# EVALUATION OF KNICKPOINT MIGRATION POTENTIAL DUE TO SEDIMENT REMOVAL IN A RESERVOIR

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# ABSTRACT

Reservoir sedimentation is a pressing issue that has great effect on the ability of dams to store sufficient water for flood control, water supply, and recreation. Potential viable options to reduce sediment stored in a reservoir and increase water storage capacity include dredging or dry excavation of sediment. Sediment removal can cause the reservoir inlet to become locally steep, potentially creating a base level drop leading to formation of a knickpoint that could migrate upstream and cause damage to infrastructure and property. This paper presents results of an analysis of the potential for a knickpoint to migrate upstream due to sediment removal in the upper portion of the Prado Basin in southern California along the Santa Ana River.

A one-dimensional HEC-RAS analysis was conducted to simulate the effects of sediment removal and the construction of a channel to connect the existing river bed and the sediment trap, otherwise known as a transition. One-dimensional, mobile-bed HEC-RAS models were run with existing and proposed conditions with varied hydrologic events for a ten-year period. Sediment transport was estimated within the model using the Engelund and Hansen (1967) total load equation. Proposed conditions included simulations with and without grade control structures within the transition channel to determine the need and efficacy of grade control to prevent excess scour within the reach. A sensitivity analysis of transition channel slope, reservoir level, bed material gradation, and incoming sediment load gradation was conducted to determine the input parameters which contribute the most to the propensity of knickpoint migration and scour/deposition.

It was found that the steepened face will act as a rotating knickpoint which flattens over time. The reach just upstream of the transition channel will degrade due to the downdrain of the flow as it accelerates over the knickpoint lip. The grade control structures will help to maintain the bed elevation within the transition channel to near pre-run conditions and will form stepped knickpoints on the downstream side. The effect of the grade control was not as evident upstream of the transition channel, which is still found to degrade. The results of the sensitivity analysis indicate that the transition channel slope, reservoir level, and incoming sediment gradation have the largest impact on the scour and deposition upstream of the transition channel.

# 1 INTRODUCTION

Many reservoirs built in the early part of the 20th century did not account for sediment management in their initial design. As these structures age, sediment accumulation has become a major problem due to decreased storage capacity and blockage of outflow structures and intakes. Many alternatives have been developed to decrease sediment accumulation and reduce stored sediment within reservoirs. Dredging or dry excavation of sediment, while expensive, is a viable solution to remove sediment from a reservoir (Annandale et al., 2016). This process has the potential, in certain situations, to cause a knickpoint to form at the upstream end of the sediment removal area which could propagate upstream and endanger property and infrastructure as well as disturb instream and riparian habitat. The formation and propagation of knickpoints in alluvial channels can be described using sediment transport equations. Bed material transport is commonly calculated as a function of the Shields parameter, $\tau_*$, of the flow regime (Shields, 1936). This is compared to the critical Shields parameter, $\tau_{*c}$, and if $\tau_{*c}$ is exceeded for a given flow scenario, sediment transport will occur. The Shields parameter is bed shear stress, $\tau_0$, non-dimensionalized by grain size. The Shields parameter is dependent on channel geometry, flow depth, roughness, water surface slope, sediment grain size, and sediment particle density. After sediment is removed from a reservoir, the bed slope, and subsequently, the water surface slope will increase, which will cause an increase in bed shear stress and could lead to erosion in the vicinity of the slope increase. This increased slope is a knickpoint. Over time, with the erosion of the increased slope, the knickpoint could migrate upstream.

Much research has been conducted to determine the effects of knickpoint migration within streams with alluvial beds (Holland & Pickup, 1976; Bennett, 1999) and in bedrock streams (Gardner, 1983; Seidl et al., 1994). Research on knickpoint migration in the vicinity of reservoirs is usually related to dam removal and stored sediment mobilization (Randle et al., 2015; Sawaske & Freyberg, 2012; Gartner et al., 2015). These studies generally characterize knickpoint migration as either stepped or rotating. Stepped knickpoints maintain the same longitudinal profile as they migrate upstream. Rotating knickpoints have a flattening of the knickpoint face with a steepening of the drawdown reach immediately upstream of the knickpoint lip until the two reaches trend toward the same slope (Holland & Pickup 1976). Holland & Pickup (1976) noted that the stepped knickpoints require a functioning plunge pool to maintain their profile and will disappear if the plunge pool is eliminated. It was found that rotating knickpoints are unstable, erode quickly, and diminish. The scenarios modeled for this paper have an overall channel slope of approximately 0.17%. Bennett (1999) found that at low overall channel bed slopes less than 2%, the scour depth did not vary much in the longitudinal direction and that the lower slope migration is dominated by plunge pool scour. This paper analyzes a system where the bed slope is increased from existing conditions but without the presence of a distinct plunge pool at the base of the knickpoint. Gardner (1983) analyzed the likelihood of obtaining a stepped retreating vs. rotating knickpoint migration based on several factors. It was found that, as is the case for this research, if the ratio of knickpoint face height to upstream water depth is greater than 1, knickpoint retreat could occur. However, Gardner also found that the drawdown reach upstream of the knickpoint lip causes erosion upstream of the lip. This could erode away the knickpoint lip and produce a rotating knickpoint. Seidl et al. (1994) argues that one of the more important factors in knickpoint migration is the change in base level. A channel was studied that was steepened to 60% over 300 vertical meters due to a landslide. The knickpoint, which was imposed, retreated and maintained a stepped profile during modeling simulations. This paper looks at a scenario with a lowered base level due to an excavation. Randle et al.'s (2015) study of dam removal on the Elwha River found that flows of near average annual magnitude are required for knickpoint migration. Median grain size, level of cohesion, and spatial variability were found to be the largest factors when observing knickpoint migration according to Swaske (2012). Again, Swaske found that dam removal affects base level which directly relates to step size and rate of migration. Gartner (2015) found that spatial sediment transport gradients are important and that a knickpoint can increase sediment transport due to increased slope but the knickpoint will only erode and migrate upstream if the threshold for erosion is exceeded.

However, not as much work has been done to determine the effects of sediment removal within an intact reservoir on knickpoint creation and migration. This paper discusses analysis performed to quantify the potential for long-term knickpoint migration following a sediment removal project in the upper reaches of a reservoir to manage reservoir sedimentation. A knickpoint migration in these cases is problematic due to the potential for damage to infrastructure and property that could occur if not properly managed. For these reasons the study of knickpoint migration potential is important to sediment management practices.

Another aspect that must be considered in analyzing sediment management practices involving sediment removal are the risk factors that could arise from varied management of the system. Several parameters have the potential to impact how the river, especially upstream of the knickpoint lip, responds to the removal of sediment. These include increased channel slope, reservoir water level, bed gradation upstream of the knickpoint, and incoming sediment load to the system. A sensitivity analysis of these parameters can indicate which have the greatest impact on channel stability and risk to infrastructure.

## 2 METHODS

The US Army Corps of Engineers (USACE) HEC-RAS software was chosen for the study of the potential knickpoint migration following reservoir sediment management practices. A one-dimensional sediment transport model was constructed to simulate the existing conditions as well as alternatives of the river alignment after sediment removal. To evaluate the most critical parameters contributing to knickpoint migration potential, a sensitivity analysis was conducted by varying several inputs from measured or proposed conditions.

### 2.1 Study Area

The area of interest for this study is the Prado Basin on the Santa Ana River near Corona, California. The reservoir was created by construction of the Prado Dam in 1941, which was authorized by the Flood Control Act of 1936. A major flood in 1938, resulting in 68,400 acres inundated and 19 deaths, reinforced the need for the dam. The sediment continuity in the Santa Ana River has been disrupted since construction which has caused a reduction in storage capacity within Prado Basin, channel incision, armoring, and reduction in riparian habitat downstream of the dam. Figure 1 shows the study area upstream of the Prado Basin.

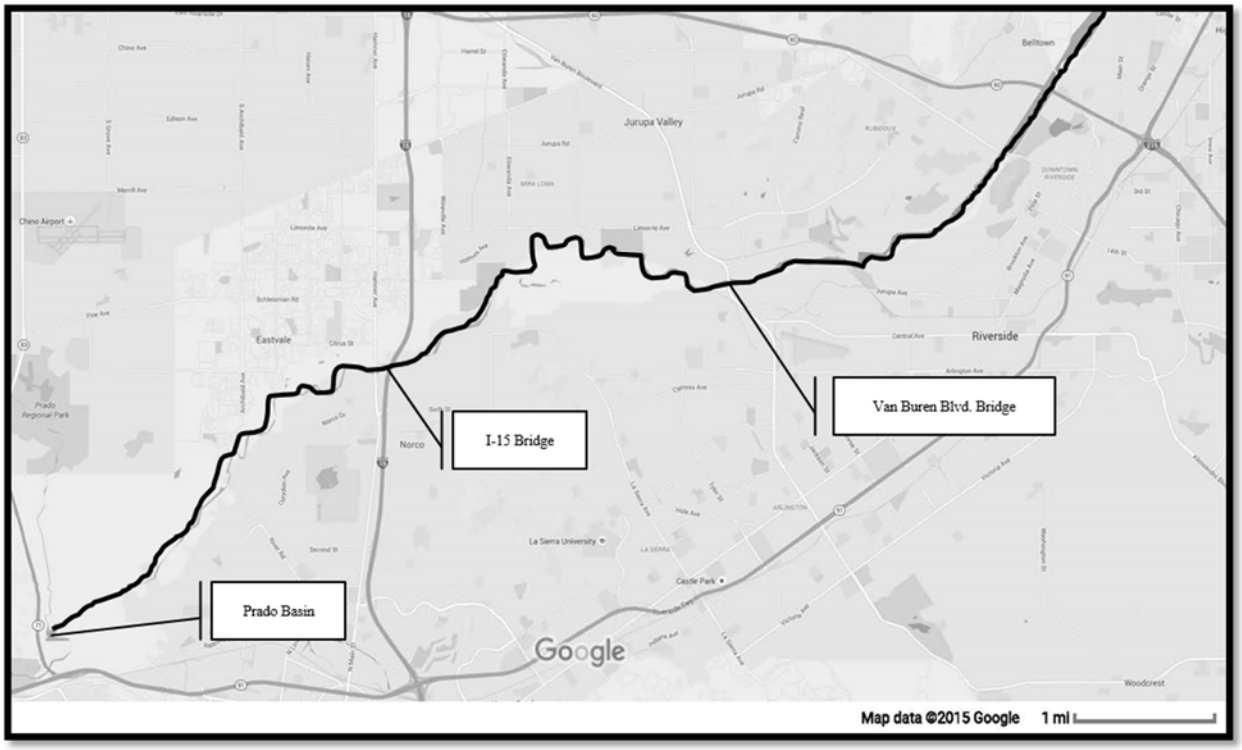

**Figure 1**. **Study Area along the Santa Ana River Upstream of Prado Basin**

## 2.2 Current Issues and Potential Solution

USACE and Orange County Water District (OCWD) are analyzing options to increase storage volume in Prado Basin, and reverse or halt channel incision, remove armoring, and restore riparian habitat downstream in the Santa Ana River. The current preferred alternative for sediment removal within Prado Basin involves excavating sediment from the upstream end of the reservoir within the main flow path of the Santa Ana River creating a sediment trap, dewatering the sediment, and re-entraining it downstream of the dam (USACE, 2014). When the sediment is removed, the main channel will be straightened and steepened to the bottom of the sediment trap to create a transition channel. It is planned that the sediment trap will be cleaned out every year before the beginning of the winter storm season.

The steepening of the river to create a transition channel will create a knickpoint because of the steep channel relative to the existing river longitudinal slope. Figure 2 shows a comparison of the existing channel and transition channel thalweg profiles. The existing channel slope is approximately 0.17% and the proposed transition channel slope is 0.3%. This knickpoint has the potential to migrate upstream along the Santa Ana River. If the knickpoint were to travel far enough upstream, infrastructure and property could be threatened due to erosion around bridge piers and undercutting of river banks which support houses.

**Figure 2**. **Existing and Transition Channel Thalweg Profile Comparison**

## 2.3 HEC-RAS Modeling

Several scenarios were simulated using the one-dimensional HEC-RAS model for a period of ten years. In general simulations were divided between existing and proposed alternatives after the introduction of the sediment trap. Proposed alternative simulations were divided between an option with grade control structures along the transition channel and an option without grade control. Several ten-year hypothetical flow series were simulated to determine dependence on hydrology in the translation of a knickpoint. A sensitivity analysis was conducted by varying several input parameters with the proposed alternatives with a sediment trap, both with and without grade control, to determine which input parameters have the greatest effect on the knickpoint migration potential and overall channel degradation.

### 2.3.1 Data

LiDAR data for the Santa Ana River and the Prado Basin were obtained by USACE. One-meter topographic LiDAR was collected July 7-15, 2015 along approximately 70 miles of the Santa Ana River, including the study reach (USACE 2017). The LiDAR coverage includes the main channel, overbanks, and floodplain. Five cross-sections surveyed as part of the sediment monitoring project were compared with the LiDAR data to determine the validity of the channel topography obtained by LiDAR. An analysis of the two datasets showed that vertical differences were within 0.5 feet. This is likely due to low flow depths in the summer which can be one foot or less. This validates the LiDAR dataset for use in this model.

A 35 year hypothetical future daily flow series based on historical flow records for the Santa Ana River upstream of Prado Basin, as well as the reservoir's water level response to the flow series, was developed by USACE. The 35 year series was developed by USACE looking at historic flows and accounting for changes in land use and climate. Three ten-year duration time series were selected from this 35 year dataset using visual observation to determine a mean, low, and high flow series. These time series make up the upstream boundary condition of the modeling. The Prado Basin water level as a result of these inflow series was also developed by USACE. This response makes up the downstream boundary condition for each of the simulated flow events.

Sediment monitoring has occurred within the Santa Ana River upstream of Prado Dam for the last two years over a range of flows. These data, collected by Scheevel Engineering, consist of bed material load gradations, bedload rates and gradations, and suspended load rates and gradations. The data were analyzed to determine current bed gradations within the study reach as well as incoming total sediment load and gradation.

Bedload measurements were obtained by wading and bridge sampling within the modeled reach at Van Buren Boulevard, Hamner Avenue, and River Road. Wading samples were collected using a BLH-84 sampler typically at any flows less than 300 cfs. Samples were collected at a regular spacing across the entire cross section (typically a spacing of 1, 2 or 3 feet). Samples were composited in the field to approximately 1/3 of the cross section, and 3 samples sent to the lab for analysis. Bridge samples were collected using a BL-84 sampler typically at any flow rate greater than 300 cfs. Samples were collected at approximately 1/3 spacing of the cross section and whenever possible multiple samples were taken within a 1/3 section and composited. Some very difficult sampling events and stations resulted in only 1 or 2 bed load samples taken.

Suspended sediment load measurements were also obtained by wading and bridge sampling at the same locations. Wading samples were collected using a DH-48 sampler typically at any flows less than 300 cfs. Wading depth integrated samples were collected at 3 stations across the flow with one duplicate sample at one of the stations. Bridge samples were collected using a DH-59 sampler typically at any flow rate greater than 300 cfs. As with the DH-48 samples, DH-59 depth integrated samples were collected at 3 stations across the flow with one duplicate sample at one of the stations. Table 1 below summarizes the bedload and suspended sediment sample dates, locations, and flows.

**Table 1. Summary of Sediment Monitoring Dates, Locations, and Flows**

| | Flow at Location During Sampling (cfs) | | |
|---|---|---|---|
| **Date** | **Van Buren Blvd.** | **Hamner Ave.** | **River Rd.** |
| 1/18/2016 | 52 | 85 | |
| 1/19/2016 | | | 86 |
| 1/31/2016 | 550 | | |
| 12/16/2016 | 1,200 | | |
| 12/22/2016 | | 1,930 | |
| 12/24/2016 | | | 3,010 |
| 1/23/2017 | 2,700 | | 3,700 |
| 2/18/2017 | | 1,805 | |
| 4/28/2017 | 34 | | |
| 8/28/2017 | | | 54 |
| 9/3/2017 | | 64 | |
| 9/22/2017 | | | 63 |
| 10/1/2017 | | 63 | |

### 2.3.2 Model Setup

After data were analyzed for the study site, the model input parameters were developed for existing and proposed conditions scenarios based on the available data. An initial set of base model runs was established with these parameters with mean, low and high flow time series to understand how the existing conditions and currently proposed modifications would be expected to behave. A set of nine base runs were initially set up which included existing conditions, and two scenarios modeling the proposed trap. Refer to Figure 2 above for differences in thalweg profile between the existing and trap scenarios. One trap scenario included grade control structures placed in the transition channel while another did not have grade control. Actual grade control structures were not designed and implemented in the model, but grade control was approximated in model runs by specifying no allowable scour at cross sections that have grade control. The three geometric scenarios had three different ten-year flow series applied to them: a mean flow, low flow, and high flow. A summary of the nine base runs using collected data and proposed designs is provided below in Table 2.

**Table 2. Summary of Base Existing and Proposed Model Runs**

| **Run** | **Geometry** | **Flow Data** |
|---|---|---|
| Existing Mean | Existing Geometry | Mean Flow Series |
| Trap with GCS Mean | Trap with Grade Control | |
| Trap without GCS Mean | Trap without Grade Control | |
| Existing Low | Existing Geometry | Low Flow Data |
| Trap with GCS Low | Trap with Grade Control | |
| Trap without GCS Low | Trap without Grade Control | |
| Existing High | Existing Geometry | High Flow Data |
| Trap with GCS High | Trap with Grade Control | |
| Trap without GCS High | Trap without Grade Control | |

Following the initial set of base runs to study existing and proposed conditions, sensitivity analyses were performed on several of the input parameters, in addition to flow series, to determine inputs which have the greatest impact on knickpoint migration potential. Input parameters studied were the transition channel slope, reservoir level, bed material gradation, and incoming sediment load gradation.

The incoming sediment load rate was initially planned to be studied with a sensitivity analysis. While developing the most appropriate sediment load for use in the base model runs it was noted that the system was highly dependent on the incoming load and minor variations in the rating curve used caused either unreasonable scour throughout the reach or large unreasonable deposition in the first cross-section or two at the upper end of the modeled reach. Therefore, it was decided that the incoming sediment rating curve would not be modified because the results of the analysis would likely not be relevant. A summary of the trap slope sensitivity analysis runs is given in Table 3 below. All sensitivity analysis runs were conducted with mean flow data and a sediment trap from the base model run series.

**Table 3. Summary of Sensitivity Analysis Model Runs**

| **Run** | **Sensitivity Parameter** |
|---|---|
| Trap with GCS Low Slope | Transition Channel Slope |
| Trap without GCS Low Slope | |
| Trap with GCS High Slope | |
| Trap without GCS High Slope | |
| Trap with GCS Low Reservoir | Reservoir Water Level |
| Trap without GCS Low Reservoir | |
| Trap with GCS High Reservoir | |
| Trap without GCS High Reservoir | |
| Trap with GCS Fine Bed Material | Transition Channel Bed Material Gradation |
| Trap without GCS Fine Bed Material | |
| Trap with GCS Coarse Bed Material | |
| Trap without GCS Coarse Bed Material | |
| Trap with GCS Fine Incoming Sediment | Incoming Sediment Gradation |
| Trap without GCS Fine Incoming Sediment | |
| Trap with GCS Coarse Incoming Sediment | |
| Trap without GCS Coarse Incoming Sediment | |

Note: All sensitivity analysis runs were conducted with mean flow data and a sediment trap

#### *2.3.2.1 Geometry Data*

After studying aerial imagery and consulting with OCWD and Scheevel Engineering, it was determined that the critical area upstream of the proposed sediment trap extended along the Santa Ana River approximately 12 miles. For the existing scenario, cross-sections were sampled at approximately 750 foot intervals and at bridge crossings from the LiDAR data along this alignment. For the proposed scenario, the existing geometry was modified to include the transition channel. Current sediment trap conceptual designs were provided by Scheevel Engineering. The transition channel has a slope of 0.3% and a length of about 12,500 feet for a total drop of about 37 feet. This is compared to the existing river which has an approximate slope of 0.17% in this area for a total drop of 21 feet over the same distance. Configurations have been considered both with grade control and without. Manning's n-values were estimated to be 0.032 within the main channel banks, 0.045 in low-density vegetation areas in the floodplain, and 0.1 in dense vegetated portions of the floodplain. Maximum scour depths along the study reach were estimated to be five feet over the ten-year simulation except for areas where grade control structures are assumed. These locations do not have any allowable scour.

Where grade control structures were assumed to be installed, ten grade control structures were implemented into the model by setting cross-section allowable scour at assumed grade control locations to 0 feet. One each of these structures were input at the upstream and downstream ends of the transition channel with the remaining structures generally evenly spaced along the transition channel.

For the sensitivity analysis, additional geometry files were created which varied the transition channel slope. The base run transition channel has a slope of 0.3%. A low-slope channel was designed with a longitudinal slope of 0.15% and a high-slope channel was designed with a 0.5% slope.

#### *2.3.2.2 Flow Data*

For the existing and proposed conditions models, the synthetic flow series was analyzed to determine a ten-year period of daily flows with roughly a mean flow, low flow, and high flow which was used as the upstream boundary condition for the existing and proposed models. For the sensitivity analysis, only the mean flow time series was used. The flow series are shown below in Figures 3 through 5. Recurrence interval storms are shown as dashed lines across the flow series for reference. The recurrence interval storms were obtained from a gauge at Van Buren Blvd. which is the upstream end of the modeled reach (USGS 2018). As mentioned, Randle et al. (2015) found that, for long-term knickpoint migration studies, flows of magnitude near average annual floods are required for knickpoint migration. The flow series below show that each year simulated reaches at least the annual average flood value several times.

The downstream boundary condition was based on the reservoir level corresponding to the inflow to the reservoir. For the sensitivity analysis using the mean inflow time series, the reservoir level was varied to simulate varied reservoir operating rules. The obtained reservoir level was modified to create both a high and low reservoir level. The reservoir levels used in the modeling are also shown below in Figures 3 through 5. Sensitivity analysis models varying the reservoir level are summarized below in Table 4.

