation based on drainage ditch capacities determined to provide sufficient drainage for a contributing cropland area; it is assumed that this approximately corresponds to a two-year return interval storm event.

Land Management

Conservation Tillage

To assess the potential effects of changes in land management on GR canal flood stage, a brief review of literature on conservation tillage and controlled drainage was conducted. Conservation tillage (CT) includes practices such as no-till, mulch-till, ridge-till, zone-till and strip-till and is generally characterized by practices which disturb less than 30% of the soils' surface (Duiker & Myers, n.d.) (Figure 1). Several studies across the United States and North Carolina including various soil types in the Piedmont and Atlantic Coastal Plain documented reductions in runoff ranging from near zero to around 80% (Crozier & Brake, 1999; Endale et al., 2014; Raczkowski et al., 2009; Wuest et al., n.d.); however, reduction rates and reporting methods were inconsistent, limiting the direct application of any research findings. Instead, the mechanisms which could influence runoff volume and peak flow as a result of adoption of CT were considered.

Figure 1. Corn emerging through crop residue, example of conservation tillage.

CT minimizes soil disturbance which, overtime, improves the soil tilth by preserving micropores created by insects and worms (Duiker & Myers, n.d.). Micropores and insect activity aerate the soil which increases the soil's infiltration rate (Duiker & Myers, n.d.), thus reducing runoff. Additionally, CT leaves substantial crop residue on the soil surface. The presence of crop residues creates small barriers to slow runoff, increase surface storage, and promote infiltration (Duiker & Myers, n.d.). Considering the NRCS Curve Number (CN) Method for estimating runoff volume:

$$Q = \frac{(I - 0.2S)^2}{1 + 0.8S}$$

$$S = \frac{25400}{CN} - 254$$

where $Q =$ direct surface runoff (mm)

$I =$ storm rainfall depth (mm)

$S =$ maximum potential difference between rainfall and runoff (mm)

$CN =$varies between 0 and 100; it depends on soil type, land use, ground cover, and soil water conditions

The variable S includes both equivalent rainfall depth lost to infiltration and storage on the soil's surface (Huffman et al., 2013). Therefore, increases in surface storage or infiltration will reduce the amount of runoff produced. Considering the available research and using a conservative engineering judgement, it is assumed that a potential runoff volume reduction of approximately 30% could be achieved by the adoption of CT. The NRCS CN method was then used to back-calculate the proposed reduction in CN value assumed to produce this reduction (i.e., an existing condition CN of 78 would be reduced to 69 following adoption of CT). These CN values were then used in the NRCS TR-55 Graphical Peak Discharge Method to determine the resulting reduction in peak discharge following a theoretical reduction in CN from 78 to 69. Using this theoretical method, a 10% reduction in peak runoff rate could be expected following the adoption of CT on a land area.

Controlled Drainage

A similar literature review of controlled drainage (CD) was conducted. CD uses subsurface hydraulic control structures to moderate shallow groundwater drainage (Figure 2). Control structures would typically be connected to drain tiles and used to control the water table above the elevation of the tile. Depending on the time of year, crop, and conditions the water table could be managed to optimize benefits for crop growth, water quality, and drainage quantity.

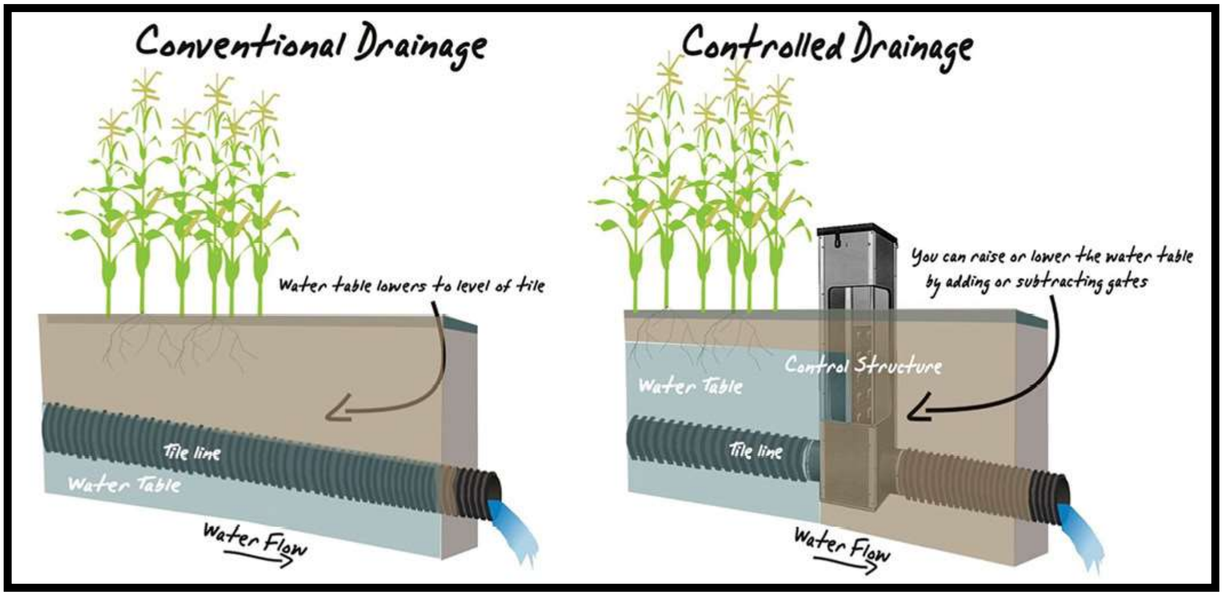

Figure 2. Principle elements of controlled or precision drainage.

Among available research reductions in drainage volume varied substantially from less than 10% to greater than 45% (Helmers et al., 2012; Ross et al., 2016; Wang et al., 2020; Williams et al., 2015); a reduction of 20-30% is realistic. Similar to CT, the reduction in runoff volume needs to be correlated to a reduction in discharge rate; this was accomplished with the same procedure previously discussed for CT. The adoption of CD, therefore, can be assumed to result in 10% reduction in peak discharge from a watershed. Flow rates at a model cross-section determined using the canal design discharge equation were reduced by 10% to represent the adoption of either CT or CD and reduced by 20% to represent the adoption of both CT and CD.

Canal Modifications

Two-stage canals can provide additional capacity by increasing canal cross-sectional area above a certain stage. The second stage area can resemble an artificial floodplain within the existing canal top of bank elevations. The goal is to provide approximately two times the existing channel bankfull width in additional second stage area. Typically, the two-stage area would be added equally to both sides of the canal (Figure 3); however, in areas of confinement or conflicts it can be added to only one side of the canal. The elevation of the second stage is anticipated to be the elevation of flow for approximately a two-year storm event. Therefore, storm flows at or above a two-year event will result in water spilling on to the two-stage floodplain.

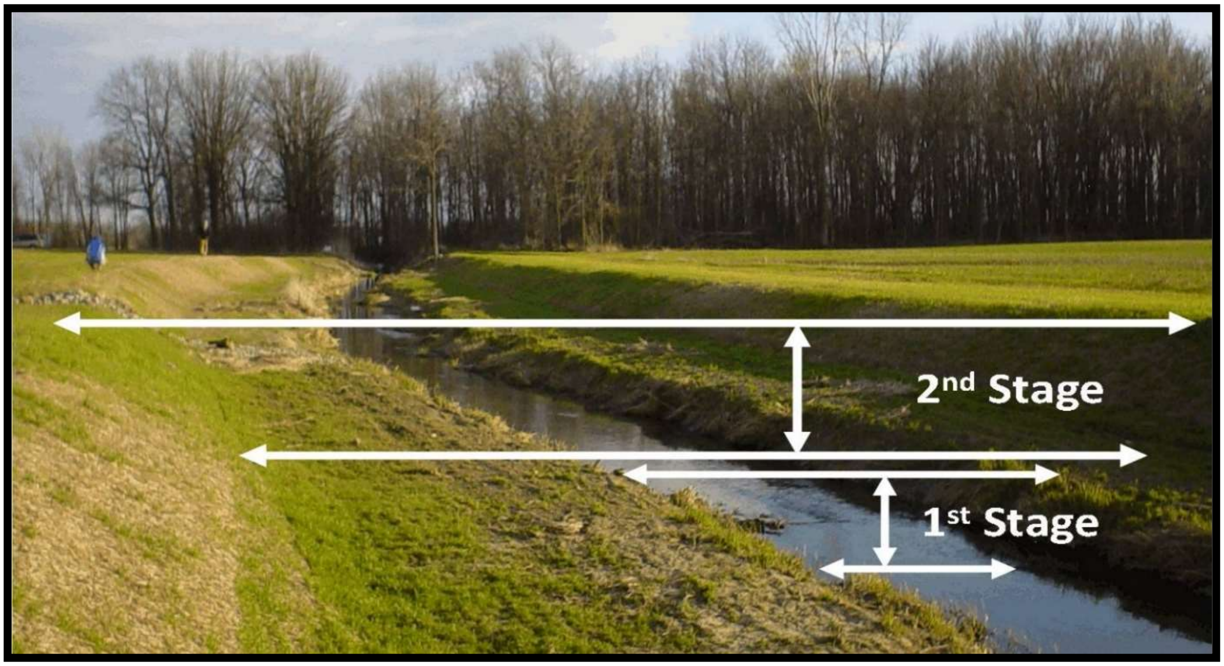

Figure 3. Example of a two-stage canal.

The canals at GR are paralleled on one or both sides by various types of roads (e.g., paved road, dirt road, field road). In all instances, two-stage additions were made only to one side of the canal. In some cases, this still resulted in the loss of or need to move a field road. At each model cross-section, the canal width at top of bank was measured and two times that width was added to one side of the canal where the least impact to roads would take place. The elevation of the second stage was placed at approximately 3.5 feet to 4.5 feet above the canal bed.

Results

GR hydraulic model was not intended to recreate actual storm events or to determine water surface elevations of historical events with accuracy; instead, it was intended to provide an analogous system to which land management and geometric changes could be made in order to observe the effects. The model results, therefore, should not be interpreted as the precise outcomes given adoption of land management changes or canal geometry modifications described herein. Instead, the model results represent a direction and magnitude of change given the adoption of land management changes or canal geometry modifications described herein.

Existing Conditions

Canal bed slopes, generally, consist of a shallower section in the upper reach near the PLNWR border, a steeper section in the mid reaches, followed by a shallower slope in the downstream reach as the canal moves toward the Pungo River (Table 1). Canal bed profile plots illustrate the location and relative magnitude of canal slope changes (Appendix 2: Canal Bed Profile Plots). Canal bed slopes are the steepest as the canals fall from higher elevations on and near the PLNWR toward the Pungo River. The Boerema complex, including Allen and Clayton, experience the steepest fall on Allen and in the mid reach of Boerema; the Ponzer complex, including Evans and De-hoog, experience the steepest fall on Ponzer; and Hyde Park experiences its steepest section in its mid reach. Boerema and Hyde Park appear to experience some flattening and possible negative slope in the downstream reach nearest the Pungo River, possibly due to siltation as the canal experiences tidal influence.

Table 1. Canal bed slopes.

CANAL	UPPER REACH SLOPE (%)	MID REACH SLOPE (%)	DOWN REACH SLOPE (%)
ALLEN	0.05	0.08	0.03
BOEREMA	0.02	0.09	-0.01
CLAYTON	0.03	0.03	0.04
DE-HOOG	0.015	0.003	0.004
EVANS	0.01	0.01	0.01
PONZER	0.08	0.09	0.09
HYDE PARK	0.02	0.05	-0.007

Canal Crossings

Some roadway crossings are unable to convey the design discharge, this causes roadway overtopping and overbank flow in upstream sections of Allen and Hyde Park (Figure 4). This indicates that some culvert crossings are undersized and should be increased in size to allow additional capacity.

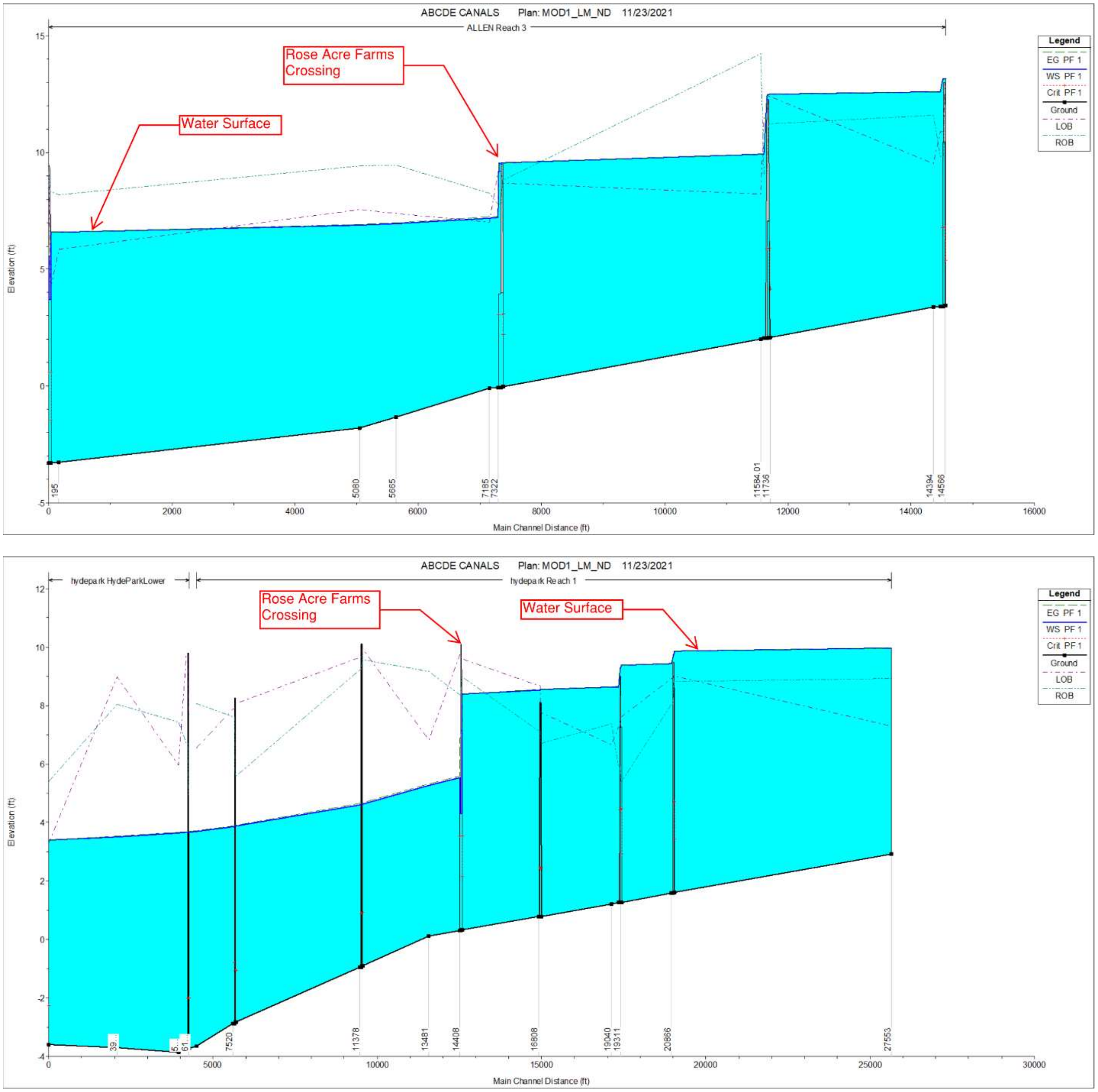

Figure 4. Existing condition model with undersized culverts seen by overtopping of design discharge flow rates Allen (upper) and Hyde Park (lower). All results hereafter will include 7 feet diameter culverts; however, in practice, a bridge crossing performs better. Dashed lines represent canal top of bank; water surface over top of bank lines represents water entering adjacent fields. Vertical lines are canal roadway crossings.

Lower water levels can be observed after the increase of culvert diameters to 7 feet (Figure 5). Efforts have been made in GR to increase the capacity of culverted crossings to prevent flow backups. These efforts will be critical to the success of any additional efforts to reduce flooding or provide additional canal capacity. Modeling results seen hereafter will use culvert diameters of 7 feet for all crossings and will be referred to as the Baseline condition. In reality, if a culvert needs to be upsized to a larger diameter, it would be better to install a bridge instead of a larger culvert.

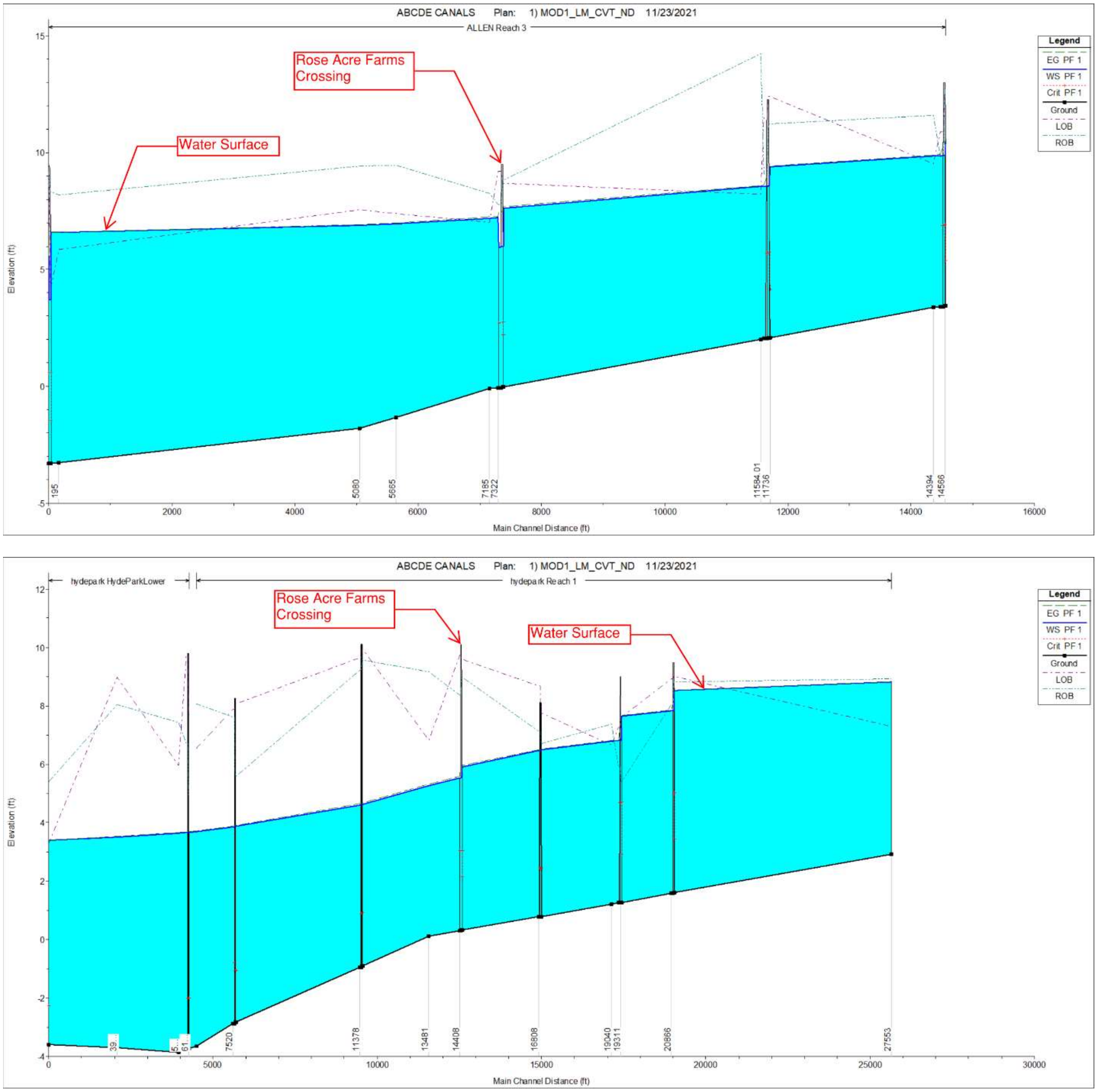

Figure 5. Water surface plot on Allen (upper) and Hyde Park (lower) after all culvert diameters were increased to 7 feet in diameter. Dashed lines represent canal top of bank; water surface over top of bank lines represents water entering adjacent fields. Vertical lines are canal roadway crossings.

Dredging

The downstream reaches of Hyde Park and Boerema were lowered to produce a constant slope of 0.001%. These profiles were used to simulate the effects of dredging on the design discharge water surface elevations (WSE) (Figure 6 & Figure 7). The resulting maximum depth of dredging was approximately 0.75 feet on Boerema and 0.3 feet on Hyde Park. These changes resulted in an approximately 0.3 feet change in the WSE at the location of dredging which diminished as you move upstream (Appendix 3: Effects of Dredging on Boerema and Hyde Park Canal Water Surface Elevations, Table 2). Dredging provides some limited ability to affect WSEs; however, the largest benefits of flood reduction will occur where dredging takes place, in these cases, far downstream near the Pungo River.

