Hydraulic Simulations of Pipeline and Wellfield Network in West Texas

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Study Purpose

The purpose of this study is six-fold. In general, such analysis is required by (cite/link relevant TAC)…. The computer software EPANET was employed to simulate hydraulic behavior under a variety of conditions. These simulations are to:

1. Establish reasonable control rules to maintain supply to the downstream (terminal) storage tanks while maintaining s desirable system pressure under varying discharge conditions.
2. Understand effects of control on the supply wellfield (roughly 20 miles upstream of the terminal storage) under varying discharge conditions.
3. Identify the magnitude and location of high and low pressures in the system under varying discharge conditions.
4. Identify and suggest locations for pressure relief valves to protect the pipeline.
5. Identify and suggest locations for air-release valves to prevent vapor lock in the pipeline.
6. Estimate the potential water hammer issues that could occur in the pipeline during a sudden shutdown. (EPANET was not used for this item because it cannot simulate surge hydraulics)

In addition, useful references are included in the appendix, and the entire model is stored at http://freeswmm.ddns.net/. The model is executable from this website by anyone with credentials; changes can be implemented and tested as needed.

Study Area

Figure 1 is an annotated map of the model area. The three main parts are shown as the Terminal Storage Portion, the Transmission Pipeline Portion, and the Wellfield Portion (Collection is used interchangeably).

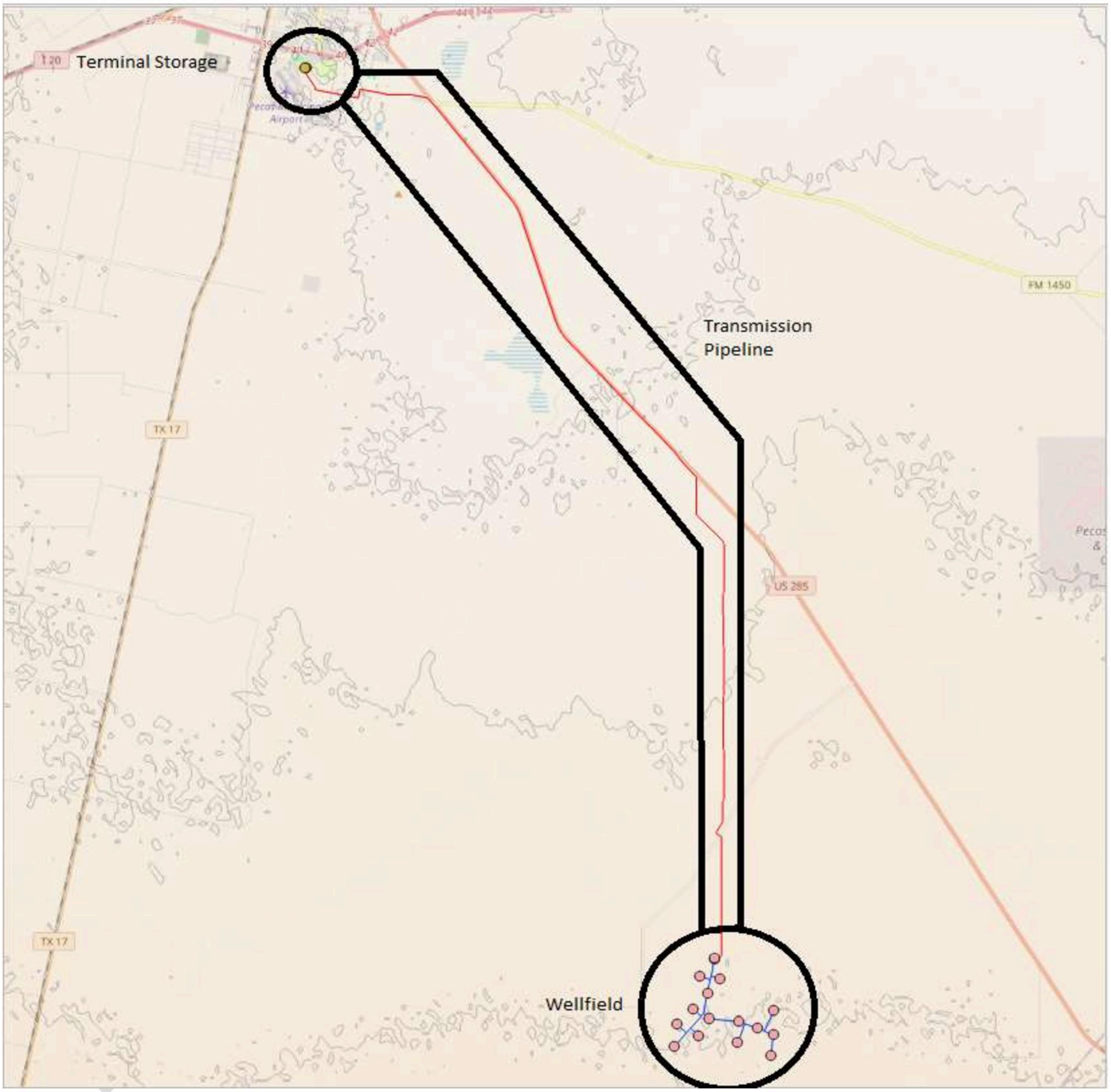

Figure 2. Study Area Overview Map

The unlabeled contour interval is 100 feet. The approximate elevation of the wellfield is 2800 feet, and the terminal storage area is approximately 2600 feet.

The KML file that contained the coordinates of the wellfield components, pipeline alignment, and terminal storage were loaded into QGIS to build an EPANET network. A 30-meter DEM was downloaded from the public STRM database.[1] The STRM data were re-projected onto the Zone 31N UTM coordinate system (approximately Cartesian at the study scale; it will render nicely in ordinary EPANET, and the auto-length algorithm can determine pipe lengths from node locations)

A "plug-in" named "QEPANET" was used in QGIS to map nodes and tanks. The remainder of the EPANET model is built directly in the US EPA supplied software.[2]