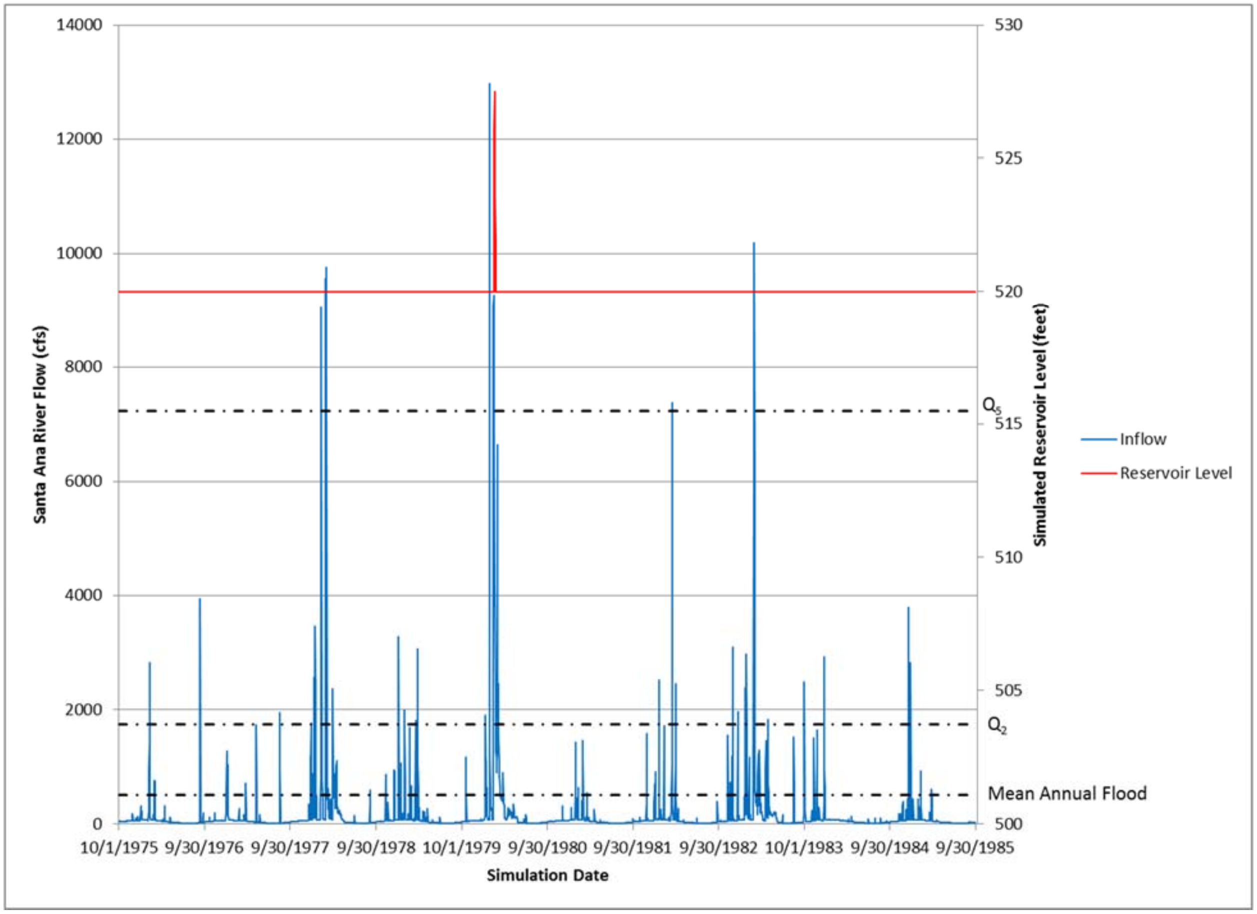

**Figure 3**. **Santa Ana River Mean Flow for Simulations**

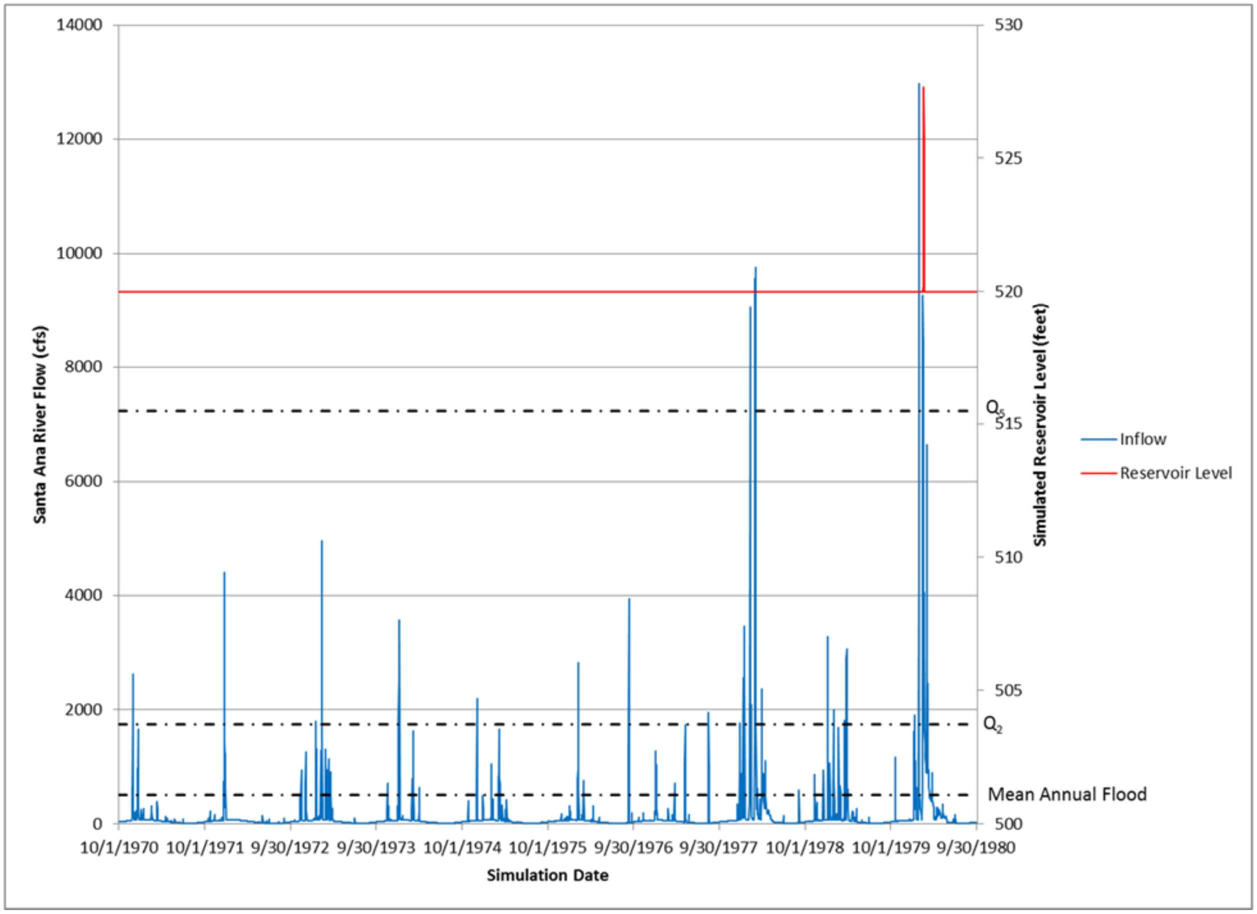

**Figure 4**. **Santa Ana River Low Flow for Simulations**

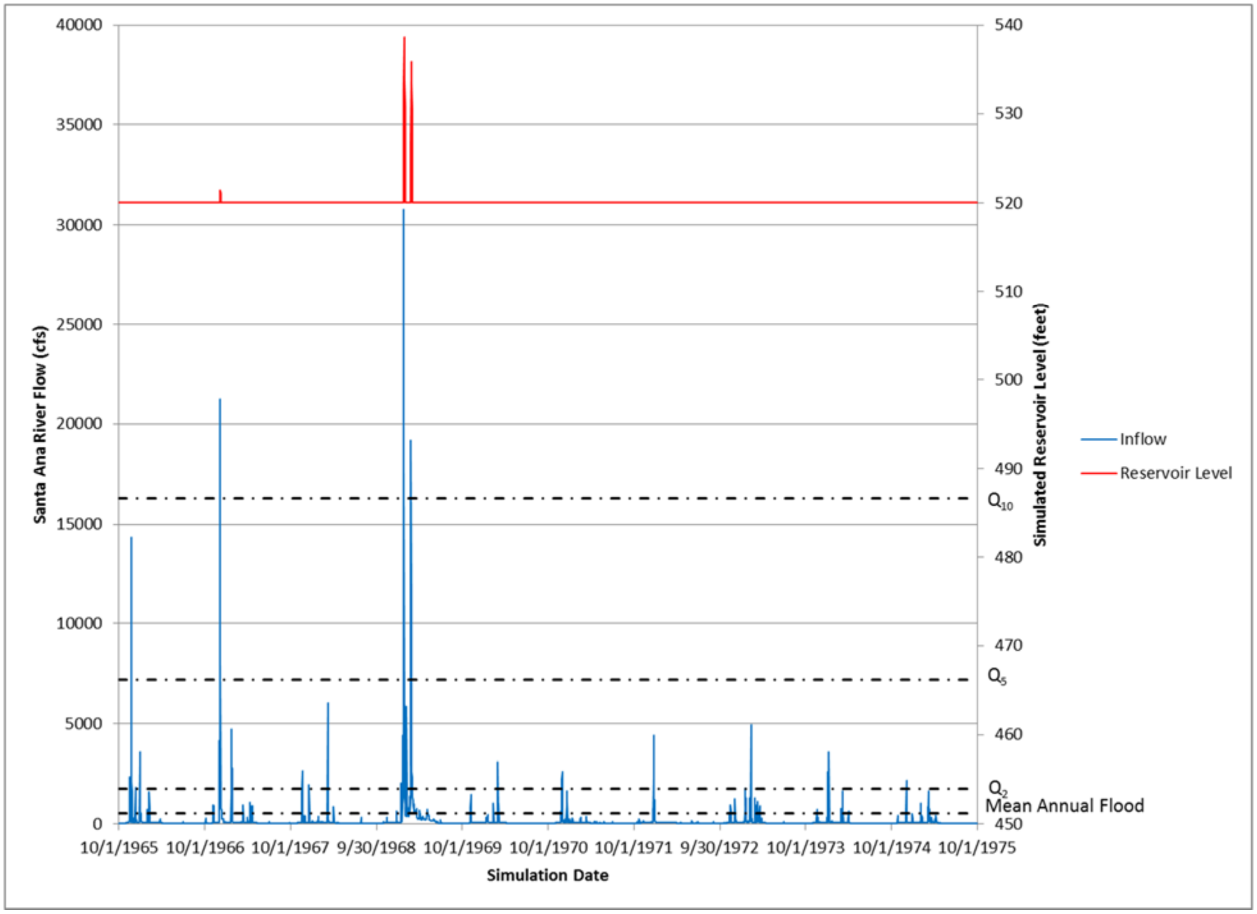

**Figure 5**. **Santa Ana River High Flow for Simulations**

**Table 4. Reservoir Level Adjustment for Sensitivity Analysis**

| **Run** | **Reservoir Level Modification** |
|---|---|
| Trap with Low Reservoir Level | Operated Reservoir Level -10 feet |
| Trap with High Reservoir Level | Operated Reservoir Level +10 feet |

A flow diversion from the Santa Ana River is present to deliver water to the OCWD wetland areas adjacent to the Prado Basin. The diversion point is just downstream of River Road Bridge in the existing conditions and is at the entrainment groin location for the proposed condition. The flow diversion rule within all runs, base and sensitivity, is to divert half of the river flow up to a maximum of 150 cfs.

### *2.3.2.3 Bed Gradation Data*

The bed gradations sampled at Van Buren Blvd., Hamner Ave., and River Road were used for the model inputs at these bridge crossings. Figure 6 shows bed material gradations along the study reach and Table 5 has calculated values of grain size statistics. For the purposes of inputting bed gradation data into the model, the bed gradation was interpreted between these locations for sections without sampled bed gradations.

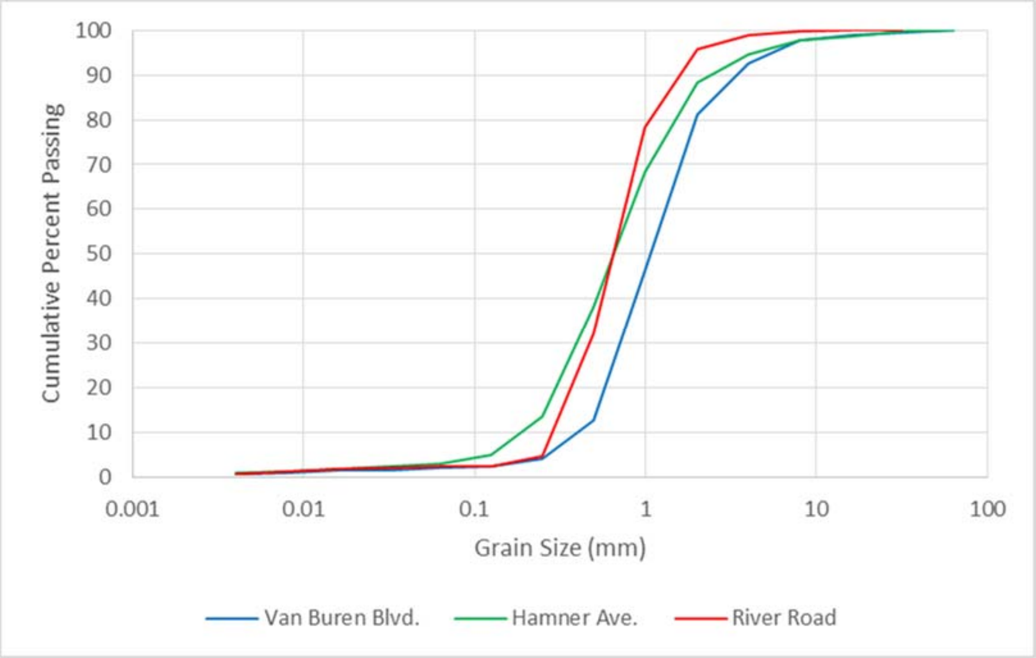

Figure 6. Bed Gradation Inputs

**Table 5. Bed Gradation Statistics**

| | Van Buren Bridge | Hamner Avenue Bridge | River Road Bridge |
|---|---|---|---|
| $D_{16}$ (mm) | 0.53 | 0.27 | 0.33 |
| $D_{50}$ (mm) | 1.08 | 0.66 | 0.65 |
| $D_{84}$ (mm) | 2.38 | 1.72 | 1.26 |
| Geometric Standard Deviation, $\sigma_g$ | 2.12 | 2.52 | 1.95 |

For the sensitivity analysis, the downstream most measured bed gradation, River Road, was varied to both a finer and coarser gradation to affect the transport rates in the transition channel and upstream of the transition channel where a knickpoint might propagate. The sensitivity analysis bed gradations used at River Road for the sensitivity analysis are shown on Figure 7 below. Grain size statistics are summarized in Table 6 below.

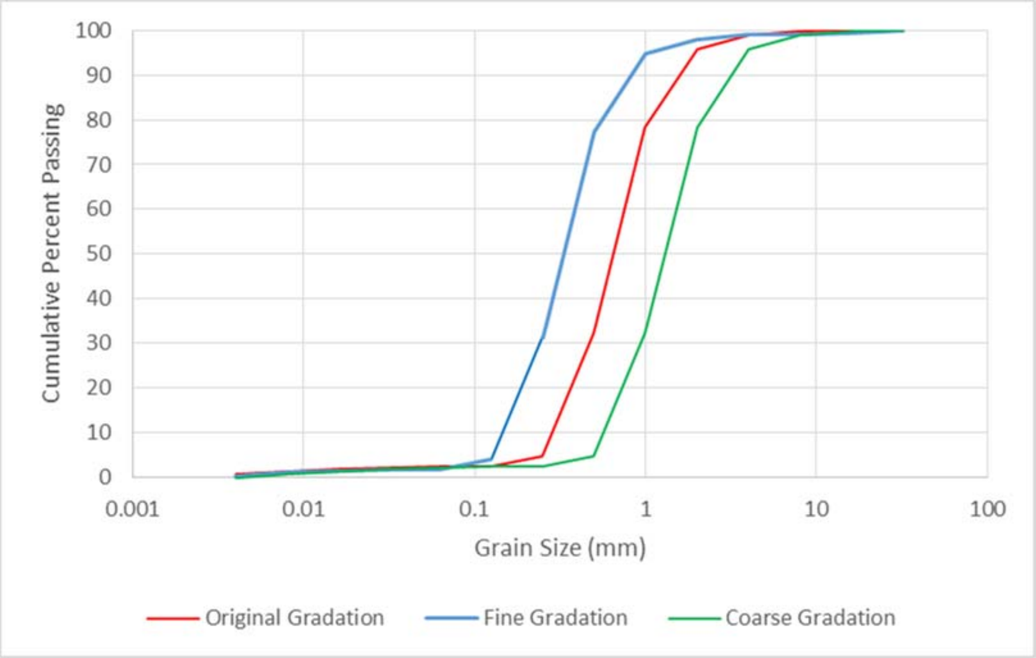

**Figure 7. River Road Bridge Bed Gradations for Sensitivity Analysis Runs**

**Table 6. River Road Bridge Bed Gradation Statistics for Sensitivity Analysis Runs**

| | **Original Gradation** | **Fine Gradation** | **Coarse Gradation** |
|---|---|---|---|
| **$D_{16}$ (mm)** | 0.33 | 0.18 | 0.66 |
| **$D_{50}$ (mm)** | 0.65 | 0.33 | 1.31 |
| **$D_{84}$ (mm)** | 1.26 | 0.65 | 2.52 |
| **Geometric Standard Deviation, $\sigma_g$** | 1.95 | 1.90 | 1.95 |

### *2.3.2.4 Incoming Sediment Load Data*

Figure 8 shows the calculated incoming sediment load vs. river flow at Van Buren Blvd. As discussed above, small changes in the incoming load led to large depositions at the upstream most cross-sections modeled, or large scour depths across the entire reach and therefore, the incoming sediment load rating curve was not modified throughout the analysis.

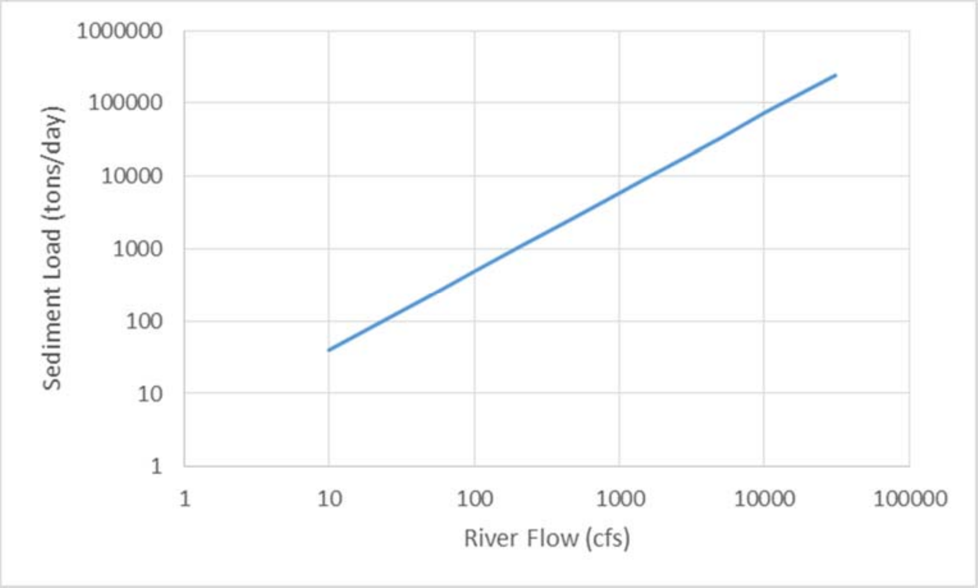

**Figure 8**. **Sediment Load vs. River Flow for Incoming Sediment Load Rating Curve**

The calculated incoming sediment gradation is shown below in Table 7. For sensitivity analysis runs, the gradation was shifted to both a finer gradation and coarser gradation. Figure 9 presents the sensitivity analysis gradations used for the incoming sediment load. Table 7 shows the incoming load sensitivity grain statistics.

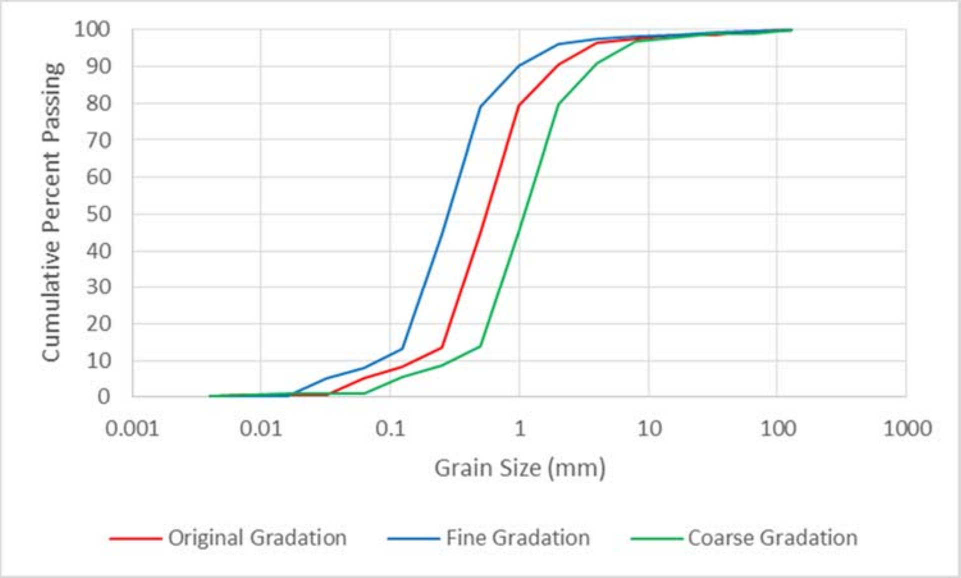

**Figure 9. Calculated Incoming Sediment Load and Sensitivity Analysis Gradations**

**Table 7. Calculated Incoming Sediment and Sensitivity Analysis Grain Statistics**

| | **Original Gradation** | **Fine Gradation** | **Coarse Gradation** |
|---|---|---|---|
| **$D_{16}$ (mm)** | 0.26 | 0.13 | 0.52 |
| **$D_{50}$ (mm)** | 0.55 | 0.28 | 1.10 |
| **$D_{84}$ (mm)** | 1.33 | 0.68 | 2.61 |
| **Geometric Standard Deviation, $\sigma_g$** | 2.26 | 2.29 | 2.24 |

### 2.3.3 Assumptions

The largest assumption made in the analysis is that a one-dimensional flow regime is suitable for estimating the sediment transport characteristics in the study reach. Flow in this reach is mostly one-dimensional in nature, however, as the channel erodes, lateral expansion of the channel is possible which could endanger more property and infrastructure than is represented with a one-dimensional model. Additionally, the sediment trap itself is not modeled in this analysis. Once flow and sediment enter the trap, the regime will become two-dimensional. The modeled scenarios represent a conservative representation of the potential for knickpoint migration due to the fact that as sediment builds up in the trap, the effects of the knickpoint will likely be dampened.

Other major assumptions made during the modeling process were mostly limited to the sediment inputs. After calculations were made to determine bed material and total incoming load rating curve and gradations, simulations were conducted for existing conditions using calculated sediment data. The incoming sediment rates and gradations had to be modified to provide reasonable results based on observations in the Santa Ana River which reflect a quasi-equilibrium state in the study reach. The modifications made to the incoming sediment rating curve and gradations were made with the sampled data in mind to maintain the integrity of the sediment monitoring studies. The modeled reach was allowed to erode and deposit across the entire cross-section.

The sediment equation chosen for all model runs is the Engelund-Hansen (1967) equation. Annandale (2007) showed that the Engelund and Hansen equation responds appropriately as a total load predictor to changes in total turbulence as opposed to only responding to changes in near-bed turbulence (bed load) or only to turbulence in the water column above the near-bed region (suspended load).

As described in Section 2.3.2.2 above, the flow series used for the model runs has a daily timestep. Within HEC-RAS, shortening the computational increment allows sediment transport calculations to occur several times throughout the timestep increment to maintain the assumption that hydrodynamics remain constant throughout the computational time period. Higher flow periods require the timestep to be reduced to maintain model stability (USACE 2016). For all model runs, flows less than 100 cfs had a one-hour timestep, flows between 100 and 500 cfs had a 0.5-hour timestep, and flows above 500 cfs had a 0.1-hour timestep.

The other major assumption made is the way the bridge crossings were simulated. The bridges were not input to HEC-RAS in the traditional sense by using an inline structure. Conversations with Stanford Gibson with USACE indicate that the necessity of four cross-sections at each bridge crossing causes instabilities within the sediment transport module. It was recommended to model the bridge crossings as lidded cross-sections with the piers simulated using additional ground points. This allows for bridges to be modeled with only a single cross-section. A full hydraulic analysis of the bridge, for example pressure flow through the opening, is not conducted in this scenario but it is a reasonable approximation for the purposes of sediment transport modeling.

## 3 RESULTS

### 3.1 Existing and Proposed Base Run Results

Results are presented for the existing and proposed condition base runs with and without grade control structures for a ten-year historic flow series adjusted for future land use and climate considerations. Figure 10 shows the thalweg longitudinal profile at the beginning of the model run and again at the end of the model run for the existing conditions, mean flow model run. Figure 11 shows the thalweg longitudinal profile at the beginning and end of the model run for the proposed condition, mean flow run with grade control structures and Figure 12 shows the effects of not including grade control in the transition channel.

Figure 10 shows that the existing conditions thalweg degrades over the modeled reach. The same degradation is seen in Figures 11 and 12 for proposed conditions upstream of the transition channel. All three figures, 10 through 12, indicate that the thalweg degrades in the first five years and then stabilizes somewhat as the thalweg elevation does not change much in the second five years of the model run. For proposed conditions, Figure 11 shows that grade control structures placed within the transition channel will maintain the beginning slope of the transition channel and will not allow for wide ranging thalweg degradation within the transition channel. In contrast, Figure 12 shows that without grade control in the transition channel, the channel will have significant thalweg degradation throughout. The transition channel slope will flatten some and smooth out the knickpoint between the existing river bed and transition channel in the scenario without grade control.