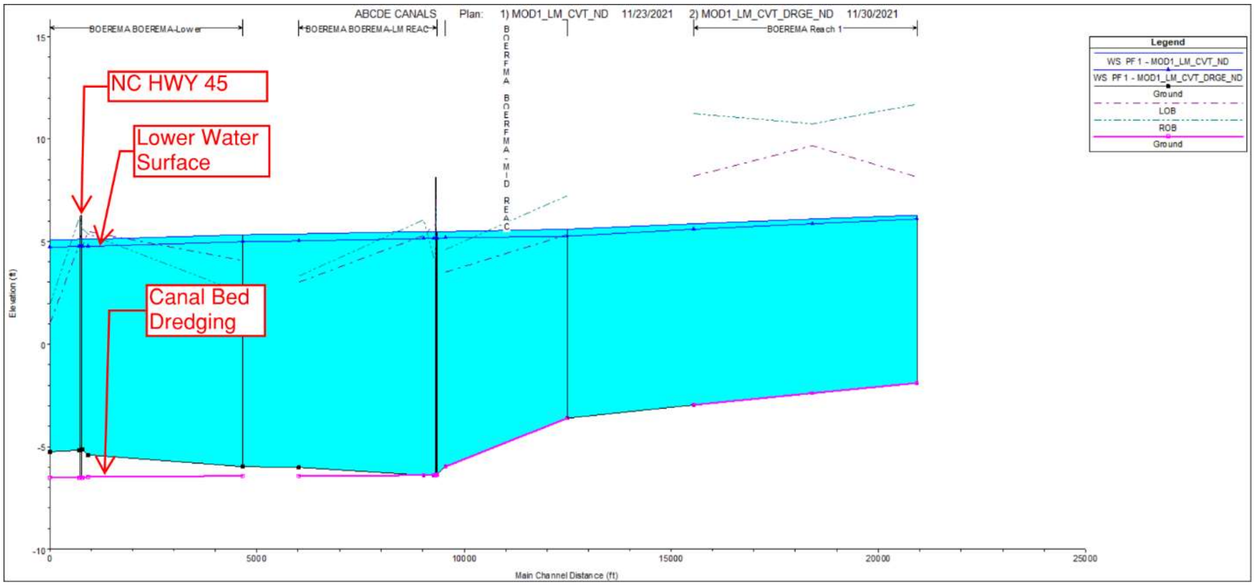

Figure 6. Boerema dredged profile in pink with lower water surface profile as a result. Dashed lines represent canal top of bank; water surface over top of bank lines represents water entering adjacent fields. Vertical lines are canal roadway crossings.

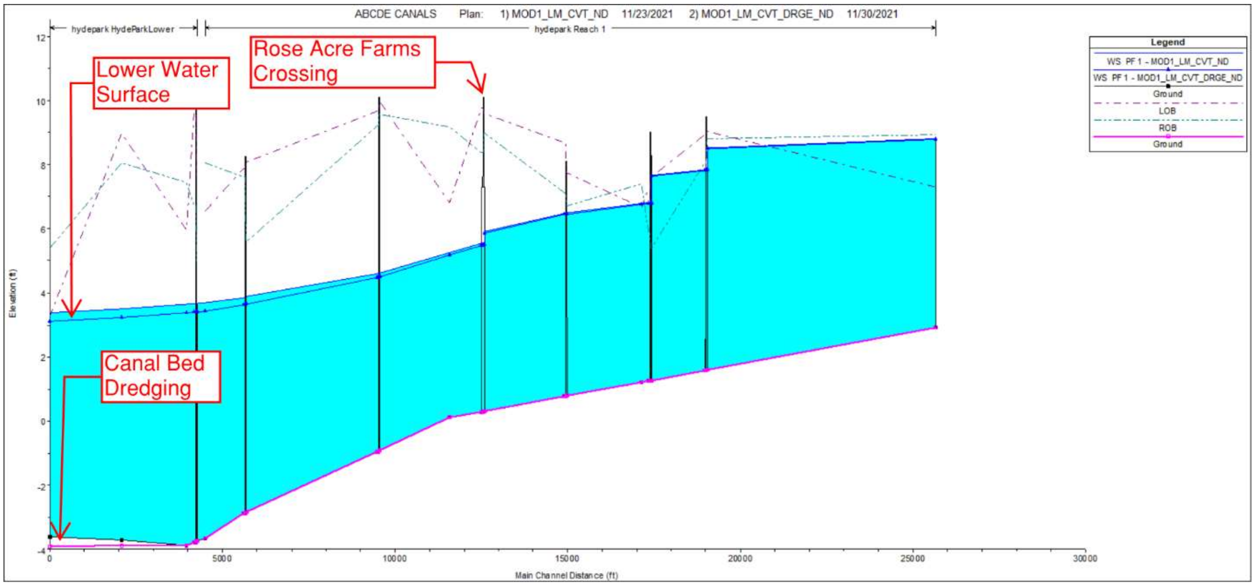

Figure 7. Hyde Park dredged profile in pink with lower water surface profile as a result. Dashed lines represent canal top of bank; water surface over top of bank lines represents water entering adjacent fields. Vertical lines are canal roadway crossings.

Land Management

The land management alternatives are represented by a reduction in the design discharge flow rates of 10% for the adoption of CT or CD and the adoption of CT and CD is represented by a reduction in design discharge flow rates of 20%. Appendix 4: Effects of Land Management on Canal Water Surface

Elevations, Table 3 contains table data of the change in WSE from the baseline condition following the adoption of CT or CD and adoption of CT and CD. Adoption of CT or CD in GR would reduce the canal WSE by approximately 0.5 feet from the baseline condition. Similarly, the adoption of CT and CD in GR canal flow rates would reduce the canal WSE by approximately 0.9 feet from the baseline condition.

These results are most applicable to smaller more frequent events, 1-year, 24-hour (3.3 inch) to 5-year, 24-hour (5.2 inch) return interval storms. As larger, more prolonged events occur the benefits of additional surface or shallow groundwater storage will be diminished and all additional rainfall will be converted to surface runoff. Generally, the runoff rate increases by approximately 20% as you move from one return interval to the next higher event (i.e., 1-year, 24-hour (3.3 inch) to 2-year, 24-hour (4.0 inch) or 10-year, 24-hour (6.2 inch) to 25-year, 24-hour (7.6 inch)); therefore, the ability to reduce canal flow rates by 20% can approximately represent the ability to assimilate one event larger before overbank flooding occurs, but this is only applicable to smaller more frequent events. For example, if a canal's current capacity causes it to overtop following a 1-year, 24-hour storm (3.3 inch), the adoption of CT or CD would allow that canal to receive a 2-year, 24-hour storm (4.0 inch) without overtopping.

Canal Modifications

The benefits of two-stage geometry modifications are experienced at the location where modifications are made and to a lesser, but compounding degree upstream. The flow area created by the two-stage geometry lowers the WSE for a given flow rate and also creates additional total flow capacity inside the canal at the top of bank elevation. Appendix 5: Effects of Two-Stage Canal on Canal Maximum Capacity, Table 4 illustrates the benefit of two-stage geometry over the baseline condition as a percent increase in canal capacity. The increase in canal capacity ranges from 0% to around 230%. The largest capacity increases occur in the Ponzer-Evans-De-hoog canal complex and the mid to low reaches of Hyde Park. The largest increases occur where the canal bed slopes are steeper. Generally, more modest (5-40%) capacity increases occur elsewhere.

Comparisons of canal rating curves between baseline cross-sections and the two-stage cross-sections provide a tool to visualize the increase in capacity at a given WSE. A two-stage cross-section at Allen station 11,645 provides an increase in flow rate of 19% (Figure 8). Similarly, Ponzer station 4,567 has the ability to carry 150% more flow than the baseline model with the addition of a second stage (Figure 9). Rating curves are compared within the top of bank elevations; higher flow rates at lower WSEs represent a potential reduction in flooding magnitude and flood frequency and greater resiliency for GR farm land. Additional rating curves are available in Appendix 6: Rating Curves.

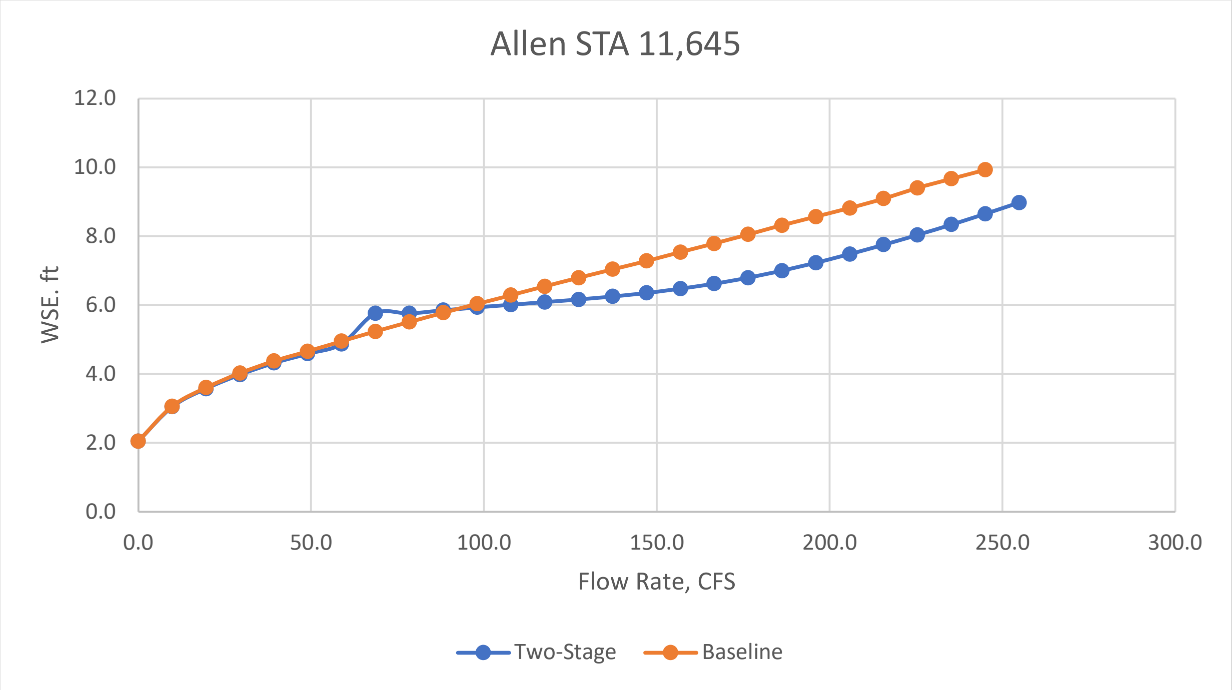

Figure 8. Allen STA 11,645 comparison of rating curves from the baseline model cross-section and the two-stage model cross-section. The two-stage canal has the ability to carry 19% more flow within the canal top of bank elevations than the baseline model.

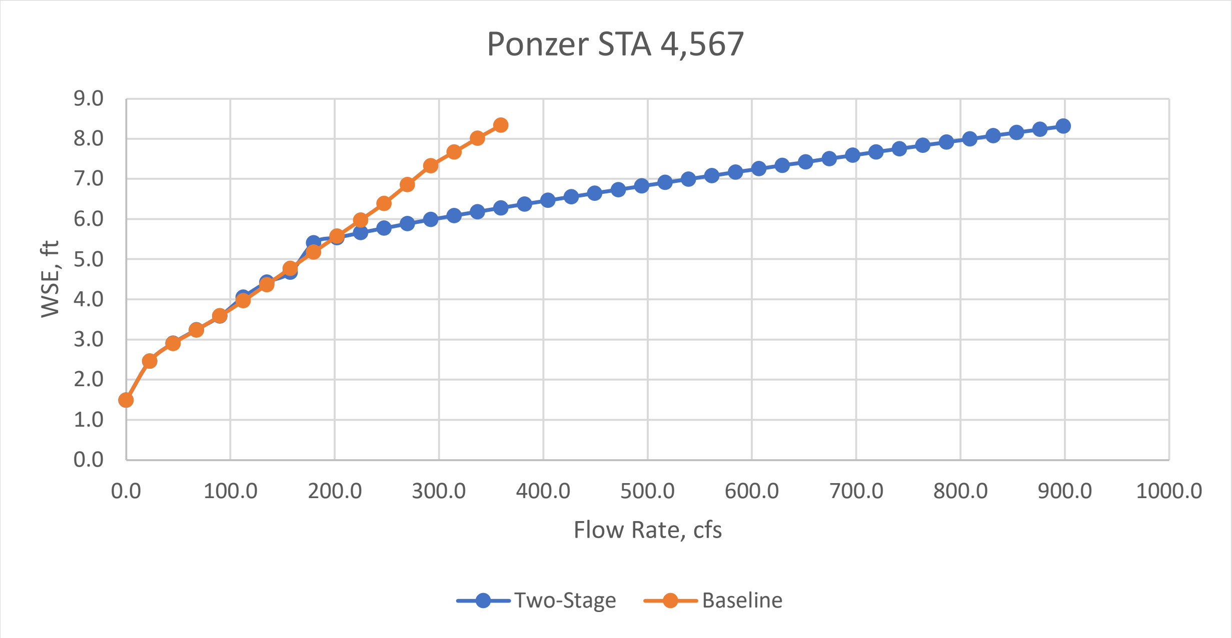

Figure 9. Ponzer STA 4,567 comparison of rating curves from the baseline model cross-section and the two-stage model cross-section. The two-stage canal has the ability to carry 150% more flow within the canal top of bank elevations than the baseline model.

Discussion

Roadway crossings in GR create hydraulic pinch points. Undersized culverts limit the canals' flow capacity and cause water to back-up, overtop banks, and enter adjacent fields. In some locations levees adjacent to fields may prevent water from reentering the canals resulting in prolonged field saturation. Efforts throughout the region to increase the capacity of roadway crossings should continue. The results herein were simulated using culvert diameters no smaller than 7 feet. In locations where culvert diameters are to be increased, installation of a bridge should be considered. Bridges provide improved capacity, are less susceptible to obstruction, and are less prone to damage. Eliminating hydraulic pinch points will be critical to achieving the greatest flood reduction benefits from any additional flood reduction measures undertake.

Dredging the canal bed in downstream sections of Boerema and Hyde Park to ensure a positive slope of 0.001% resulted in minor reductions, approximately 0.3 feet, in the WSE at the design discharge. While dredging appears to have some limited ability to lower the WSE at the location where dredging occurs and to a lesser extent upstream, the bed slope in these areas is likely the result of natural, fluvial geomorphic processes related to the energy and sediment content of the canal in these locations. Attempts to dredge and increase capacity would, therefore, become a recurring process needed to maintain canal capacity. In addition to the limited benefits gained from dredging, regulatory approval for dredging in the lower reaches and disposal of dredge materials presents serious challenges that make dredging less desirable than other more secure alternatives.

Land management alternatives such as CT and CD represent realistic opportunities for farm managers to increase their resilience to flooding events by reducing surface runoff or controlling shallow groundwater discharge. The flood reduction benefits would be accompanied by ancillary benefits such as increased drought resistance, carbon sequestration and increased soil organic carbon, reduced soil erosion, and increased yields (Busari et al., 2015; Crozier & Brake, 1999; Duiker & Myers, n.d.; Endale et al., 2014; Helmers et al., 2012; Raczkowski et al., 2009; Ross et al., 2016; Wang et al., 2020; Williams et al., 2015; Wuest et al., n.d.). Together these benefits can sustain agricultural production for future generations and improve the resiliency of this highly productive farming region.

Management of shallow groundwater discharge and its effect on canal flows could likely be observed relatively quickly following the adoption of CD; however, the capital investments in tile drainage systems (currently in limited use) and hydraulic control structures would likely mean adoption would be slow. Similarly, adoption of CT methods would require managers to acquire new equipment with the full benefits of reduced runoff and improved soil quality taking several years to mature (Duiker & Myers, n.d.). Additionally, widespread adoption of either CT or CD would be required to achieve a modest canal flow reduction of around 10%. These methods should be encouraged and adoption can benefit farm and regional resiliency, but they are likely only a component of and not the major component of a flood reduction strategy.

Two-stage canal modifications offer the opportunity to produce moderate to substantial reductions in flood magnitude both at the location of installation and upstream. In this way, seemingly unused land, redundant roads, or flood prone areas adjacent to canals could be converted to two-stage floodplain and produce measurable increases in canal capacity. Additionally, areas which experience the most frequent or highest magnitude flooding can be targeted as initial implementations of two-stage geometry. If the proposed land for two-stage floodplain was previously occupied by cropped land, the potential crop loss in these areas can be avoided while providing more robust protection for adjacent croplands and croplands upstream.

Two-stage implementation should (1) target property and land managers interested in reducing flooding on properties adjacent to a canal, (2) then target the most flood prone areas in the canal complex where canal characteristics may be exacerbating the flooding conditions (e.g., a low bank allows canal flow to enter a field, but minimizes its ability to reenter the canal). Benefits will be experienced upon the completion of the canal modification. Efforts should then continue working upstream. The flood reduction benefits will compound moving upstream as additional two-stage modifications are made. On Boerema, two-stage modifications much below the confluence with Clayton may provide minimal benefit, so efforts should likely be focused upstream of this area. Hyde Park and the Ponzer-Evans-Dehoog complex experience the greatest benefits in the downstream reaches; therefore, efforts should begin downstream and work upstream. The best two-stage canal modification will include a detailed design and analysis that will limit the loss of existing cropland, improve yields on remaining cropland, ensure existing canal crossing hydraulics do not limit the potential benefits, and still allow long term canal access. Based on our observations along these canals, there are many opportunities to provide all the benefits of this technique without sacrificing productivity.

Conclusions

Grassy Ridge (GR) is an area of rich farm land located in Hyde County in eastern North Carolina, just north of the Pungo River and south of the Pocosin Lakes National Wildlife Refuge (PLNWR). The PLNWR and agricultural lands in GR are drained by a network of canals and lateral ditches. Flooding of croplands has prompted efforts to improve the conveyance of rainfall runoff from the area. Kris Bass Engineering (KBE) was contracted to expand upon previous work in the region and use hydraulic modeling to assess the feasibility of several methods for flood reduction.

KBE developed a hydraulic model using field collected and digitally available data. Modeling efforts studied the affects of canal crossings, dredging in downstream reaches, the effects of land management practices on flood magnitudes, and the effects of canal conversion to two-stage geometries. Canal crossing improvements can provide local reductions of canal WSE. Upstream of undersized canals, flow back-ups lead to in-field flooding. Increasing culvert sizes to at least 7 feet in diameter is preferable; however, the use of full-span bridge crossings would be best. Dredging shows some limited ability to reduce canal WSE locally and less upstream. This would become a recurring process, needing to be repeated as sedimentation occurred and is likely not a sustainable long-term solution.

Land management alternatives such as conservation tillage (CT) and conservation drainage (CD) provide an opportunity to reduce surface runoff and shallow groundwater drainage by as much as 20% while improving runoff quality and reducing in-field erosion. Additionally, CT will improve soil organic carbon, soil tilth, and increase drought resistance. These ancillary benefits will improve farm resiliency in the face of climate uncertainty while reducing the risk of flooding. The full benefits of these practices will require several years of implementation and wide spread adoption to reach maturation while requiring capital investment in new farm equipment, education and technology.

Two-stage canals provide the most direct opportunity to decrease flood magnitudes and increase canal capacity. Canal modifications to create a second stage floodplain inside the existing top of bank elevations will create flood reduction benefits at the location of implementation and upstream. Starting on the property of interested landowners or locations where flooding occurs most frequently, flood prone areas can be targeted for two-stage modifications, while simultaneously reducing flood magnitude and increasing canal capacity. Working upstream, the creation of additional two-stage geometry will compound the benefits of canal modifications.

