- An upward/rising slope that is too steep to allow the critical particle sizes and densities to be mobilized can cause buildup at the full pipe section of the siphon, reducing capacity. Inclusion of maintenance structures or upstream rock catchers can reduce or treat this issue.

DESIGN STEPS FOR SEDIMENT AND AIR TRANSPORT IN INVERTED SIPHONS

There are a number of tools available to designers that can help them understand, quantify, and attempt to predict if a problem is likely to occur. These include empirical, numerical, and physical modeling. The decision regarding when to use each method will depend on the stage of design progression, the nature and complexity of the conveyance system, and the consequences of the issue. The design steps for sediment transport and air transport need to be considered together, because the designed and installed system will have to deal with both issues. Air transportation is generally a limiting factor in the declining slope, whereas sediment deposition is generally a limiting factor in the inclining slope. The limitations of constructability will necessitate a trade-off between these factors. The design will likely be iterative as the limitations are balanced against one another.

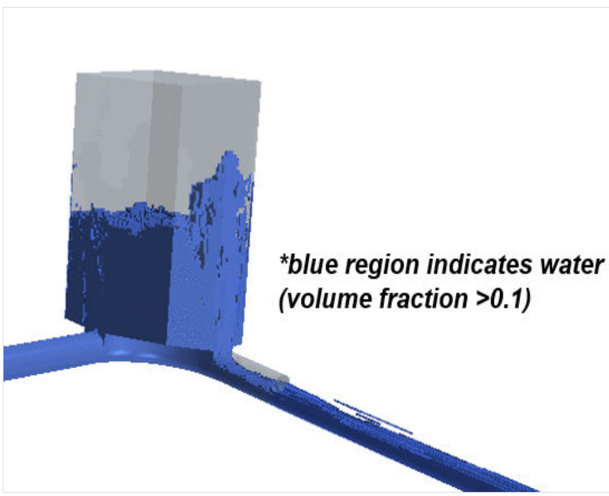

Figure 2. Large air pocket release into an unvented inlet structure.

Figure 3. Damage from a lifted top slab due to chamber pressurization.

Design Steps for Sediment Transport

The empirical design steps undertaken for sediment transport in inverted siphons for the case studies considered in this paper are summarized below.

<u>**Step 1:** Select the incline slope angle for the inverted siphon based on constructability.</u>

By reviewing the reference sources above, and understanding site and constructability constraints and limitations select a slope that fits within the range suggested in this paper (between 22.5 and 45 degrees). For the domestic sewage case study, the slope selected was 18 percent (10.2 degrees) due to site limitations.

<u>**Step 2:** Select the pipe size to provide hydraulic capacity and determine the velocities for the range of operation.</u>

It is key to understand how often the flow rates will occur and the critical flow rates that will govern the design. It is impractical to design an inclined slope that can eliminate all deposition risks, particularly at low flows. The domestic sewage case study was focused on an intermediate flow (a more frequently occurring condition) and the peak flow rate.

<u>**Step 3:** Analyze what bedload sediment size can be mobilized (as flume traction) with the inverted siphon inclined slope.</u>

The key formula was based on the paper by May (2000). The equation can be solved for "V". The term "C_v" represents the sediment concentration.

- Eq. 21 for minimum cleansing velocity for particles with different specific gravity:

$$C_V = (0.0150 - 0.00835 \sin\theta)\left(\frac{4}{\pi}\right)\left(\frac{d_{50}}{D}\right)^{0.6} \times \left(1 - \frac{\sigma V_T}{V}\right)^4 \left[\frac{sV^2}{g(s-1)D\cos\theta}\right]^{3/2}$$

The graph in Figure 4 below presents the minimum velocities for a range of sand/grit particles (ranging from 50-micron to 4,000-micron) with varying specific gravities (ranging from 1.8 to 2.6) and concentrations (19 parts per million [ppm] to 77 ppm) in the flume traction transport type for the domestic sewage case study.