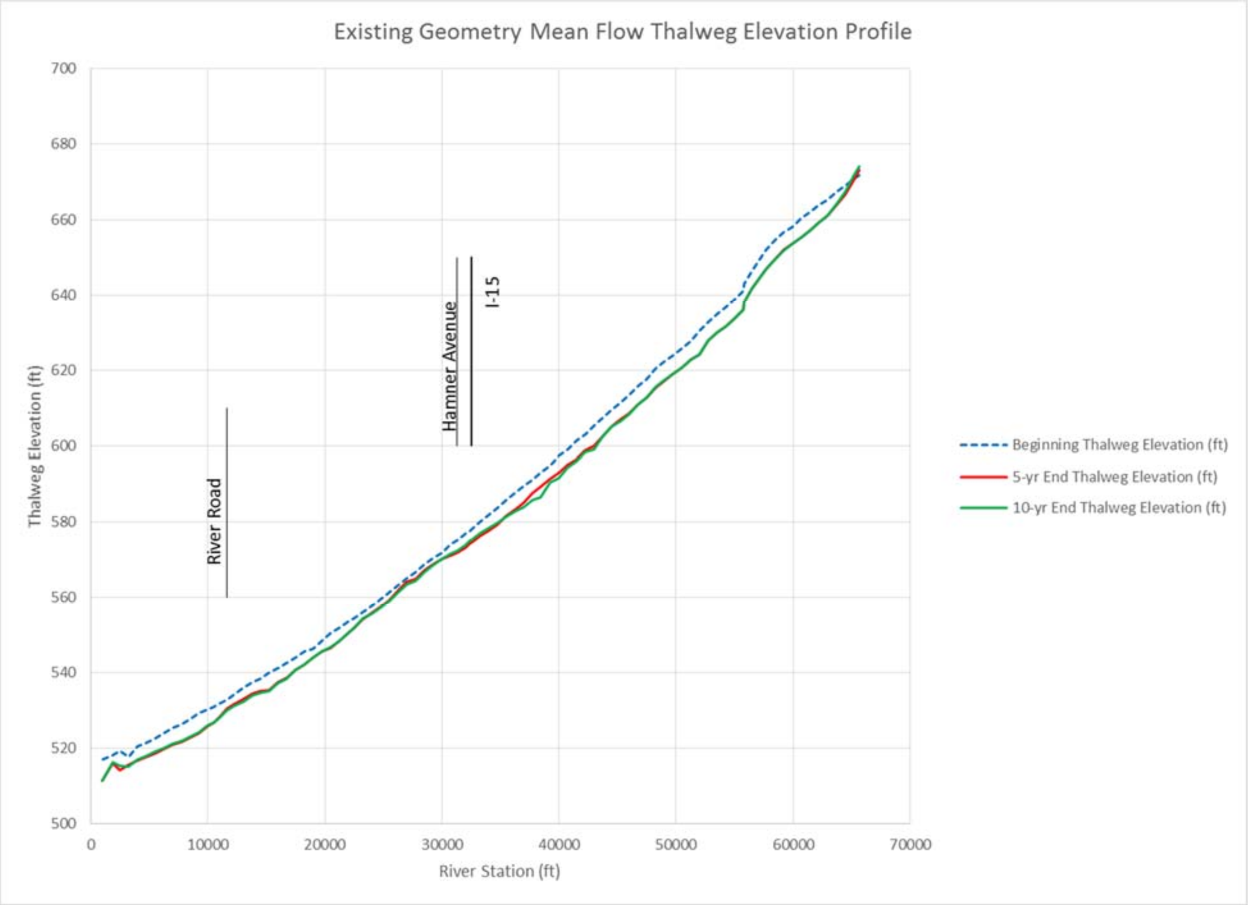

**Figure 10. Thalweg Elevation throughout Model Run of Study Reach with Existing Conditions and Mean Inflow**

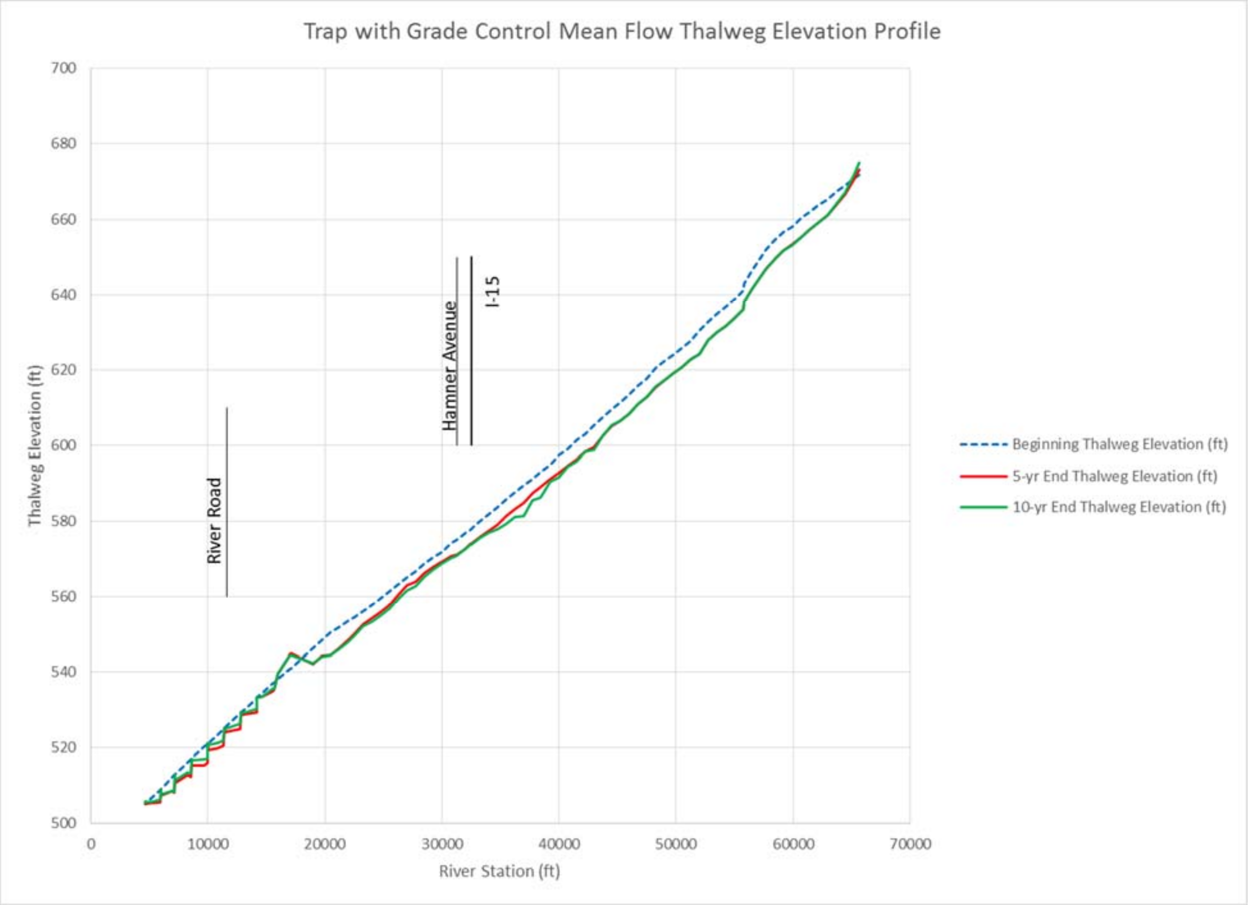

**Figure 11. Thalweg Elevation throughout Model Run of Study Reach with Proposed Conditions, Grade Control, and Mean Inflow**

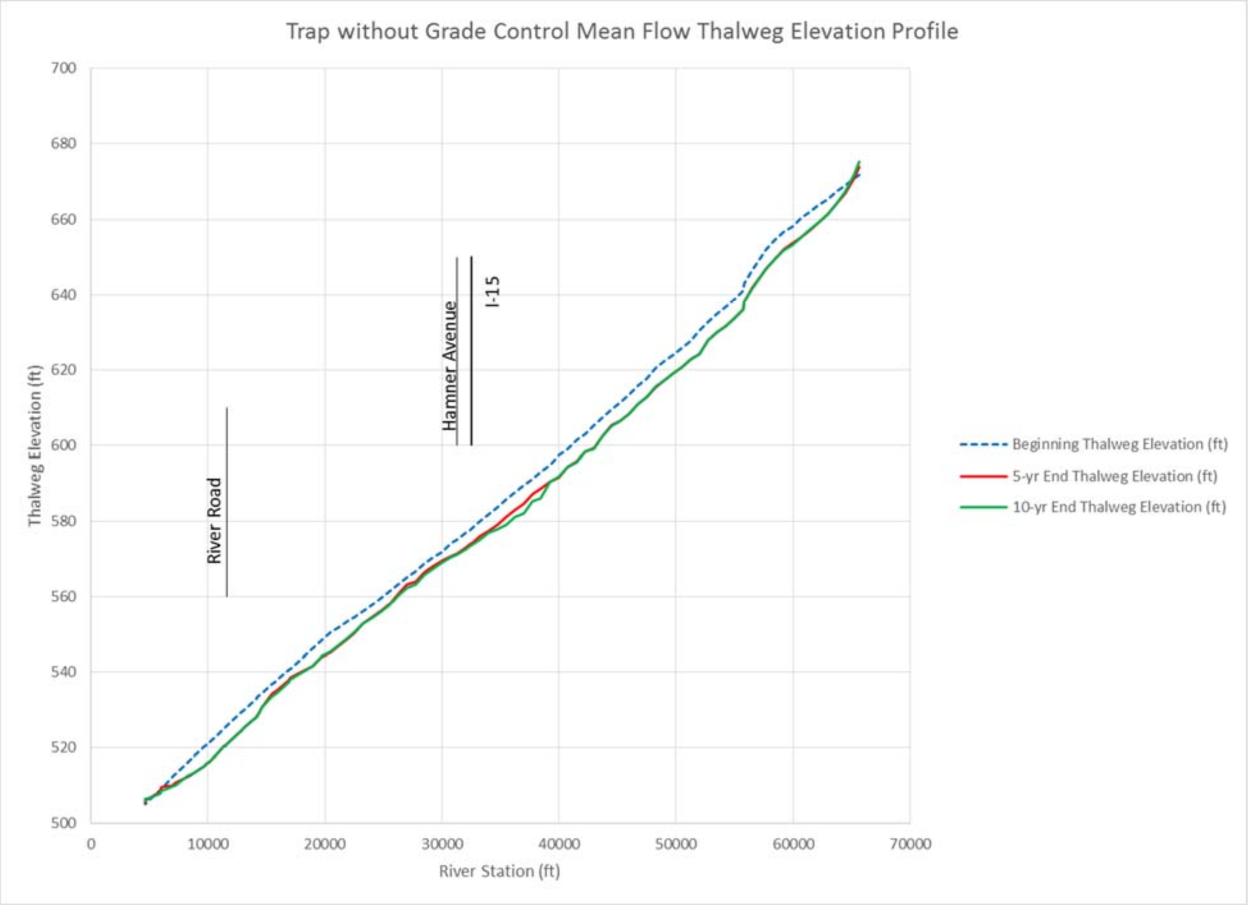

**Figure 12. Thalweg Elevation throughout Model Run of Study Reach with Proposed Conditions, No Grade Control, and Mean Inflow**

Using the low flow time-series, the general trend of the results are similar to the mean flow series. Low flow results for the base runs are shown on Figures A-1 through A-3. These figures show that there is more degradation in years five through ten than is seen in the mean flow runs. The downstream end of the transition channel in the low flow run without grade control actually aggrades within the thalweg in the first five years of the run before obtaining a net degradation after ten years. The results shown on Figures A-4 through A-6 for the high flow scenario are similar to the mean flow results with similar thalweg degradation after five years as after ten years.

### 3.2 Sensitivity Analysis Results

Results of the sensitivity analysis show that simulations which vary transition channel slope, downstream reservoir water surface elevation, and incoming sediment gradation from base conditions show an appreciable difference in longitudinal thalweg elevation profile when compared to base runs. The profiles shown in Figures 13 and 14 are focused on the reach between Hamner Avenue and the proposed entrainment groin. The “Control Trap” profile shown is the results of the mean flow series proposed condition model run with or without grade control depending on the scenarios being studied to be able to compare the sensitivity of the selected parameter. Changes in this area vs existing conditions due to knickpoint migration will be seen first. These figures present results of the studied scenarios after the full ten year run.

Figures 13 and 14 present a comparison of longitudinal thalweg elevation profiles between the sensitivity runs analyzing a varied transition channel slope when compared to base scenarios and the base scenarios. Figure 13 shows that thalweg elevations are higher in this reach with a lower transition channel slope. A steeper transition channel slope does not necessarily lead to more thalweg degradation in this reach. The effect of transition channel slope is dampened without the presence of grade control structures, as shown on Figure 14. The low slope transition channel still develops thalweg aggradation at the entrainment groin in this scenario, but the remaining channel reach analyzed is relatively close to base conditions.

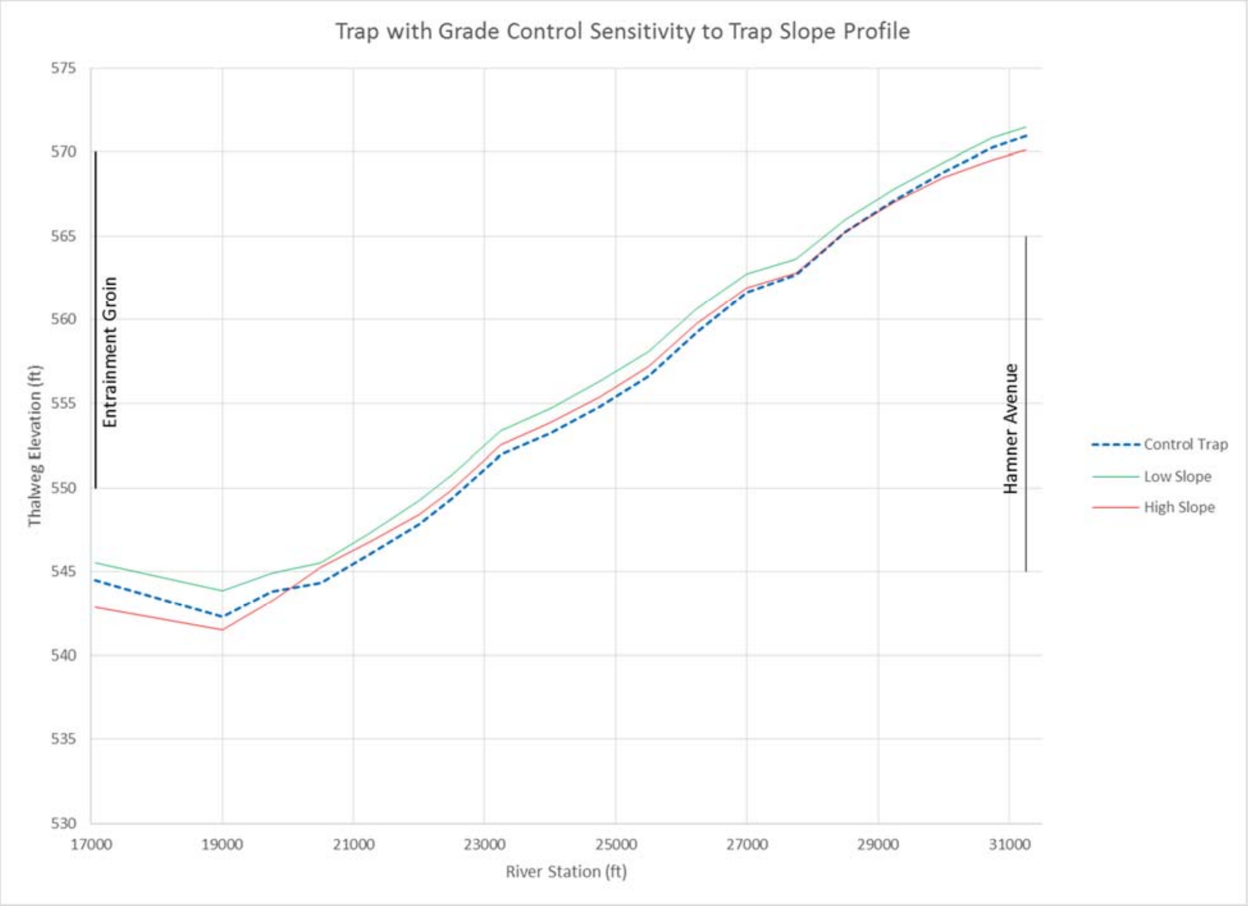

**Figure 13. Thalweg Elevation Profile of Transition Channel Slope Sensitivity between Hamner Avenue and the Proposed Entrainment Groin**

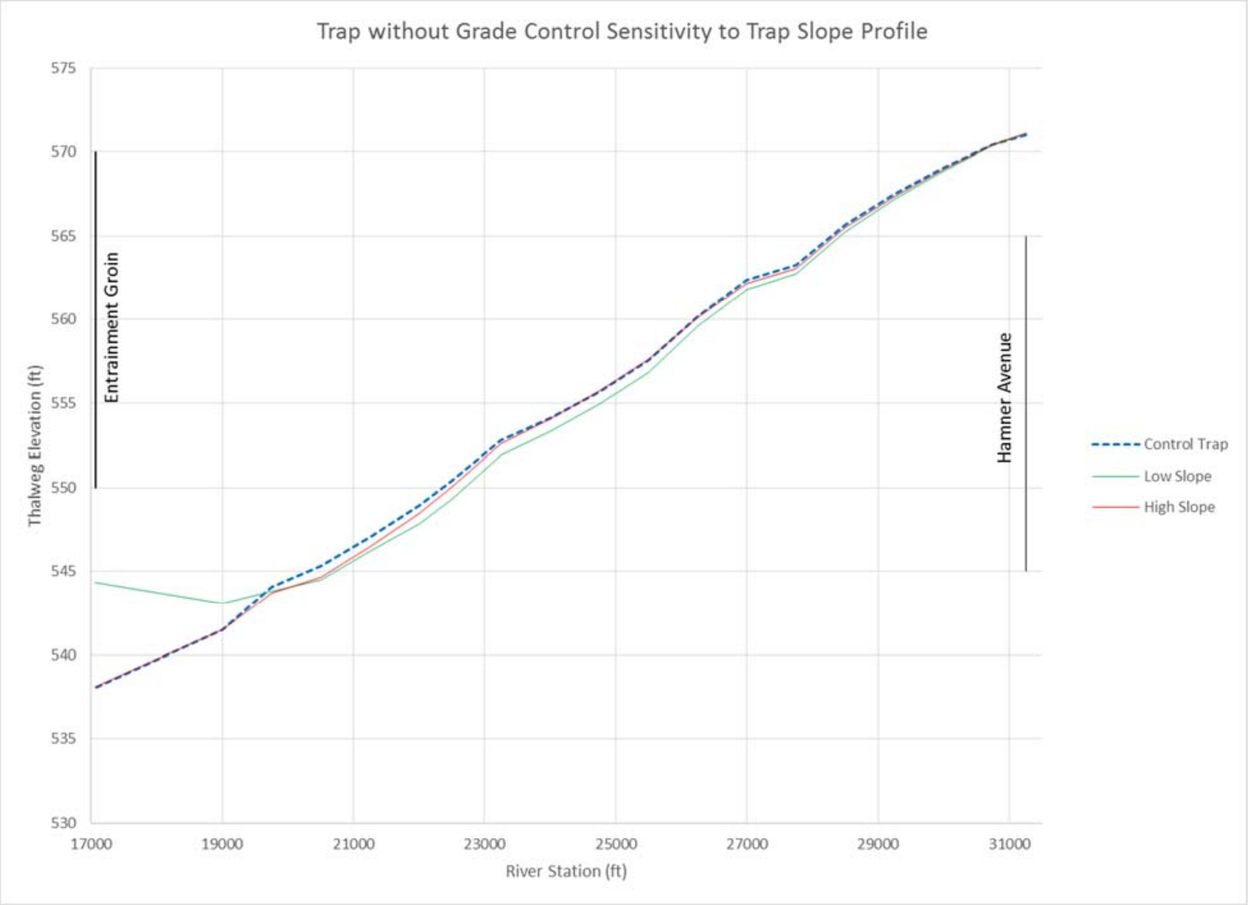

**Figure 14. Thalweg Elevation Profile of Transition Channel Slope Sensitivity without Grade Control between Hamner Avenue and the Proposed Entrainment Groin**

Figures 15 and 16 show the sensitivity results between Hamner Avenue and the entrainment groin of a varied reservoir elevation when compared to base conditions. The lower reservoir creates more thalweg degradation near Hamner Avenue for the scenario with grade control. The higher reservoir elevation does not have an appreciable effect with assumed grade control. The effect of a low reservoir elevation is eliminated if grade control is not assumed to be in place as shown on Figure 16. This figure shows a small area of increased thalweg degradation with the higher reservoir water elevation.

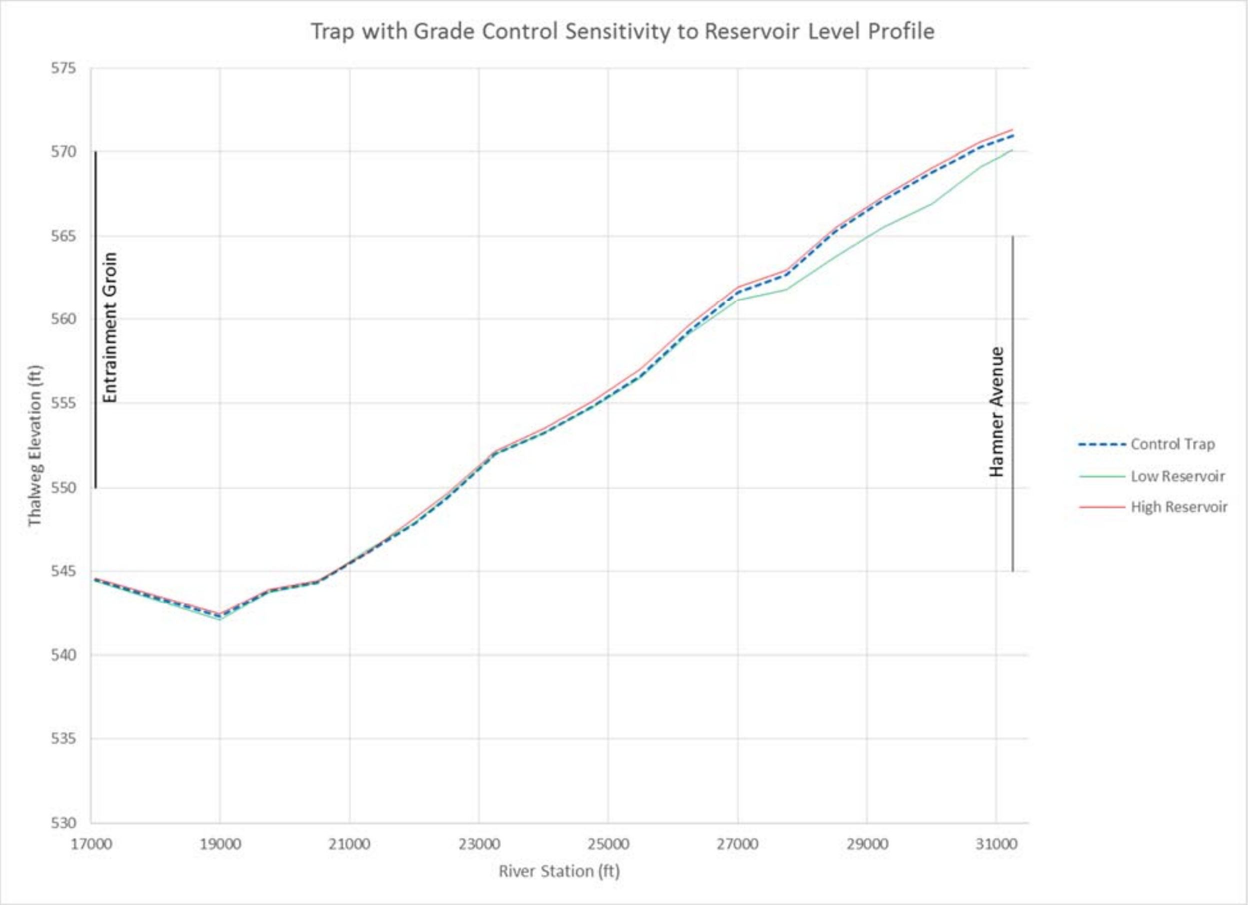

**Figure 15. Thalweg Elevation Profile of Reservoir Water Elevation Sensitivity with Grade Control between Hamner Avenue and the Proposed Entrainment Groin**

**Figure 16. Thalweg Elevation Profile of Reservoir Water Elevation Sensitivity without Grade Control between Hamner Avenue and the Proposed Entrainment Groin**

Modifications to the incoming sediment load have an effect on the scour and deposition upstream of the transition channel as seen on Figures 17 and 18. If the incoming load is actually finer than assumed for base scenarios, there is the potential for increased scour downstream of Hamner Avenue for the scenario with grade control as shown on both Figures 17 and 18.