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Appendix 1: Grassy Ridge Modeling Cross-Sections Map

Grassy Ridge Modeling Cross Sections

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Appendix 2: Canal Bed Profile Plots

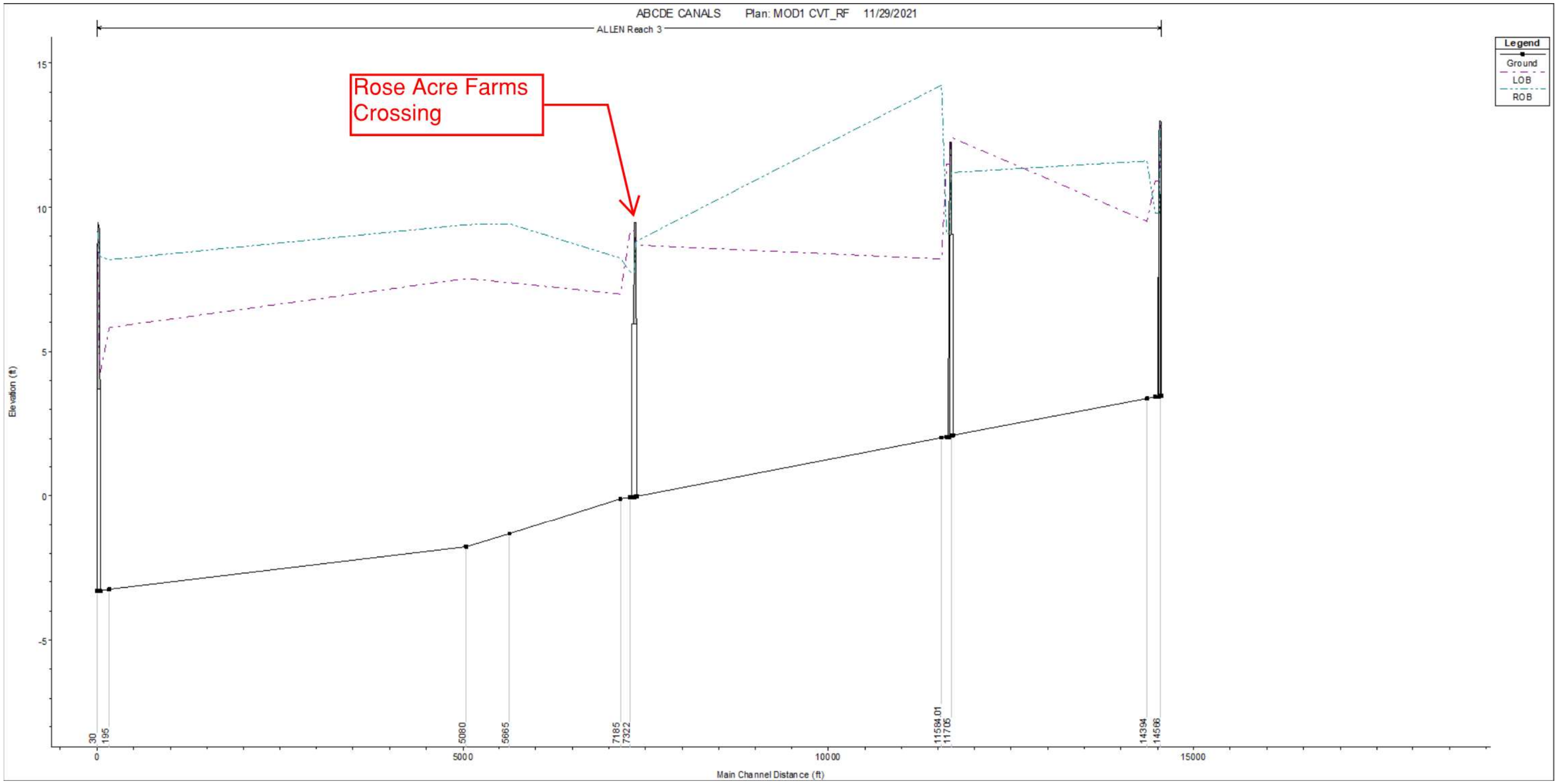


Figure 10. Allen canal bed profile. Dashed lines represent canal top of bank. Vertical lines are canal roadway crossings.

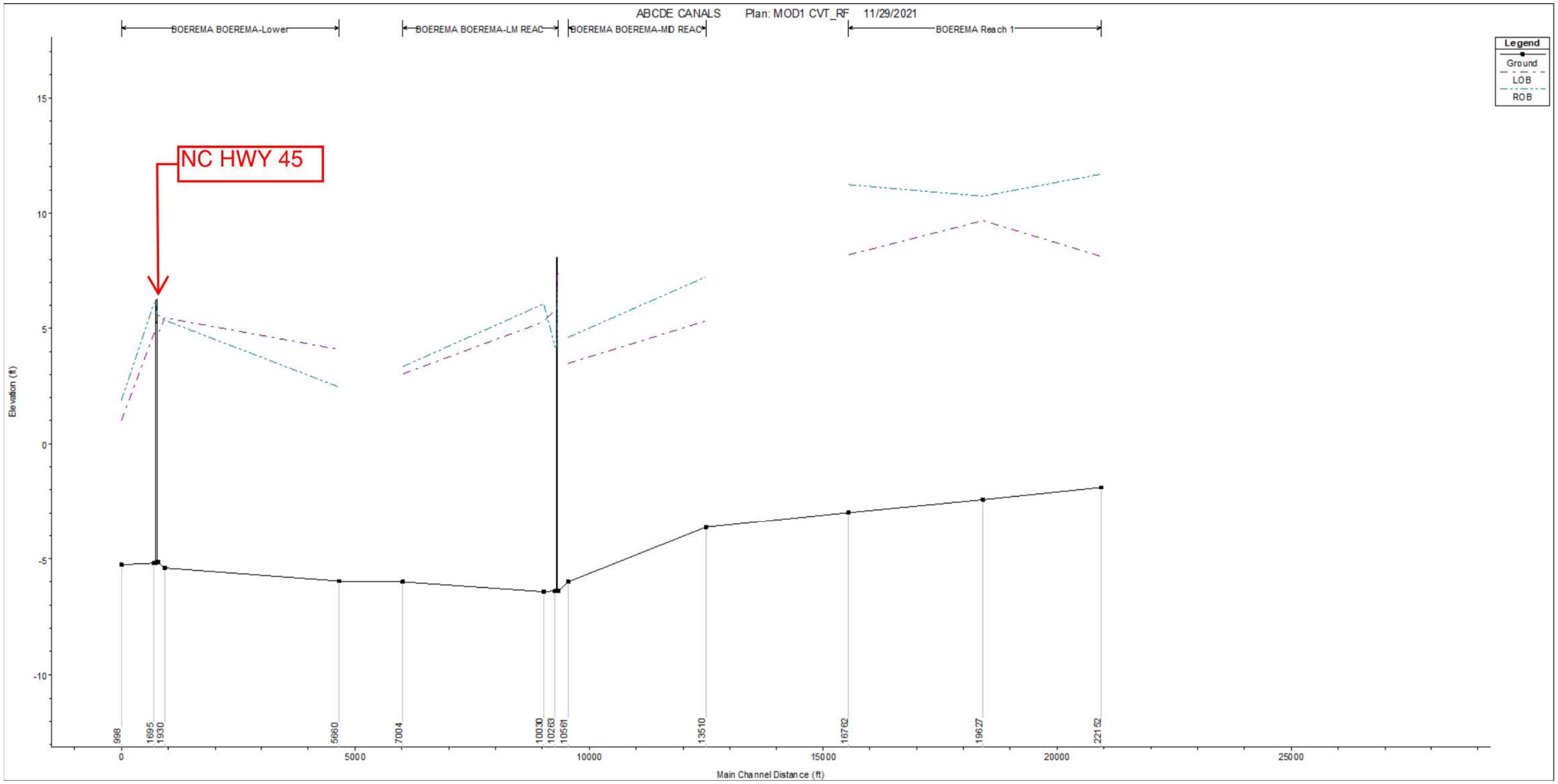


Figure 11. Boerema canal bed profile. Dashed lines represent canal top of bank. Vertical lines are canal roadway crossings.

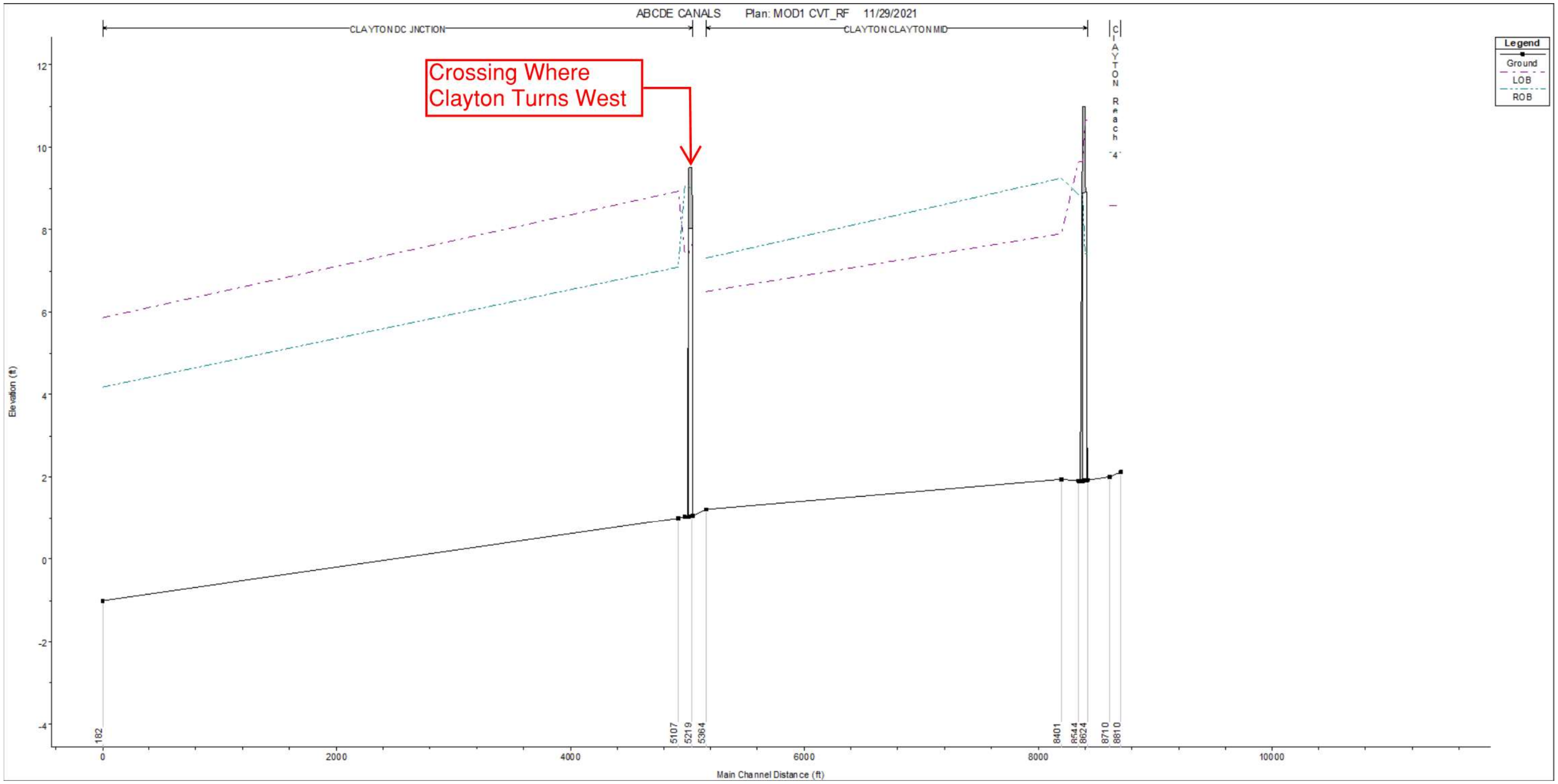
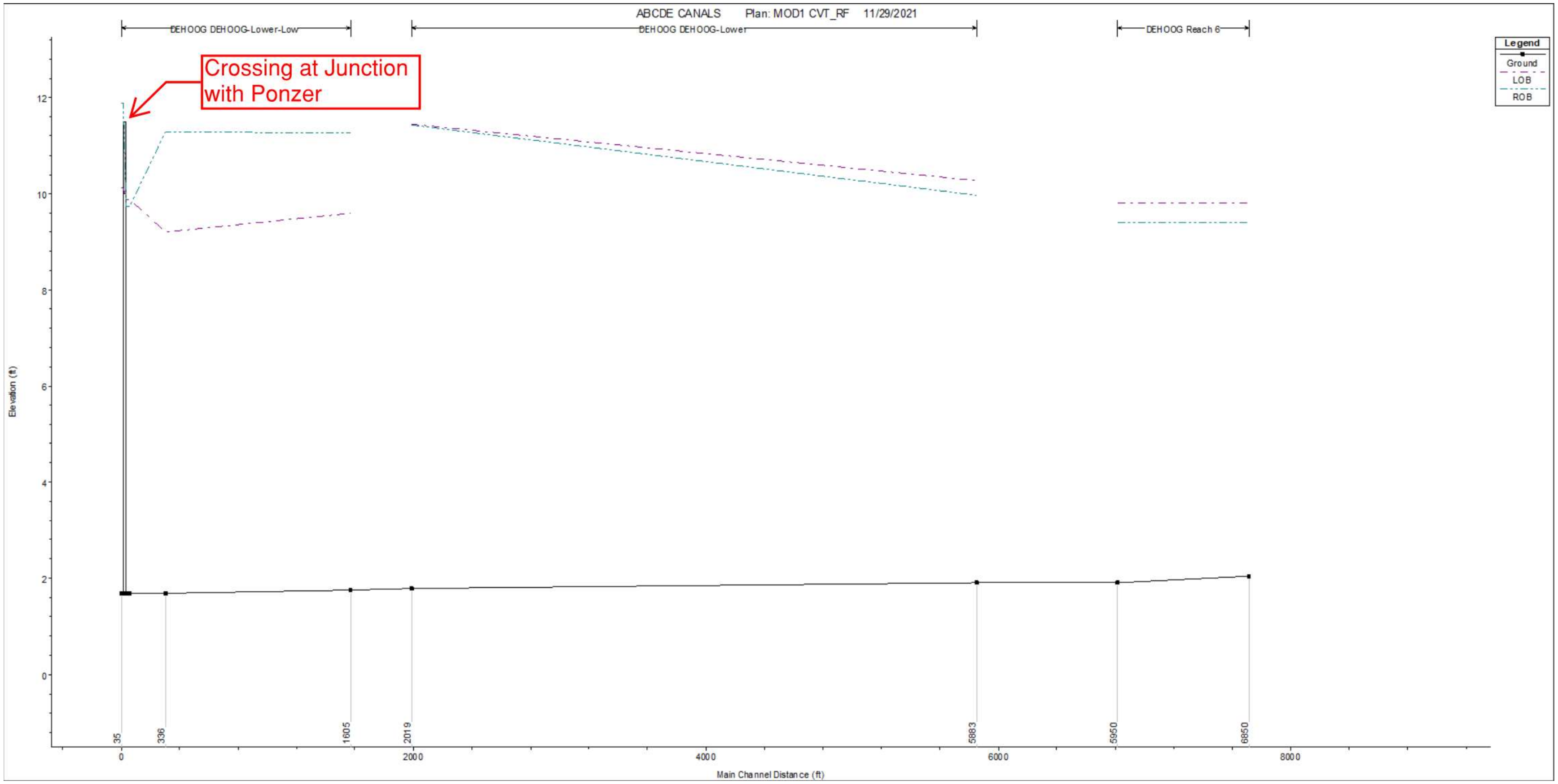


Figure 12. Clayton canal bed profile. Dashed lines represent canal top of bank. Vertical lines are canal roadway crossings.



Crossing at Junction with Ponzer

Figure 13. De-hoog canal bed profile. Dashed lines represent canal top of bank. Vertical lines are canal roadway crossings.

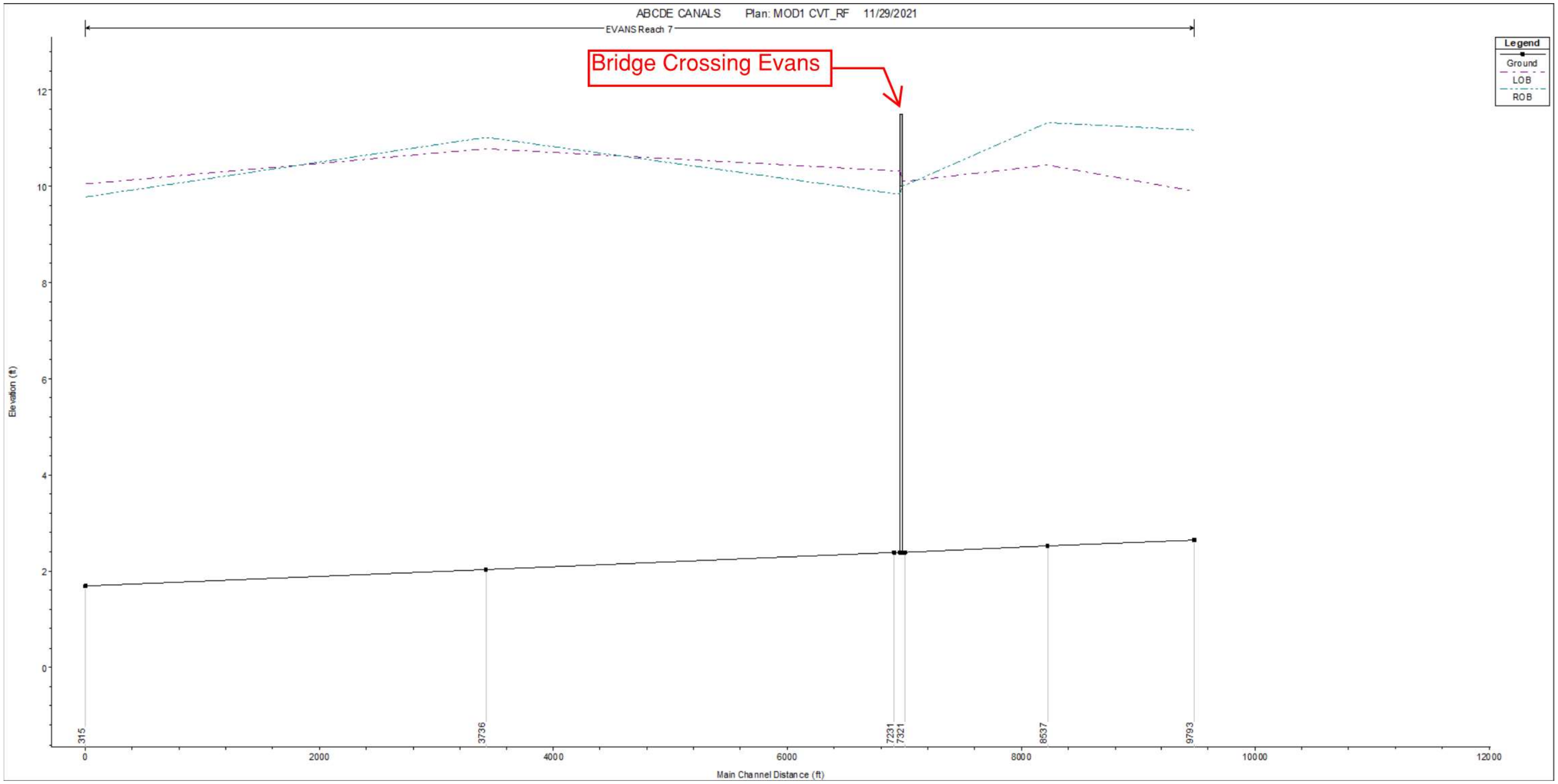
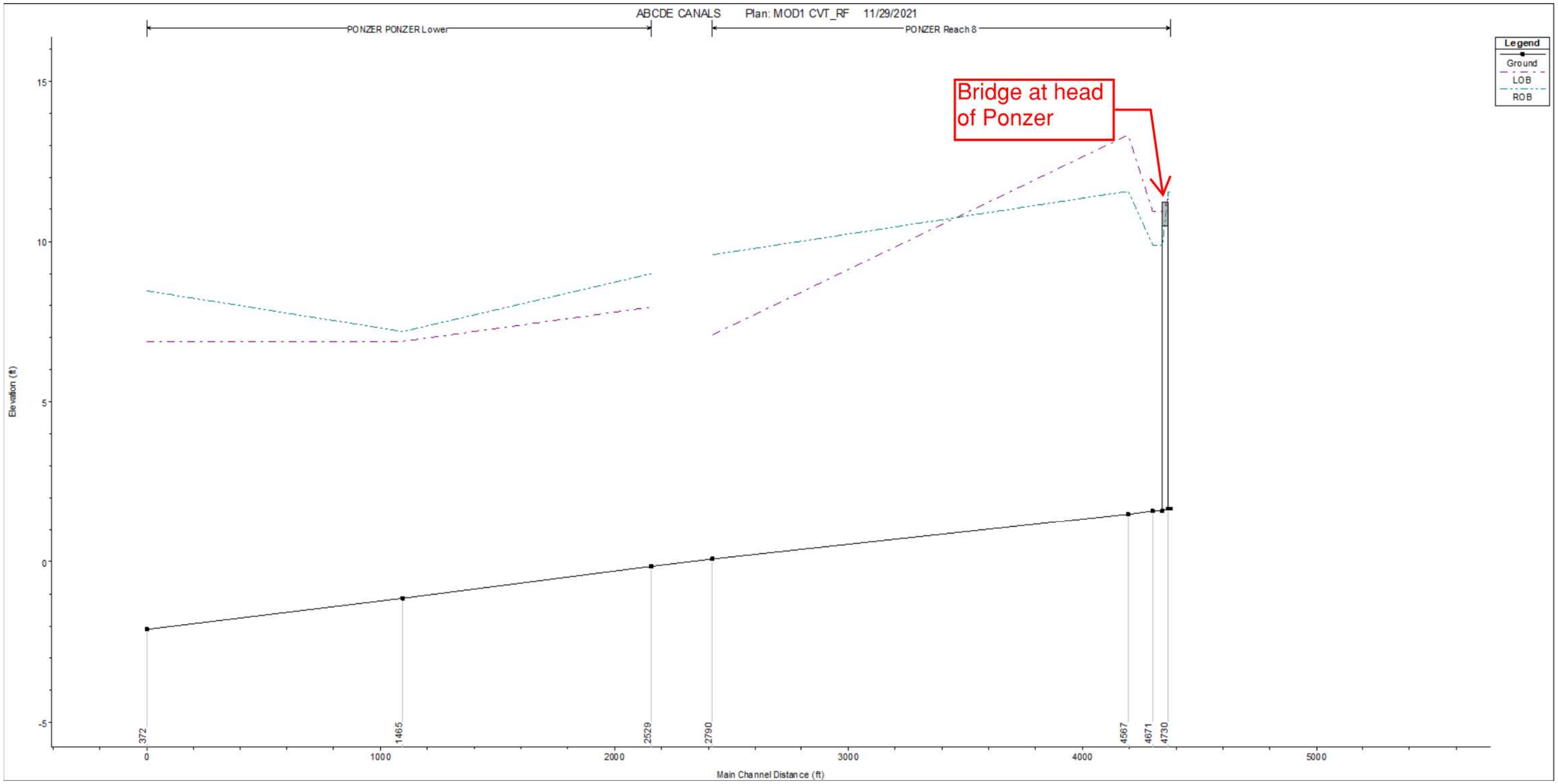


Figure 14. Evans canal bed profile. Dashed lines represent canal top of bank. Vertical lines are canal roadway crossings.