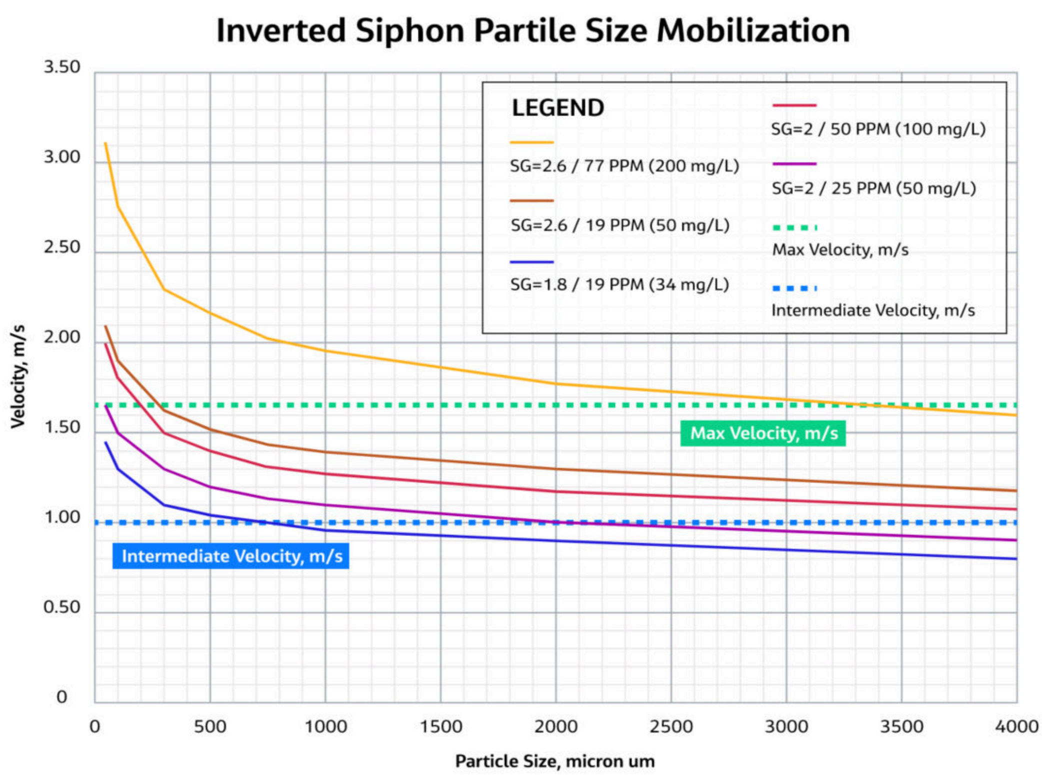

Figure 4. Inverted siphon particle size mobilization.

<u>**Step 4:** Check the threshold velocity for sediment mobilization in a near-horizontal pipe.</u>

This step will assist in determining what size particle, settled in the full pipe section of the siphon, could be re-suspended.

The key formula was based on the paper by May (2000) as follows:

- Eq. 17 for particle threshold velocity in a near horizontal pipe:

$$V_T = 0.125\sqrt{g(s-1)d_{50}}\left(\frac{D}{d_{50}}\right)^{0.47}$$

<u>**Step 5:** Determine the target sediment characteristics that can and cannot be mobilized.</u>

The last step is to compare the sediment characteristics from Steps 1 to 4 against those anticipated for the conveyance system and fluid (either from field particle measurements or from published resources, as discussed above). This will assist in identifying those problem particle sizes and characteristics (concentrations and densities) which should be eliminated as much as practical upstream from the inverted siphon.

For the domestic sewage case study it was determined that particles greater than 1,000 microns with a specific gravity of 2.6 and concentrations in the order of 20 milligrams per liter or greater would be a sedimentation risk. As such, these were the target sizes for the upstream rock catcher.

The key findings are as follows:

1. When being transported in flume traction, the smaller sand/grit particles will not be mobilized similar to larger particles in an inverted siphon. At high enough flow velocities, the smaller particles that have settled in the flatter portion of the siphon will be re-suspended and will then move more readily up the inclined portion.
2. For the inclined portion, the minimum velocity (V) increases as particle size reduces; however, the threshold velocity (Vt) to move a particle in a near horizontal pipe increases as particle size increases.
3. For the inclined portion, as concentration increases for the same specific gravity, the velocity required to move the particle increases (via flume traction transportation mode).

Design Steps for Air Transport

An inverted siphon, particularly one that is used intermittently or in high flow activation cases, has the potential to create a fully developed hydraulic jump that can reduce capacity. The empirical approach to evaluating whether an inverted siphon's geometry will create a fully developed hydraulic jump includes the following considerations.