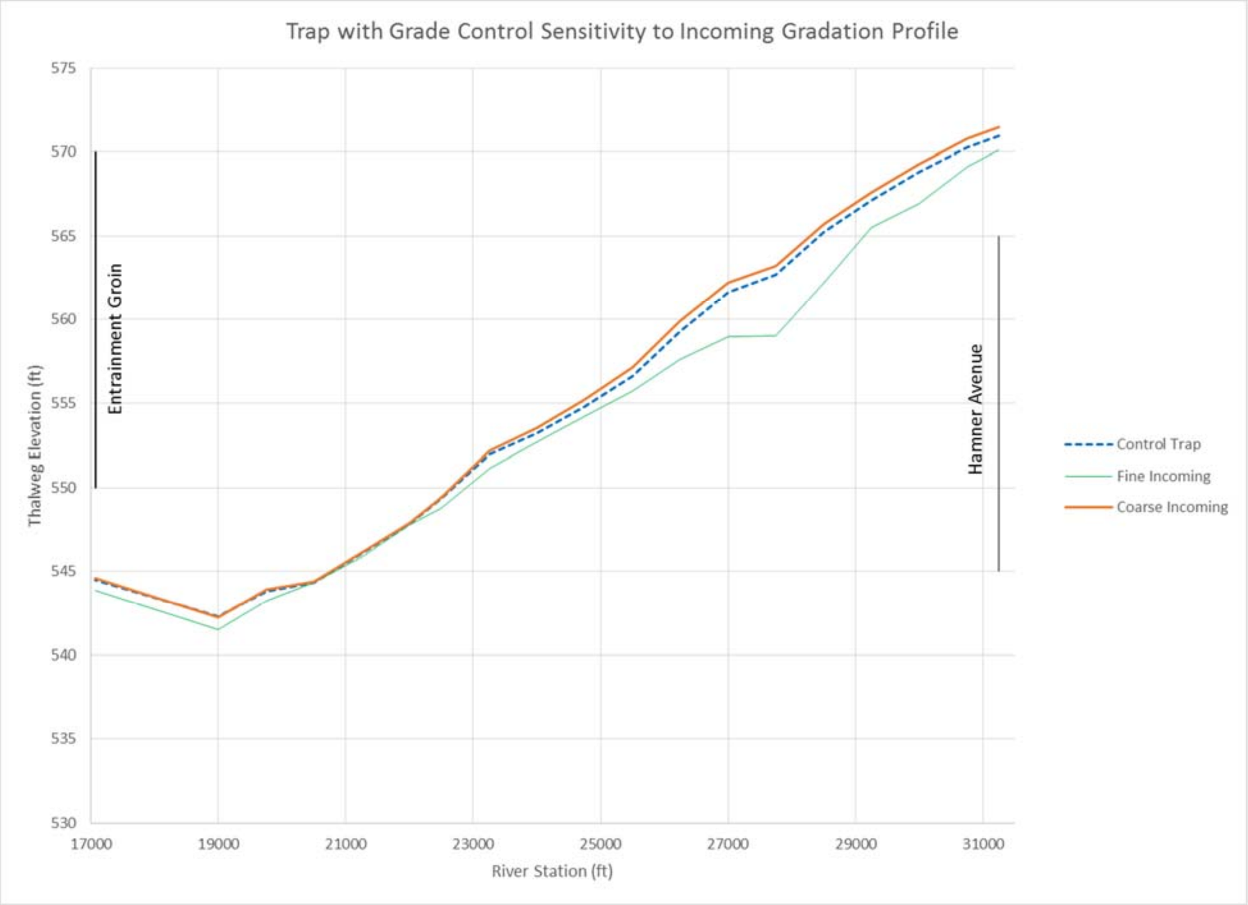

Figure 17. Thalweg Elevation Profile of Incoming Sediment Gradation Sensitivity with Grade Control between Hamner Avenue and the Proposed Entrainment Groin

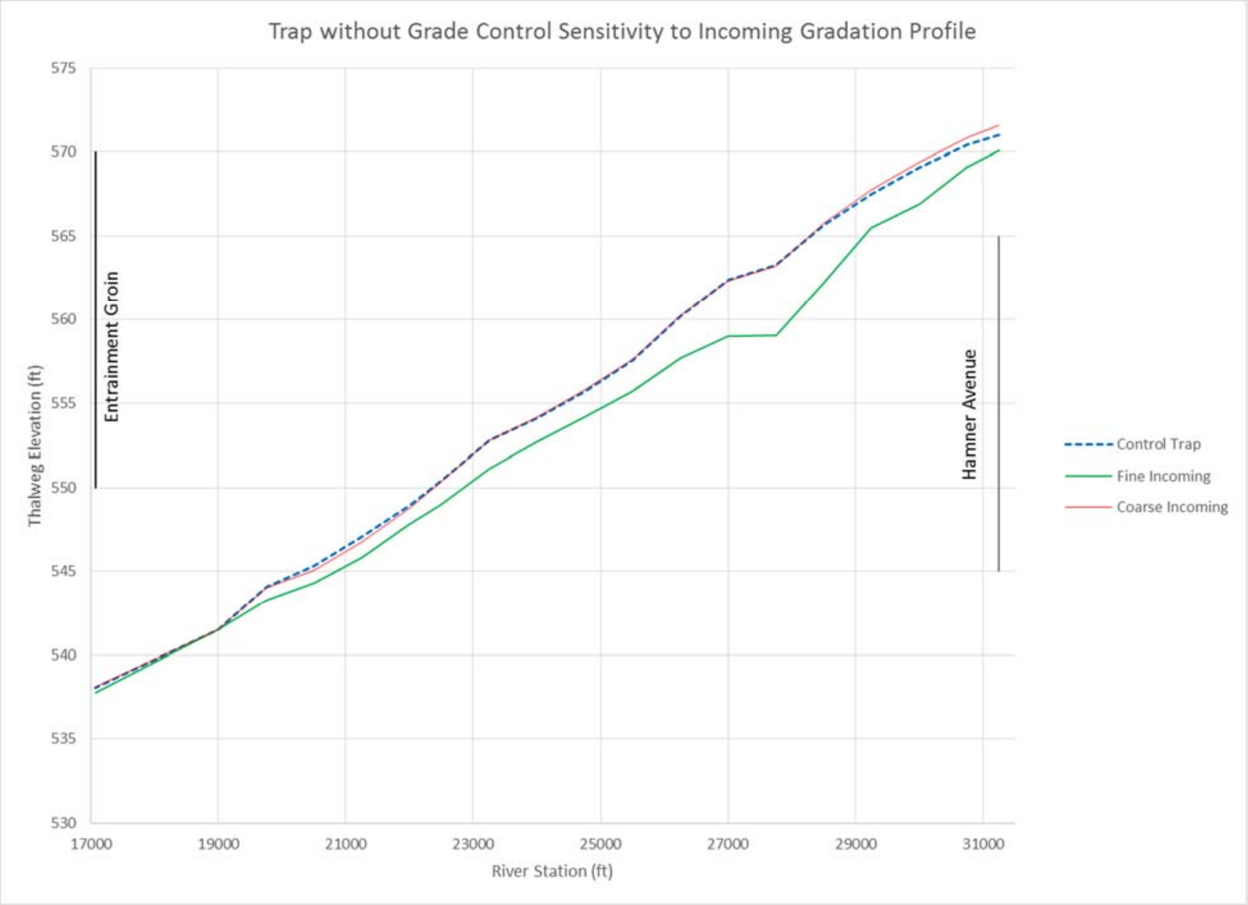

**Figure 18. Thalweg Elevation Profile of Incoming Sediment Gradation Sensitivity without Grade Control between Hamner Avenue and the Proposed Entrainment Groin**

Remaining results for sensitivity analysis scenarios are presented in Appendix B Figures showing the change in thalweg elevation profile after both five and ten years using the mean flow time series for the sensitivity parameter being studied are shown on Figures B-1 through B-16. The results of the trap slope sensitivity are presented on Figures B-1 through B-4, reservoir level is presented on B-5 through B-8, bed material gradation is shown on B-9 through B-12, and incoming load gradation is shown on B-13 through B-16. These results show, as described above, that thalweg elevation profile trends are similar to base conditions for the sensitivity parameters of hydrology and bed gradation in the vicinity of the transition channel and the trap slope, reservoir level, and incoming sediment load do have an impact on the magnitude of thalweg deposition and scour within the study reach.

Also presented in Appendix B are the remaining close-up views of the longitudinal thalweg elevation profiles not presented above comparing the results of the longitudinal profile after ten years for each sensitivity parameter. The area shown is just upstream of the transition channel. This location would see the most immediate effects if a knickpoint were to propagate upstream. Only results after ten years are shown because and analysis of the results shown in the first part of Appendix B shows that little change occurs in the thalweg elevation profile from year 5 to year 10 during the simulation.

Figures B-17 and B-18 show the effects of various flow series. Figure B-17 shows the results after ten years of the three flow scenarios' effect on thalweg elevation for existing conditions (dashed lines) and the proposed transition channel (solid lines) with grade control. The three scenarios trend together for both existing and proposed conditions which indicate that the hydrology used does not have a major impact on the thalweg elevation profile. Figure B-18 shows similar results for existing conditions and the transition channel without grade control. Again, the results show that hydrology does not play a large role in the thalweg elevation.

Figures B-19 and B-20 show the results of the sensitivity of the bed material gradation in the vicinity of the transition channel. The bed gradation in the vicinity of the transition channel does not show any appreciable difference between the base case, fine, and coarse gradations for both the scenario with grade control and without.

## 4 ANALYSIS

### 4.1 Existing and Proposed Conditions

The results show that the existing and proposed conditions thalweg degrades to some extent over the simulation timeframe with the modeled inputs. A lot of effort went into maintaining a quasi-equilibrium for the existing conditions by varying bed material gradation, incoming sediment load rate, and incoming sediment load gradation. The parameters selected represent the most stable balance between too much degradation reach wide and too much deposition in the first couple cross sections. It is possible that the model is using the first few years of the simulation period to obtain a stabile bed profile based on incoming load & gradation, bed gradation, and channel geometric parameters. Also, results presented to this point are for the thalweg elevation profile. The HEC-RAS User's Manual argues that the thalweg, or lowest channel, elevation may not be indicative of geomorphic changes throughout the entire cross-section (USACE 2016). For this reason, an available output is the effective channel elevation. This is calculated by subtracting the average channel bed elevation from the water surface elevation.

Results of the proposed conditions also indicate that the transition channel thalweg can be assumed to degrade which has the potential to cause a knickpoint to migrate upstream. However, the grade control structures can help to reduce erosion and maintain the channel near the profile at the beginning of the trap simulations. The area of aggradation shown in proposed conditions results with grade control in Figure 11, A-1, and A-4 just downstream of station 20000 is likely due to the presence of an "entrainment groin" which is a transverse structure approximately four feet in height which has the purpose of directing the flow into the transition channel up to flows of approximately 10,000 cfs. Interestingly, this deposition is not seen in the proposed conditions models without grade control. This is likely due to the lack of grade control downstream of the entrainment groin allowing the water surface slope to increase and prevent deposition from occurring. This is evidence that, while not necessarily definitively representing a propagating knickpoint, the steepening of the river as it approaches the sediment trap could have effects upstream of the modified channel reach. This is coupled with a flattening of the slope of the transition channel on Figure 12 which may indicate that the channel is self-adjusting for the presence of the steepened transition channel.

When analyzing the area just upstream of the sediment trap, Figures B-17 and B-18 show that the river does degrade below existing conditions with the introduction of the sediment trap. It is unclear whether the scour would continue upstream or not, and whether the depth of scour would increase more than shown. However, it was noted that the river profile did not change appreciably between years five and ten which may indicate that the depth and extent of introduced scour would not continue indefinitely. It can be seen from Figures B-17 and B-18, the hydrology of the system has very little effect on the likelihood of knickpoint propagation within each scenario modeled.

### 4.2 Sensitivity Analysis

The results of the sensitivity analysis were studied to determine if any definitive conclusions could be reached on the dependence on a particular parameter. Figure 13 shows that a lower transition channel slope will lead to higher bed thalweg elevations in the reach just upstream of the transition channel. The lower slope will lead to aggradation at the entrainment groin for the case without grade control structures. A steeper transition channel slope does not lead to more degradation when compared to base runs. This indicates that the grade control will maintain the longitudinal thalweg profile even if the transition channel becomes steeper, but a flatter slope could allow for a reversal back to existing conditions.

Figure 15 shows that there is the potential for a low reservoir condition to lead to more scour upstream of the transition channel with grade control structures, however, no discernable difference is seen in the scenario without grade control on Figure 16. The area of the increased scour is not immediately upstream of the transition channel but is near Hamner Avenue. If the reservoir elevation would lead to degradation propagating upstream, it would be expected that there would be increased degradation immediately upstream of the transition channel. It is unclear how the lower reservoir level affects the degradation that far upstream.

Modifying the bed gradation in the vicinity of the transition channel has only minimal effects on the scour upstream of the transition channel as seen on Figures B-19 and B-20. This indicates that the hydraulics of the flow have a greater impact on the scour and deposition upstream of the transition channel than the sediment parameters.

Figure 17 shows that modifying the incoming sediment load to a finer gradation leads to more scour upstream of the transition channel for the case with grade control. This may be due to the lack of coarse grained sediment continuing to be transported downstream of Hamner Avenue. A coarser incoming sediment load does not lead to more deposition in this area however. The finer incoming sediment load does not affect the degradation in this area for the scenarios without grade control as shown on Figure 18.

### 4.3 Relative Thalweg Elevation Change

To quantify the relative amount of scour or deposition due to the different proposed model runs, a calculation was made to determine the amount of sediment being removed from the reach between Hamner Avenue and the entrainment groin. This calculation uses the previously described effective channel elevation to determine the volume per unit width that is removed from the section by multiplying the change in effective channel elevation by the channel length of influence of each cross-section. This value is then multiplied by the effective width of the channel which is defined as the effective width of water within the mobile portion of the cross-section (USACE 2016). The volume removed in the sensitivity analysis runs are also compared to the corresponding base run (Trap with/without GCS Mean Flow). The results of this analysis are summarized below in Table 8.

**Table 8. Comparison of Volume Removed Between Hamner Avenue and the Entrainment Groin**

| | Simulation | Volume Removed per Unit Width ($ft^2$) | Effective Width (ft) | Total Volume Removed ($yd^3$) | Relative Volume Removed Compared to Base Run ($yd^3$) |
|---|---|---|---|---|---|
| Base Runs | Trap with GCS Mean Flow | 24,954 | 68 | 63,266 | - |
| | Trap without GCS Mean Flow | 22,288 | 65 | 53,952 | - |
| | Trap with GCS Low Flow | 22,541 | 67 | 56,202 | - |
| | Trap without GCS Low Flow | 21,824 | 67 | 53,977 | - |
| | Trap with GCS High Flow | 19,058 | 71 | 50,008 | - |
| | Trap without GCS High Flow | 16,207 | 67 | 40,140 | - |
| Sensitivity Analysis Runs | Trap with GCS Low Transition Channel Slope | 13,769 | 67 | 34,418 | -28,848 |
| | Trap without GCS Low Transition Channel Slope | 21,694 | 65 | 52,015 | -1,937 |
| | Trap with GCS High Transition Channel Slope | 23,484 | 66 | 57,622 | -5,644 |
| | Trap without GCS High Transition Channel Slope | 23,665 | 65 | 57,290 | 3,338 |
| | Trap with GCS Low Reservoir Elevation | 27,957 | 68 | 70,243 | 6,977 |
| | Trap without GCS Low Reservoir Elevation | 22,635 | 66 | 55,086 | 1,134 |
| | Trap with GCS High Reservoir Elevation | 23,189 | 69 | 59,224 | -4,042 |
| | Trap without GCS High Reservoir Elevation | 23,944 | 66 | 58,209 | 4,257 |
| | Trap with GCS Fine Bed Material | 25,224 | 68 | 63,658 | 392 |
| | Trap without GCS Fine Bed Material | 23,122 | 66 | 56,351 | 2,399 |
| | Trap with GCS Coarse Bed Material | 24,298 | 70 | 62,685 | -582 |
| | Trap without GCS Coarse Bed Material | 23,909 | 66 | 58,489 | 4,538 |
| | Trap with GCS Fine Incoming Sediment | 32,793 | 69 | 84,114 | 20,847 |
| | Trap without GCS Fine Incoming Sediment | 34,276 | 65 | 82,035 | 28,084 |
| | Trap with GCS Coarse Incoming Sediment | 23,986 | 68 | 60,638 | -2,628 |
| | Trap without GCS Coarse Incoming Sediment | 22,899 | 65 | 55,187 | 1,235 |

Most runs have volumes removed between 50,000 and 65,000 yd$^3$ throughout the ten-year simulation run except for those highlighted above. Simulations where the volume removed is less than this range are the run without grade control simulating the high flow series and the run with grade control and the low transition channel slope. Section 4.2 above described the low transition channel slope having more aggradation in this reach when studied with visual observation. The simulation with the high flow time-series and no grade control was not observed to have an appreciable difference from mean flow conditions. However, after this analysis, it can be seen in Figure A-6 that the thalweg elevation after five and ten years shows less degradation than in Figure A-5. The higher flows will carry more sediment into the system and it appears that some has deposited downstream of Hamner Avenue for these simulations.

Simulations with more sediment removed than the average runs are the low reservoir sensitivity analysis with grade control and both simulations with a fine incoming sediment gradation. All three of these simulations were observed to have more degradation than average when the thalweg elevation profiles were examined.

# 5 DISCUSSION

The analysis to date has shown that a knickpoint is formed by creation of a sediment trap, either through dry excavation or dredging, in the upstream end of the Prado Basin to cause increased scour upstream of the transition channel. A comparison of proposed base models and existing conditions models show this to be the case. However, determining how far upstream the excess scour propagates and the depth the scour ultimately reaches is uncertain.

Results of the base case runs without grade control indicate that if the transition channel is assumed to be a knickpoint face, it is described as a rotating knickpoint in literature. These knickpoints are in non-resistant soils and rotate to create a uniform slope on the knickpoint face and upstream of the knickpoint (Gardner 1983). The knickpoint slope is decreased but the slope upstream of the knickpoint increases. Where grade control structures are installed, the transition channel slope remains steep but the reach upstream of the transition channel will still steepen. Gardner (1983) and Swaske (2012) point to the need for layered sediment with a resistant top layer to obtain a retreating knickpoint. One of the limitations of the modeling in HEC-RAS is that only one bed particle size distribution can be input at each cross-section and therefore, developing this layering is not possible for these simulations. Holland & Pickup (1976) added that a plunge pool is evident in these knickpoints and one is not evident in the results presented here.

Base case runs with grade control show the same steepening of the reach upstream of the transition channel. However, the grade control structures maintain bed elevation at the grade control location. The downstream side of the grade control structures forms stepped knickpoints for each modeled run with grade control. The locations of the grade control are assumed to not be erodible and therefore, the knickpoints cannot migrate upstream.

In looking at the sensitivity analysis runs, the main factors which promote increased scour upstream of the transition channel are downstream water level elevation, transition channel slope, and incoming sediment gradation. It is recommended to install grade control structures along the transition channel. While this won't prevent increased scour upstream of the transition channel or allow reduction of the transition channel slope, they will maintain the elevation of the transition channel and prevent further scour. It is possible that, even with grade control structures, the area upstream of the steepened reach will still degrade to levels similar to cases without grade control due to the drawdown as the flow accelerates over the knickpoint lip. It may be advisable to install grade control structures upstream of the knickpoint lip to prevent this.

Maintaining a higher water level in Prado Basin, if possible could limit increased scour. A low water level at the downstream end of the transition channel was shown to cause increased scour upstream of the transition channel. A finer incoming sediment load was also shown to cause increased scour but this is difficult to control in the field. A two-dimensional model may be warranted to determine lateral extent of scour in critical areas where scour due to the transition channel is predicted.

## 6 CONCLUSIONS

Sediment accumulation in reservoirs is a common problem in facilities built in the early to mid-20th century. A potential solution to the decreased storage capacity is sediment removal by mechanical means or dredging. Sediment removal in the upper reaches of a reservoir and a transition channel from the existing river bed to the sediment trap, creates a scenario where a knickpoint could form and propagate upstream endangering property and infrastructure due to excessive scour. The knickpoint type characterized by this modification is a rotating knickpoint. These knickpoints tend to lengthen and flatten as the channel upstream of the steepened face becomes steeper. These knickpoints generally will not maintain their profile and migrate upstream. Therefore, the area of increased scour is limited to the area just upstream of the steepened slope.

Grade control structures have been shown to be a potential effective mitigation measure against excessive scour within a sediment trap transition channel for the scenarios modeled here. It is possible that, even with grade control structures, the area upstream of the steepened reach will still degrade to levels similar to cases without grade control due to the drawdown as the flow accelerates over the knickpoint lip. However, grade control can limit the degradation on the steepened transition channel slope. A sensitivity analysis was conducted to determine factors which influence bed thalweg change the most upstream of the transition channel. Transition channel slope, downstream reservoir level, and incoming sediment gradation were found to be the largest contributors to bed change in this reach.

The results presented here are based on the natural system of the Santa Ana River. Some of the general observations may be applicable to other systems but channel geometry, flow, and sediment data, outside of the sensitivity analysis, are site specific. The methods presented are only valid for situations where one-dimensional flow can be assumed upstream of the sediment removal area and lateral migration is limited. A two-dimensional flow model may be warranted in locations where the sediment removal and channel steepening occurs after the flow enters the influence of the reservoir.