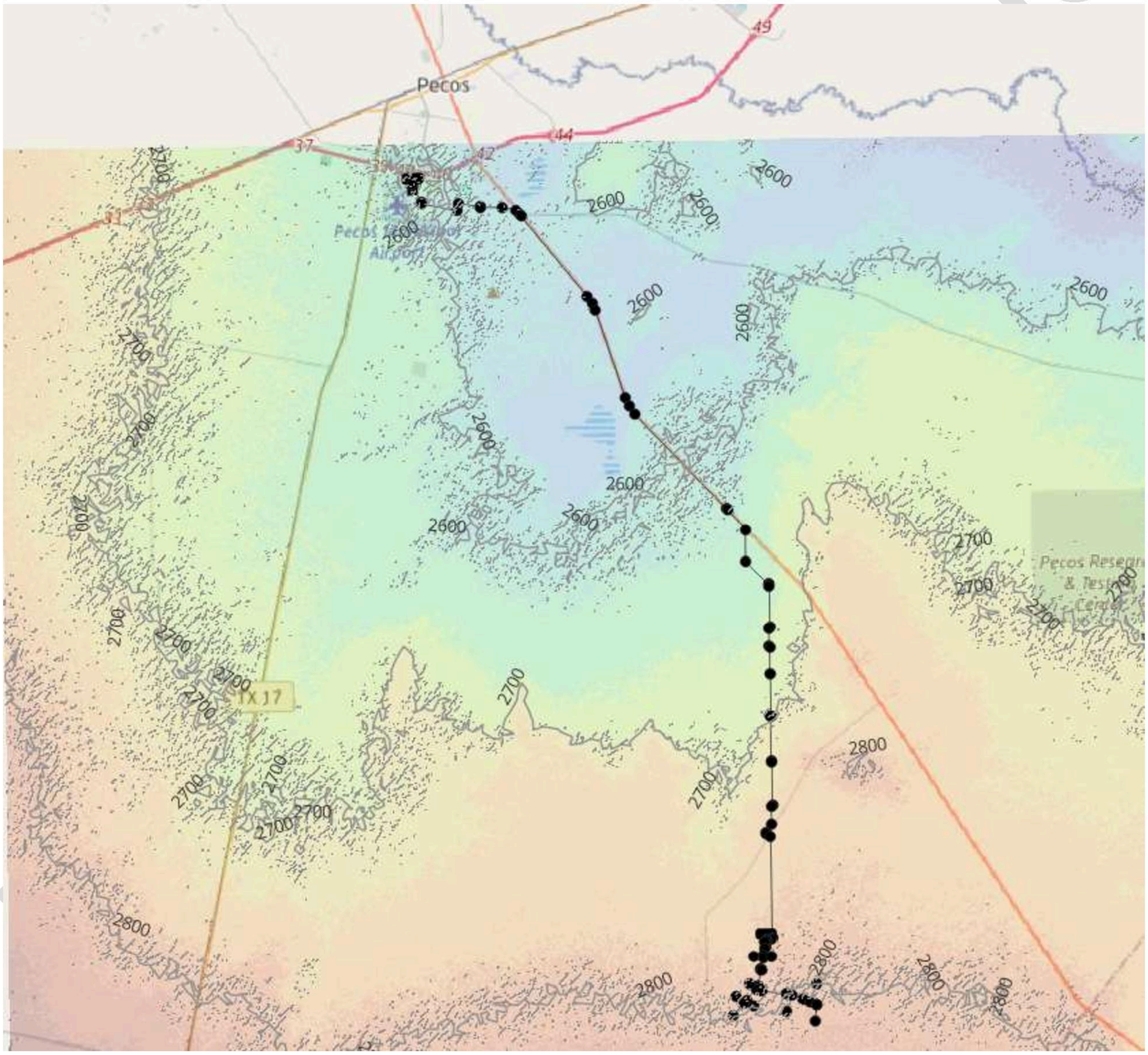

Figure 3. EPANET Model Layout on top of QGIS DEM

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[1] The Shuttle Radar Topography Mission (SRTM) was flown aboard the space shuttle *Endeavour* February 11-22, 2000. The National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA) participated in an international project to acquire radar data which were used to create the first near-global set of land elevations. *Endeavour* orbited Earth 16 times each day during the 11-day mission, completing 176 orbits. SRTM successfully collected single-pass interferometry radar data over 80% of the Earth's land surface between 60° north and 56° south latitude with data points posted every 1 arc-second (approximately 30 meters).

[2] QEPANET does not entirely work with recent QGIS; however it does work well enough to extract spatial coordinates and elevations for "node-type" objects, so it was used herein to obtain coordinates and elevations for use in the EPANET model.

Figure 4 is a map of the EPANET representation of the study area. As various junctions and pipeline features were built in the EPANET software the corresponding elevations were obtained either by re-importing into the QGIS and extracting the elevation or by arithmetic mean of the specific locations from nearby features.

Modeling Assumptions

Several **assumptions** used in the model development and implementation are listed below:

1. The raw water portion of the system is **not** required to be maintained at 35 psi.
2. Negative pressures (anywhere) are unacceptable.
3. Water in the Intermediate Storage Reservoirs (ISRs) is default raw water; furthermore, these are atmospheric storage tanks (at-grade vertical cylinders).
4. Water in the Terminal Storage Reservoirs (TSRs) is raw; water exiting this reservoir pair is boosted into the water distribution system (WDS). All water downstream of the booster station is to be at or above 35 psi for the various discharges in accordance with TAC 30.1.290.D§290.45 for water in a distribution system.
5. TSRs + ISRs total volume is 3.0 million gallons. The transmission pipeline volume is about 1.0 million gallons. The upstream ISR is used as a sand trap and should not participate in changing water levels in the simulations. Assuming the remaining tankage volume represents 7 days of average discharge, the average daily demand (to empty tanks over 7 days) about 250 gpm. This value (250 gpm) is used as a base ADD for time-varying hydraulic simulations.
6. The entire system demand is assigned (in the model) at the WDS node, which represents the current/future water distribution system.
7. The control rules at the ISRs is stipulated so the tank receiving water from the well field (the upstream ISR) is kept nearly full. The generic rule structure was to start pumps when the tank depth approached ¾ full (22.5 feet deep), and stop pumps when the tank is 95% full (29.5 feet deep). The tank was further constrained to not be allowed below 15 feet deep – so the bottom ½ of the tank is always available. The tank is to serve as a sand trap as well as storage these settings preserve ½ of the tank volume for its clarifier role. The tank that feeds the pipeline responds to system hydraulics.
8. The TSR control rules are set such that the tanks behave in tandem, and attempt to keep water levels between 1/3 and 98% full.
9. The wellfield pumps shut down/start-up rule is all pumps are on/off a more elaborate scheme is tried in subsequent simulations where the pumps are shut down from closest to the ISRs to furthest, and restarted in reverse order. – this rule set is more complex, and may introduce model instabilities.

EPANET Conceptualizations

EPANET conceptualizations are examined below – these represent how the physical system is approximated in the hydraulic model. The model includes the wellfield pumping from the underlying aquifer. These flows are collected into two storage tanks labeled ISR-1 and ISR-2, both ½-million gallon atmospheric (at grade) storage tanks. ISR-1 serves as both a storage reservoir and a grit (sand) chamber before water is transferred to ISR-2, which feeds the 21+ mile long transmission pipeline.

Transmission Pipeline

The transmission pipeline is modeled as an approximately 110880 (21 miles) feet long, 17.43-inch ID pipe with a Hazen-Williams Loss Coefficient of 130.[3] Figure 5 summarizes the various major components and water volumes.