<u>**Step 1:** Understand how the supercritical flow will behave when it interacts with the standing water level.</u>

Using the method presented in U.S. Department of Commerce (1981), assess the interaction between the supercritical flow in the declining section and the full pipe flow. For the domestic sewage case study, it is anticipated that the supercritical flow will jet/plunge into the standing water, cushioning the potential to create a fully developed hydraulic jump. Given that the depth of standing water in the pipe will be shallow, there will not be sufficient water volume to form a fully developed hydraulic jump.

Step 2: Understand at what falling grade any entrapped air will be mobilized upstream.

Given that some hydraulic jump/transition is unavoidable, there will be turbulence/mixing and air trapped in the siphon. Therefore the steeper the grade, the better the upstream movement of air bubbles will be as buoyancy forces exceed fluid interface drag forces. For the domestic sewage case study, it was found that for a declining profile of 8.7 percent, air will move upstream in both the low and high flow cases in a full-flow pipe.

Step 3: Understand the approximate duration for flow rates to reach the key design flow rate.

For the domestic sewage case study, it is anticipated that the inverted siphon will take approximately 10+ hours from the time it is activated until the full ultimate design flow is reached. This allowed for a more stable filling condition.

Step 4: If possible, create a low-turbulence flow condition prior to the siphon inlet.

This can be very challenging due to physical site constraints, but the more the turbulence is reduced before entering the siphon inlet, the less entrained air will be transported. For the domestic sewage case study, given site constraints, the project had a 6.6-foot (2-meter [m]) grade drop along with a 90 degree alignment change as the flow enters the siphon inlet structure. Figure 5 shows the effect of air entrainment through a 45 degree bend being transferred downstream.

Figure 5. Simulation of air transferred downstream due to a sharp alignment change through a maintenance hole.

EMPIRICAL METHODS VERSUS NUMERICAL MODELING

In the domestic sewage case study, a computational fluid dynamic (CFD) model allowed the validation of the empirical steps identified above for air and sediment transport. The advantage of a computational model is that it can visually assist in understanding how air and sediment move in transitioning flows in a dynamic simulation, picking up behaviors and interactions that may be a challenge to predict using the empirical methods. Other options include physical models to validate empirical calculations.

The results of the CFD model validated the empirical findings, and in addition, identified the following:

- Turbulent flow resulting from the 6.6-foot (2 m) drop and 90 degree alignment change, continued into the inverted siphon. This was reduced by the inclusion of a vortex chamber and plunge pool, with enlarged and flattened pipe into the siphon inlet structure.
- Due to the rapid rate of filling, the large air pockets migrated back to the inlet structure causing burping and rooster-tailing into the inlet structure. This was reduced by the inclusion of a breather pipe immediately downstream of the siphon inlet structure, which intercepts air before it enters the structure.

DESIGN CONSIDERATIONS TO MINIMIZE THE RISK

The lists below provide design and infrastructure considerations that can assist in reducing air and sediment operational performance or maintenance issues.

Air transport/mobilization considerations:

- Balance the inverted siphon declining slope to allow for air migration upstream across a range of key flow conditions while reducing the risk of creating fully developed hydraulic jumps.
- Install breather pipes on the upstream end of the inverted siphon to minimize rooster-tailing into the inlet structure.
- Reduce turbulence flow into the siphon inlet structure as much as possible to remove entrained air; for example, use of vortex structures with plunge pools in large grade drops.
- Use vents on upstream and downstream siphon structures to keep chambers from pressurizing, allowing air in when the siphon inlet is drowned, and allowing foul air to be removed.

Sediment transport/mobilization considerations:

- Install rock/grit chambers to remove the critical particles that cannot be mobilized easily during the operating flow range of the inverted siphon.
- Where possible, select an inclining slope less than the slope at which silt and other solids begin to accumulate for the key flow rates.
- Install an access point for cleanout near the base of the inclined section of the inverted siphon, if site constraints allow, to facilitate cleaning.

Operation and maintenance considerations:

- The design and layout of the inverted siphon should also consider the owner's operation and maintenance capabilities, such as the immediately available resources in the area for cleaning should maintenance structures be challenging or impossible to install. Other owner considerations include providing additional siphon barrels (perhaps smaller diameters) for redundancy if blockages occur, and performing regular inspection and maintenance of rock catchers/grit chambers and regular CCTV inspections of the inverted siphons to identify accumulations or blockages.