Bridge at head of Ponzer

Figure 15. Ponzer canal bed profile. Dashed lines represent canal top of bank. Vertical lines are canal roadway crossings.

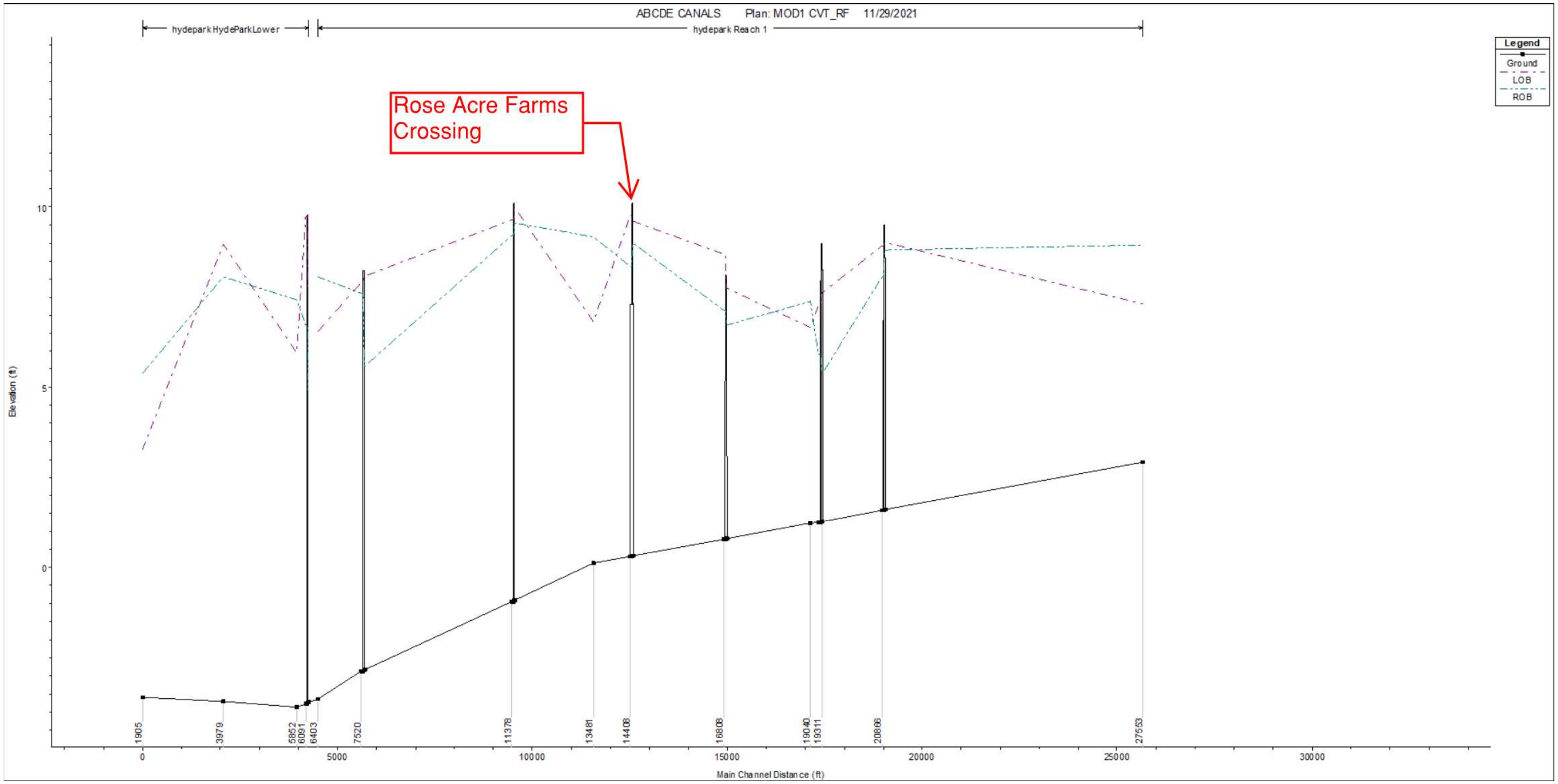


Figure 16. Hyde Park canal bed profile Dashed lines represent canal top of bank. Vertical lines are canal roadway crossings.

Appendix 3: Effects of Dredging on Boerema and Hyde Park Canal Water Surface Elevations

Table 2. Change in WSE on the Boerema complex and Hyde Park after dredging of the downstream reach to create a slope of 0.001%.

REACH	STATION	WSE CHANGE (FT)
ALLEN	**14394**	**0.07**
ALLEN	**11645**	**0.13**
ALLEN	**7322**	**0.22**
ALLEN	**7185**	**0.23**
ALLEN	**5665**	**0.27**
ALLEN	**5080**	**0.28**
ALLEN	**195**	**0.31**
CLAYTON	**8401**	**0.03**
CLAYTON	**5364**	**0.04**
CLAYTON	**5159**	**0.04**
CLAYTON	**5107**	**0.04**
CLAYTON	**182**	**0.34**
BOEREMA	**16762**	**0.27**
BOEREMA	**13510**	**0.32**
BOEREMA	**10561**	**0.34**
BOEREMA	**10263**	**0.33**
BOEREMA	**1930**	**0.34**
HYDE PARK	**20866**	**0.02**
HYDE PARK	**19040**	**0.03**
HYDE PARK	**13481**	**0.08**
HYDE PARK	**7520**	**0.24**
HYDE PARK	**5852**	**0.26**
HYDE PARK	**3979**	**0.28**
HYDE PARK	**1905**	**0.28**

Appendix 4: Effects of Land Management on Canal Water Surface Elevations

Table 3. Reductions in water surface elevations following adoption of CT or CD (10% reduction in flow) and adoption of CT and CD (20% reduction in flow) from the baseline model.

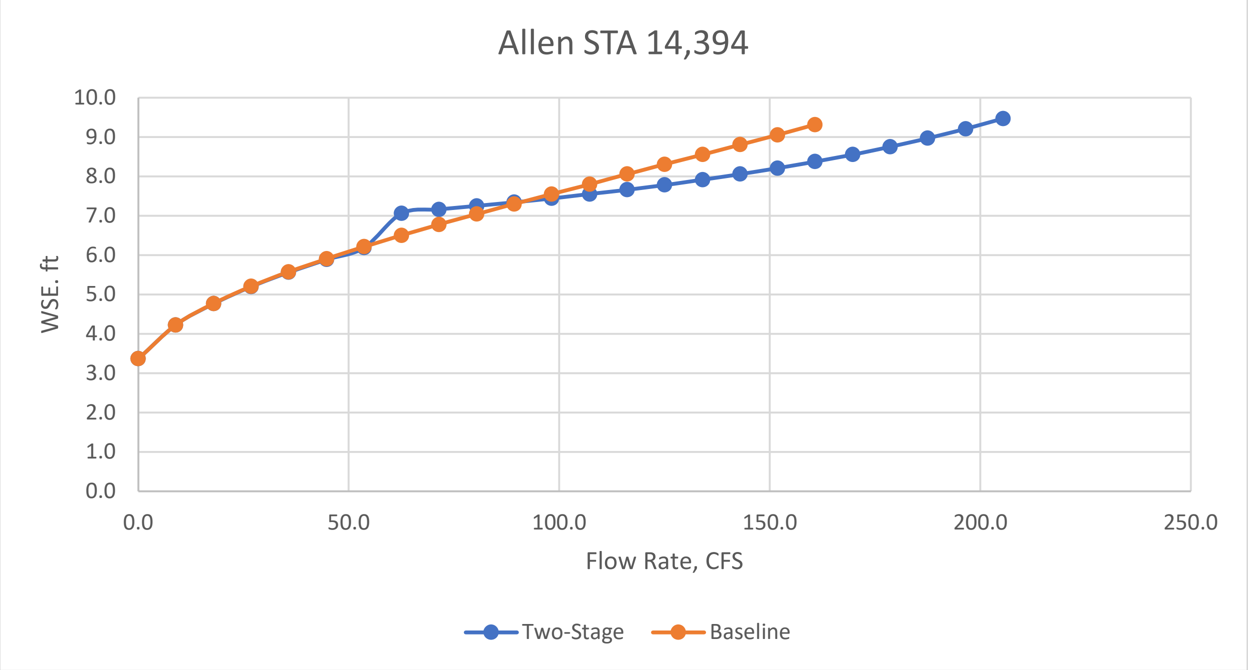
REACH	STATION	CT OR CD (10% FLOW RED.) WSE REDUCTION (FT)	CT AND CD (20% FLOW RED.) WSE REDUCTION (FT)
ALLEN	14394	0.52	1.03
ALLEN	11645	0.52	1.03
ALLEN	7322	0.56	1.12
ALLEN	7185	0.56	1.13
ALLEN	5665	0.58	1.15
ALLEN	5080	0.58	1.16
ALLEN	195	0.59	1.18
CLAYTON	8401	0.45	0.89
CLAYTON	5364	0.49	0.98
CLAYTON	5159	0.3	0.63
CLAYTON	5107	0.3	0.62
CLAYTON	182	0.41	0.83
BOEREMA	16762	0.4	0.84
BOEREMA	13510	0.4	0.82
BOEREMA	10561	0.41	0.82
BOEREMA	10263	0.4	0.82
BOEREMA	1930	0.38	0.78
DE-HOOG	5950	0.45	1.03
DE-HOOG	5883	0.46	1.04
DE-HOOG	1605	0.47	1.1
DE-HOOG	336	0.47	1.12
EVANS	7231	0.42	0.98
EVANS	3736	0.48	1.09
PONZER	4567	0.47	1.13
PONZER	2790	0.48	1.16
PONZER	1465	0.47	1.16
PONZER	372	0.48	1.17
HYDE PARK	20866	0.41	0.81
HYDE PARK	19040	0.34	0.69
HYDE PARK	13481	0.34	0.71
HYDE PARK	7520	0.41	0.84
HYDE PARK	5852	0.41	0.83
HYDE PARK	3979	0.41	0.84
HYDE PARK	1905	0.41	0.84

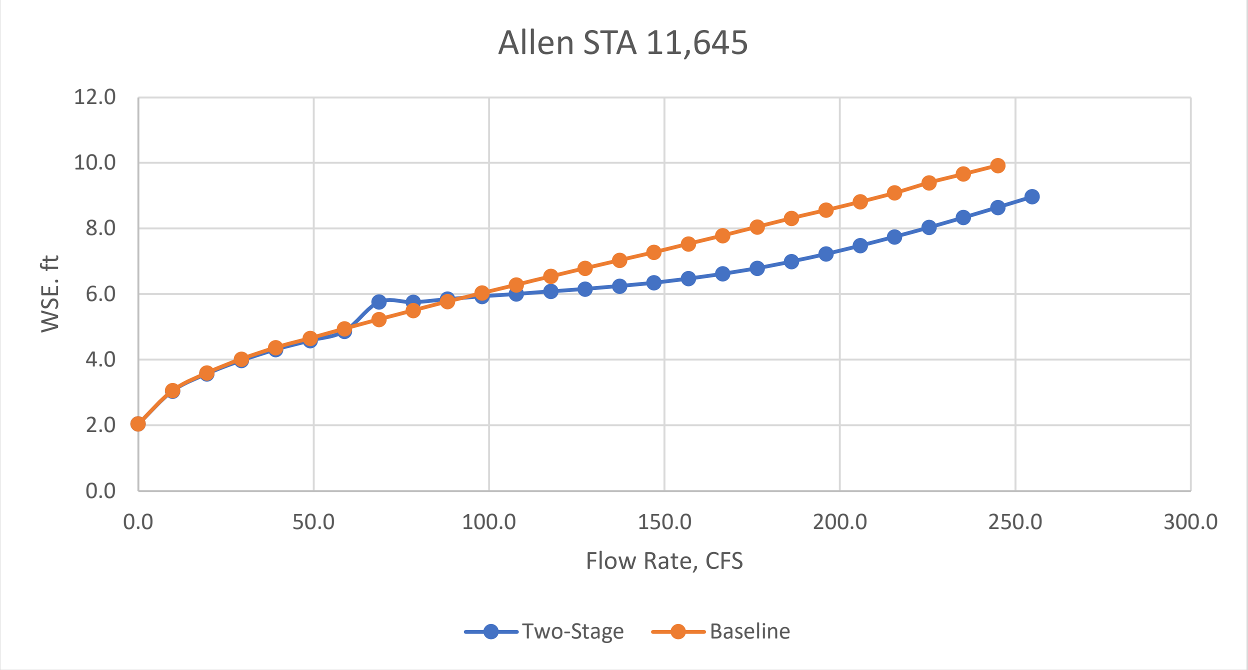
Appendix 5: Effects of Two-Stage Canal on Canal Maximum Capacity

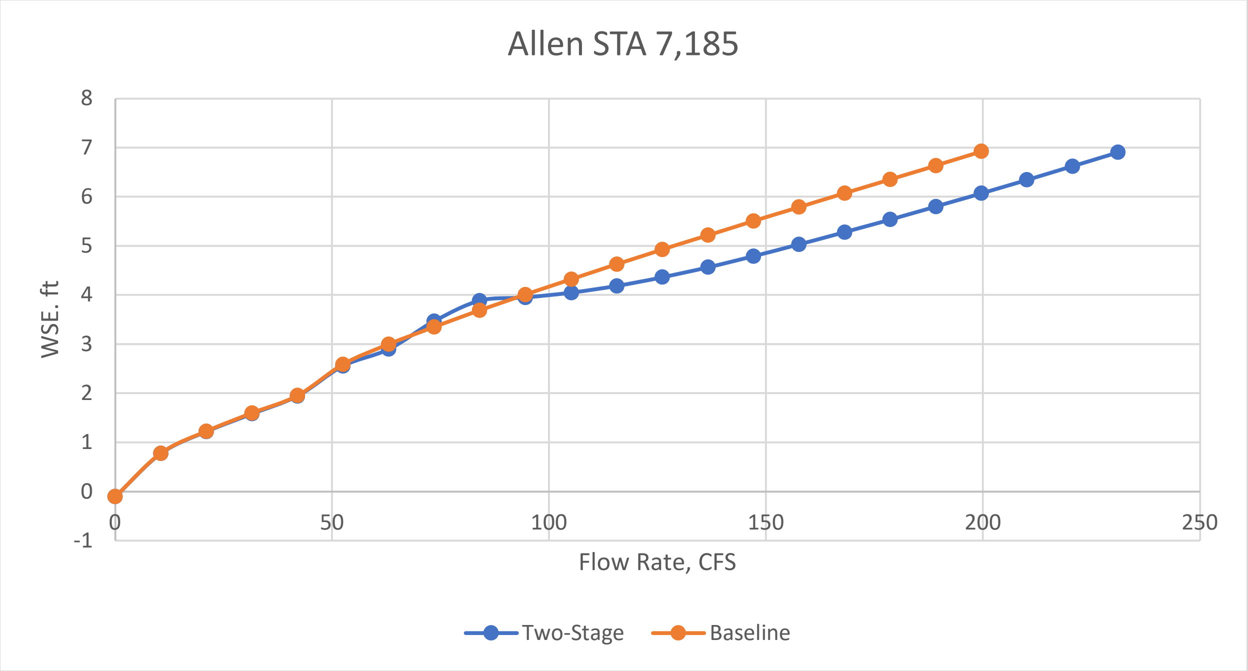
Table 4. Canal Capacity increase (%) over baseline model via the addition of two-stage geometry.

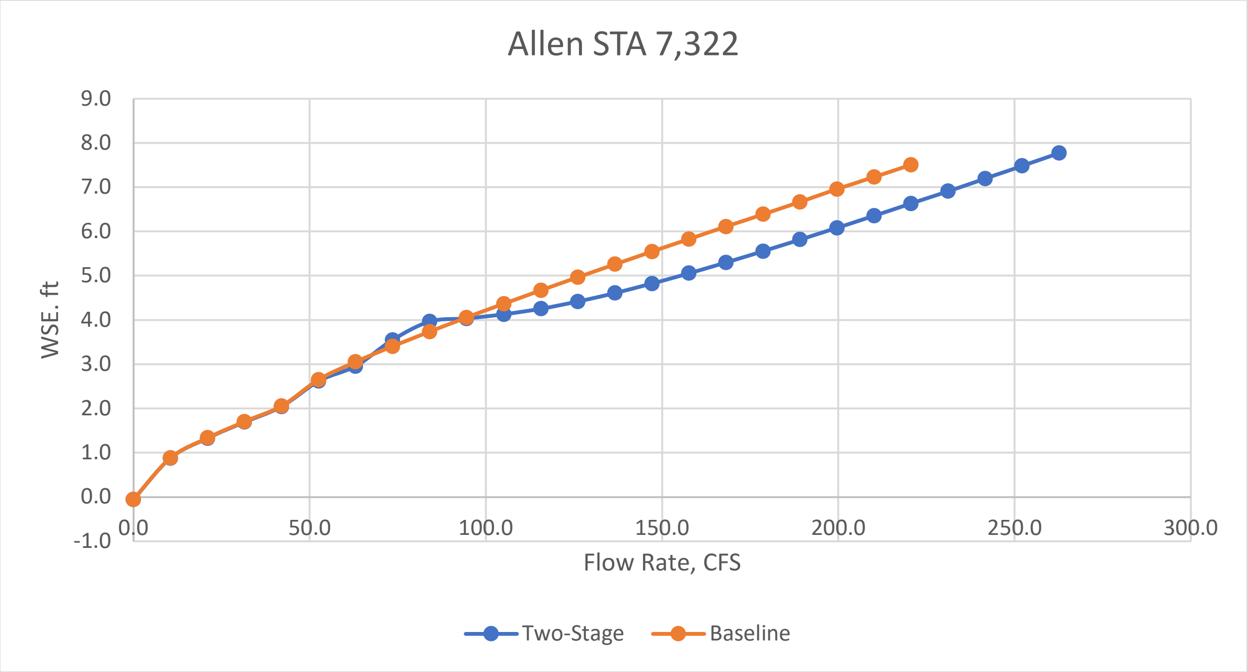
REACH	STATION	CANAL CAPACITY INCREASE (%)
ALLEN	14394	27.8
ALLEN	11645	18.2
ALLEN	7322	19.0
ALLEN	7185	15.8
ALLEN	5665	9.5
ALLEN	5080	9.1
ALLEN	195	5.9
CLAYTON	8401	23.0
CLAYTON	5364	0.0
CLAYTON	5159	42.1
CLAYTON	5107	41.2
CLAYTON	182	7.7
BOEREMA	16762	9.1
BOEREMA	13510	5.6
BOEREMA	10561	10.0
BOEREMA	10263	7.7
BOEREMA	1930	0.0
DE-HOOG	5950	37.5
DE-HOOG	5883	33.4
DE-HOOG	1605	135.3
DE-HOOG	336	135.3
EVANS	7231	137.4
EVANS	3736	135.3
PONZER	4567	150.0
PONZER	2790	153.9
PONZER	1465	175.0
PONZER	372	161.5
HYDE PARK	20866	14.3
HYDE PARK	19040	10.5
HYDE PARK	13481	114.8
HYDE PARK	7520	187.2
HYDE PARK	5852	217.3
HYDE PARK	3979	227.8
HYDE PARK	1905	89.5