Volumes							
ISR1			500,000.00	gal			
ISR2			500,000.00	gal			
TSR1			1,000,000.00	gal			
TSR2			1,000,000.00	gal			
Pipeline			977,093.12	gal	<= 21 miles of 18" ID pipe		
System Volume			3,977,093.12	gal			

Figure 5. Model Summary

The approximate total system volume is nearly 4 million gallons, and at 2100 gpm will take a little less than a day and a half to fill.

The pipeline terminates at TSR-1 which is tandem connected to TSR-2, both 1-million gallon atmospheric (at grade) storage tanks.[4] TSR-2 is assumed to store treated water, so it is boosted into the existing water distribution system. Figure 6 is a "pump" curve representing the performance of the entire booster station at the insertion point to the existing water distribution system network.

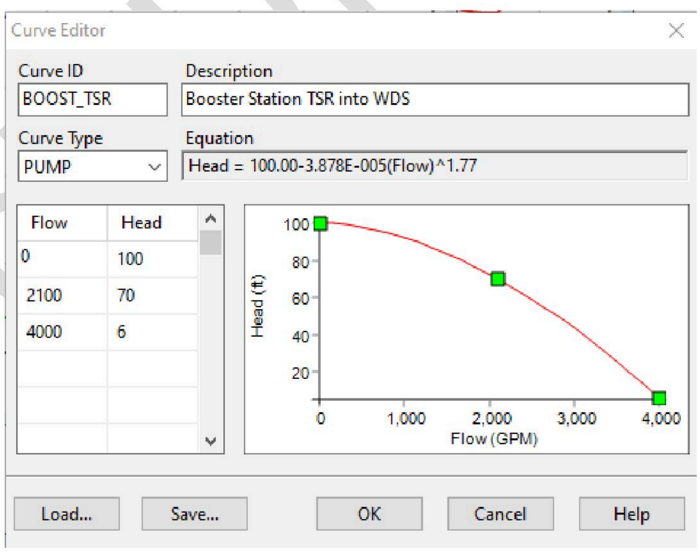

Figure 6. Booster Station at Terminal Storage Reservoir.

The performance curve was obtained by trial-and-error to produce slightly greater than 35-psi at the WDS node when the demand is 2100 gpm.

[3] A reasonable value for new pipe of various materials, HDPE probably has a higher value of around 150, so the 130 is conservative to some extent. A couple of references for loss coefficients are attached in Appendix I

[4] These two tanks are located in the north portion of the maps above; on the QGIS map the northern tank icon is apparent. The tank icon at the southern part of the model are the two ISR tanks.

Wellfield Model

Individual wells in the wellfield were modeled as specified groundwater elevations on the suction side of a pump (8FAHC). The discharge side of the pump is connected to the nearest system node (in the model) through a check-valve (backflow preventer) to only allow one-way discharge, and connection pipe that includes the riser pipe length (the static lift in the diagram in Figure 7). Figure 7 depicts the conceptual model and the equivalent EPANET representations.

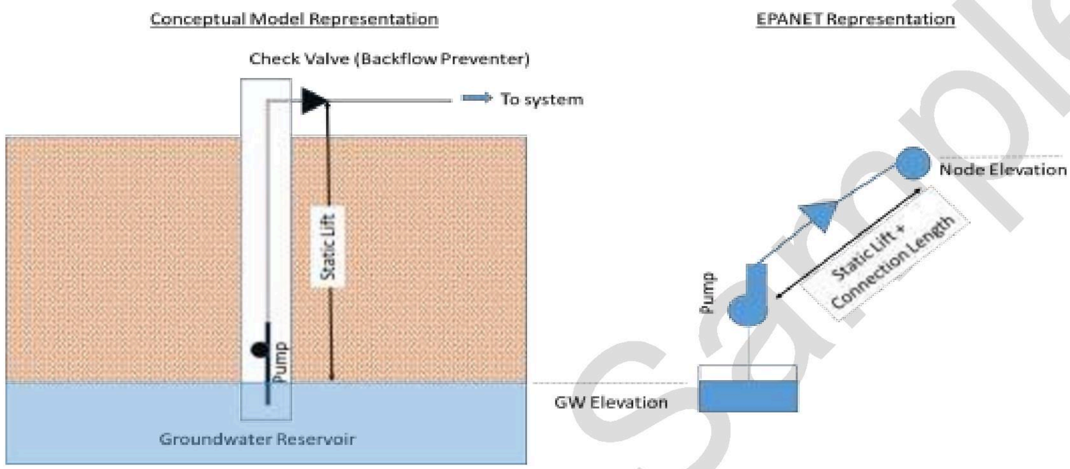

Figure 7. Conceptual and EPANET model representations of individual wells.

The groundwater elevations were specified as 2330 feet in the initial simulations. Node elevations from the `CALCS[59].pdf` file were used for the wellfield model. A pump curve with manufacturer specified behavior was supplied to EPANET and the input dialog box is shown below on Figure 8

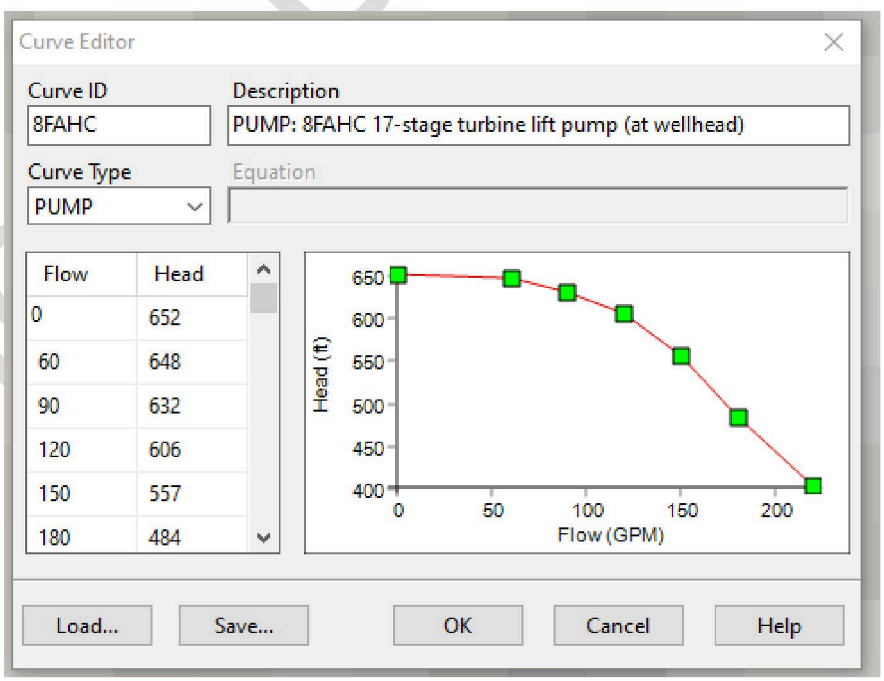

Figure 8. EPANET Representation of 8FAHC pump performance curve

Figure 9 is a screen capture of the manufacturer supplied well pump performance curve for each well.