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# APPENDIX A

## EXISTING AND PROPOSED CONDITIONS RESULTS

Figure A-1

Base Geometry Low Flow Invert Elevation Profile

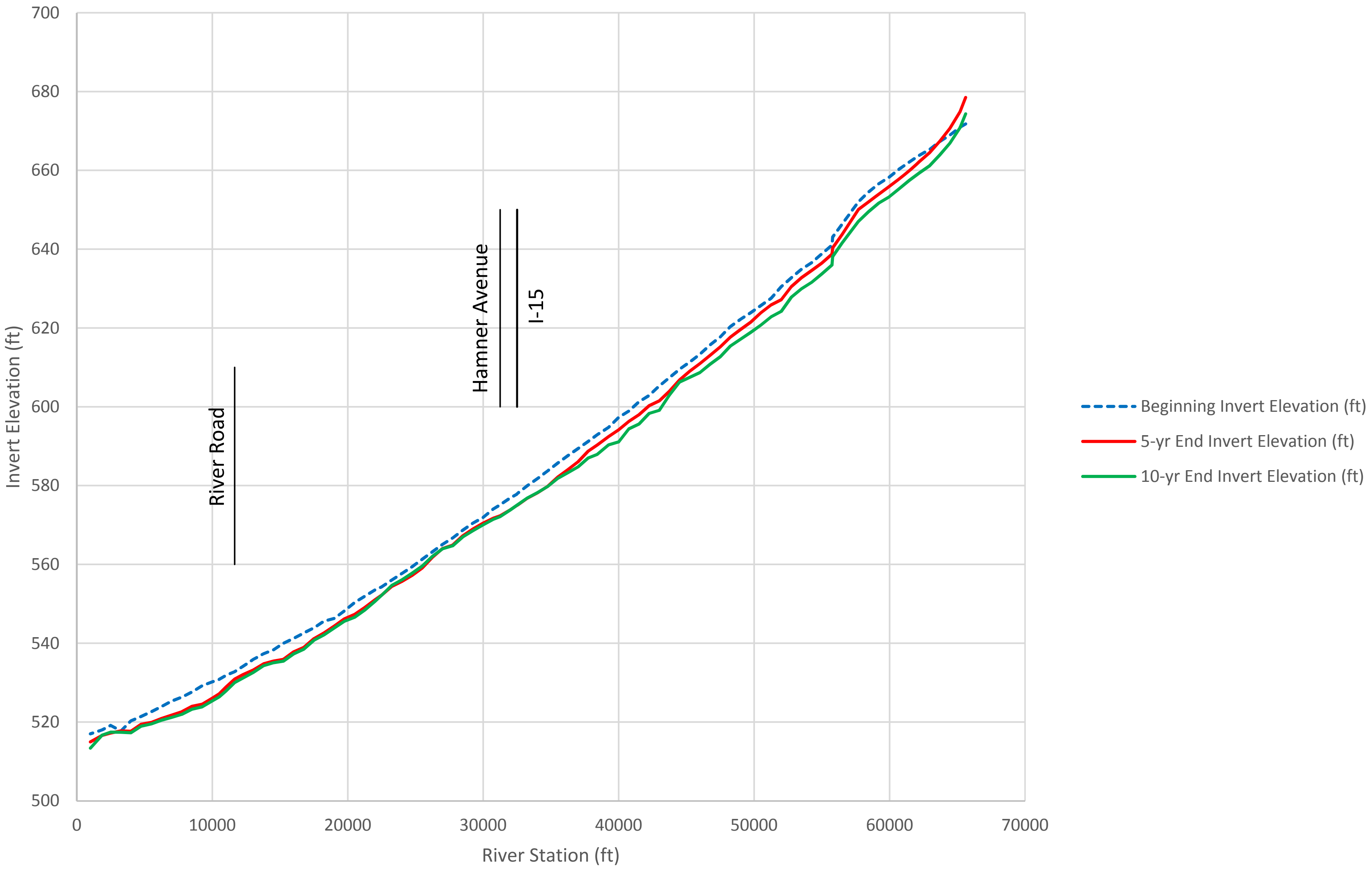
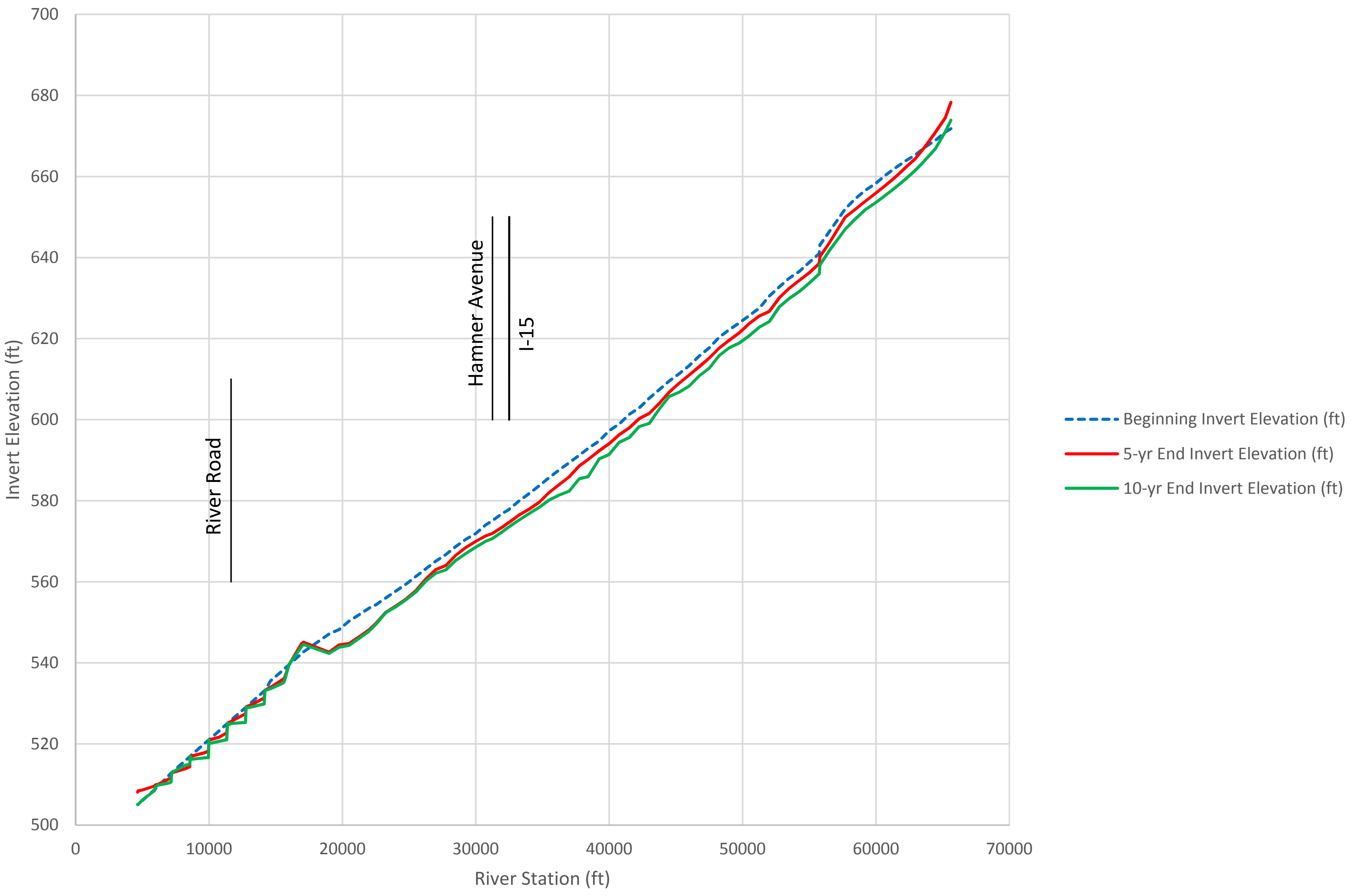


Figure A-2

Trap with Grade Control Low Flow Invert Elevation Profile



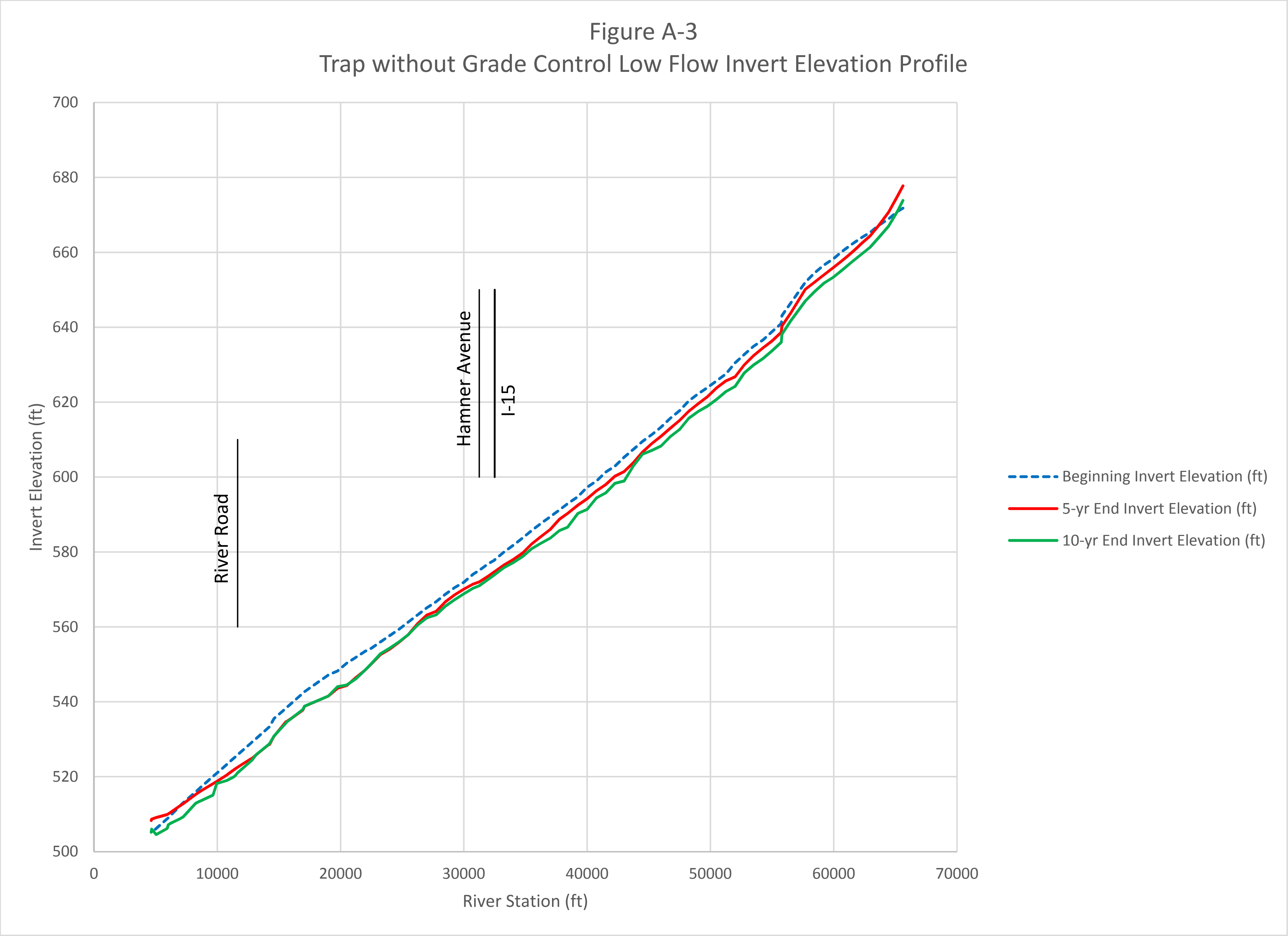
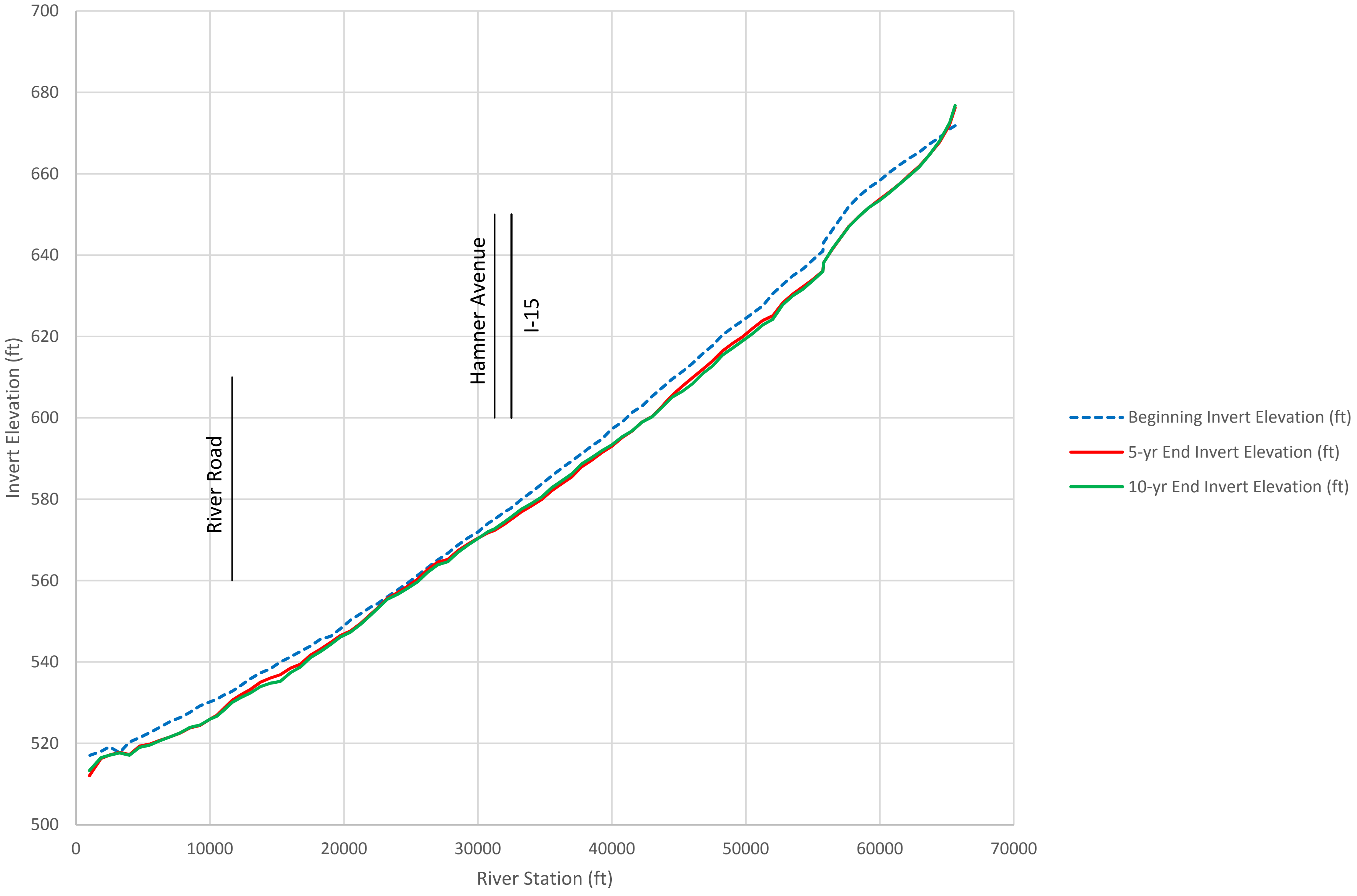


Figure A-3
Trap without Grade Control Low Flow Invert Elevation Profile

Figure A-4

Base Geometry High Flow Invert Elevation Profile



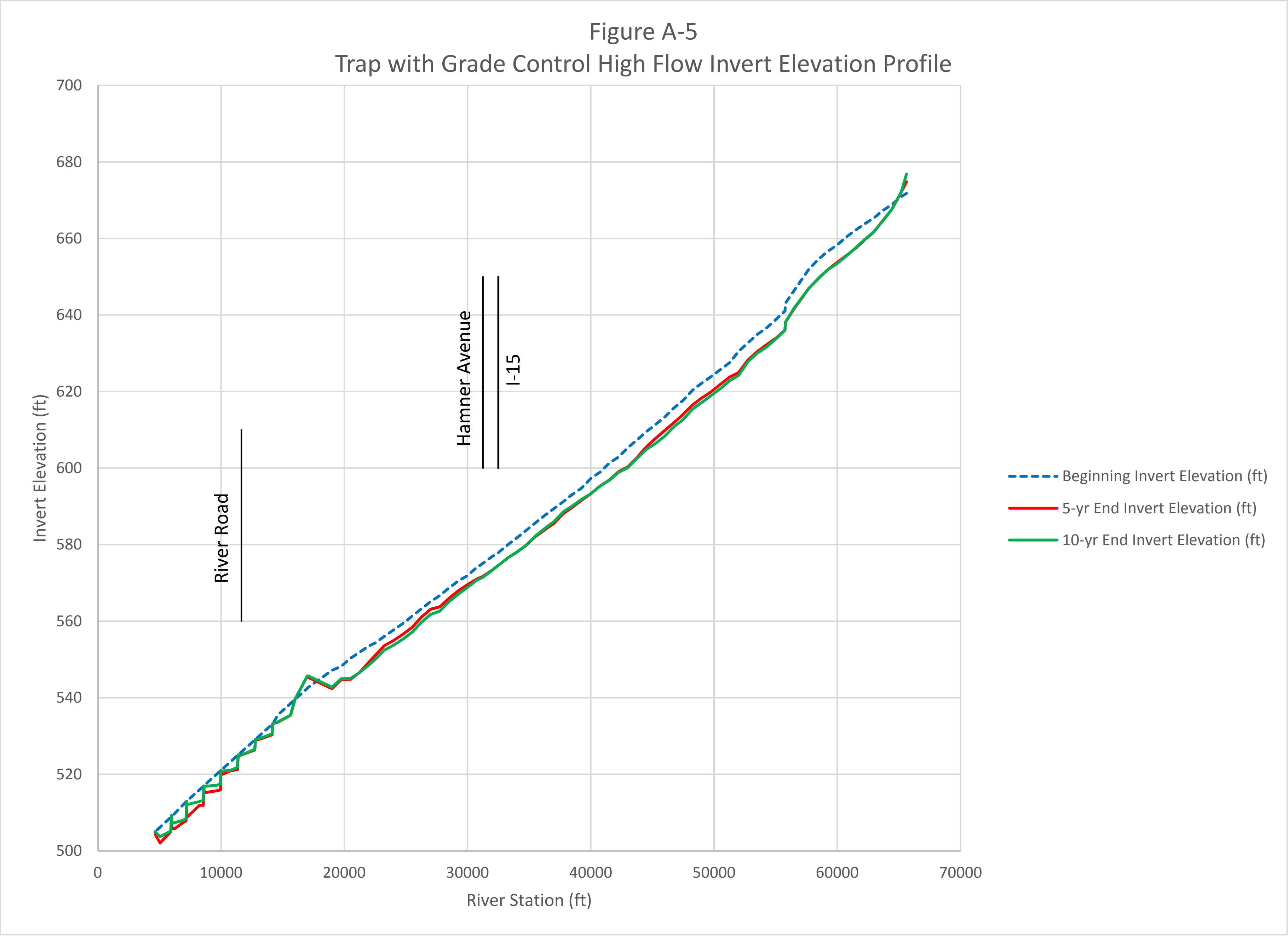


Figure A-5
Trap with Grade Control High Flow Invert Elevation Profile
Invert Elevation (ft)
700
680
660
640
620
600
580
560
540
520
500
River Station (ft)
0
10000
20000
30000
40000
50000
60000
70000
River Road
Hamner Avenue
I-15
Beginning Invert Elevation (ft)
5-yr End Invert Elevation (ft)
10-yr End Invert Elevation (ft)

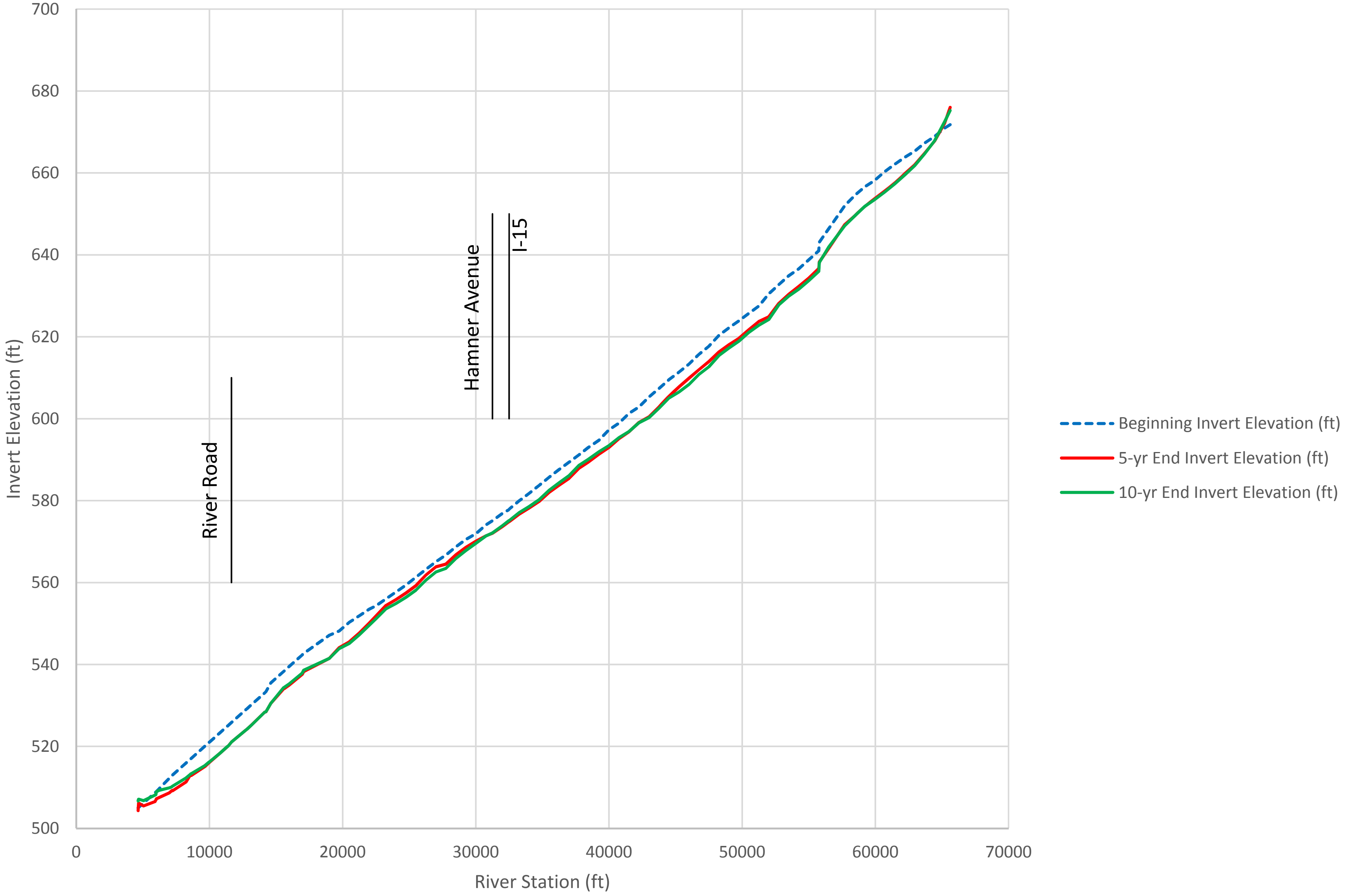
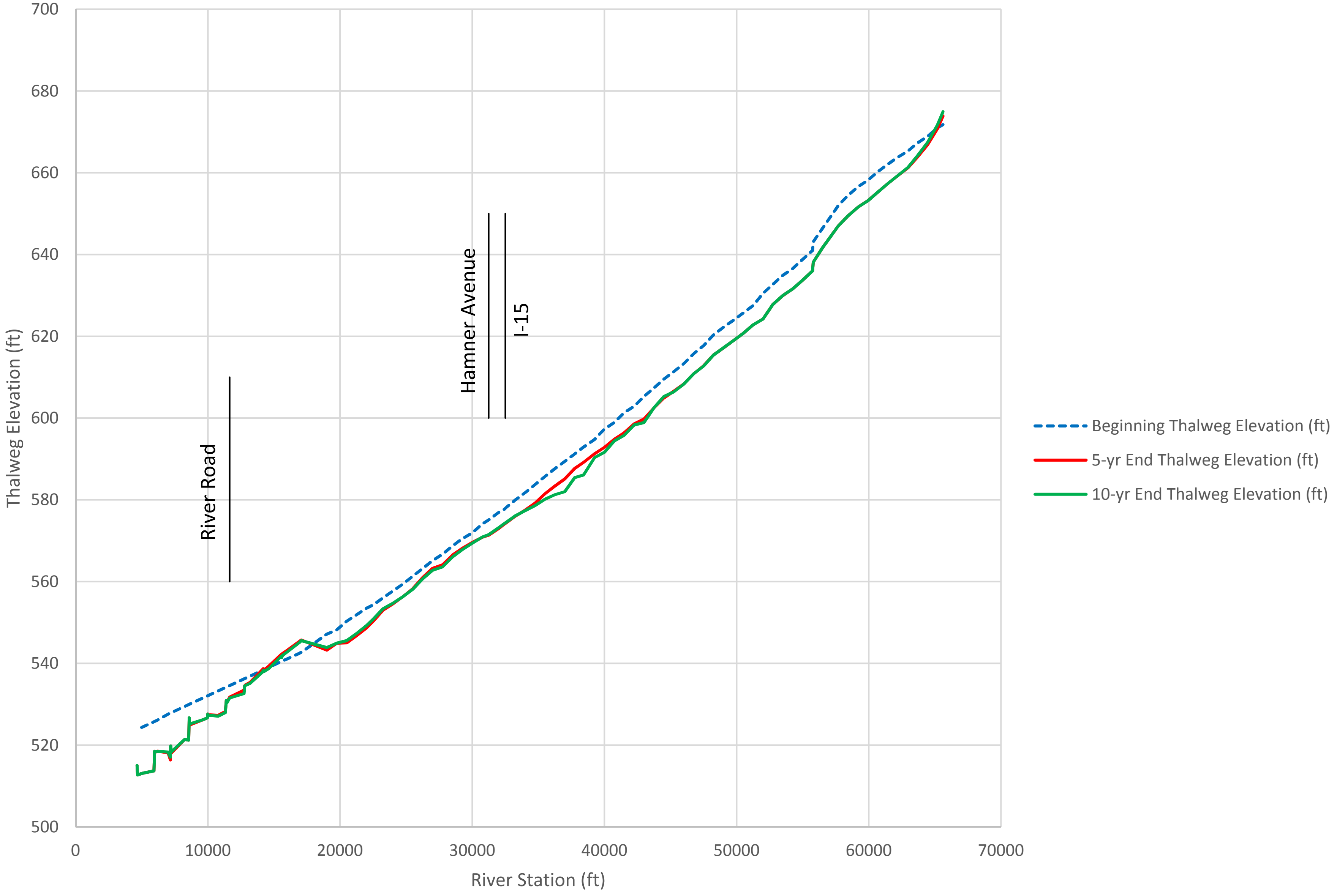