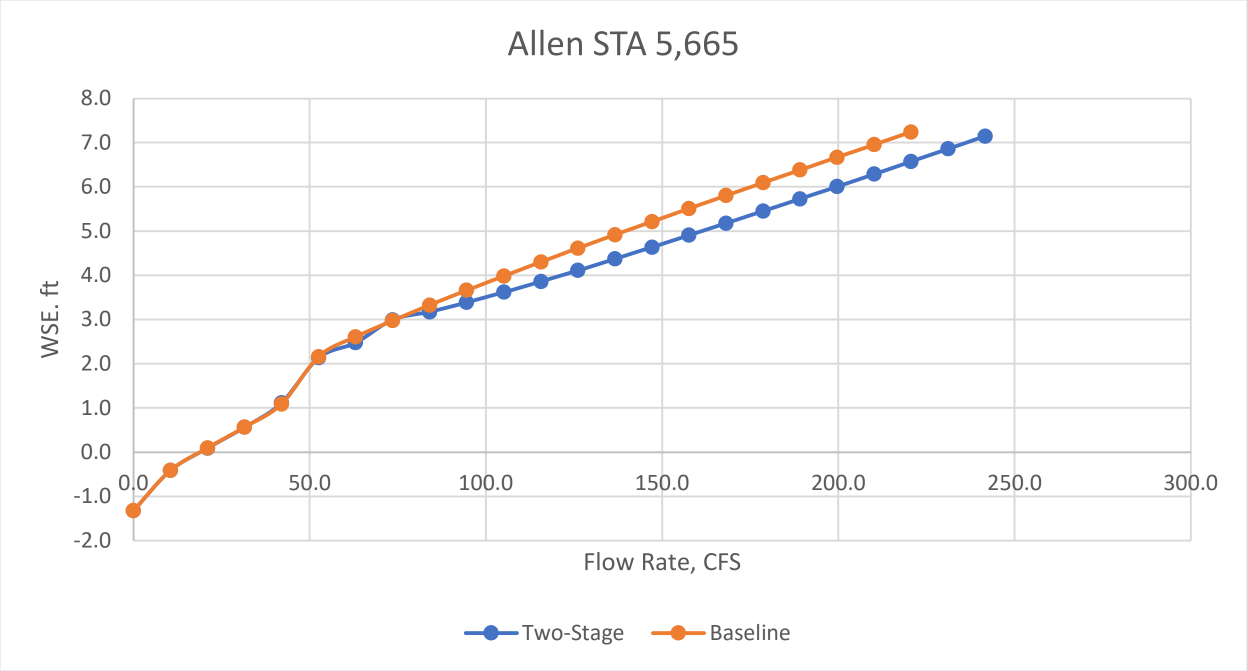
Appendix 6: Rating Curves

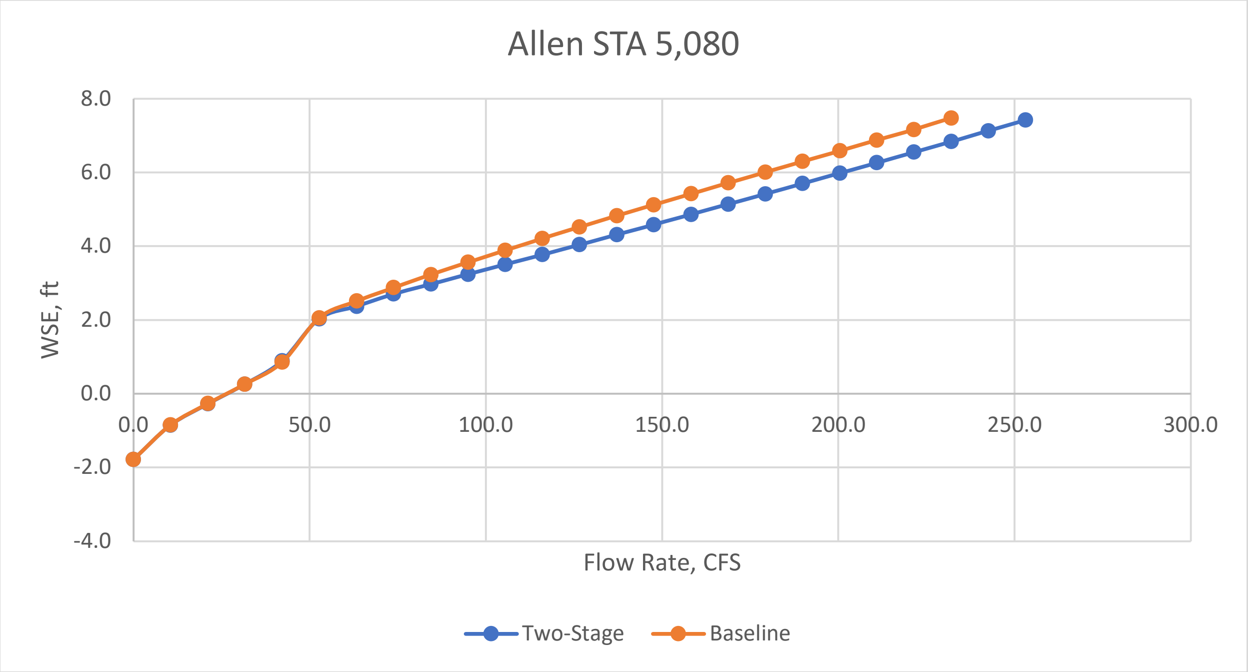


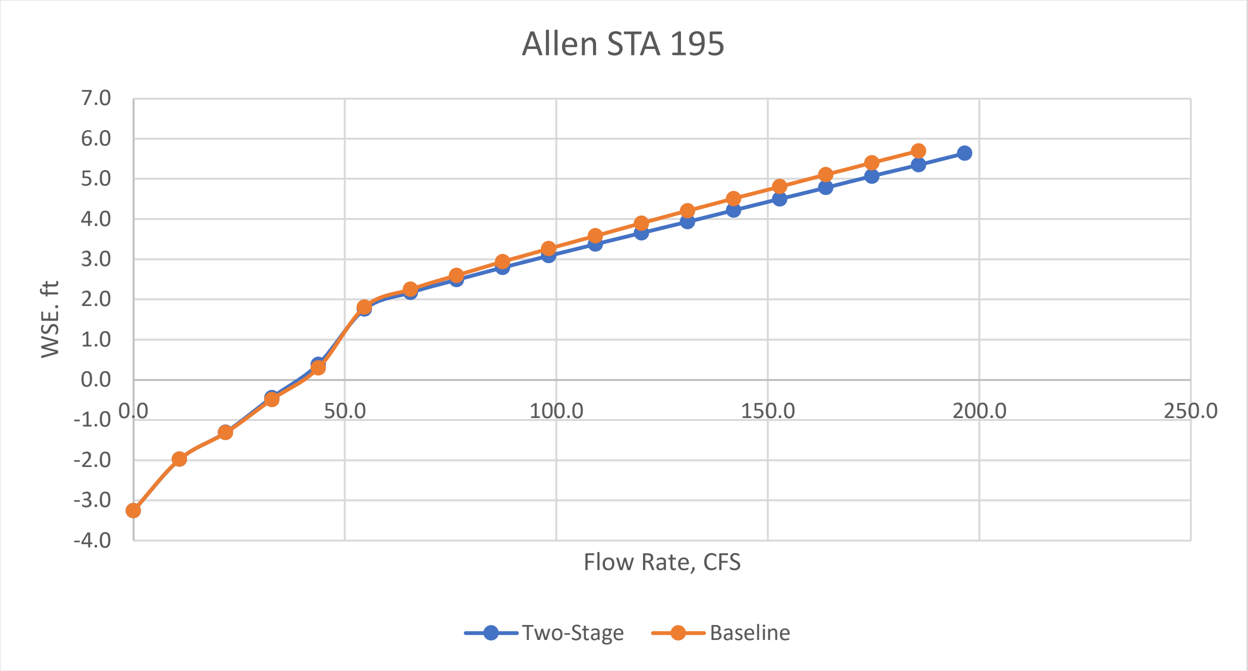


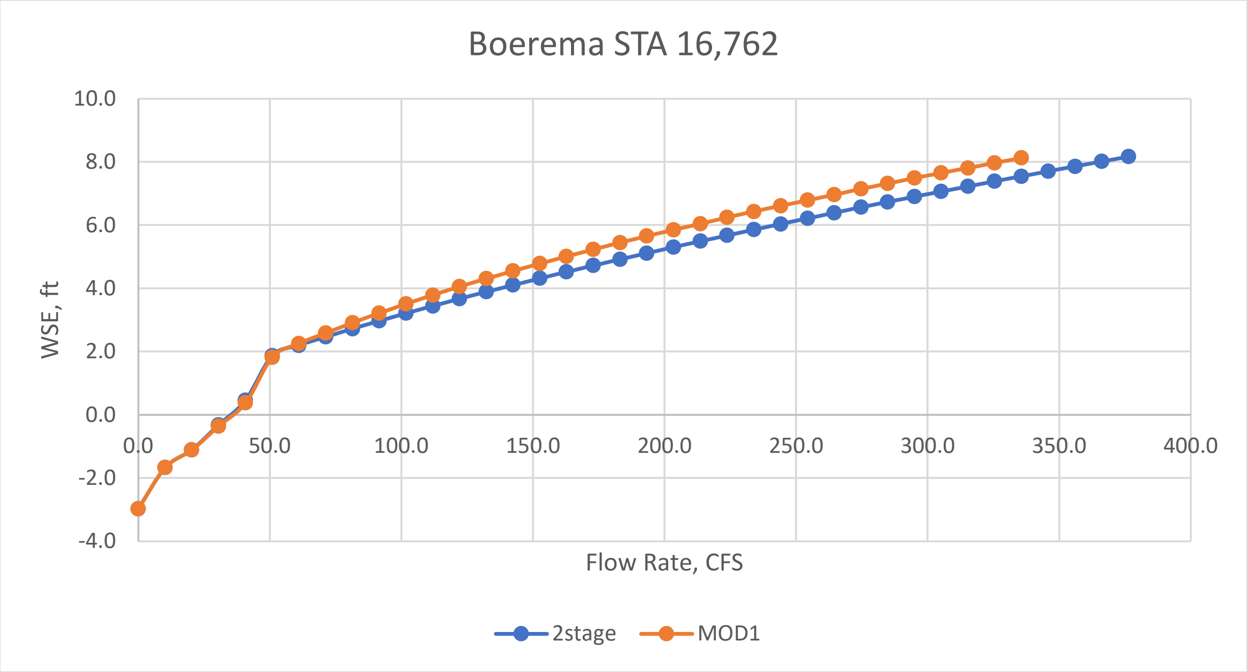

Allen STA 7,185
WSE. ft
8
7
6
5
4
3
2
1
0
-1
0
50
100
150
200
250
Flow Rate, CFS
Two-Stage
Baseline

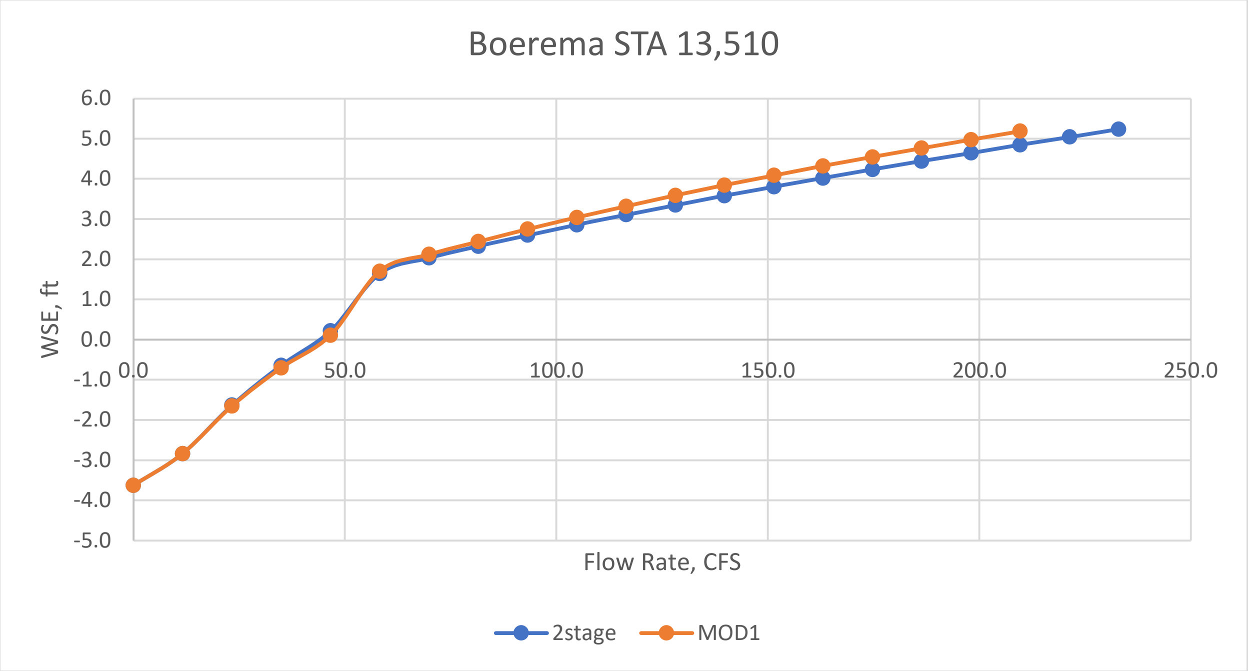

Allen STA 7,322
WSE. ft
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
Flow Rate, CFS
Two-Stage
Baseline

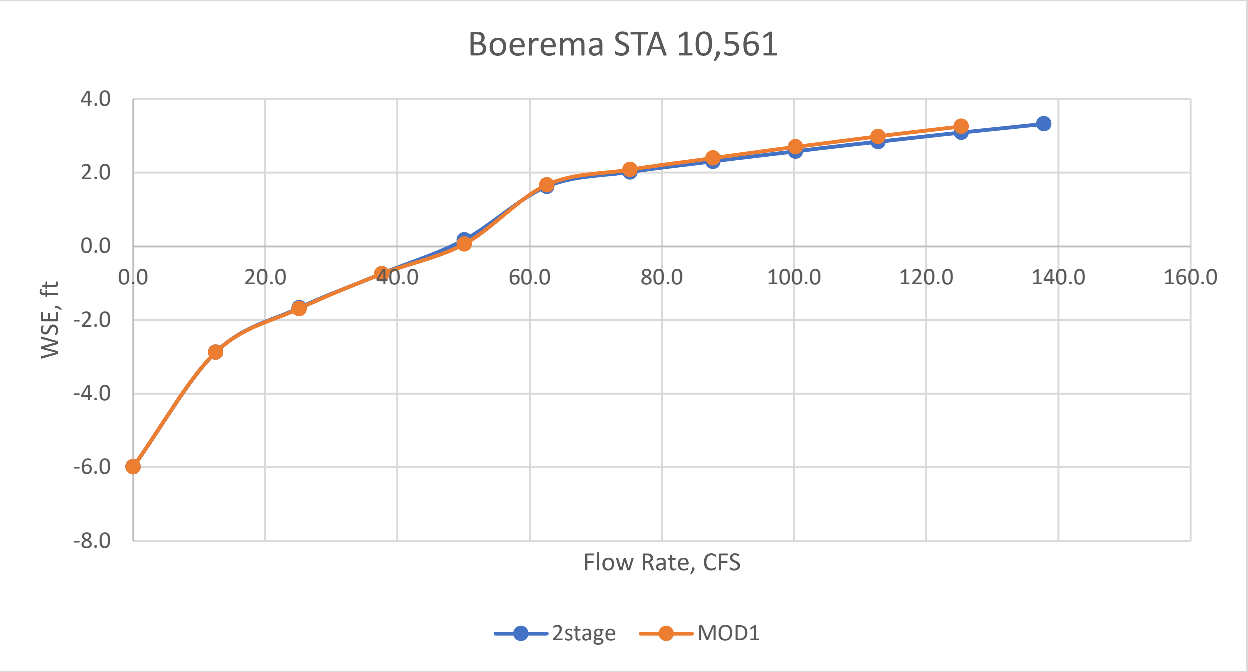

Allen STA 5,665
WSE. ft
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
Flow Rate, CFS
Two-Stage
Baseline

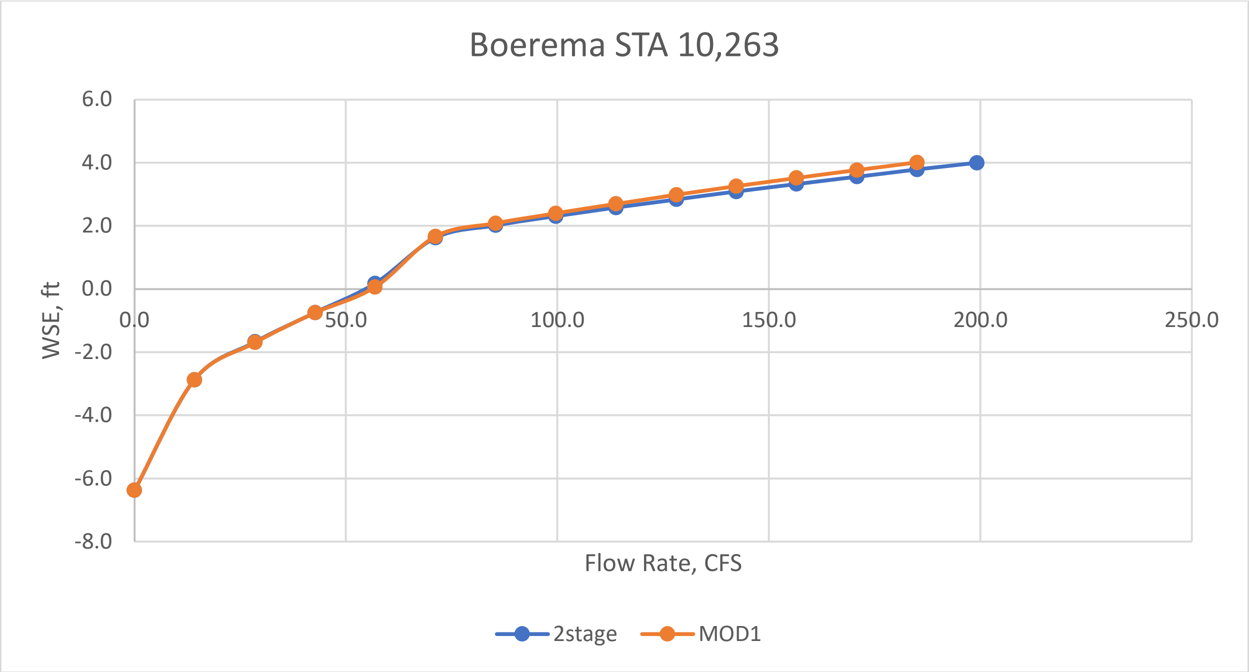

Allen STA 5,080
WSE, ft
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
Flow Rate, CFS
Two-Stage
Baseline

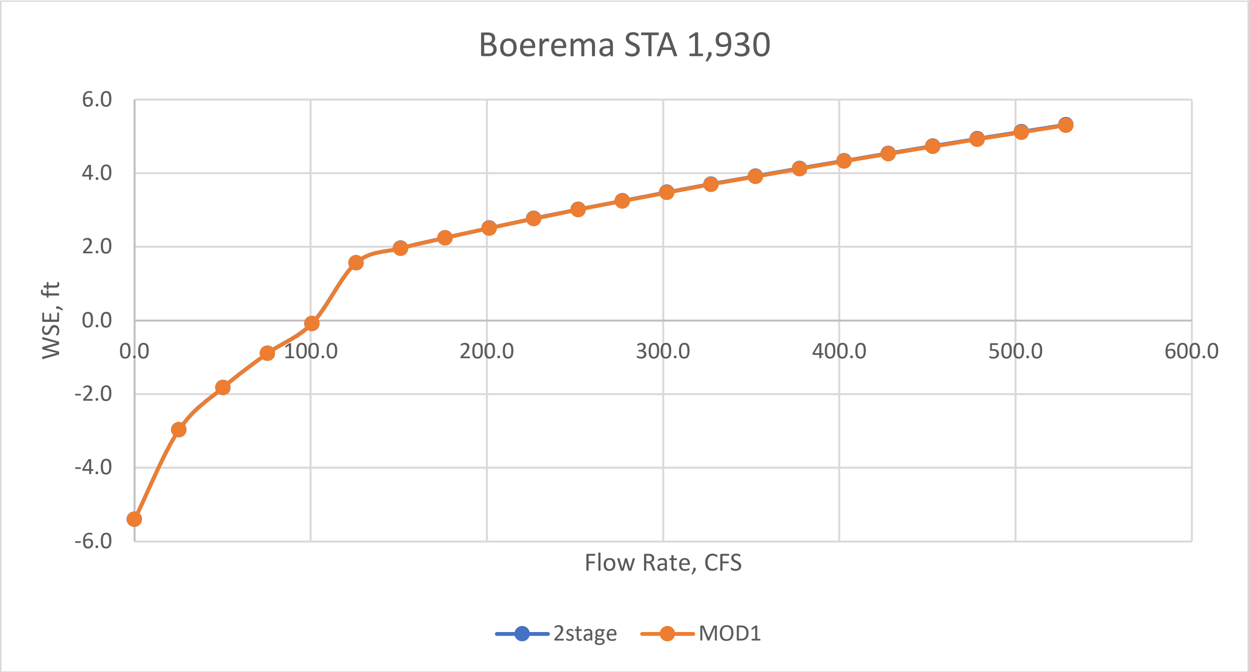

Allen STA 195
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
WSE. ft
0.0
50.0
100.0
150.0
200.0
250.0
Flow Rate, CFS
Two-Stage
Baseline