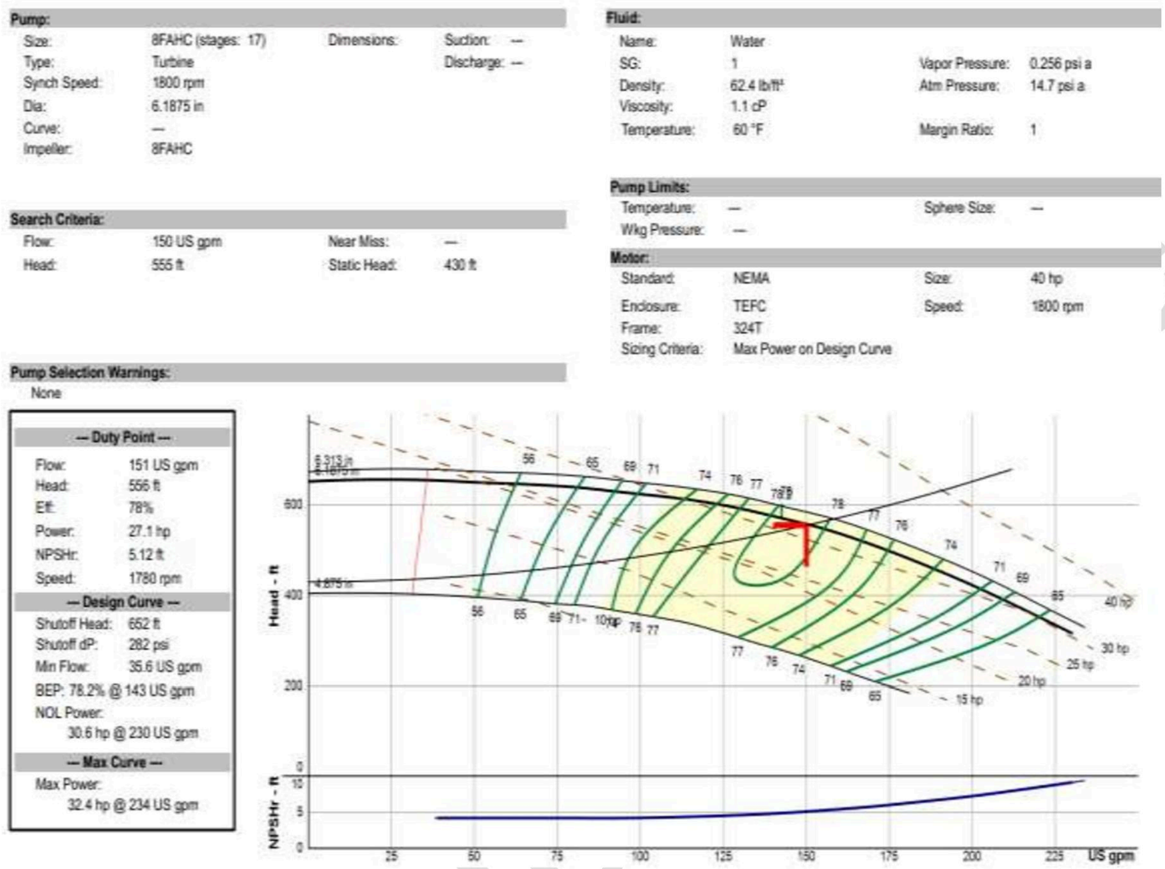

Figure 9. Manufacturer Supplied Pump Data

Figure 10 depicts the wellfield portion of the model area with the common groundwater elevation, with all wells active.

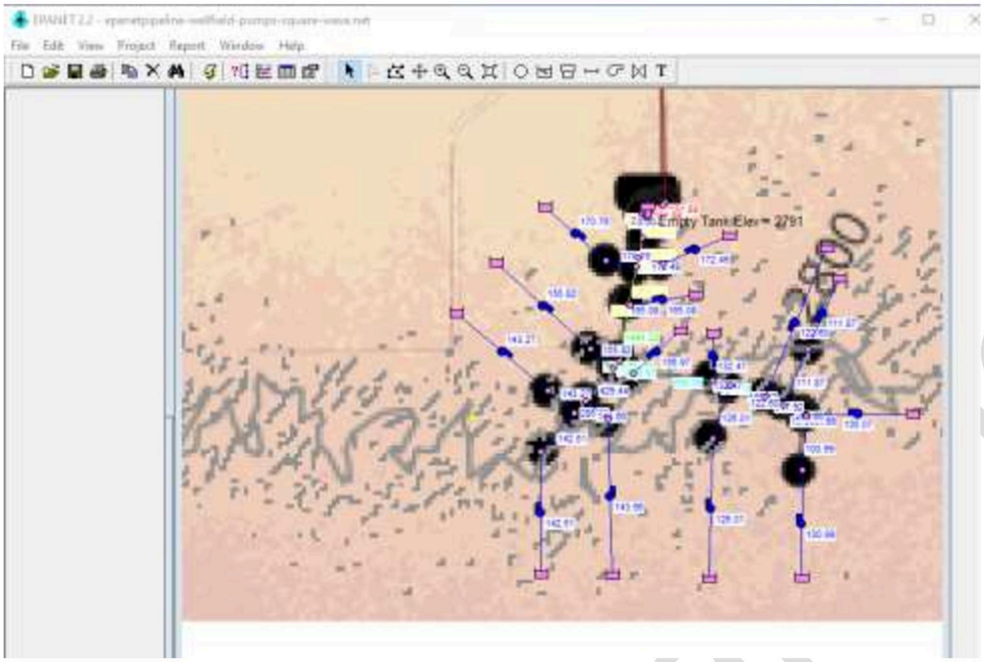

Figure 10 Wellfield portion of EPANET model

The groundwater reservoir(s) are the magenta rectangles, pumps, check valves, and connecting pipes are shown overlaid on the project base map. All the well pumps are modeled with a check valve to prevent computed (and real) backflows. In general if a well is inactive, the immediately downstream check valve should show a status of Closed in EPANET.

Demand Scenarios

Various demand scenarios are used in developing the model. Steady demand is used to get the model running and to validate the hydraulics at nominal maximum flow rates. Variable demands are implemented to test behavior of the system as demand changes to validate the tankage volumes and construct reasonable flow control rules.