CONCLUSION

The design of inverted siphons is complex and there are numerous variables to be considered. The steps for air and sediment transport presented in this paper are not exhaustive and are not applicable to every system, but they are intended to provide an initial basis for understanding and approaching the problem.

An inverted siphon that does not function as intended can be costly and disruptive. If there is uncertainty regarding the design aspects of the inverted siphon, and documents obtained in the literature search do not address the uncertainty, the use of CFD or a physical model should be considered to evaluate alternatives and to validate the decisions made.

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Local SSO Requires Regional Solutions

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ABSTRACT

The City of Houston (the City) and USEPA have recently entered a consent decree and are working to address a number of sanitary sewer overflows. One of the areas highlighted in this decree involves a periodic overflow within a low-lying area just north of the central business district, located within the historic Houston Heights neighborhood and referred to as the "Wrightwood SSO." Preliminary evaluation showed that surcharge occurs throughout the entire system during heavy rain events due to limited capacity at the downstream lift station and treatment plant. A wide range of improvement alternatives were available for consideration to improve the existing network related to this single localized overflow requires significant investment to resolve. To evaluate these options, the City of Houston used both traditional "trial-and-error" scenario modeling and intelligent algorithm optimization software to evaluate alternatives and develop low-cost, defensible solutions.

Background

The Consent Decree between the City of Houston and the United States of America, State of Texas, and Bayou City Waterkeeper (Consent Decree, or C.D.). is divided into several phases to address 9 specific areas throughout the City with repeat overflows which each have set regulatory deadlines.

The project is to eliminate a repeat Sanitary Sewer Overflow (SSO) from four manholes located along the 1200 block of Wrightwood Street between IH-45 and Houston Avenue in Northwest Houston (the Wrightwood Area).

The overflows from these four manholes, in the vicinity of a lift station which has been previously abandoned, are collectively referred to as Area 2 in the Consent Decree. Flow in the Wrightwood Area is currently being carried westward by gravity through a 60-inch tunnel feeding into a 120-inch tunnel along Main Street (the Northside Sewer Relief Tunnel, or NSSRT), ultimately traveling to the 69th Street Wastewater Treatment Plant (WWTP). See Figure 1.

The NSSRT experiences surcharging during heavy rain events due to downstream constraints. The ground elevation and manhole tops within the Wrightwood Area are significantly lower than the surrounding land areas and below the surcharged hydraulic grade line (HGL) leading to an easy relief point when the system surcharges.

The Wrightwood Area is referred to as Area 2. However, this planning study includes the entire Northside service area, which includes and has the potential to benefit C.D. Areas 1, 2 and 3. Areas 4 through 9 are not related to regional surcharge within the Northside service area.