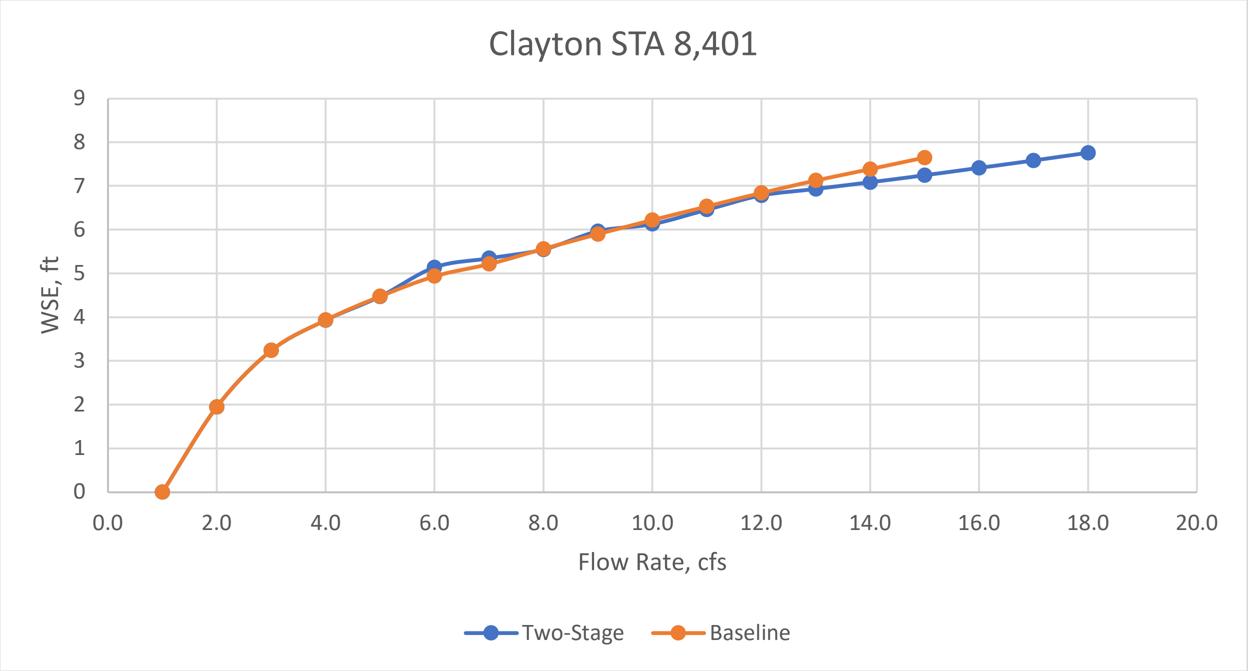

Boerema STA 16,762
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
WSE, ft
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
Flow Rate, CFS
2stage
MOD1

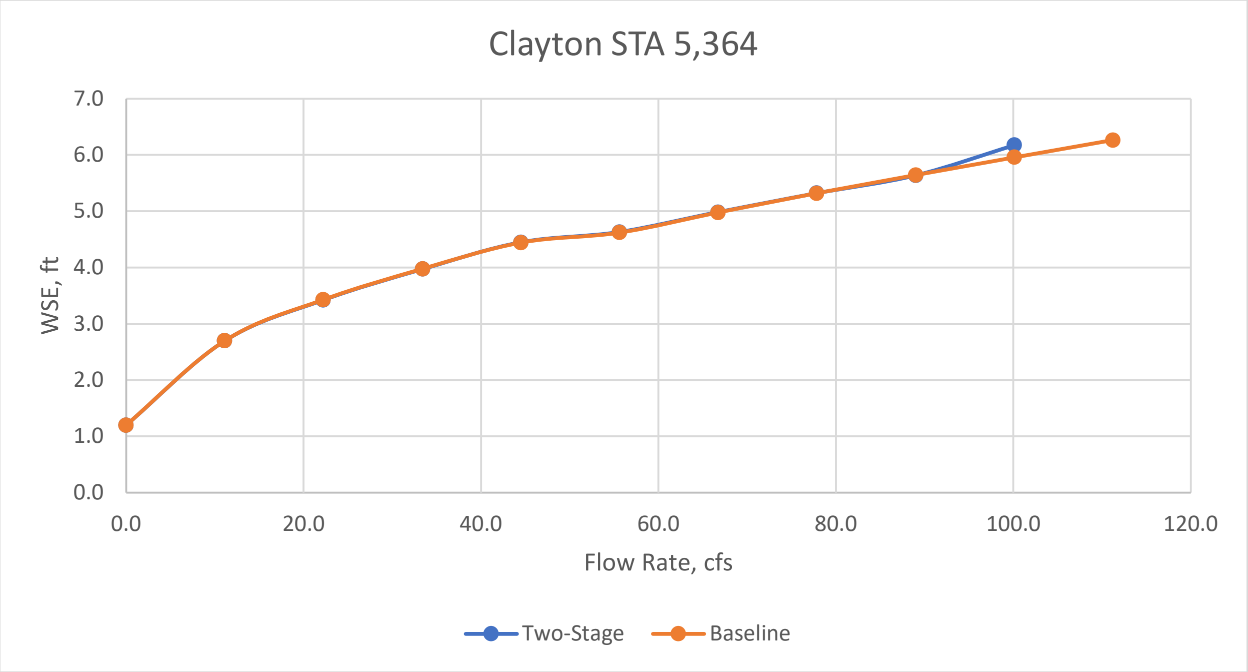

Boerema STA 13,510
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
WSE, ft
0.0
50.0
100.0
150.0
200.0
250.0
Flow Rate, CFS
2stage
MOD1

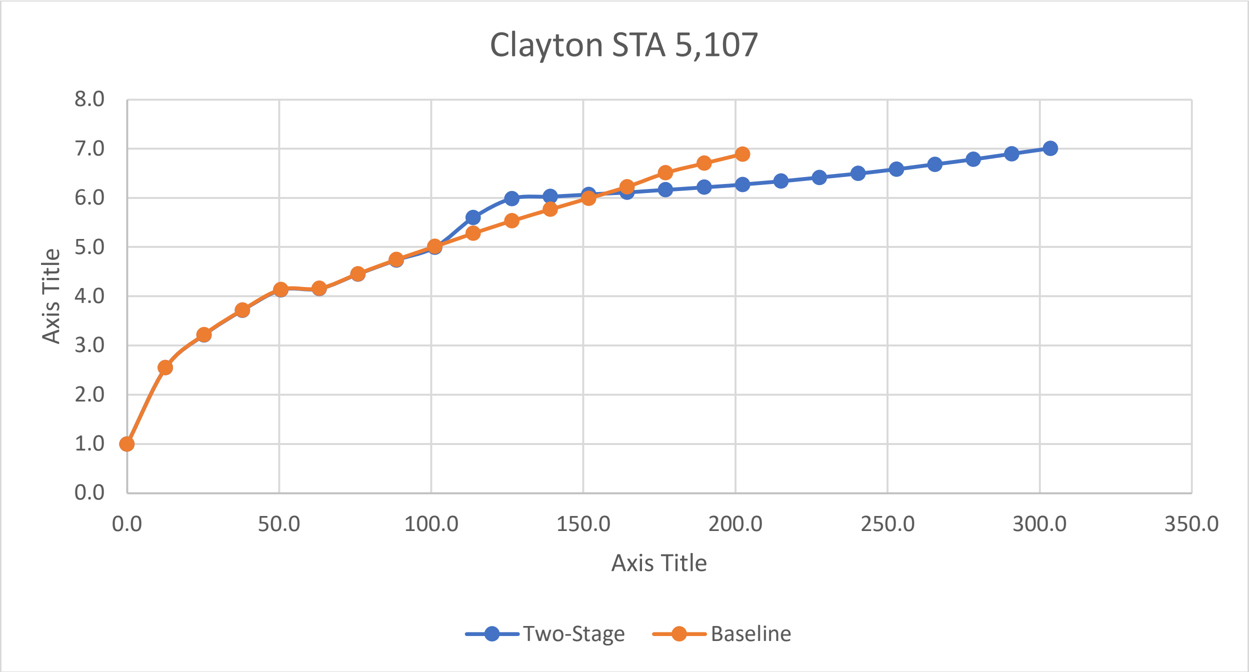

Boerema STA 10,561
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
WSE, ft
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
Flow Rate, CFS
2stage
MOD1

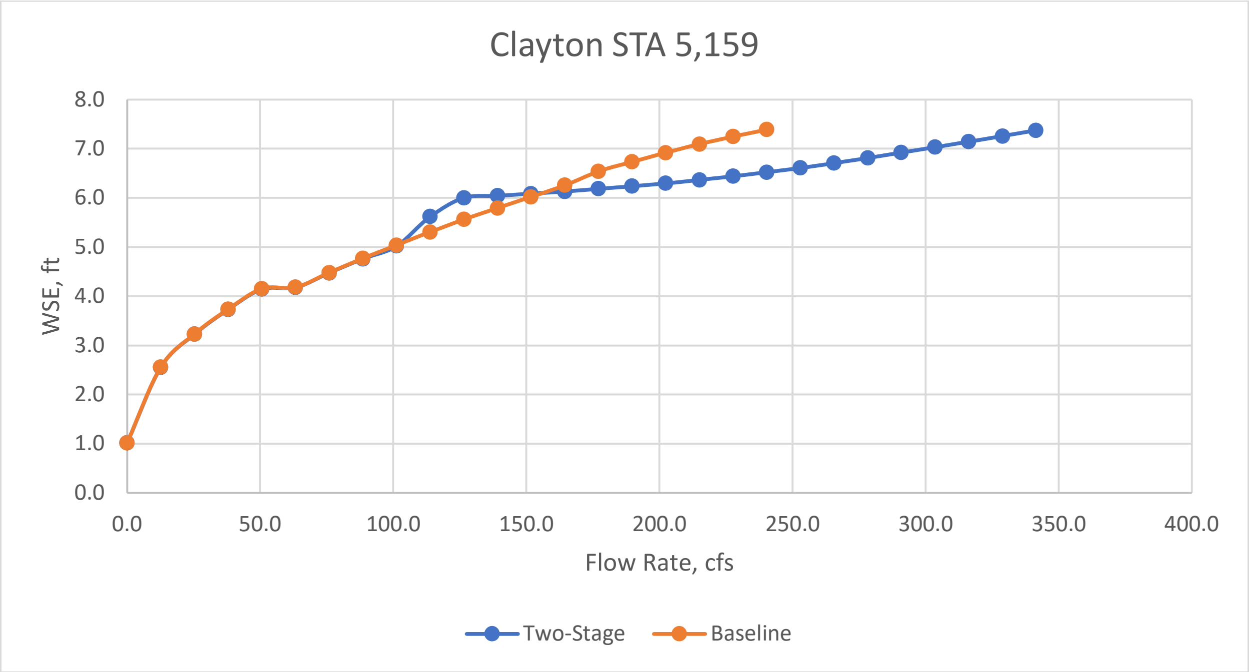

Boerema STA 10,263
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
WSE, ft
0.0
50.0
100.0
150.0
200.0
250.0
Flow Rate, CFS
2stage
MOD1

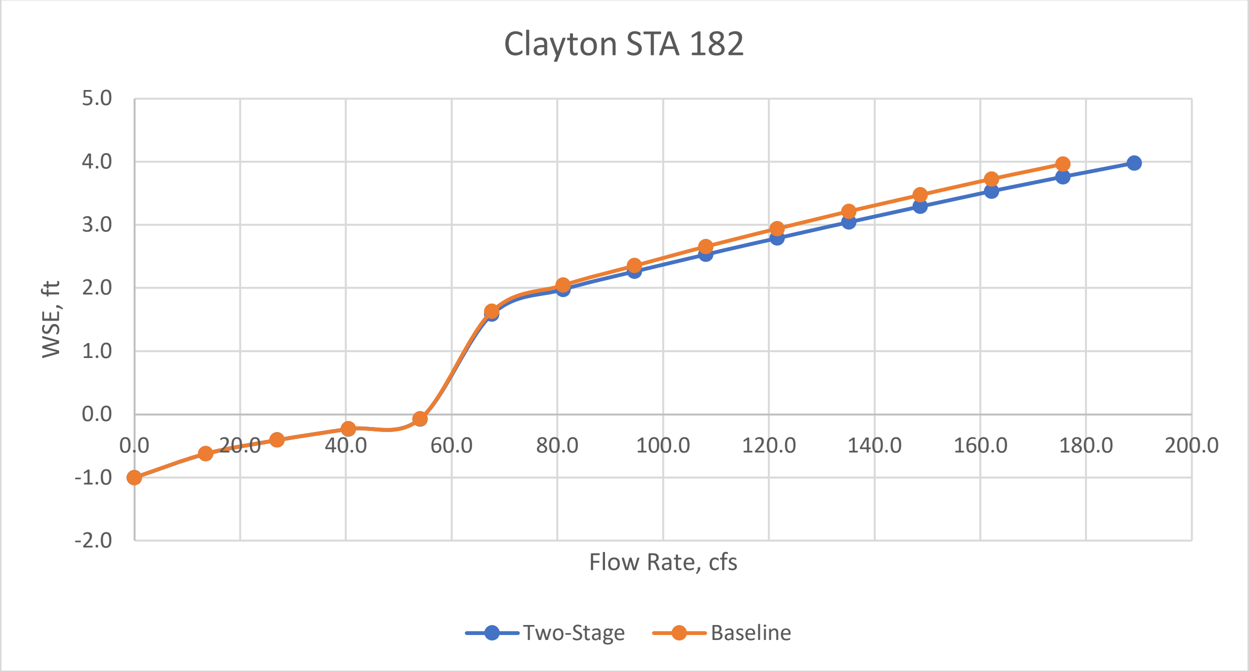

Boerema STA 1,930
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
WSE, ft
0.0
100.0
200.0
300.0
400.0
500.0
600.0
Flow Rate, CFS
2stage
MOD1

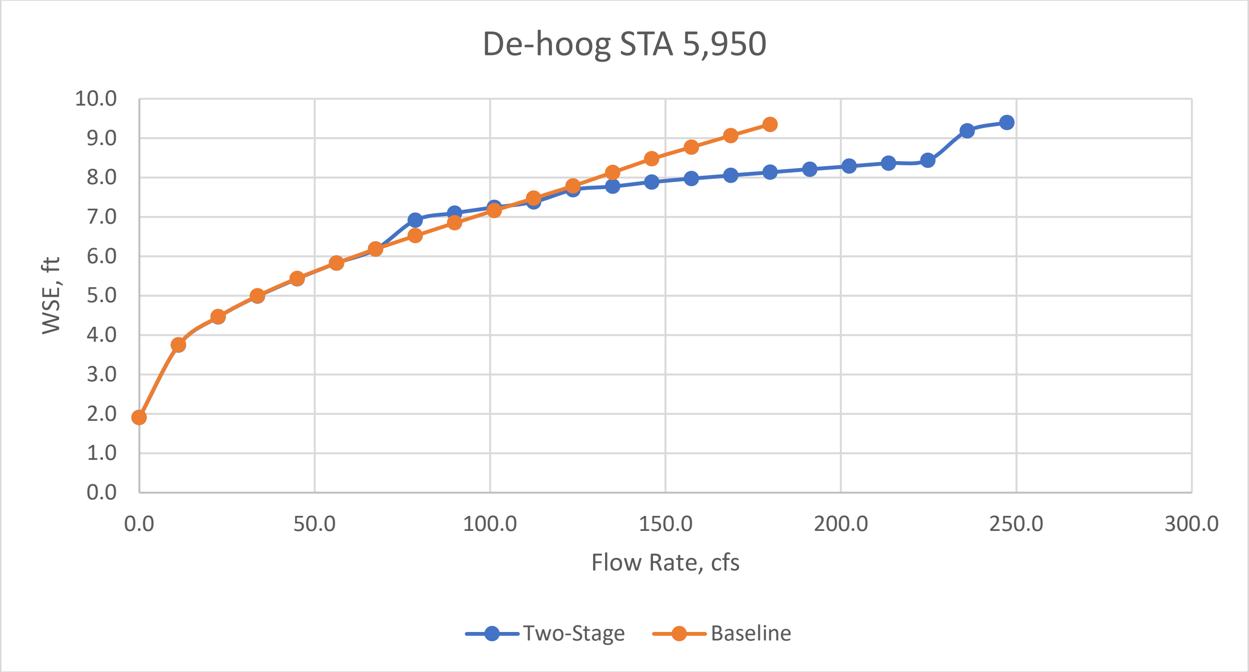

Clayton STA 8,401
WSE, ft
0
1
2
3
4
5
6
7
8
9
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
Flow Rate, cfs
Two-Stage
Baseline

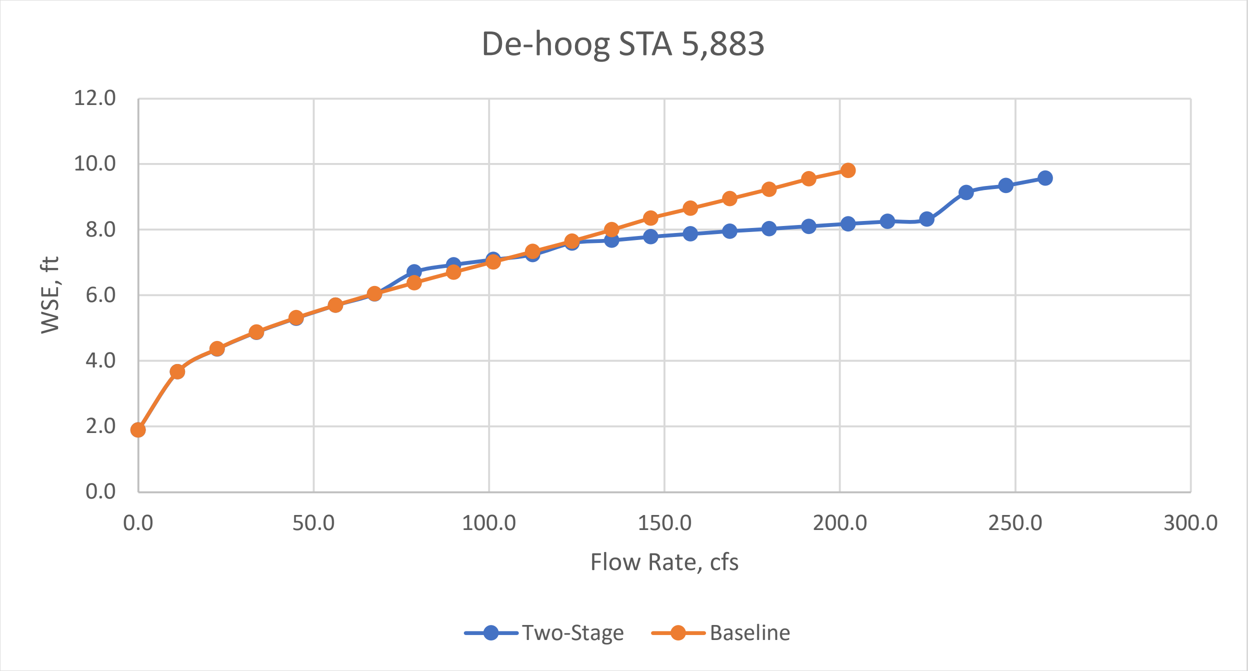

Clayton STA 5,364
WSE, ft
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
Flow Rate, cfs
Two-Stage
Baseline