Steady Demand

The steady demand scenario established the control rules and checked that a stable simulation is possible. In this instance, the demand pattern is a constant as depicted in Figure 11

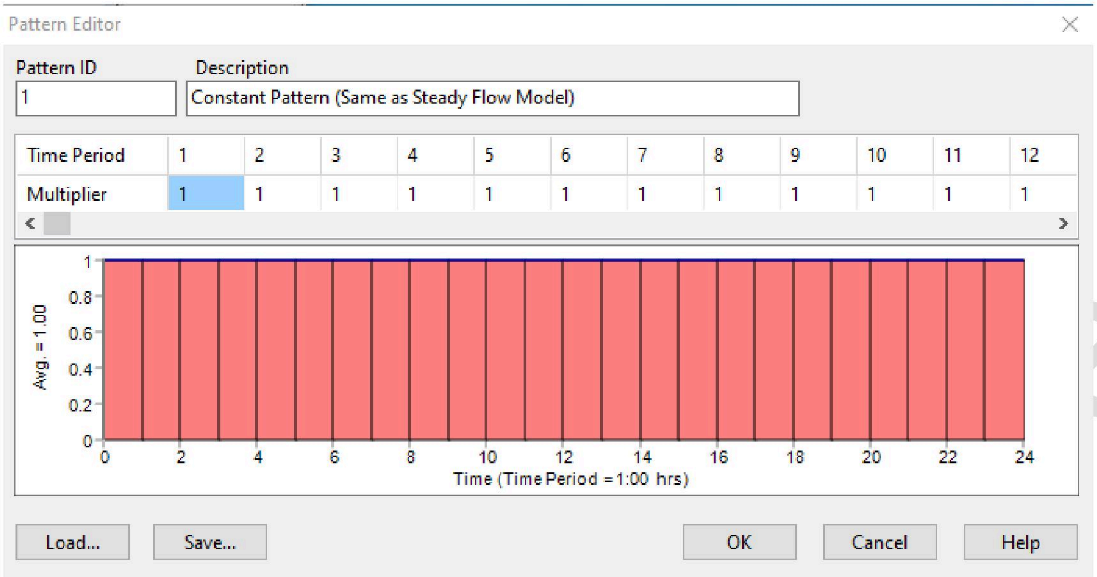

Figure 11. Steady Demand Scenario

The figure depicts multipliers that are applied to nominal demands at selected nodes; in this model the only demand node is the WDS-IN node, which represents the existing Pecos water distribution system.

The demands supplied were:

1. 210 gpm (a low flow)
2. 2100 gpm (the nominal maximum)

The pattern repeats on a 24-hour cycle for a total of 192 hours of simulation (8 days). This duration is selected as sufficient in the author's opinion to detect simulation instabilities, diagnose causes, and correct the input files.

Repeating Step-Function Demand

The repeating step-function demand stresses the simulation model by changing from a low demand to a high demand within one day, again with the goal of detecting instabilities. It also enables some measure of estimating the duration of wellfield activity and inactivity.

Figure 12 depicts the demand pattern for this scenario.

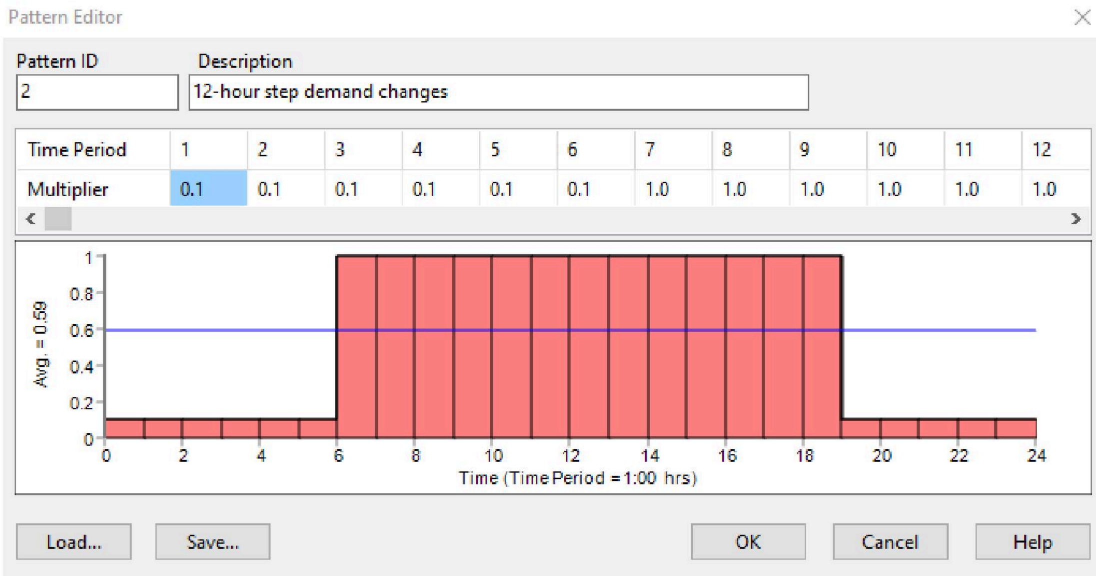

Figure 12. Step-Change Demand Pattern

The patters applies to base demands at the WDS-IN node with consideration that the pattern will pre-multiply the value by 0.1 or 1.0 depending on simulation time of day.

Repeating Hourly Variation Demand

Figure 13 depicts the repeating hourly pattern used for the "realistic" simulations. The pattern has two peak demand times one at 0800 and another at 1900. These are intended to represent morning peak demand and evening peak demand. This particular pattern is used with a low base demand (300 gpm) and the pattern adjusts each hour as dictated by the pattern.