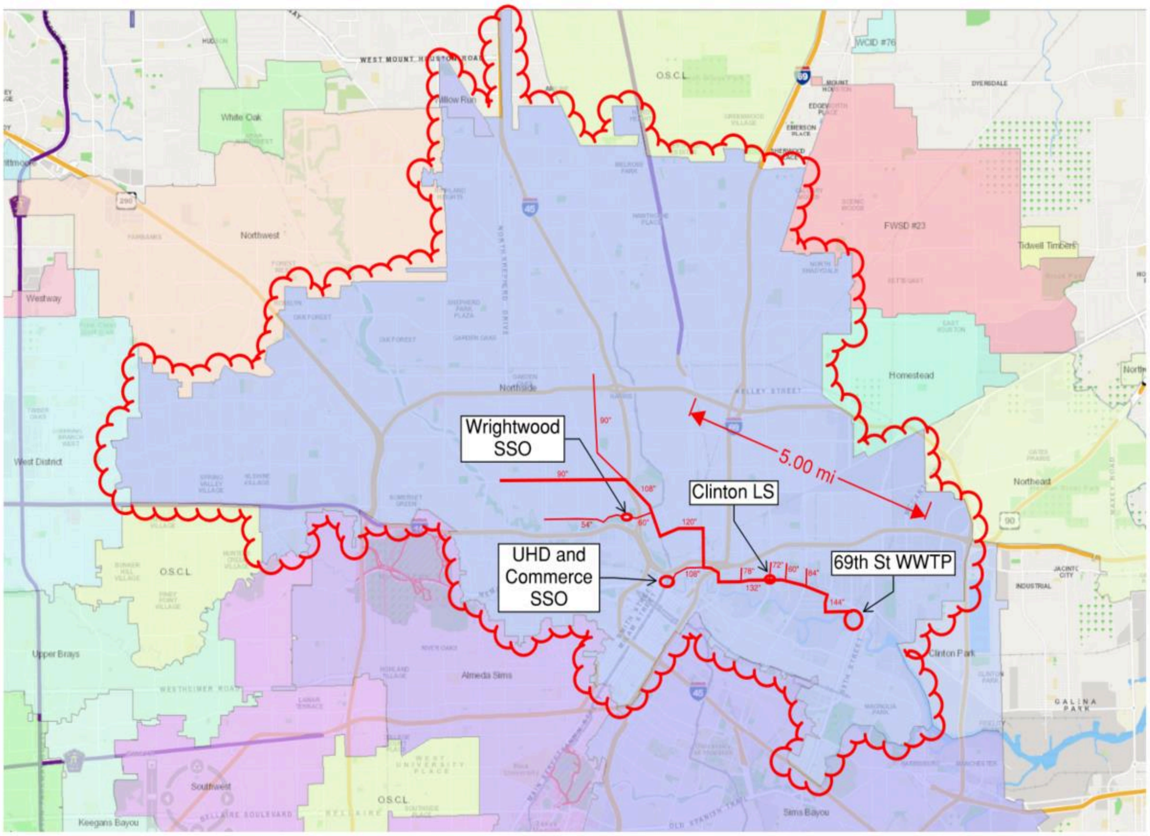

Figure 1 – Northside Service Area

EXISTING CONDITIONS - Northside System

The existing conditions in the system comprises the north and central portion of the City of Houston, generally bounded by Little York Rd to the north, Highway 610 to the east, Highway 59 to the south, and Sam Houston Tollway to the west, covering an area of approximately 30 square miles.

The current system infrastructure was provided to LAN in a model developed and verified by the City of Houston and other consultants in 2020 using Innovyze's InfoWorks ICM hydraulic modeling software version 9.0.

Key assets within the Service Area include:

1) 69th Street Wastewater Treatment Plant
    a) 400 million gallon per day (MGD)
2) Northside Wet Weather Facility
    a) Approximately 10 million gallons (MG) wet weather storage
3) Major tunnel systems
4) Lift Stations
    a) 69th St Influent lift station
    b) Clinton Drive Lift Station
    c) Local Neighborhood Lift Stations

The reoccurring SSOs in Areas 1, 2 and 3 are interrelated, and caused by a high peak wet weather flow exceeding the capacity of both the Clinton Dr LS and the treatment capacity at the 69th St WWTP. This results in a surcharge of the system during heavy rainfall events.

Areas 1, 2 and 3 all occur at low-lying locations where the natural ground elevation dips below the HGL within the pipelines.

The performance of the existing sewer network was assessed using the calibrated InfoWorks ICM model for the 5-year, 6-hour design storm and current conditions (2020). The model results summarizing sanitary sewer overflow (SSO) volume and freeboard violations are illustrated in Figure 2. The hydraulic grade lines from Area 2 and Area 3 to the treatment plant in existing conditions illustrated in Figure 3 and Figure 4 respectively show the primary cause of Area 2 and Area 3 SSOs to be related to the capacity of the regional lift station and downstream treatment plant.