Figure A-6

Trap without Grade Control High Flow Invert Elevation Profile

# APPENDIX B
# SENSITIVITY ANALYSIS RESULTS

Figure B-1
Low Slope Trap with Grade Control Mean Flow Thalweg Elevation Profile



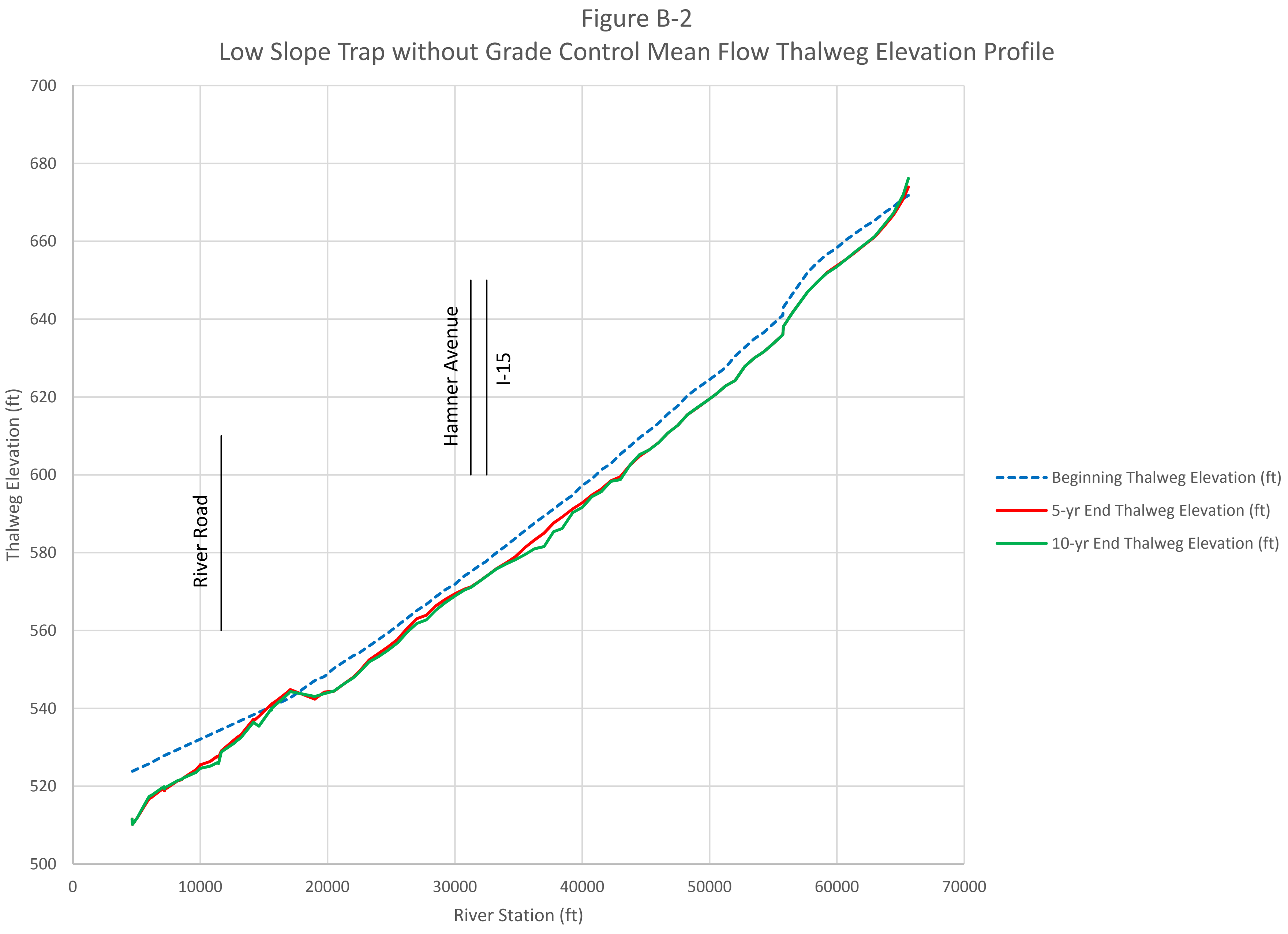


Figure B-2
Low Slope Trap without Grade Control Mean Flow Thalweg Elevation Profile
700
680
660
640
620
600
580
560
540
520
500
0
10000
20000
30000
40000
50000
60000
70000
Thalweg Elevation (ft)
River Station (ft)
River Road
Hamner Avenue
I-15
Beginning Thalweg Elevation (ft)
5-yr End Thalweg Elevation (ft)
10-yr End Thalweg Elevation (ft)

Figure B-3

High Slope Trap with Grade Control Mean Flow Thalweg Elevation Profile

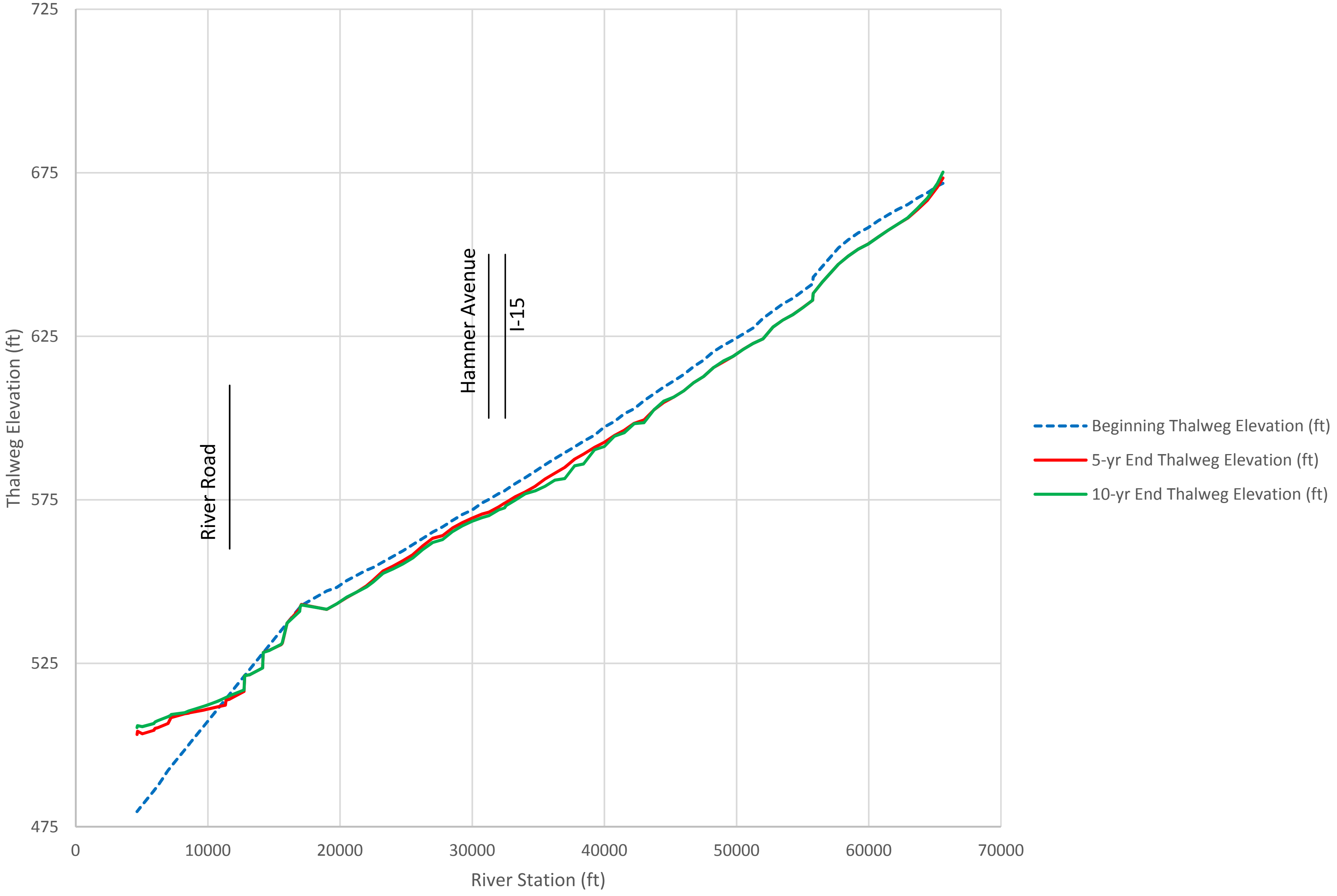
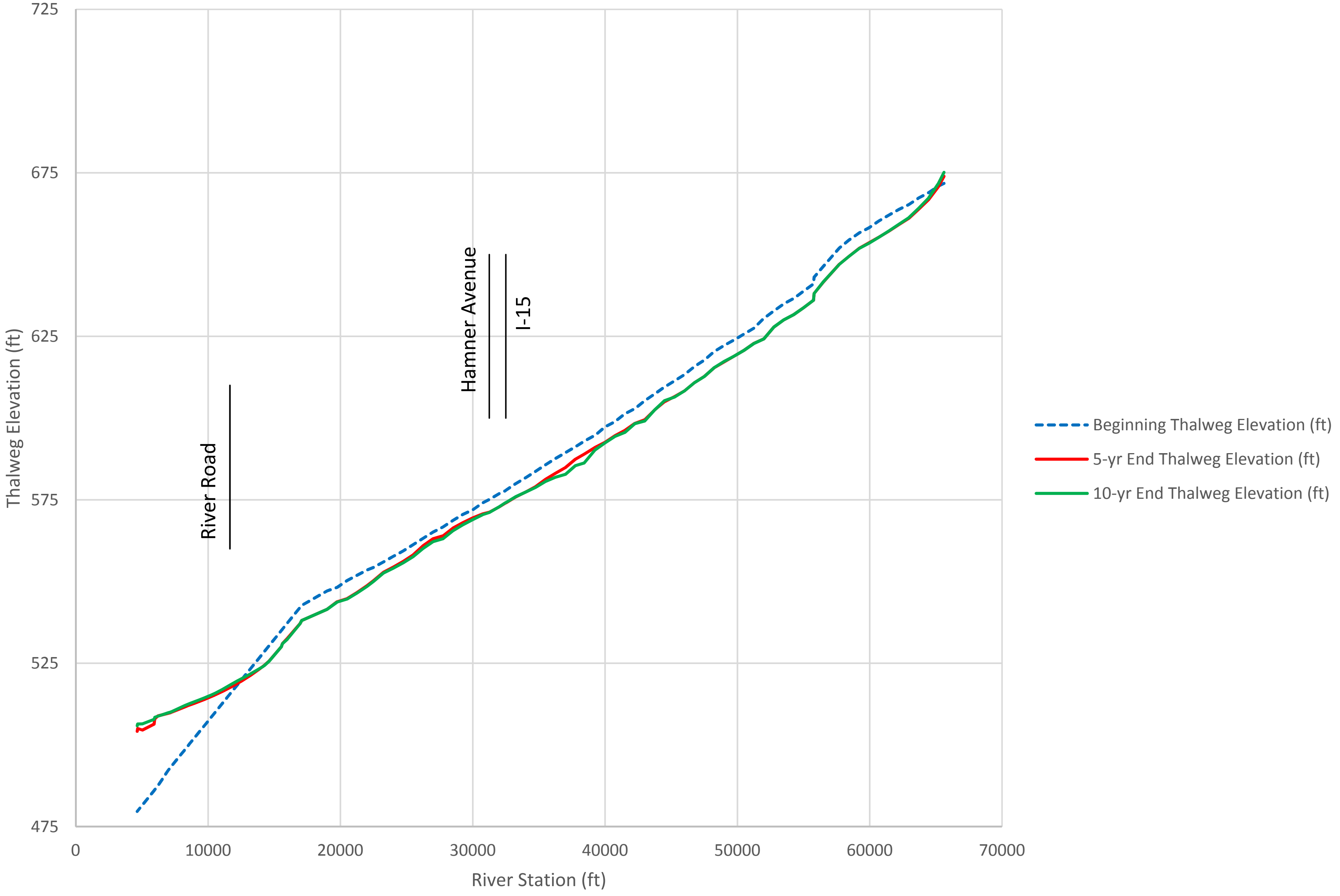


Figure B-4

High Slope Trap without Grade Control Mean Flow Thalweg Elevation Profile



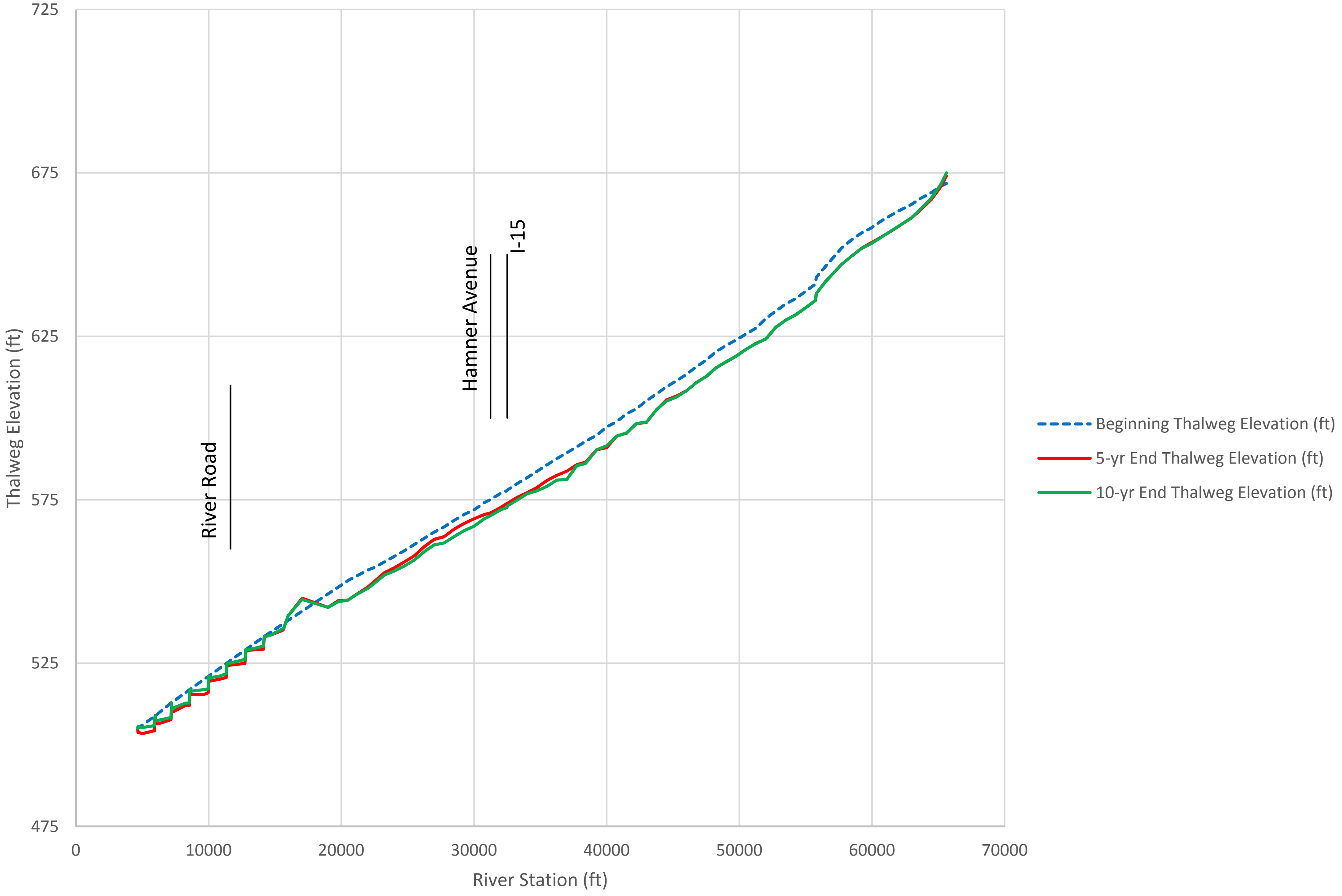


Figure B-5

Trap with Grade Control Mean Flow Low Reservoir Level Thalweg Elevation Profile

Figure B-6

Trap without Grade Control Mean Flow Low Reservoir Level Thalweg Elevation Profile