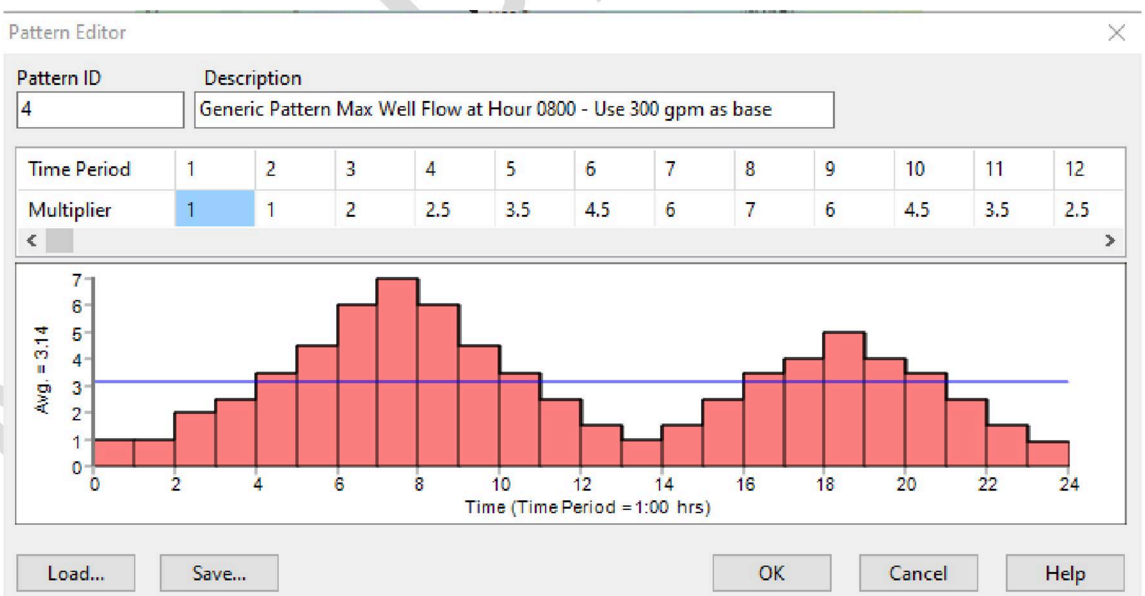

Figure 13. Hourly Demand Pattern

The pattern repeats every 24-hours for 8 days, and should identify instabilities in the simulation and other hydraulic issues.

Storage Tank(s) Model

Figure 14 is a schematic of a generic storage tank representation in the EPANET model. The actual system has two pairs of such tankage. In the schematic the important tank features are identified; the program requires specification of minimum, initial, and maximum depth the tank diameter and the tank bottom elevation. Non-cylindrical tanks can be modeled using a depth-volume curve. The check valve and booster pump are not part of tank specification; nor does the computer program actually air-gap the tanks as depicted, but this is a useable conceptualization.

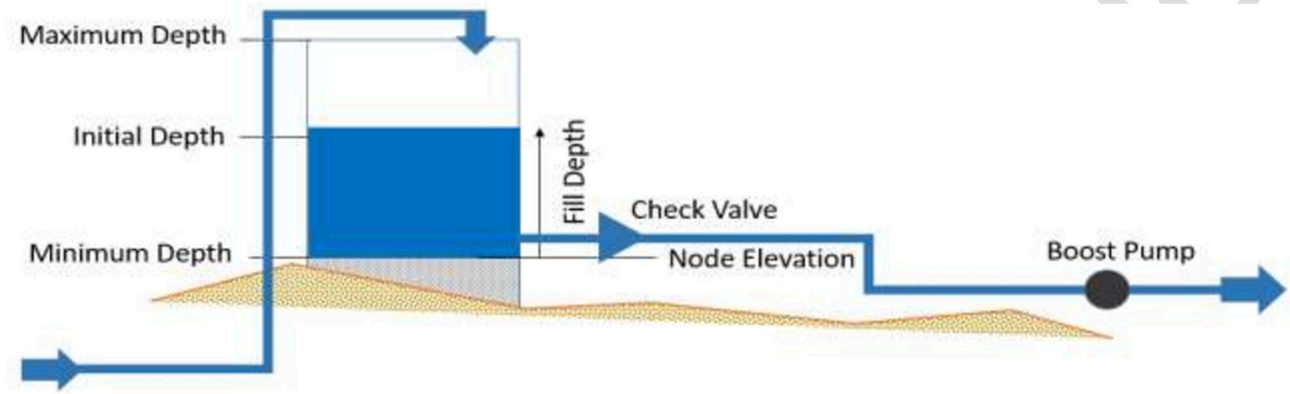

Figure 14. Generic Storage Tank Representation

The two storage areas are the intermediate storage reservoirs (ISR) located immediately adjacent to (North of) the wellfield, and the terminal storage reservoirs (TSR) located at the city yard, where the raw water would be treated (disinfected) and boosted into the water distribution system. Control rules in conjunction with a flow control valve located proximal to the first TSR tank (TSR_1) were developed to explore system behavior under varying water demands.

Terminal Storage Reservoir-Based Control Rules

The TSR rules were developed to supply water to the WDS from TSR_2 until its level is low, then transfer from TSR_1 to maintain supply. When TSR_1 is low, then the system draws from the pipeline, which is supplied from the ISR location governed by system hydraulics. The control of inflow into TSR_1 is a flow control valve (FCV_TSR), the signal to change valve settings is the water level in TSR_1.

A simple set of rules were implemented in the computer program to open and close and throttle connections based on tank water levels.

The TSR_1 rules to control overflow conditions are:

- If level > 26.5 (tank 88% full) then reduce inflows from pipeline, set FCV to 1600 gpm.
- If level > 27.5 (tank 91% full and filling) then reduce inflows from pipeline, set FCV to 800 gpm.
- If level > 28.5 (tank 95% full and filling) then reduce inflows from pipeline, set FCV to 450 gpm.
- If level > 29.5 (tank 98% full and filling) then shut FCV completely, set FCV to CLOSED.
- The default (fail mode) setting is 449 gpm.

The TSR_1 rules to control under fill (draining) conditions are

- If level < 13.5 (tank is 45% full and draining). Increase pipeline inflows, set FCV to 450 gpm.
- If level < 12.5 (tank is 41% full and draining) Increase pipeline inflows, set FCV to 800 gpm.
- If level < 11.5 (tank is 38% full and draining) Increase pipeline inflows, set FCV to 1300 gpm.
- If level < 10.5 (tank is 35% full and draining) Increase pipeline inflows, set FCV to 2200 gpm

The TSR_2 rules are:

- If level > 29.5 (98% full) then stop inflows from pipeline, by closing valve in pipe TSR_TRAN
- If level < 10.0 (tank is 33% full and probably draining) then resume TSR_1 inflows, by opening valve in pipe TSR_TRAN.

Figure 15 is a schematic of the tandem TSR tanks and the control rules implemented. These rules were created by running several simulations with different set points until a relatively long (7+ days) simulation would run without errors or warnings.[5]

Figure 16 is an example of a portion of the status report, illustrating acknowledgement of a rule induced change and a subsequent valve setting change. Warnings are listed in the same report and by program default the modeler has to examine the file before the program will complete a simulation.