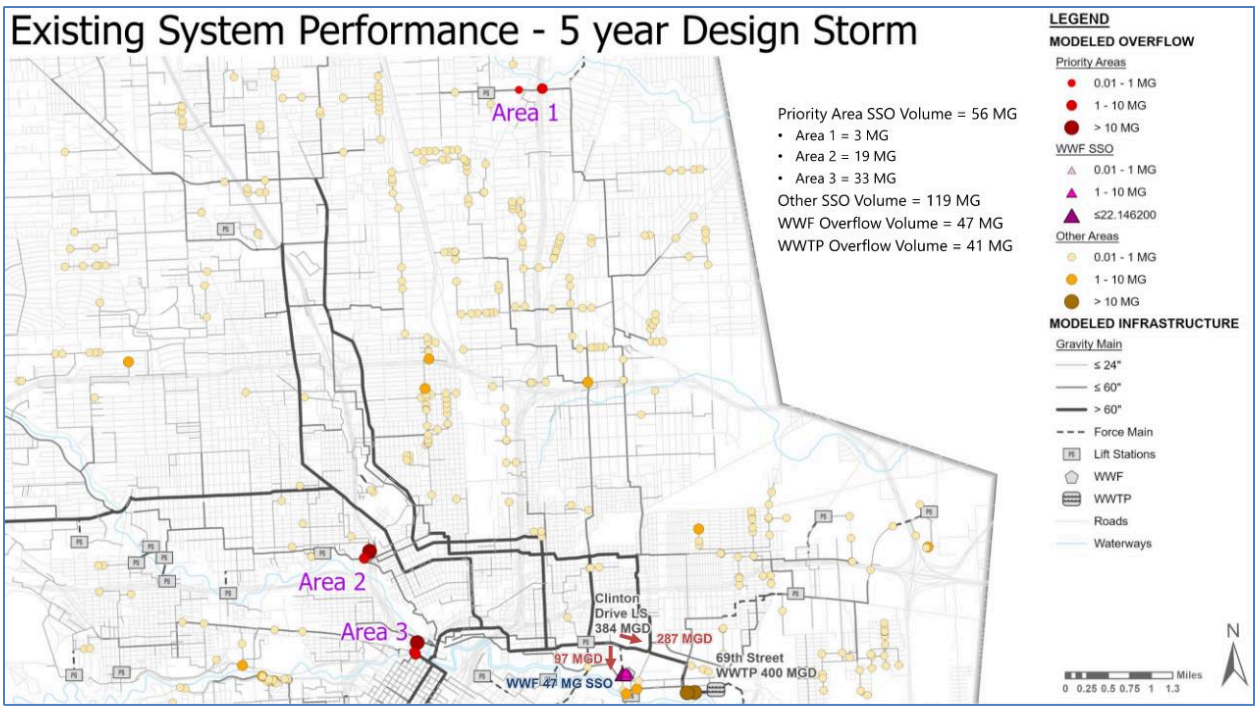

Figure 2 – Existing Northside System SSOs

EVALUTATION OF IMPROVEMENT ALTERNATIVES

The planning effort was performed in parallel by Lockwood, Andrews & Newnam, Inc. (LAN) using traditional modeling of selected scenarios and by WCS Engineering using Optimatics' *Optimizer^{TM}* software. The traditional modeling effort lead by providing basic model scenarios to be fed into *Optimizer^{TM}*. While traditional model scenarios were being fine-tuned, the optimization process could proceed in parallel. This dual approach was selected by the City to provide the fastest possible turnround of results and to provide comparison of results.