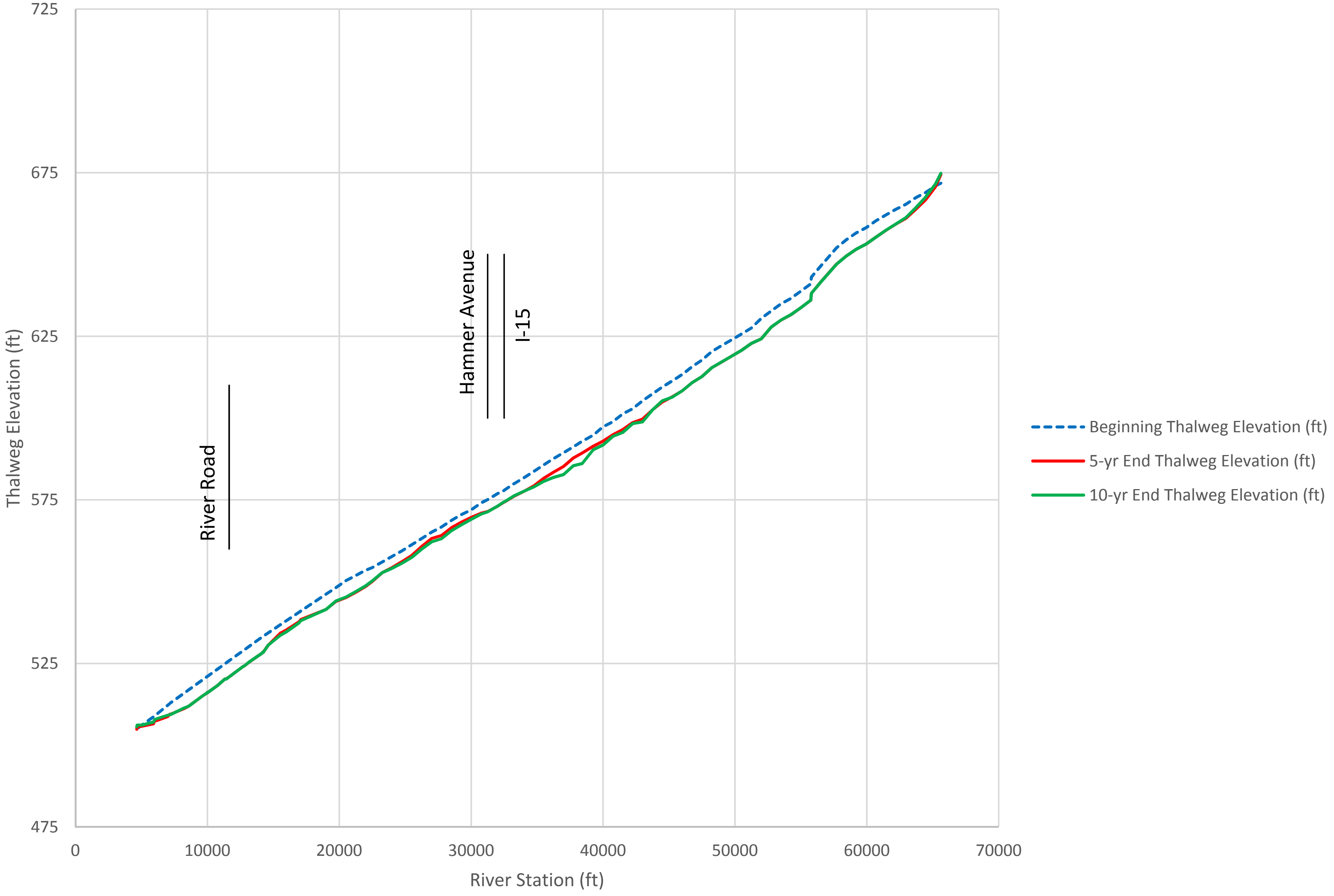


Figure B-7

Trap with Grade Control Mean Flow High Reservoir Level Thalweg Elevation Profile

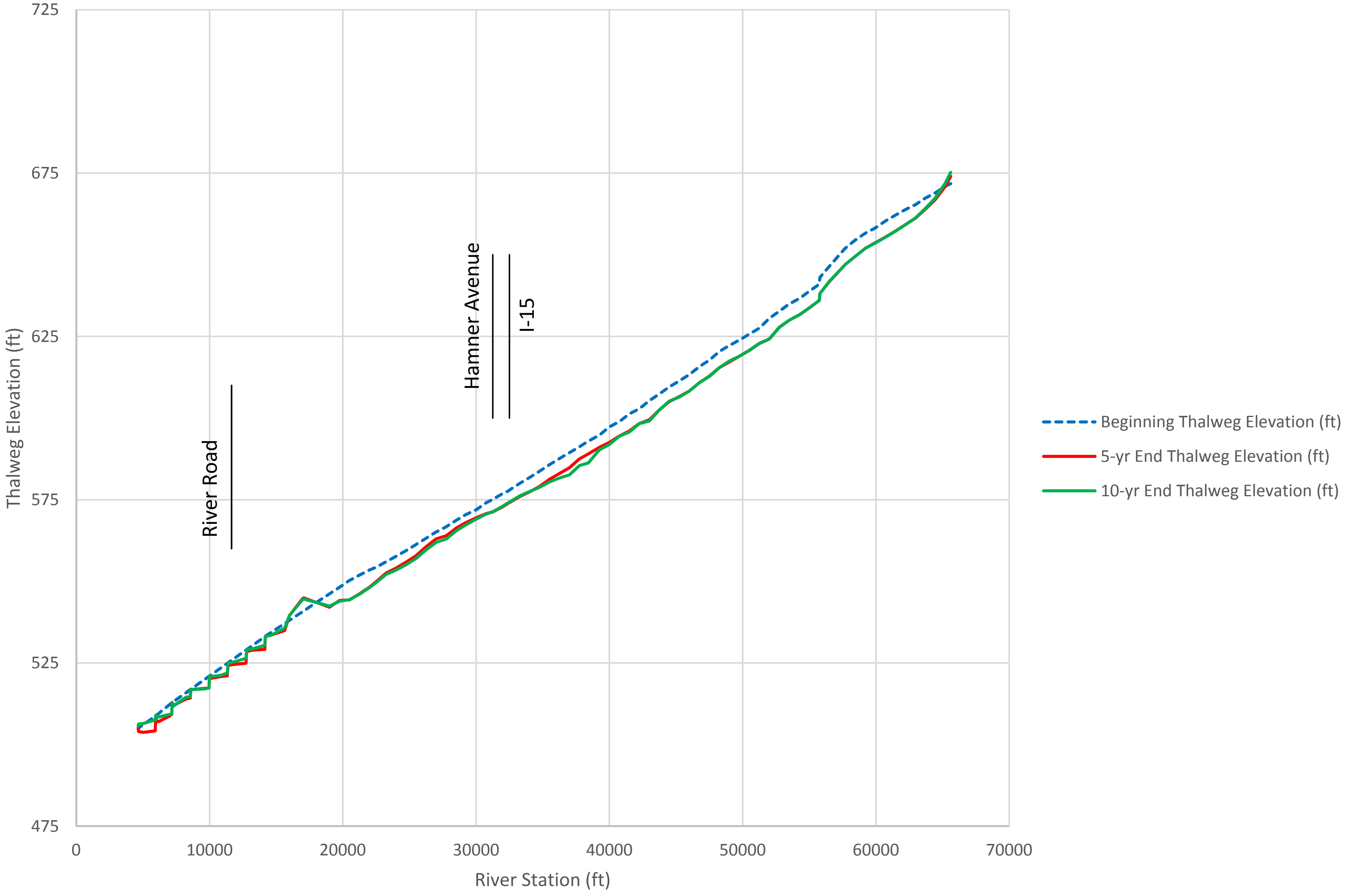
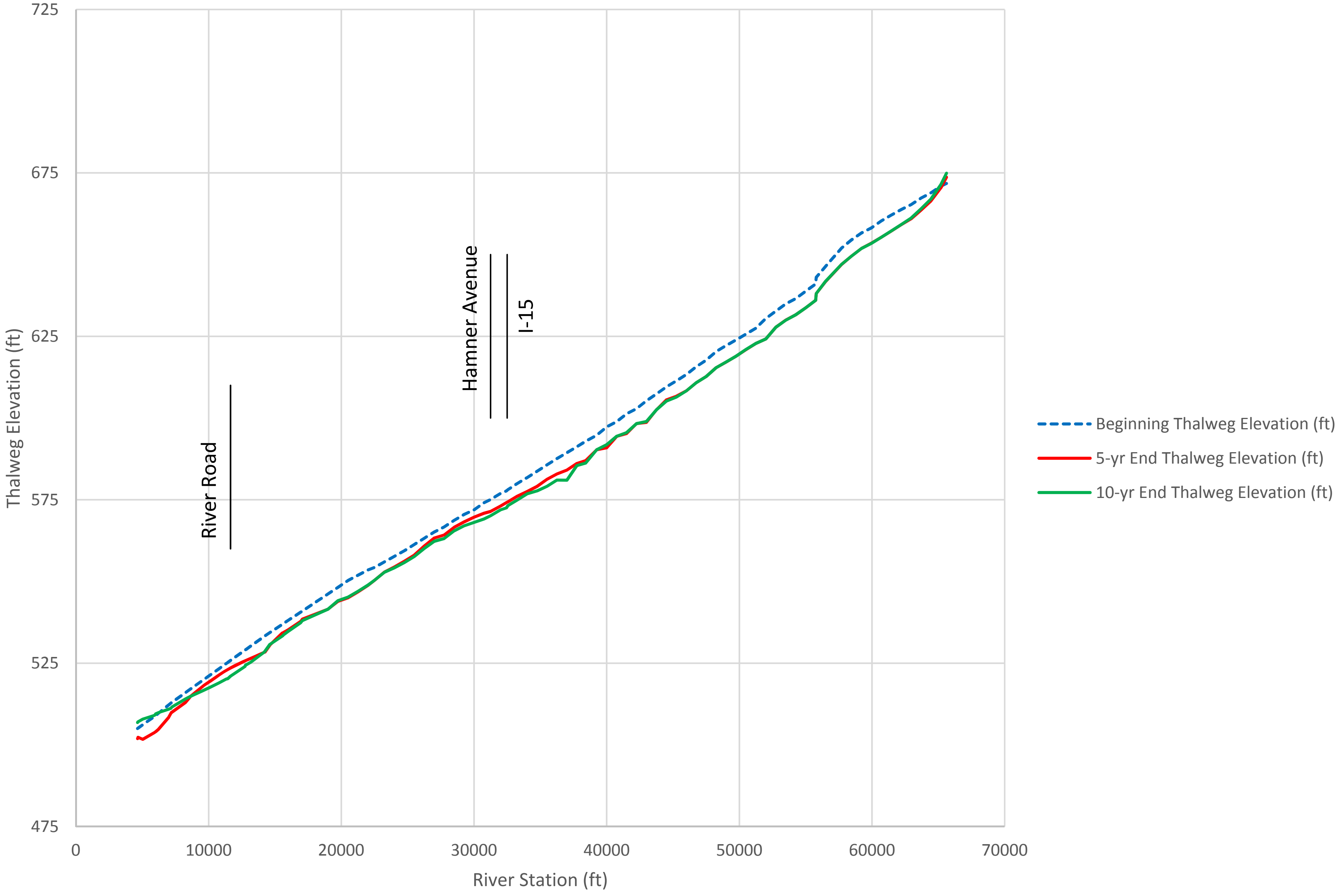
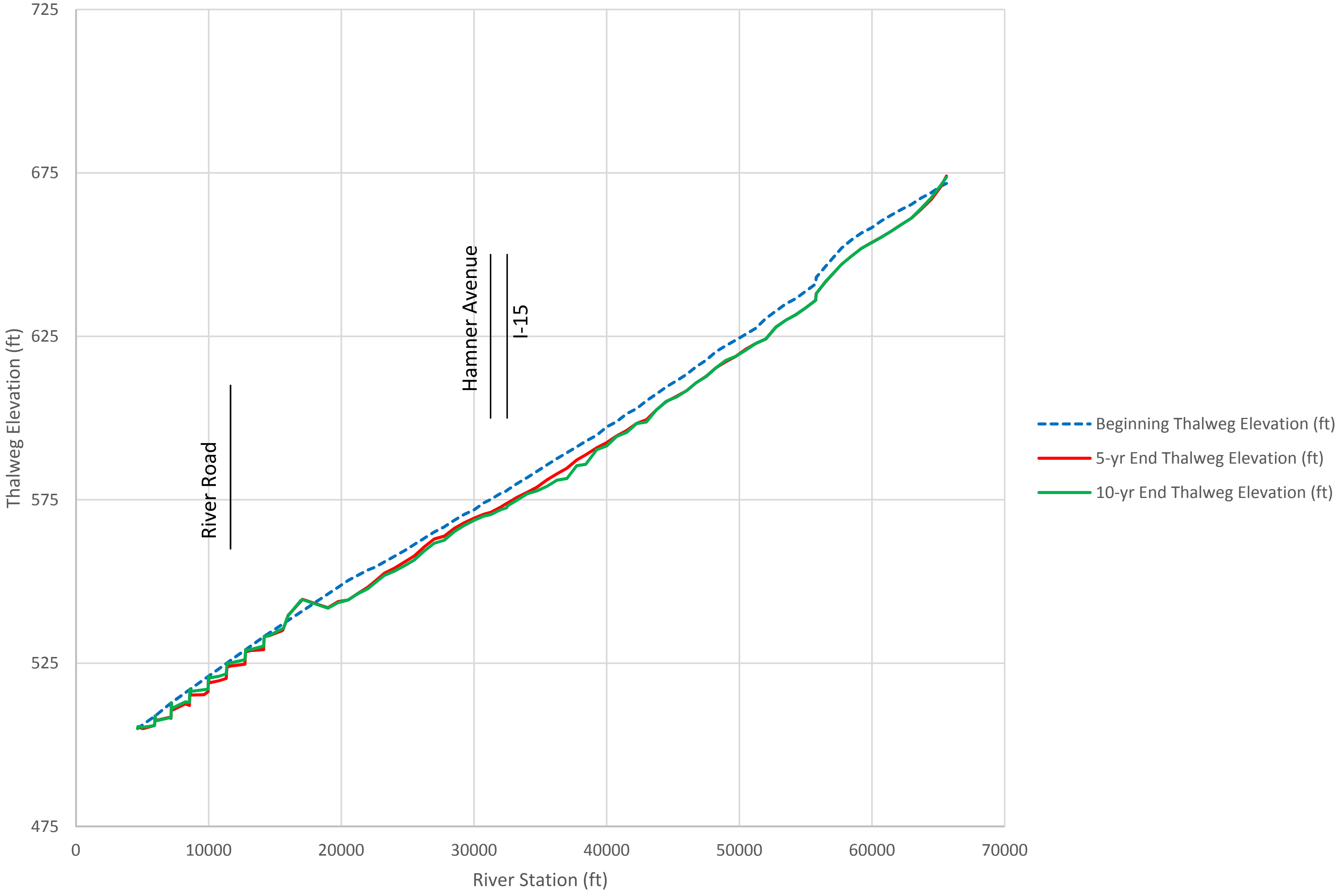


Figure B-8
Trap without Grade Control Mean Flow High Reservoir Level Thalweg Elevation Profile



# Figure B-9
## Trap with Grade Control Mean Flow Fine Bed Material Thalweg Elevation Profile



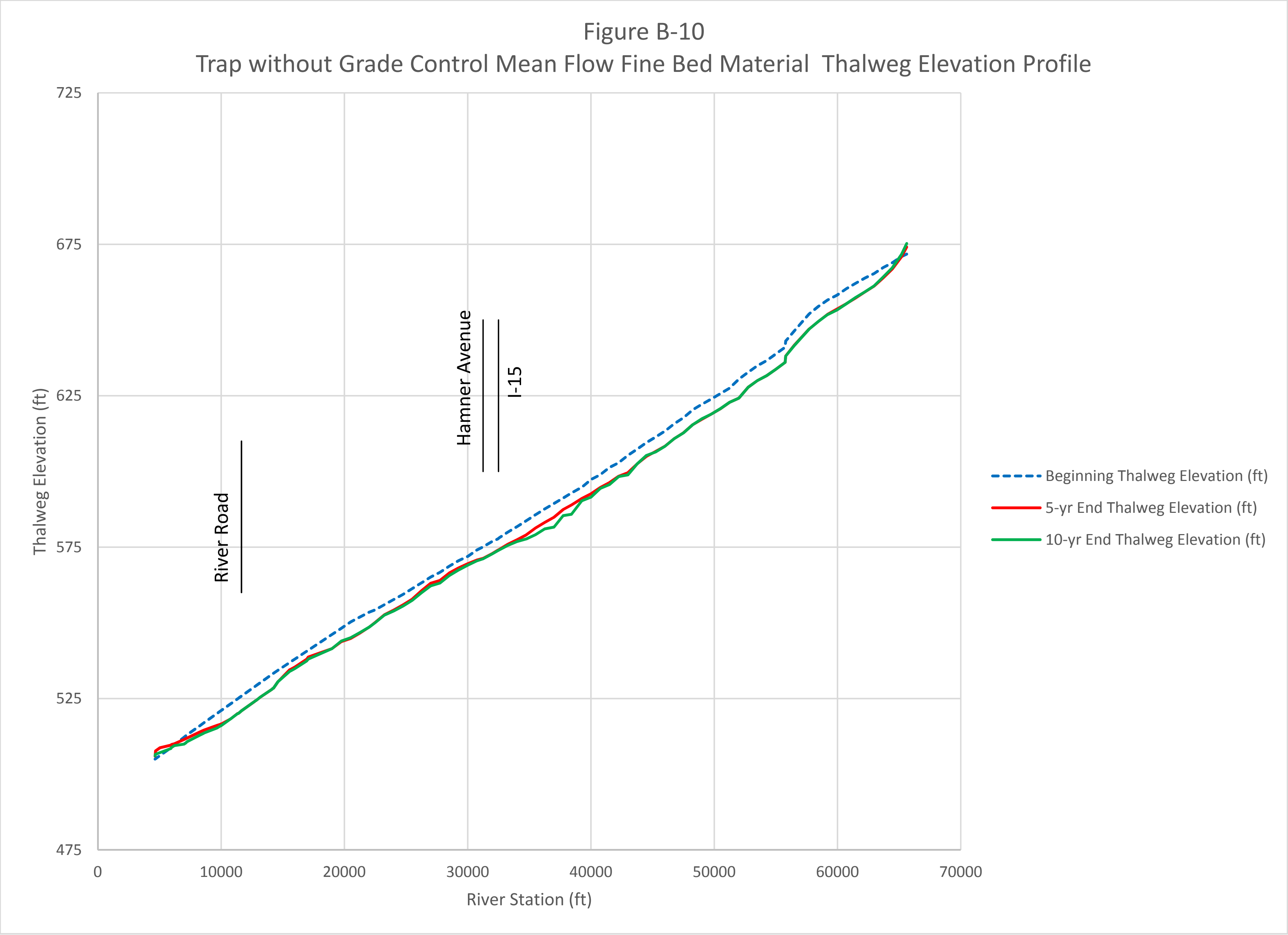


Figure B-10
Trap without Grade Control Mean Flow Fine Bed Material Thalweg Elevation Profile

Figure B-11

Trap with Grade Control Mean Flow Coarse Bed Material Thalweg Elevation Profile

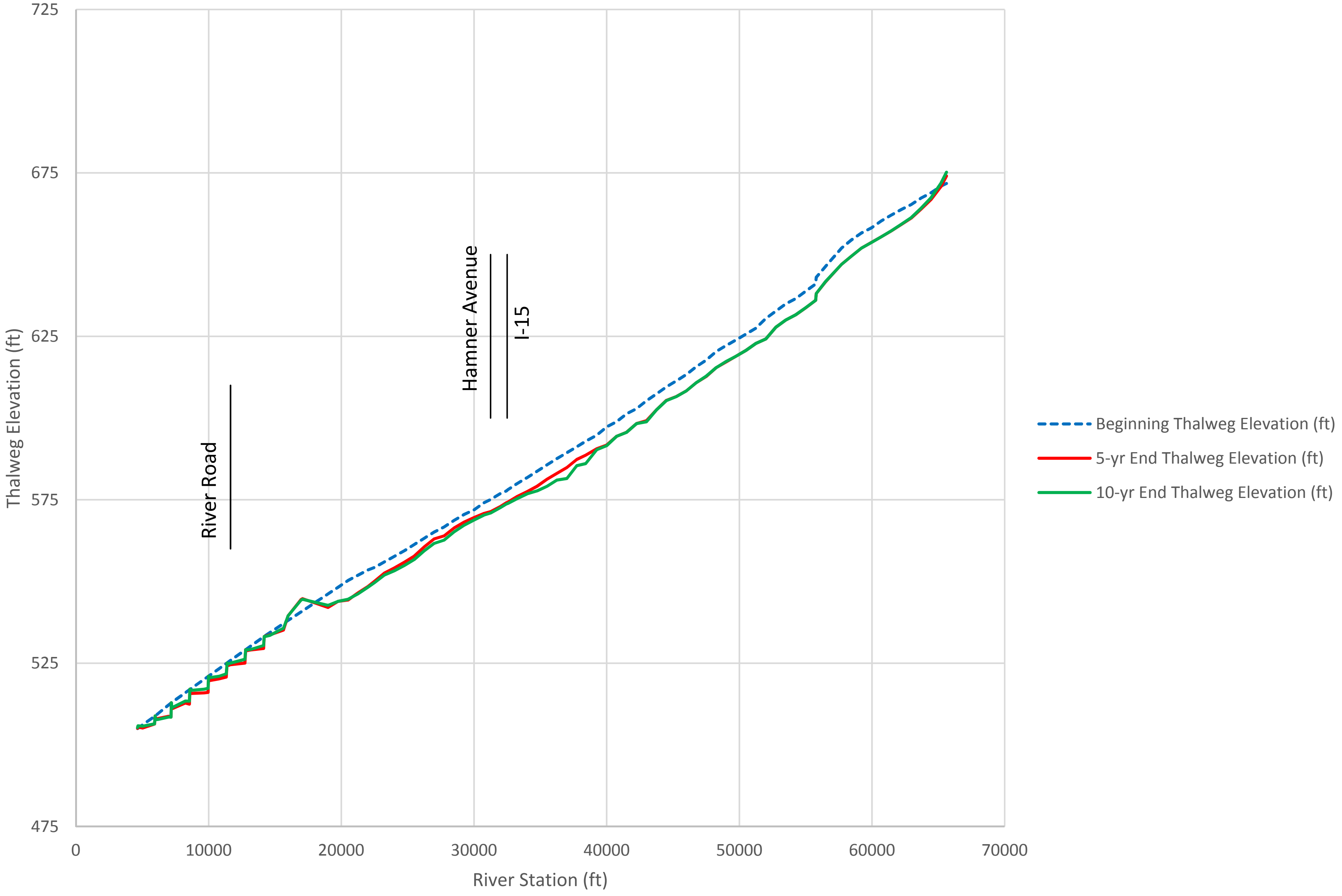


Figure B-12

Trap without Grade Control Mean Flow Coarse Bed Material Thalweg Elevation Profile

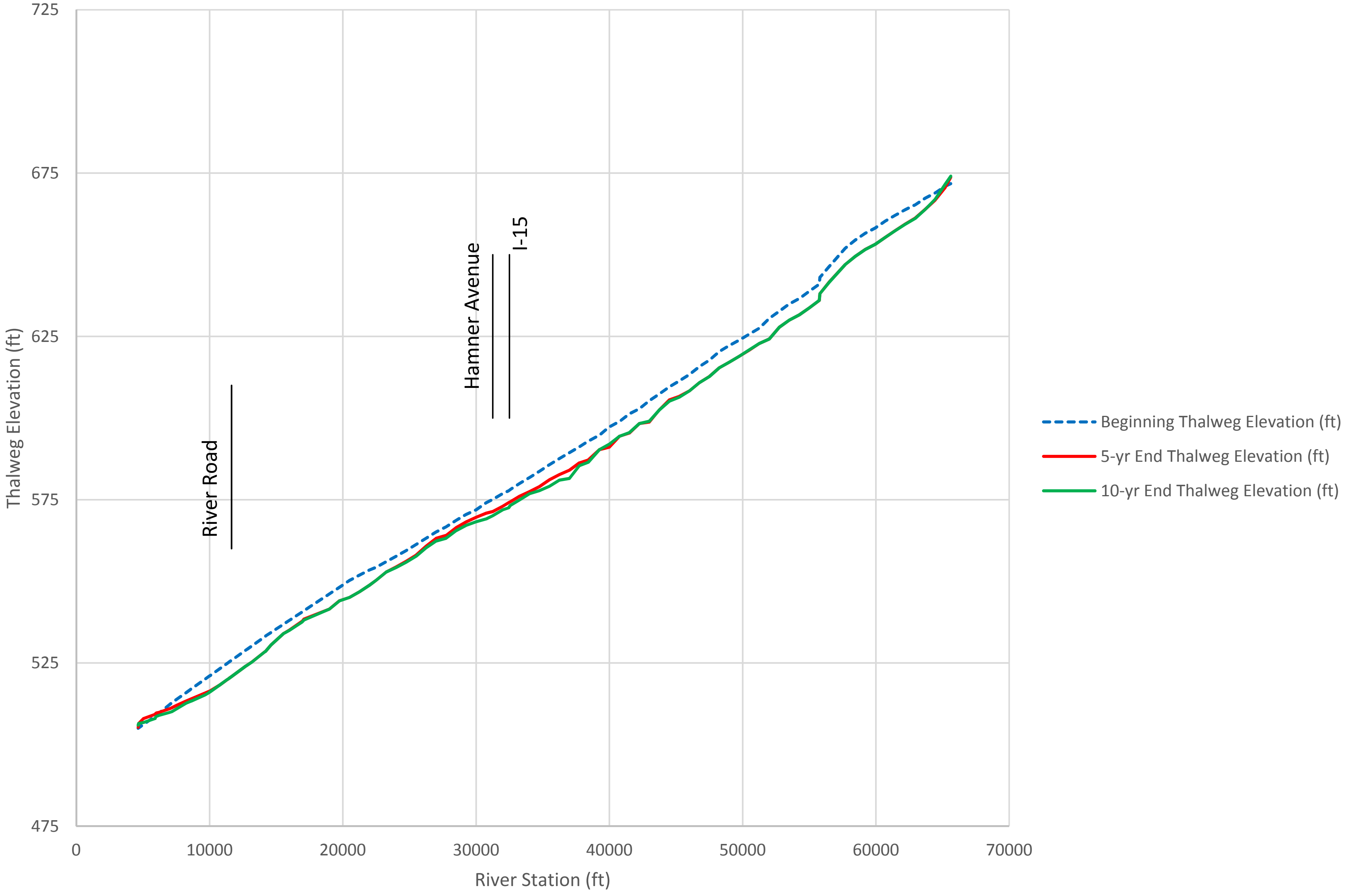


Figure B-13

Trap with Grade Control Mean Flow Fine Incoming Load Thalweg Elevation Profile

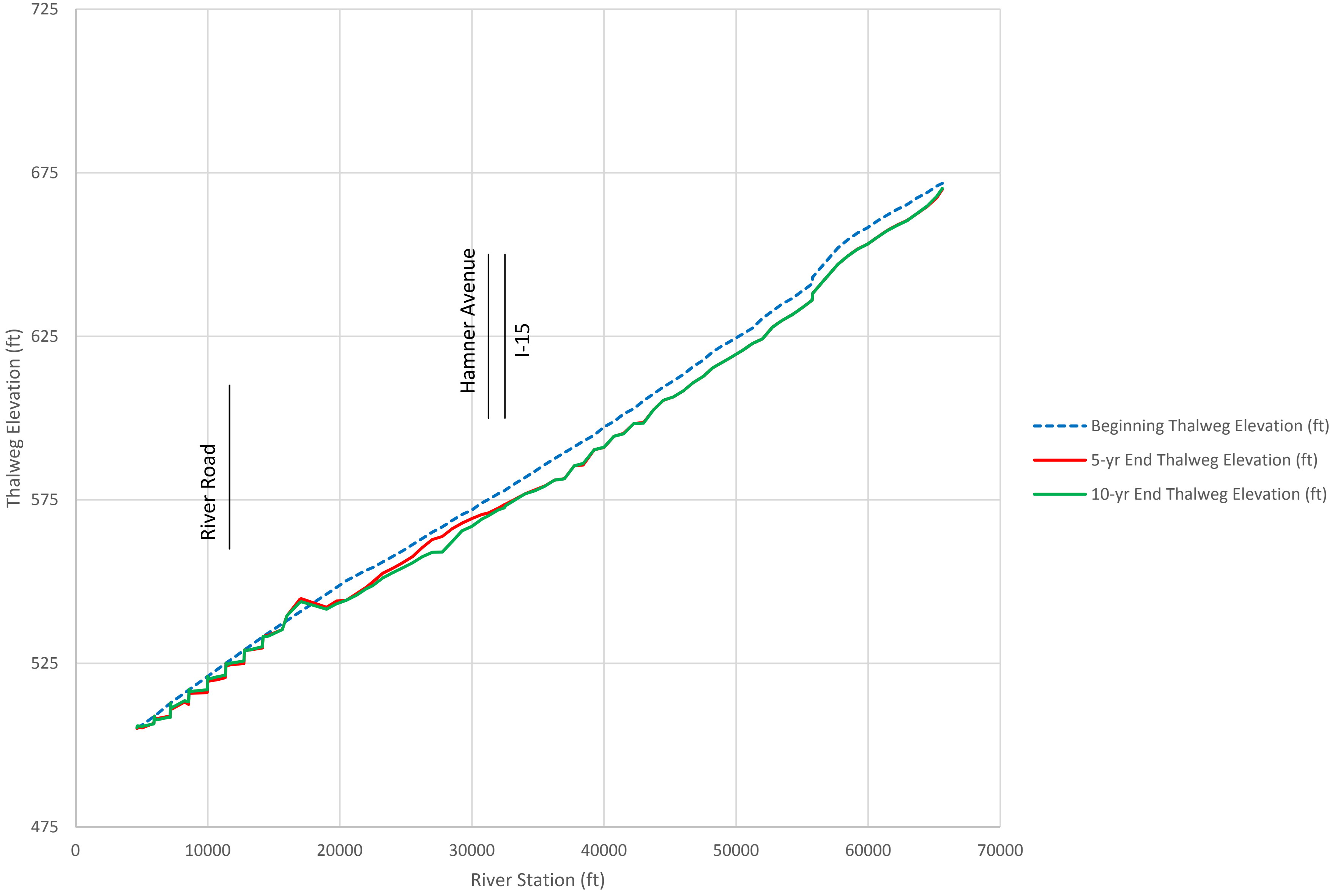


Figure B-14

Trap without Grade Control Mean Flow Fine Incoming Load Thalweg Elevation Profile