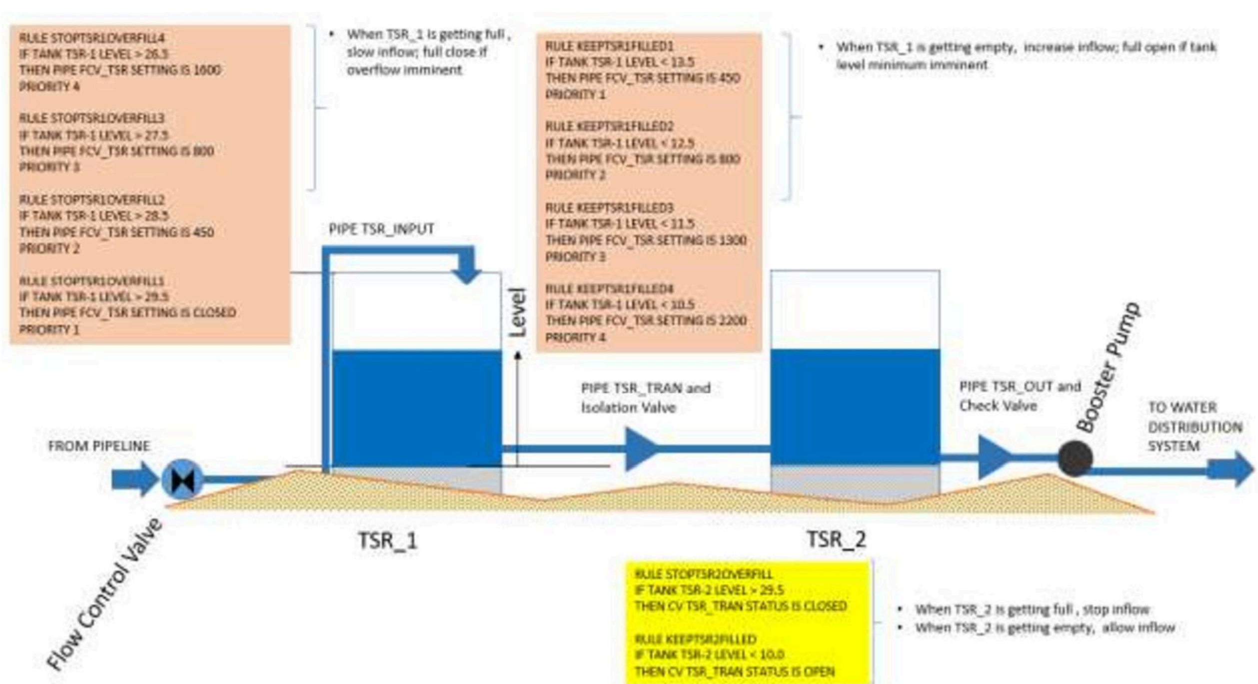

Figure 15. TSR operating rules (initial simulations)

[5] Errors stop program execution and need immediate attention. Warnings are notifications to the modeler that an unusual condition exists. Warnings do not imply something is wrong with the simulation; although negative pressure warnings need investigation.

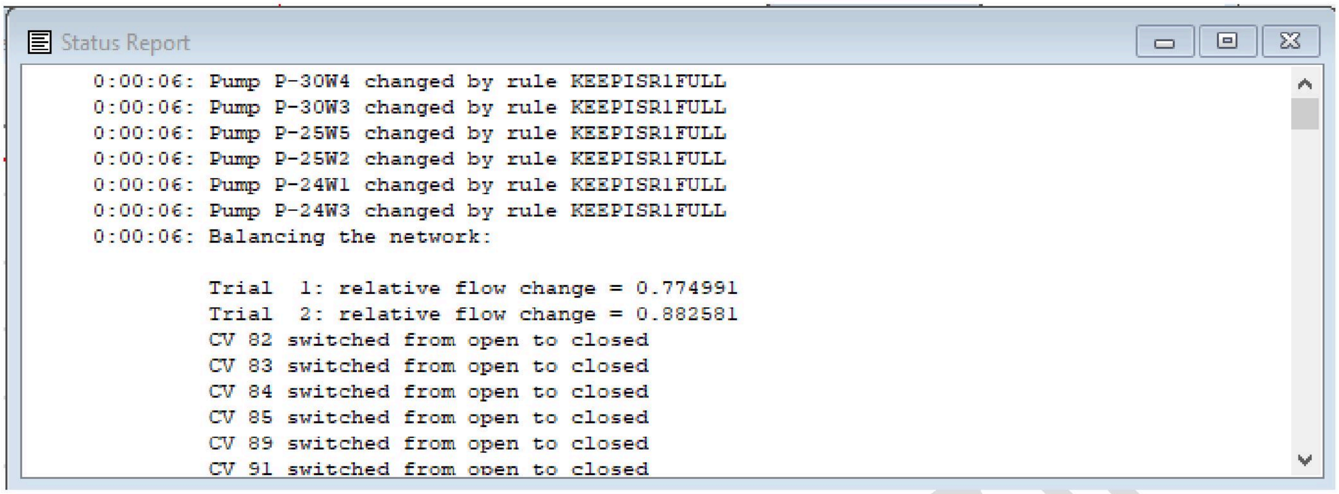

Figure 16. Portion of Status Report Listing Control Rule changes to pumps and valves.

Intermediate Storage Reservoir-Based Control Rules

The ISR rules were stipulated to supply water to the pipeline from ISR_2 until its level is low, then transfer from ISR_1 to maintain supply. When ISR_1 is low, then the system draws from the wellfield, which is supplied to the ISR location governed by system hydraulics.

These rules are more complex than the TSR rules because a stated goal is to keep ISR_1 close to full and use it as a sand trap (aka clarifier). The initial set points below are simply to get the modeled system to function.

The ISR_1 rules are:

- If level > 29 (tank is 96% full) then stop inflows from wellfield, by closing all pumps.
- If level < 27 (tank is 90% full) then resume wellfield inflows, by starting all pumps.[6]

The ISR_2 rules are:

- If level > 29 (tank is 98% full) then stop transfer from ISR_1. Set FCV to CLOSED.
- If level < 25 (tank is 83% full) then transfer from ISR_1 using FCV between ISR_1 and ISR_2. Set FCV to 450 gpm.
- If level < 24 (tank is 80% full) then transfer from ISR_1 using FCV between ISR_1 and ISR_2. Set FCV to 900 gpm.
- If level < 23 (tank is 76% full) then transfer from ISR_1 using FCV between ISR_1 and ISR_2. Set FCV to 1500 gpm.
- If level < 22 (tank is 73% full) then transfer from ISR_1 using FCV between ISR_1 and ISR_2. Set FCV to OPEN.

Figure 17 is a schematic of the tandem ISR tanks and the control rules implemented.

[6] Nearly all the pipelines connecting pumps to the collection tanks have check valves – hence stopping a pump usually causes the program to close the immediate downstream check valve. This conceptualization was employed to prevent computed backward flows.