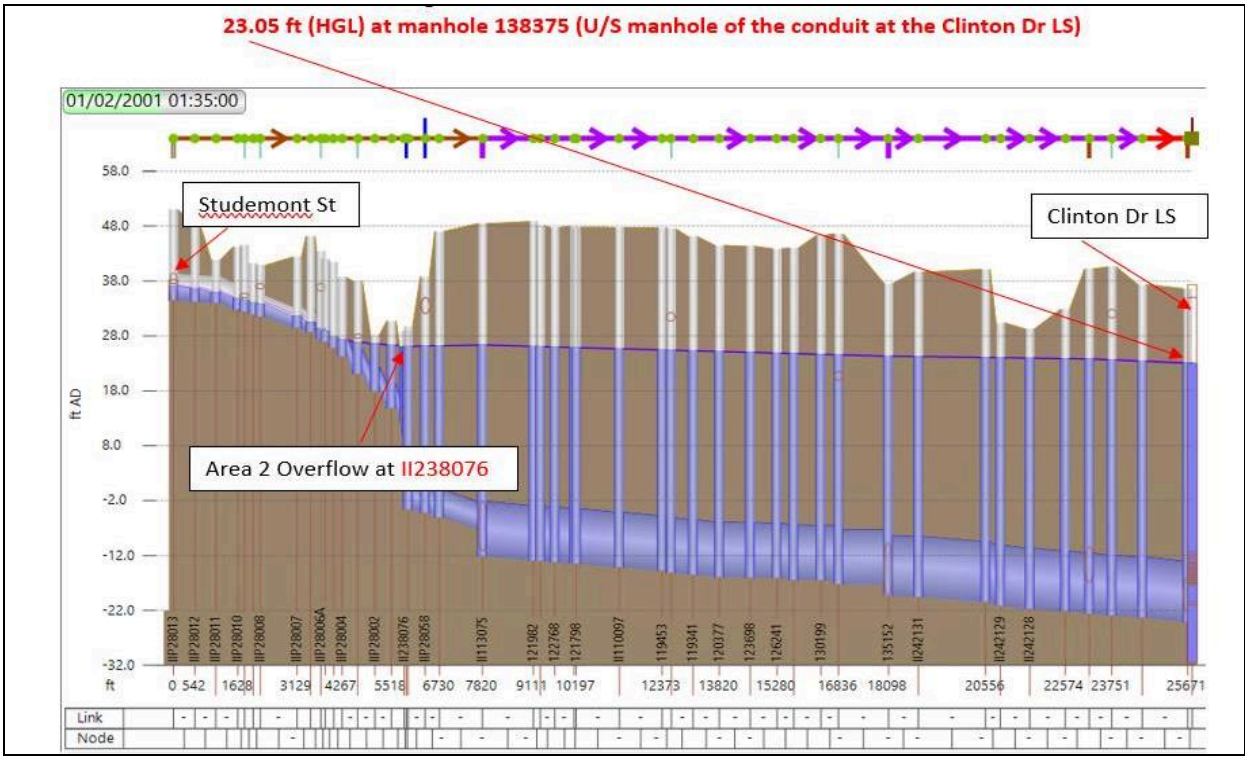

Figure 3 – Hydraulic Grade Lines from Area 2 to Treatment Plant

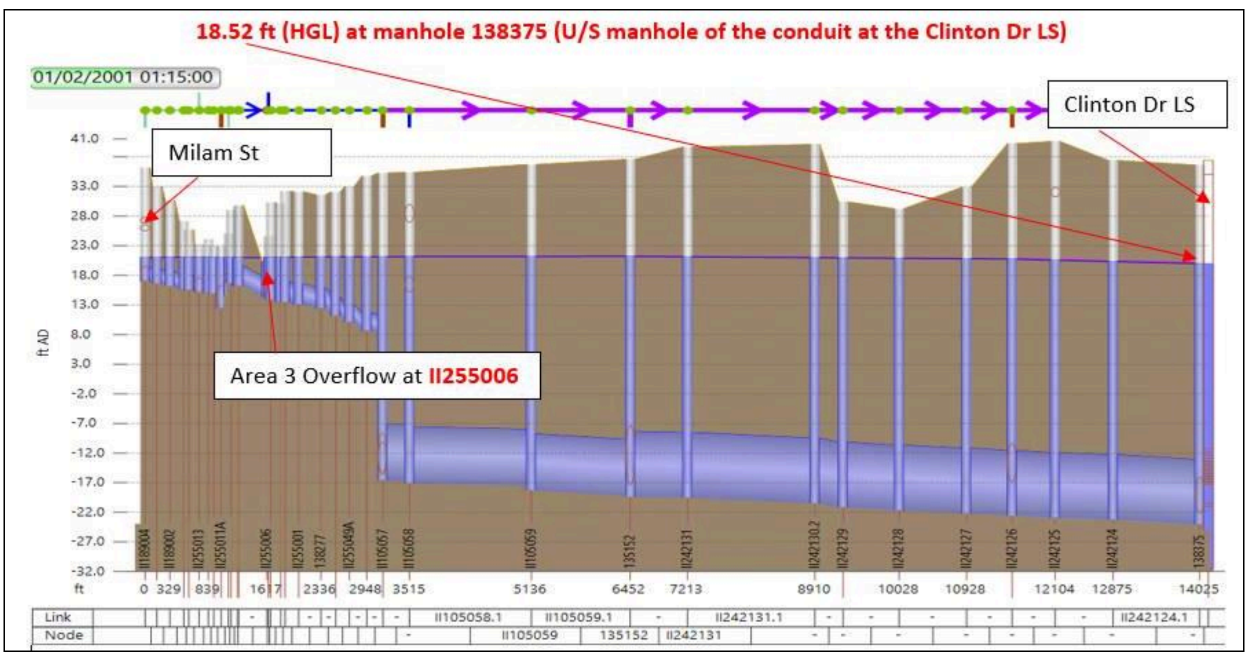

Figure 4 – Hydraulic Grade Lines from Area 3 to Treatment Plant