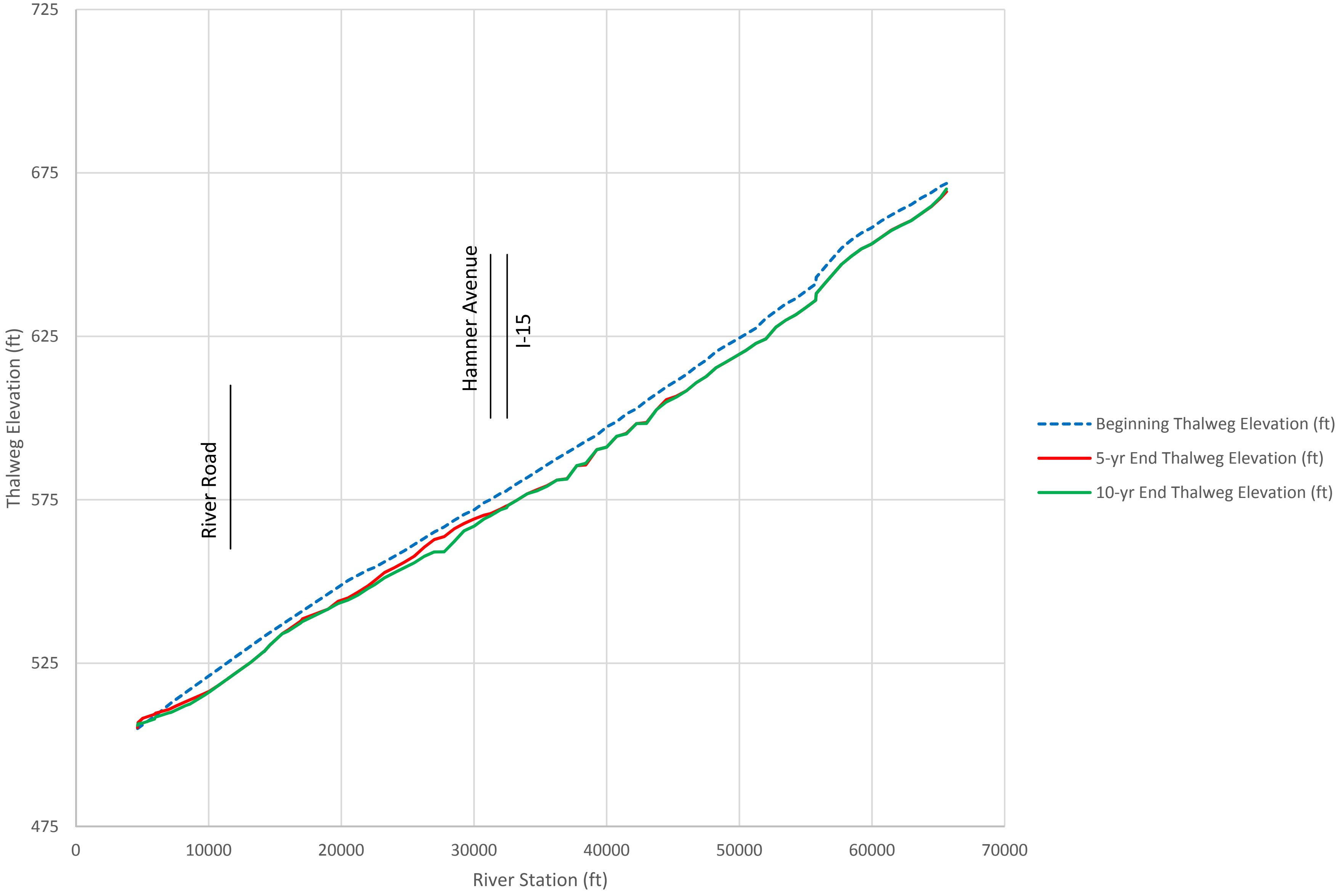
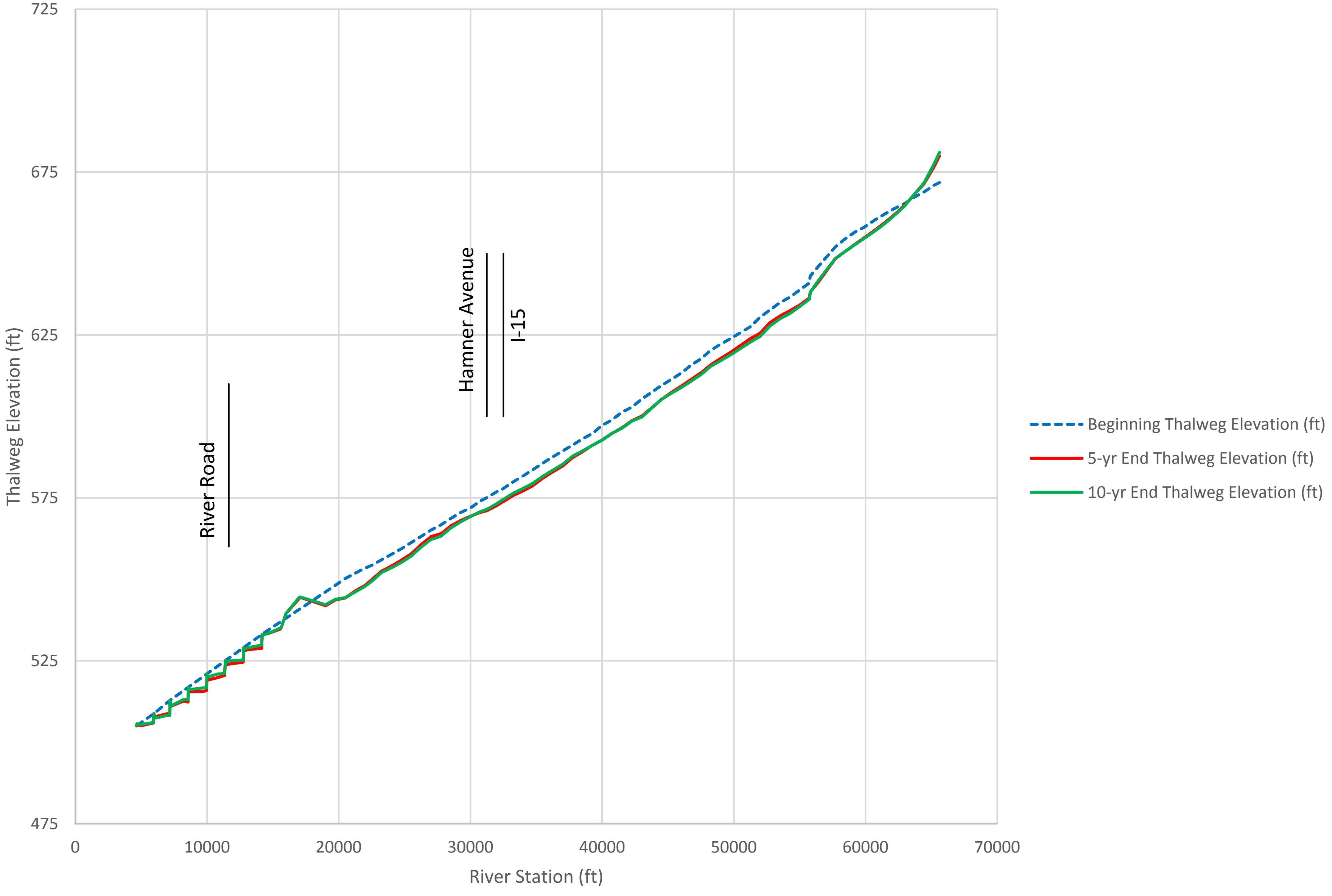
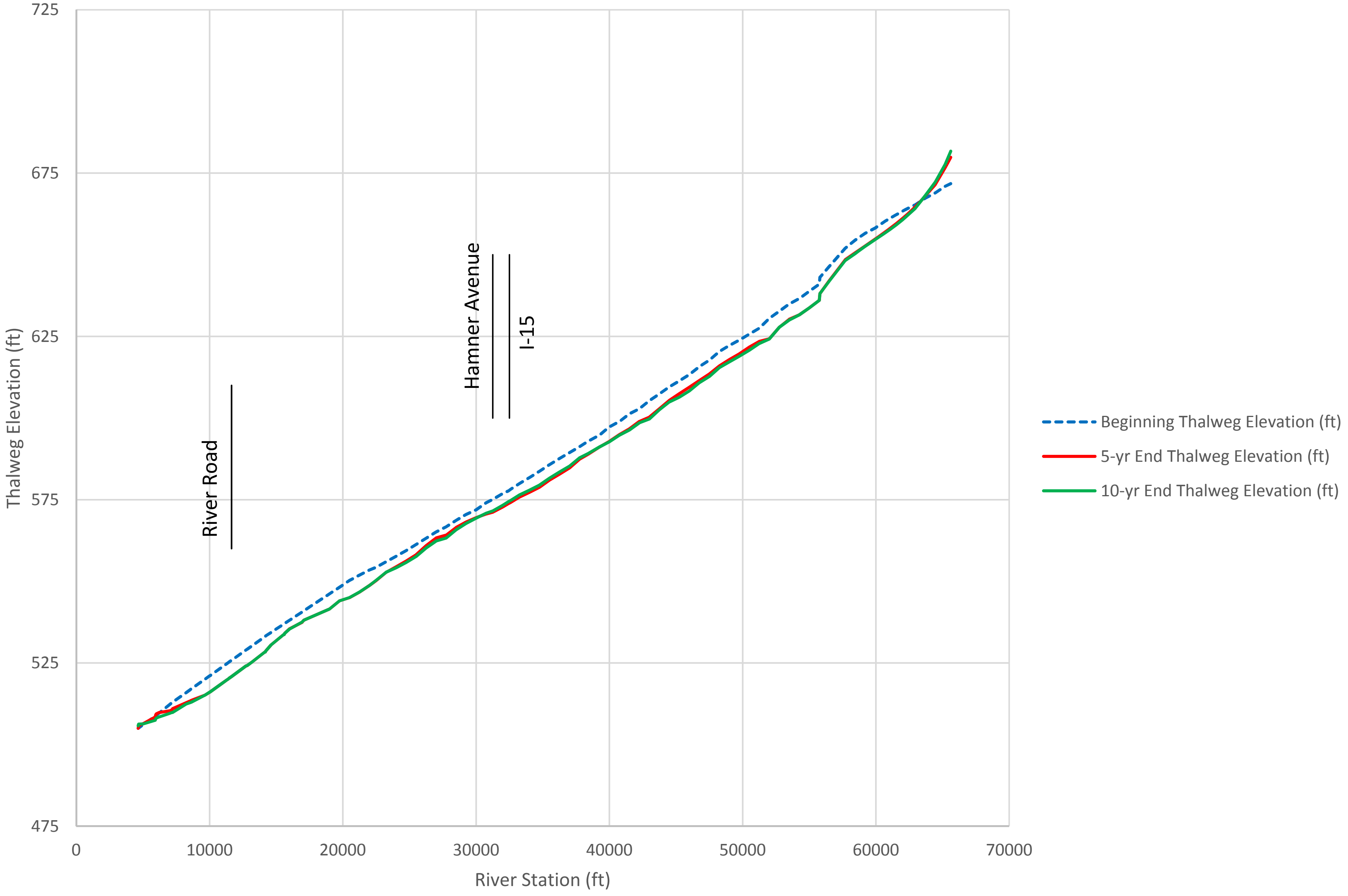


Figure B-15
Trap with Grade Control Mean Flow Coarse Incoming Load Thalweg Elevation Profile



## Figure B-16
## Trap without Grade Control Mean Flow Coarse Incoming Load Thalweg Elevation Profile



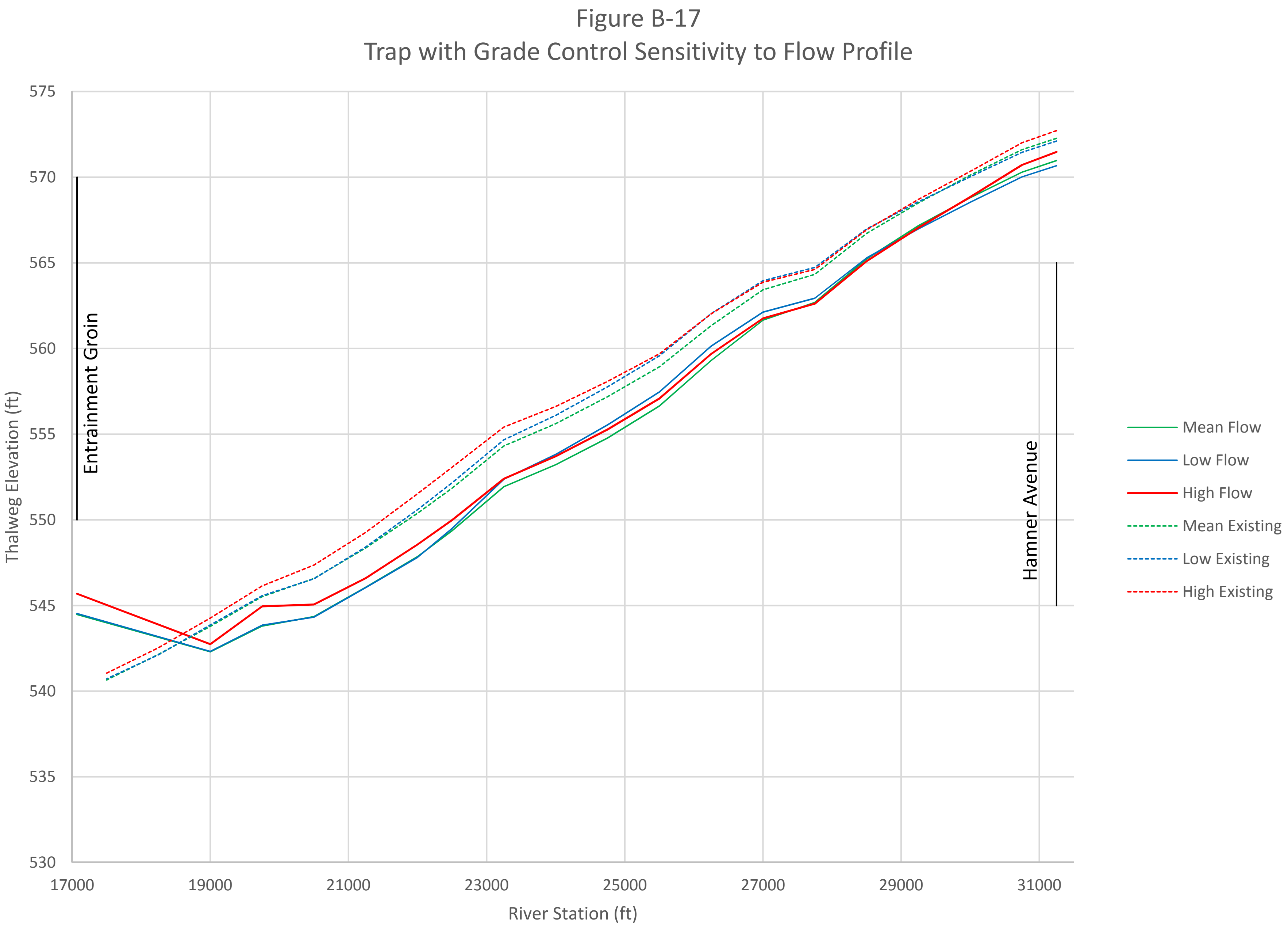
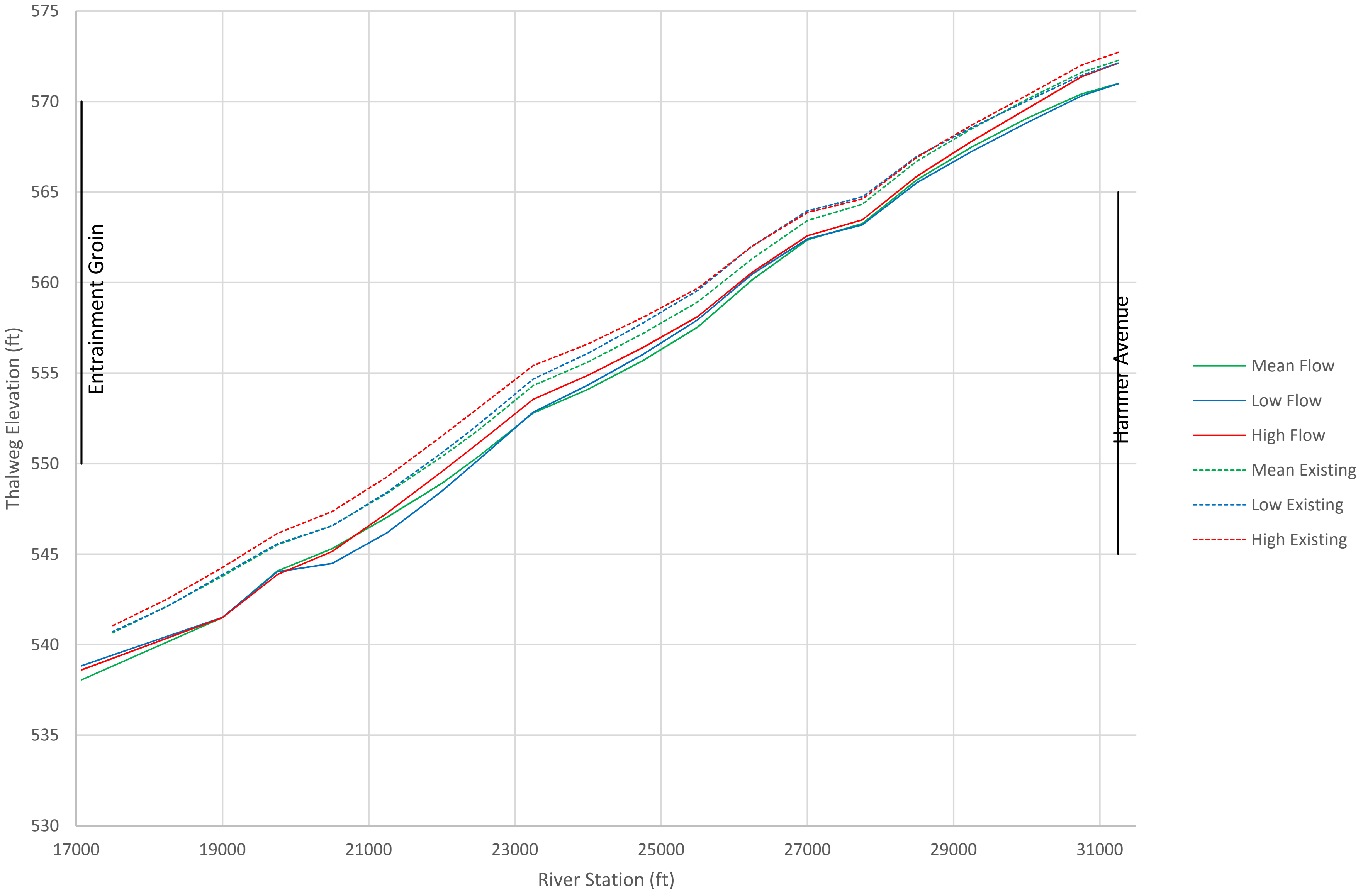


Figure B-17
Trap with Grade Control Sensitivity to Flow Profile
Thalweg Elevation (ft)
575
570
565
560
555
550
545
540
535
530
17000
19000
21000
23000
25000
27000
29000
31000
River Station (ft)
Entrainment Groin
Hamner Avenue
Mean Flow
Low Flow
High Flow
Mean Existing
Low Existing
High Existing

Figure B-18
Trap without Grade Control Sensitivity to Flow Profile



## Figure B-19
## Trap with Grade Control Sensitivity to Bed Gradation Profile

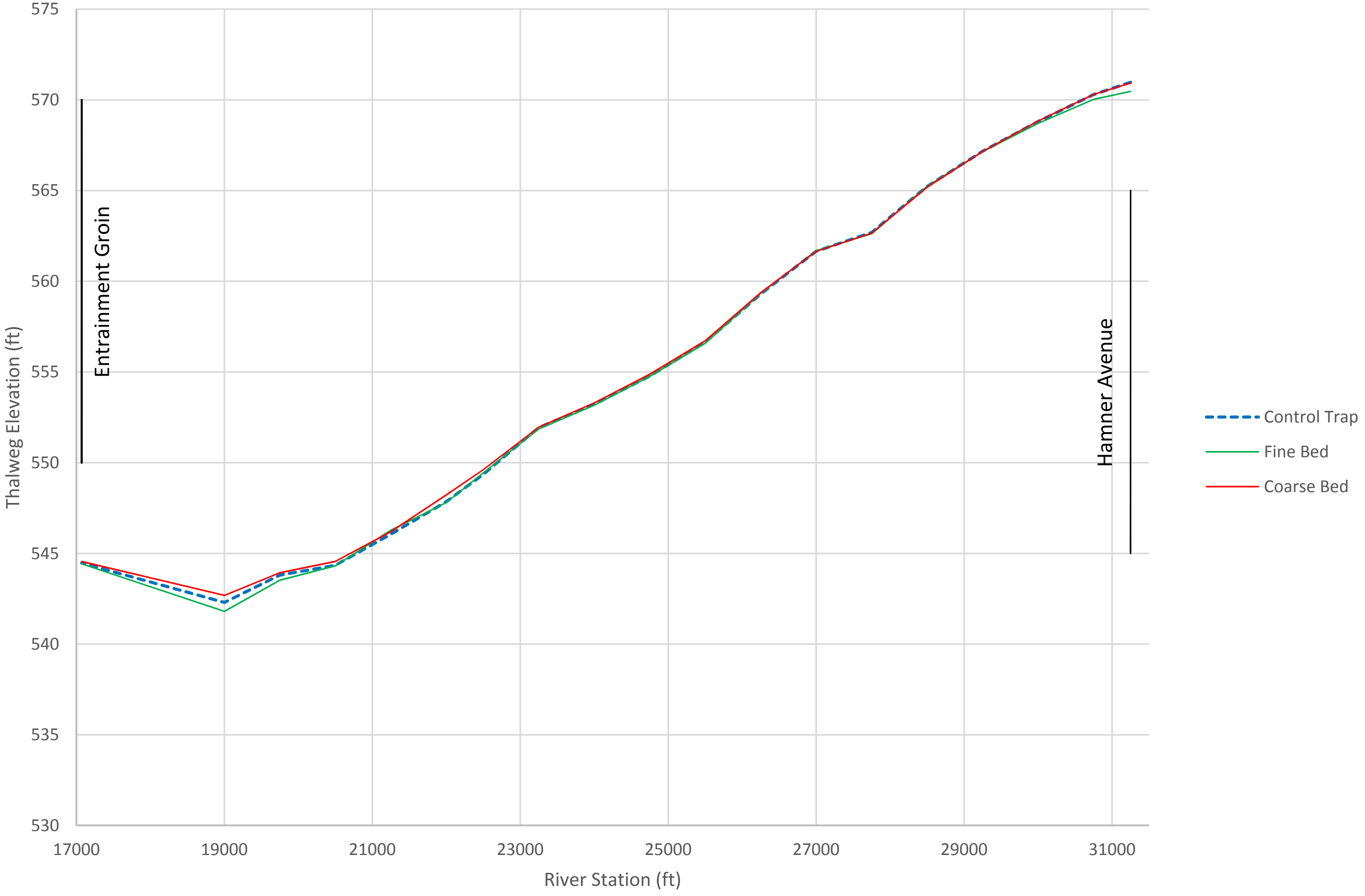


Figure B-20

Trap without Grade Control Sensitivity to Bed Material Gradation Profile