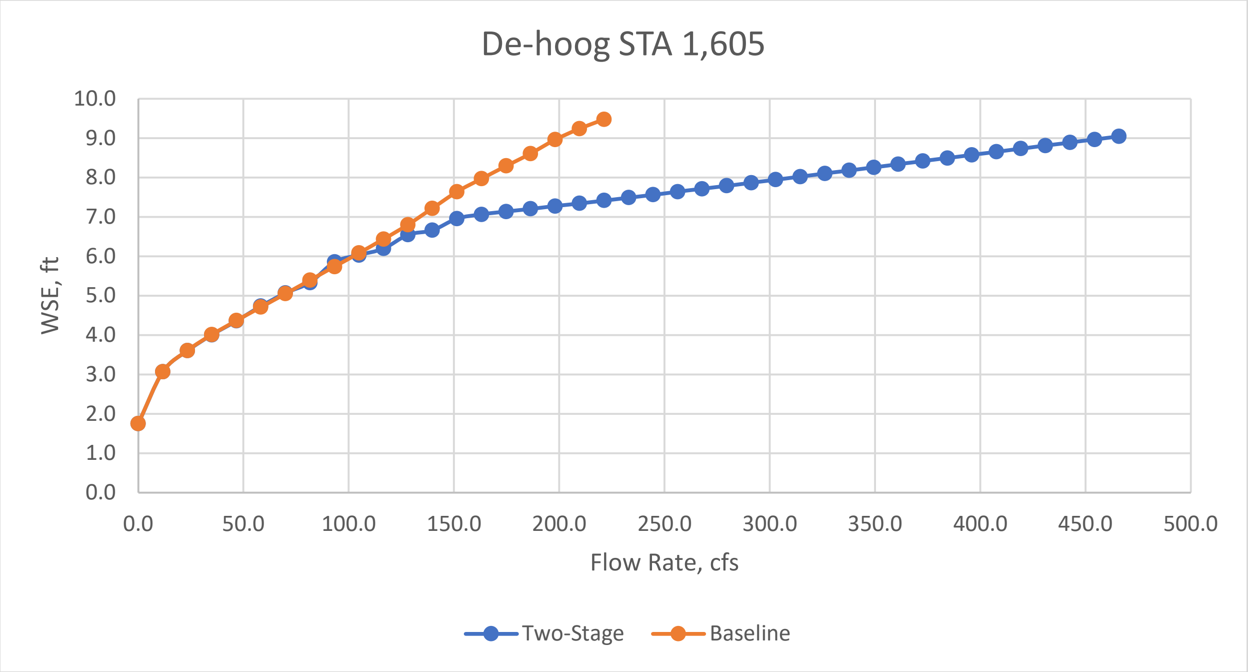

Clayton STA 5,107
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Axis Title
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
Axis Title
Two-Stage
Baseline

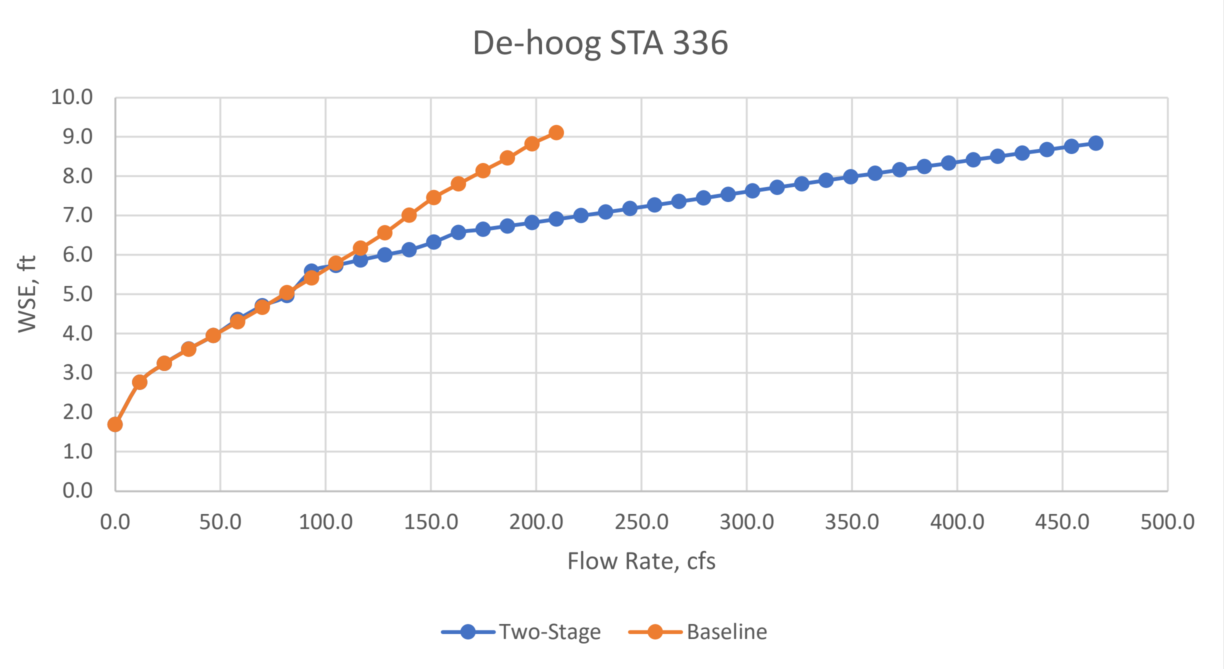

Clayton STA 5,159
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
WSE, ft
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
Flow Rate, cfs
Two-Stage
Baseline

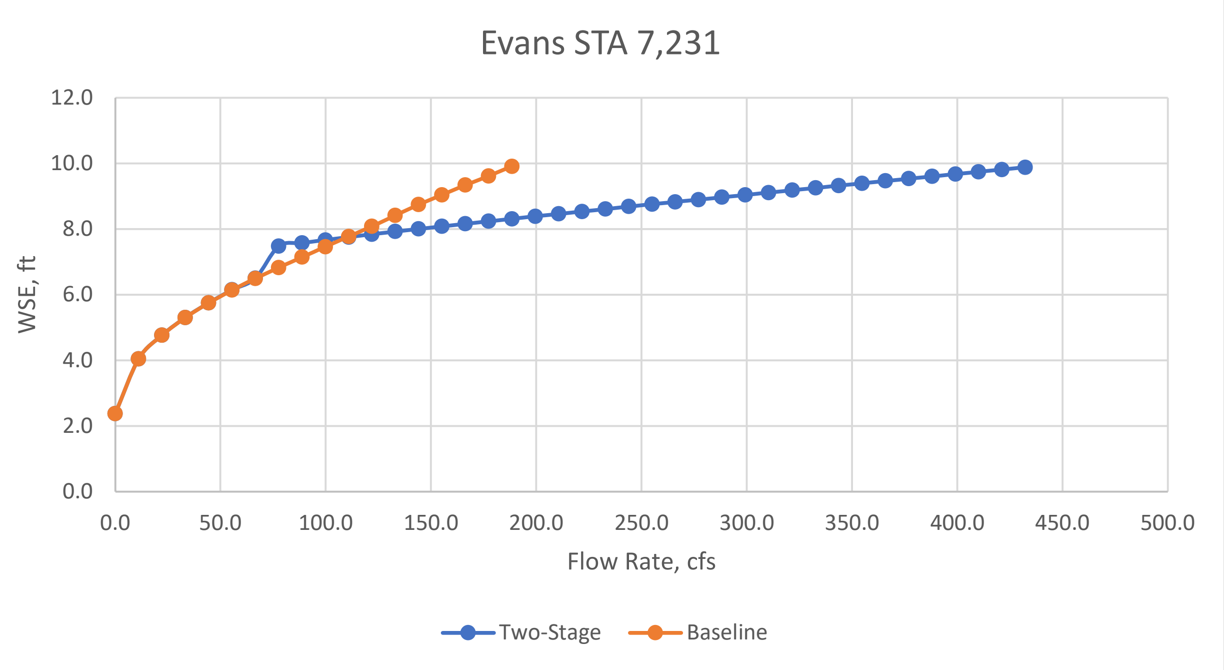

Clayton STA 182
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
WSE, ft
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
200.0
Flow Rate, cfs
Two-Stage
Baseline

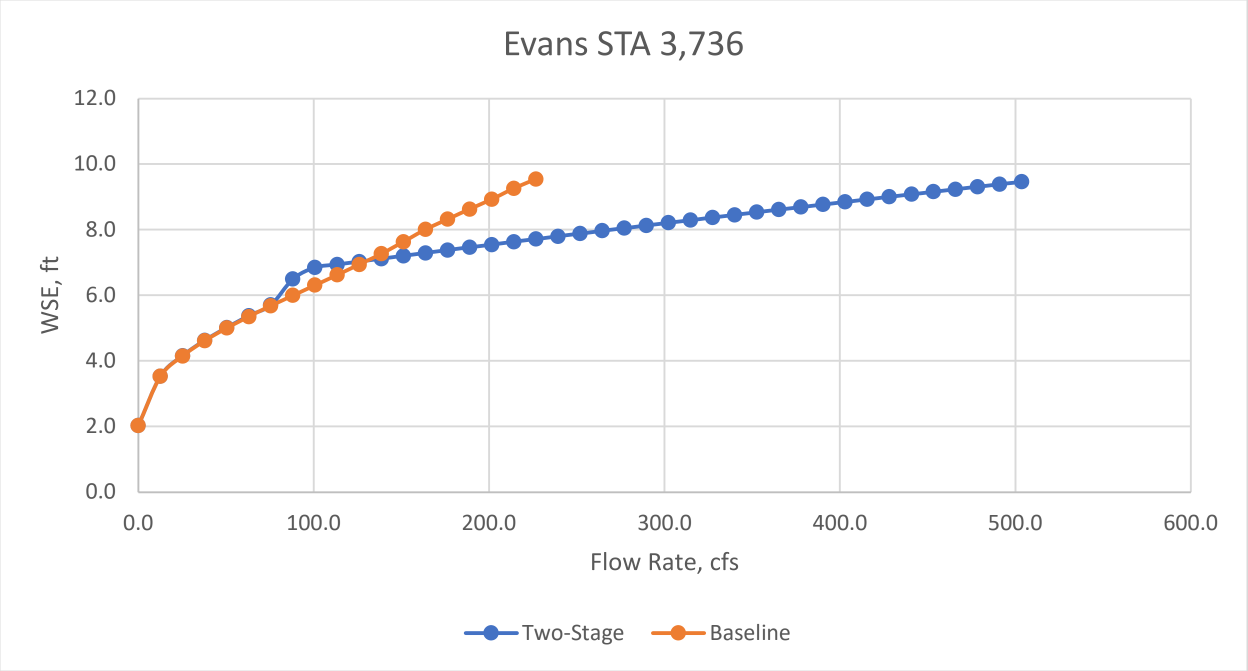

De-hoog STA 5,950
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
WSE, ft
0.0
50.0
100.0
150.0
200.0
250.0
300.0
Flow Rate, cfs
Two-Stage
Baseline

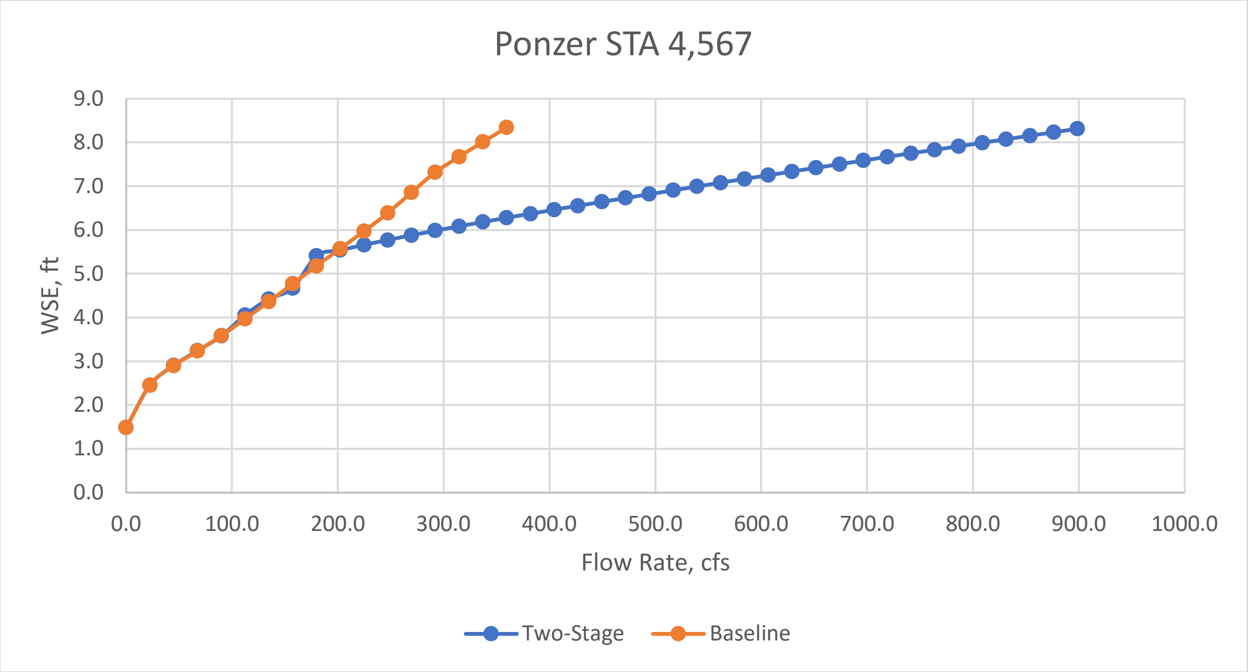

De-hoog STA 5,883
12.0
10.0
8.0
6.0
4.0
2.0
0.0
WSE, ft
0.0
50.0
100.0
150.0
200.0
250.0
300.0
Flow Rate, cfs
Two-Stage
Baseline

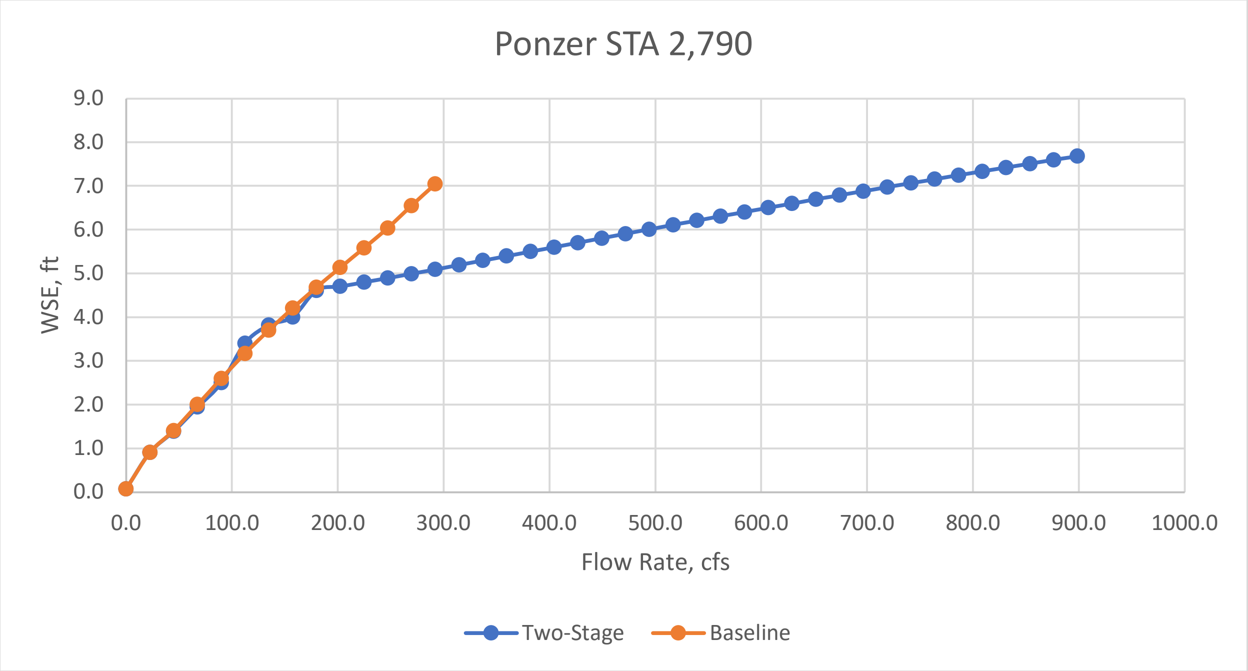

De-hoog STA 1,605
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
WSE, ft
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
Flow Rate, cfs
Two-Stage
Baseline

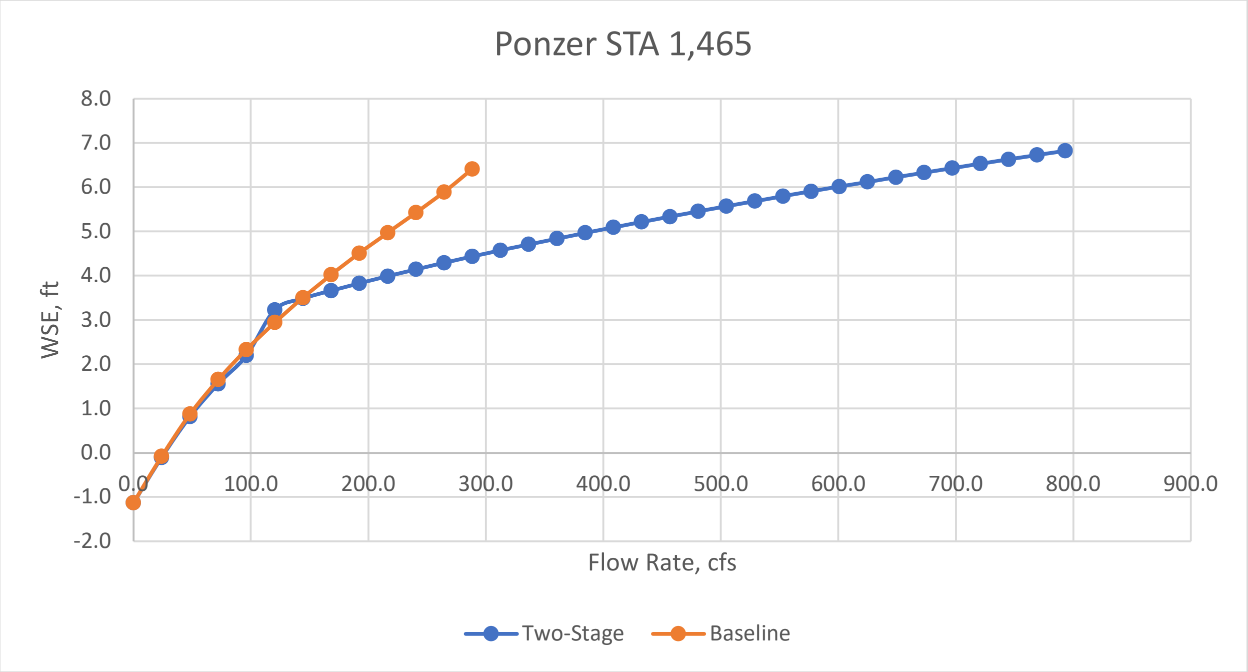

De-hoog STA 336
WSE, ft
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
Flow Rate, cfs
Two-Stage
Baseline

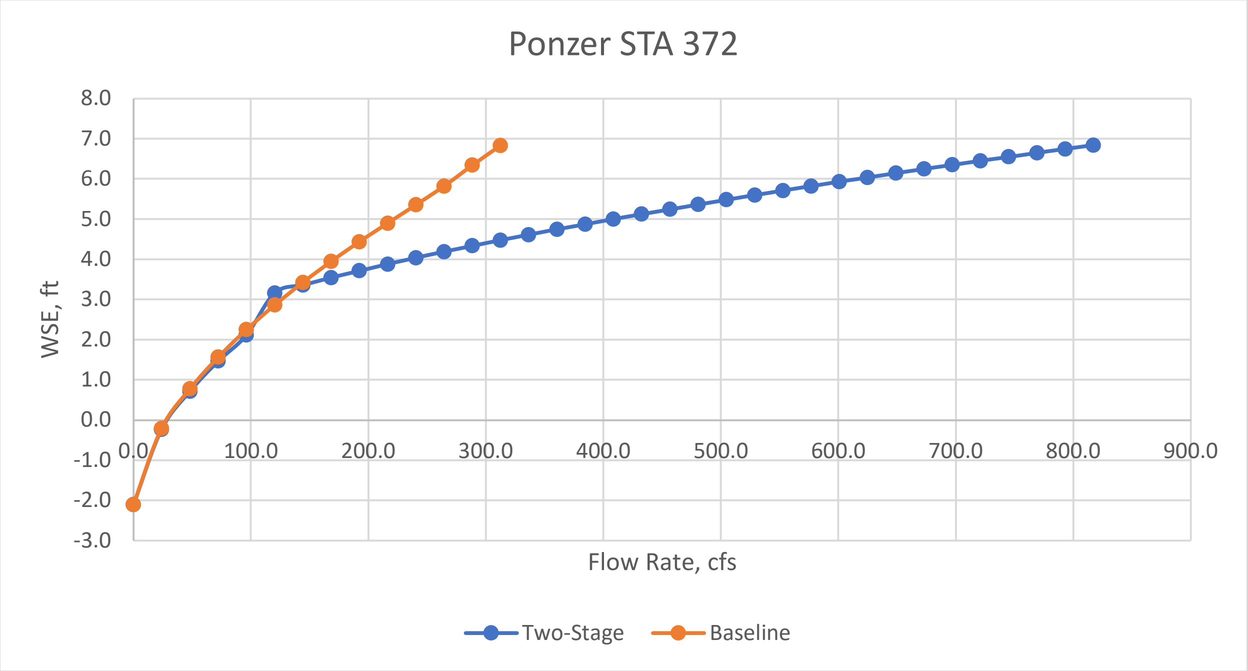

Evans STA 7,231
WSE, ft
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
Flow Rate, cfs
Two-Stage
Baseline

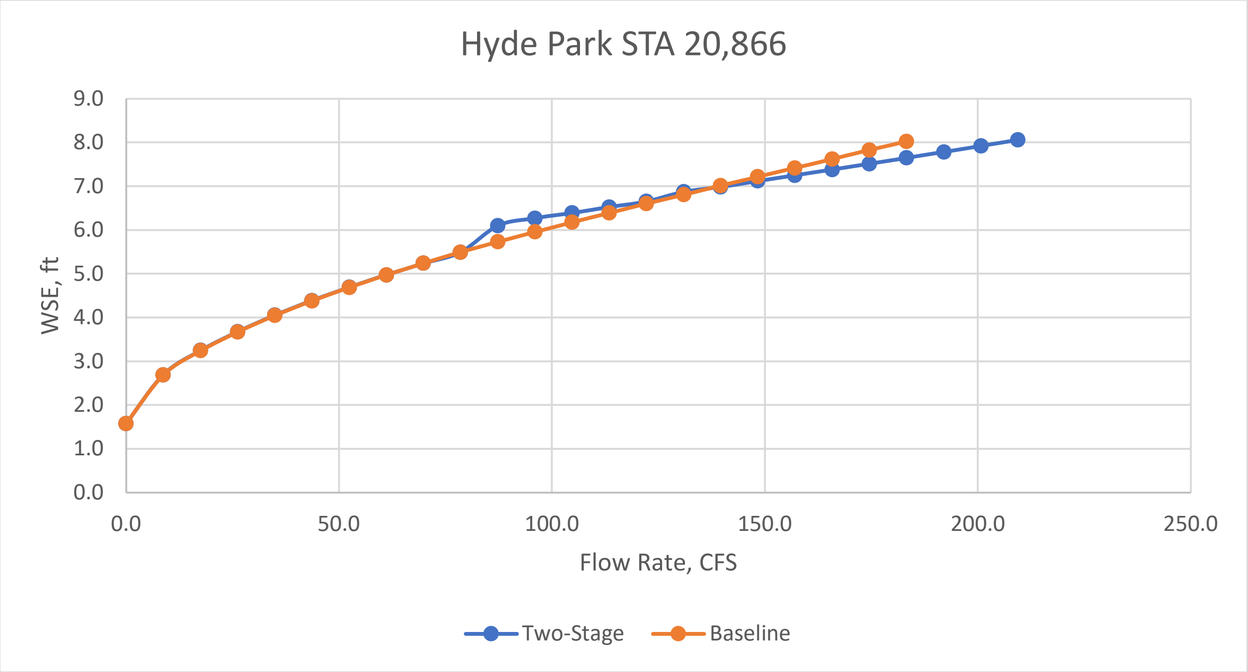

Evans STA 3,736
12.0
10.0
8.0
6.0
4.0
2.0
0.0
WSE, ft
0.0
100.0
200.0
300.0
400.0
500.0
600.0
Flow Rate, cfs
Two-Stage
Baseline

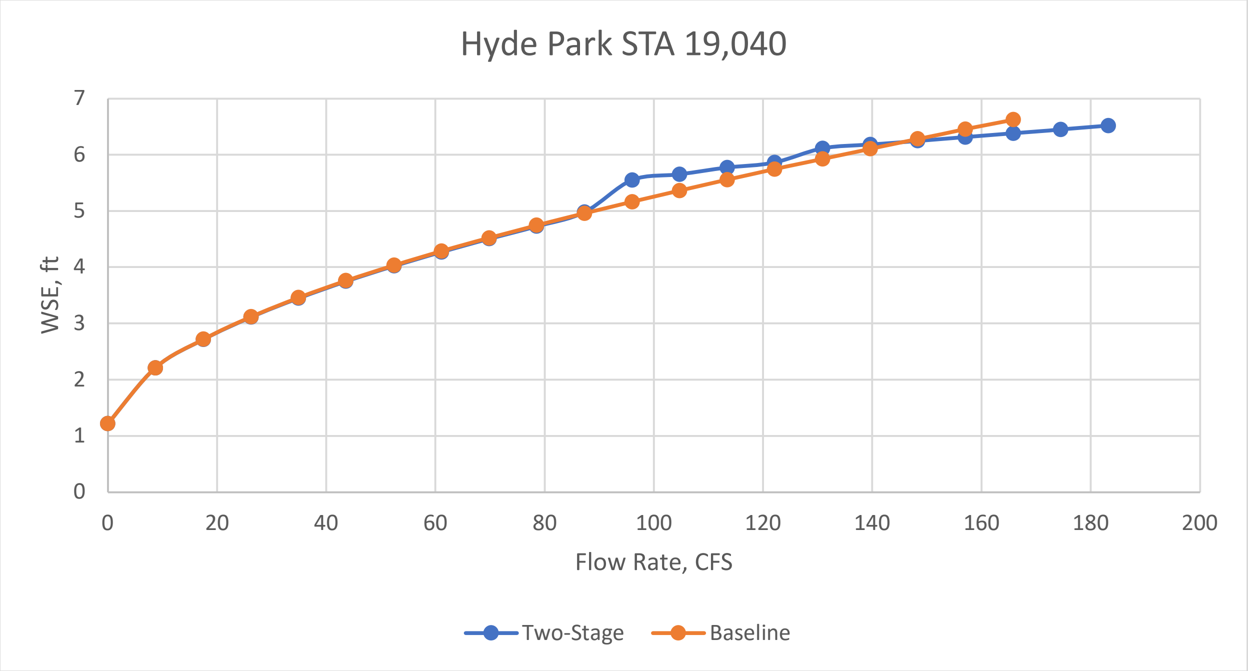

Ponzer STA 4,567
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
WSE, ft
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
Flow Rate, cfs
Two-Stage
Baseline

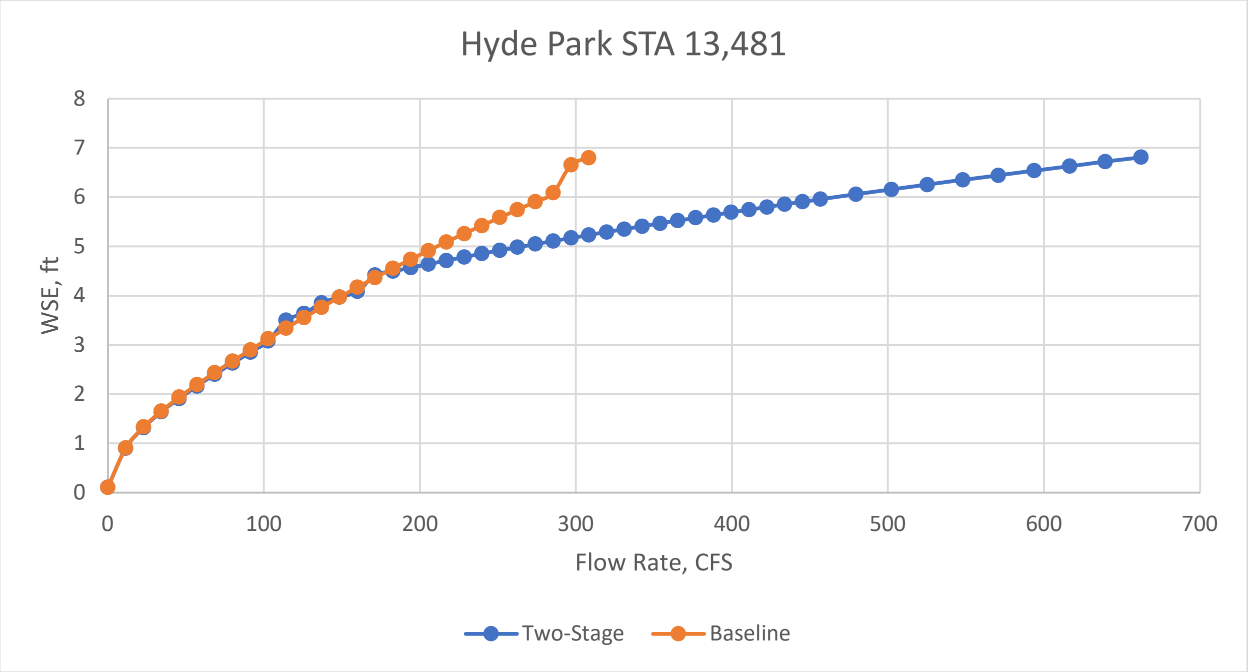

Ponzer STA 2,790
WSE, ft
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
1000.0
Flow Rate, cfs
Two-Stage
Baseline

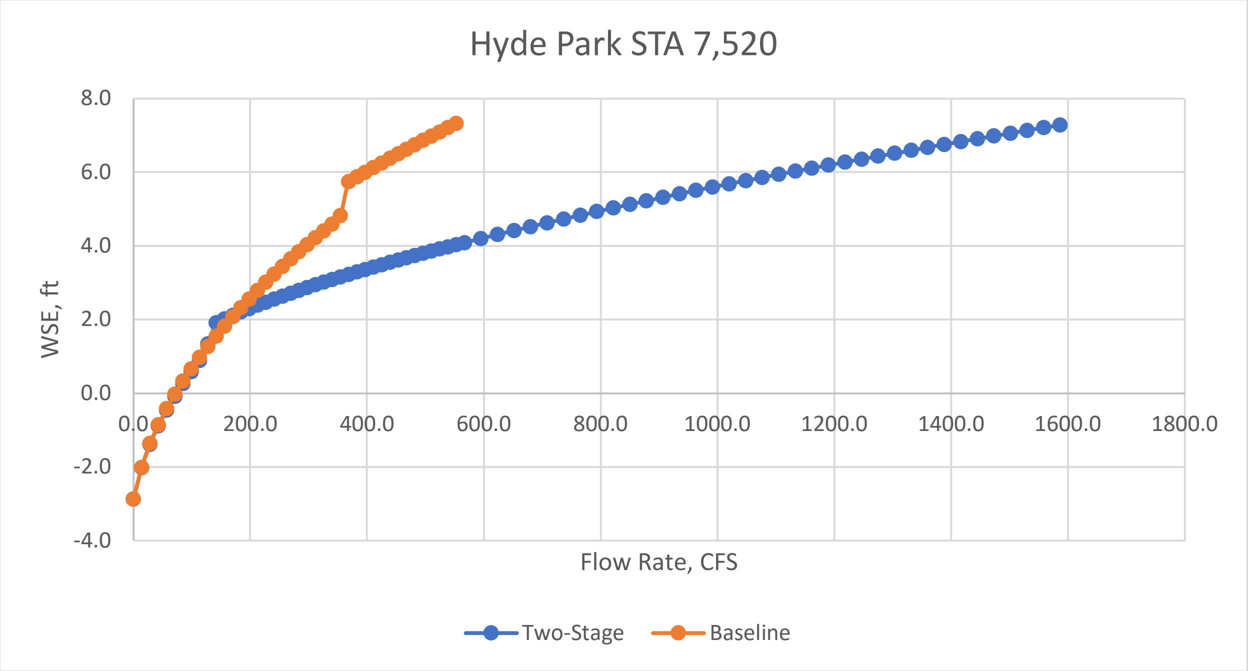

Ponzer STA 1,465
WSE, ft
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
Flow Rate, cfs
Two-Stage
Baseline

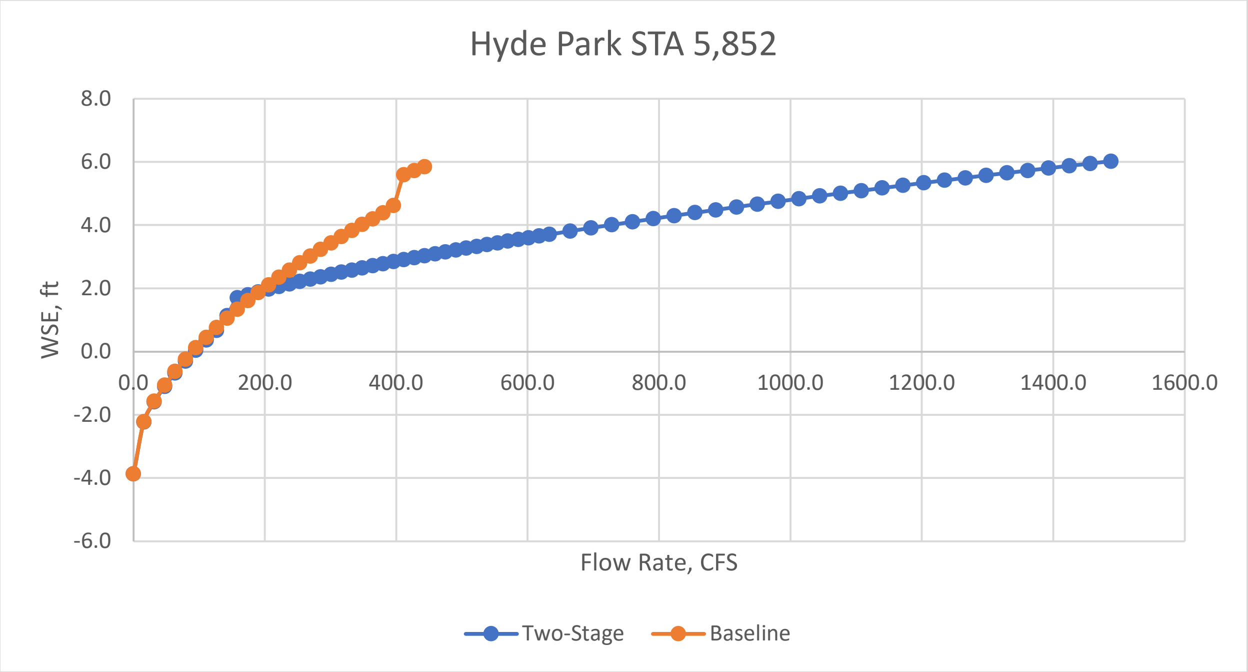

Ponzer STA 372
WSE, ft
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0
900.0
Flow Rate, cfs
Two-Stage
Baseline

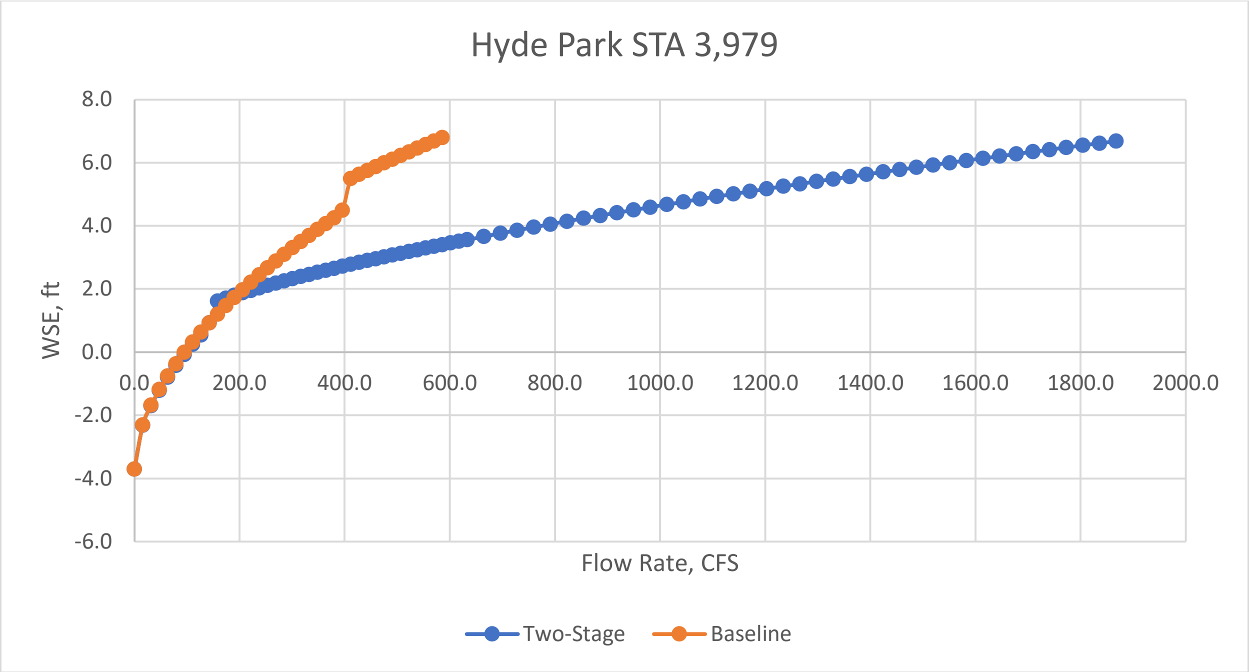

Hyde Park STA 20,866
WSE, ft
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0
Flow Rate, CFS
Two-Stage
Baseline

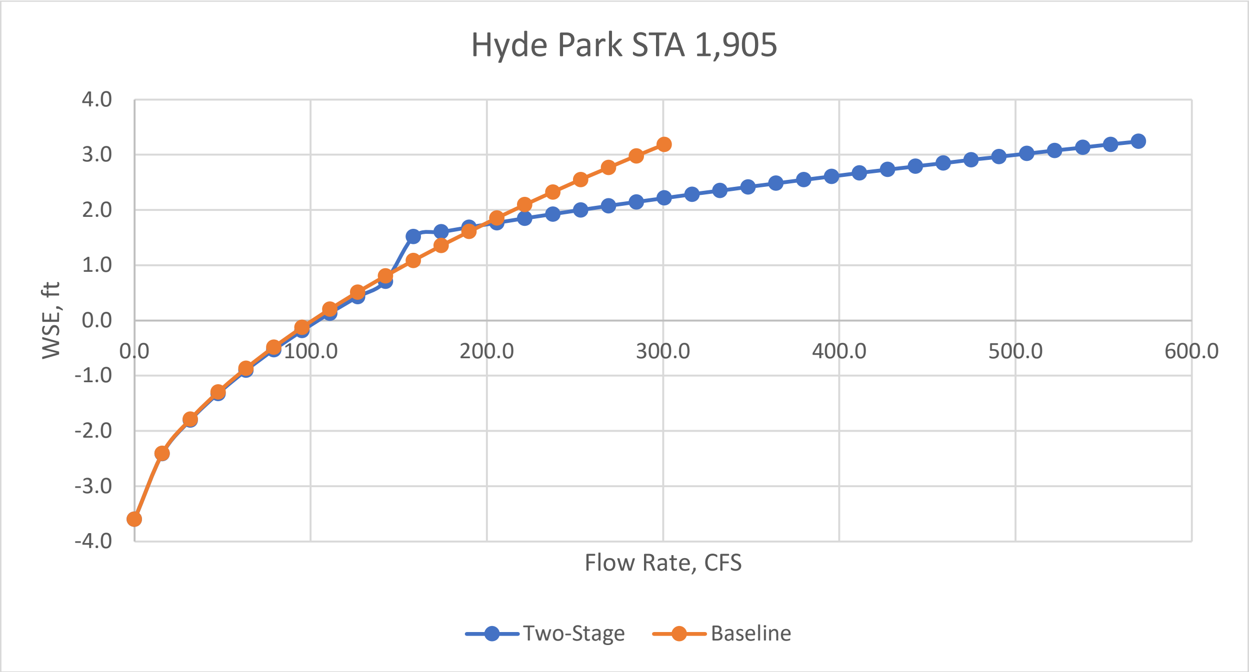

Hyde Park STA 19,040
WSE, ft
7
6
5
4
3
2
1
0
0
20
40
60
80
100
120
140
160
180
200
Flow Rate, CFS
Two-Stage
Baseline


Hyde Park STA 13,481
WSE, ft
8
7
6
5
4
3
2
1
0
0
100
200
300
400
500
600
700
Flow Rate, CFS
Two-Stage
Baseline


Hyde Park STA 7,520
WSE, ft
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
1400.0
1600.0
1800.0
Flow Rate, CFS
Two-Stage
Baseline


Hyde Park STA 5,852
WSE, ft
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
0.0
200.0
400.0
600.0
800.0
1000.0
1200.0
1400.0
1600.0
Flow Rate, CFS
Two-Stage
Baseline


Hyde Park STA 3,979


Hyde Park STA 1,905