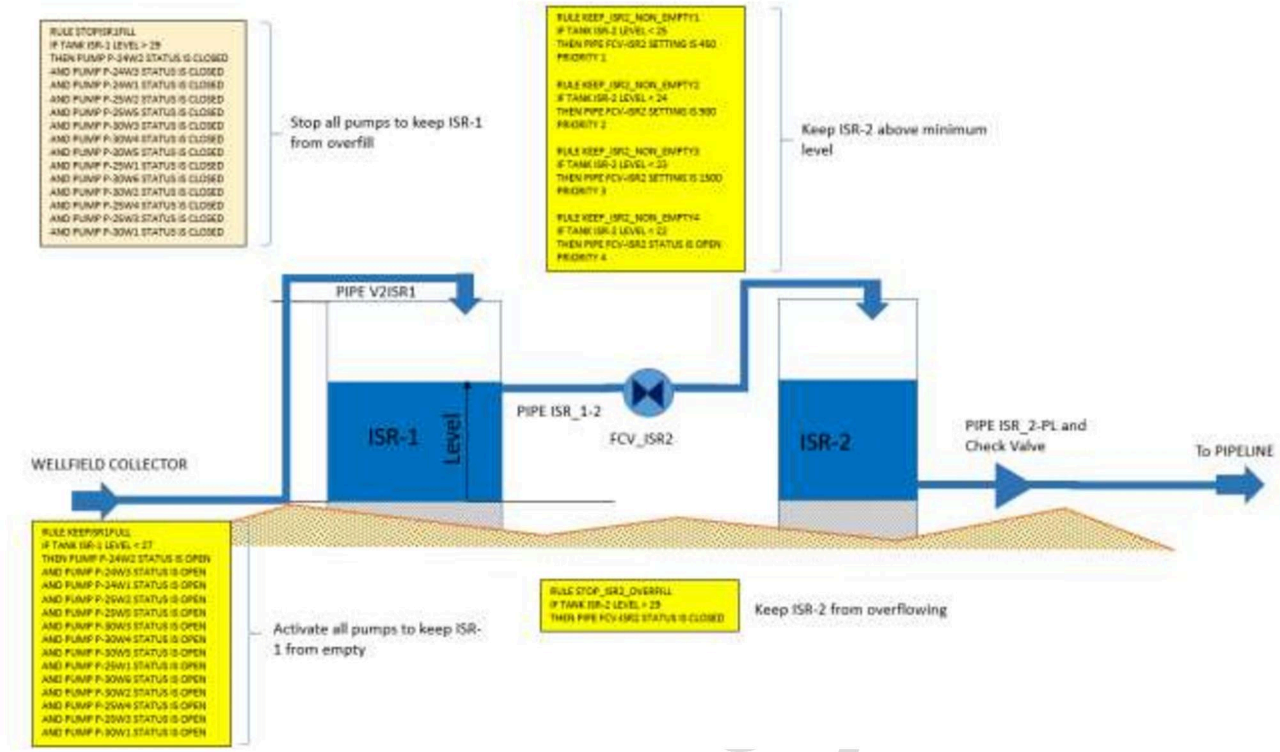

Figure 17 ISR operating rules (initial simulations)

EPANET Simulation Results

The following subsections present selected simulation results including hydraulic grade line plots under the different conditions. The script used to generate these plots is included in Appendix V

Constant Demand of 1500 gpm

A constant demand of 1500 gpm was simulated as representative of a substantial flow rate maintained indefinitely. The demand pattern at the WDS-IN node is displayed in Figure 18.

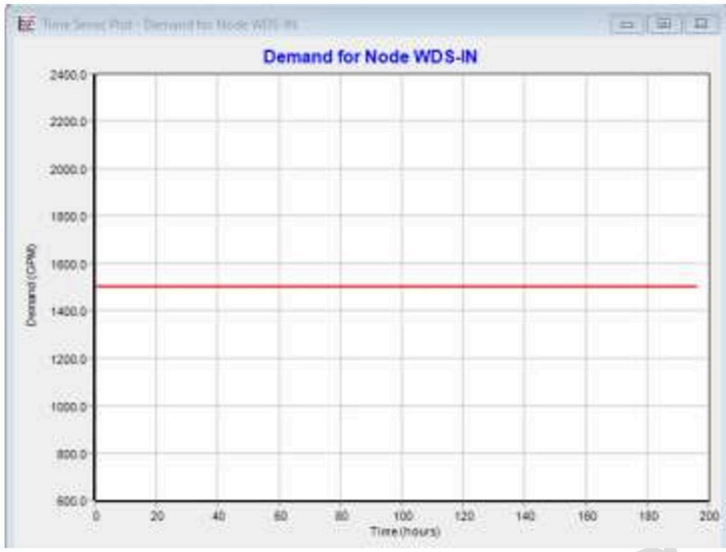

Figure 18. Constant Demand Pattern.

Figure 19 is a plot of the heads in the TSR and ISR tanks.

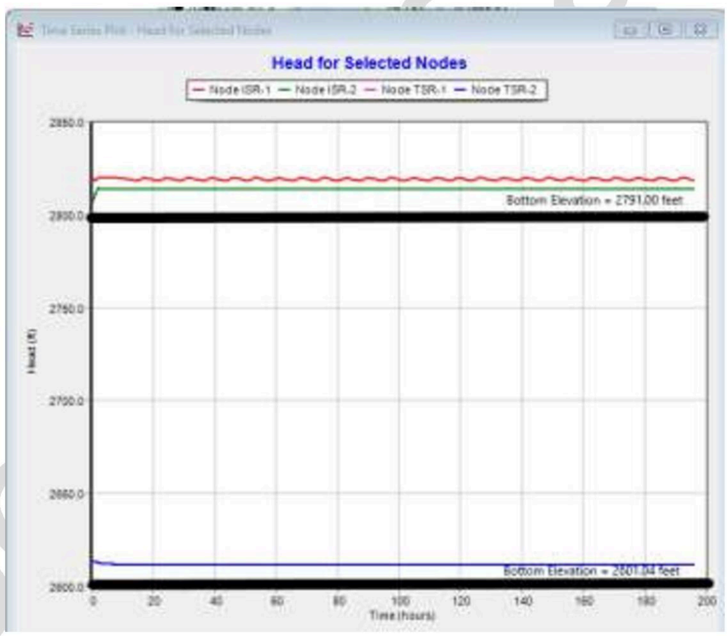

Figure 19. Water surface and base elevations in ISR and TSR tanks.

A plot of the hydraulic grade line (in red) is displayed on Figure 20. The profile grade line is the surface elevation obtained from the QGIS system. The left side of the figure is the TSR location, the drop in HGL at the left edge is located at the Flow Control Valve (FCV), and the sudden rise is the head in the storage tank just downstream of the valve.

Also displayed is system pressures in pounds per square inch. The minimum pressure and maximum pressures are reported in the plot title. In most simulations, the minimum pressure is just downstream of the FCV before entry into the TSR tanks. The rise in pressure (head) at the left side of the plot is the added head from the booster pump station to insert flow into the WDS-IN node.

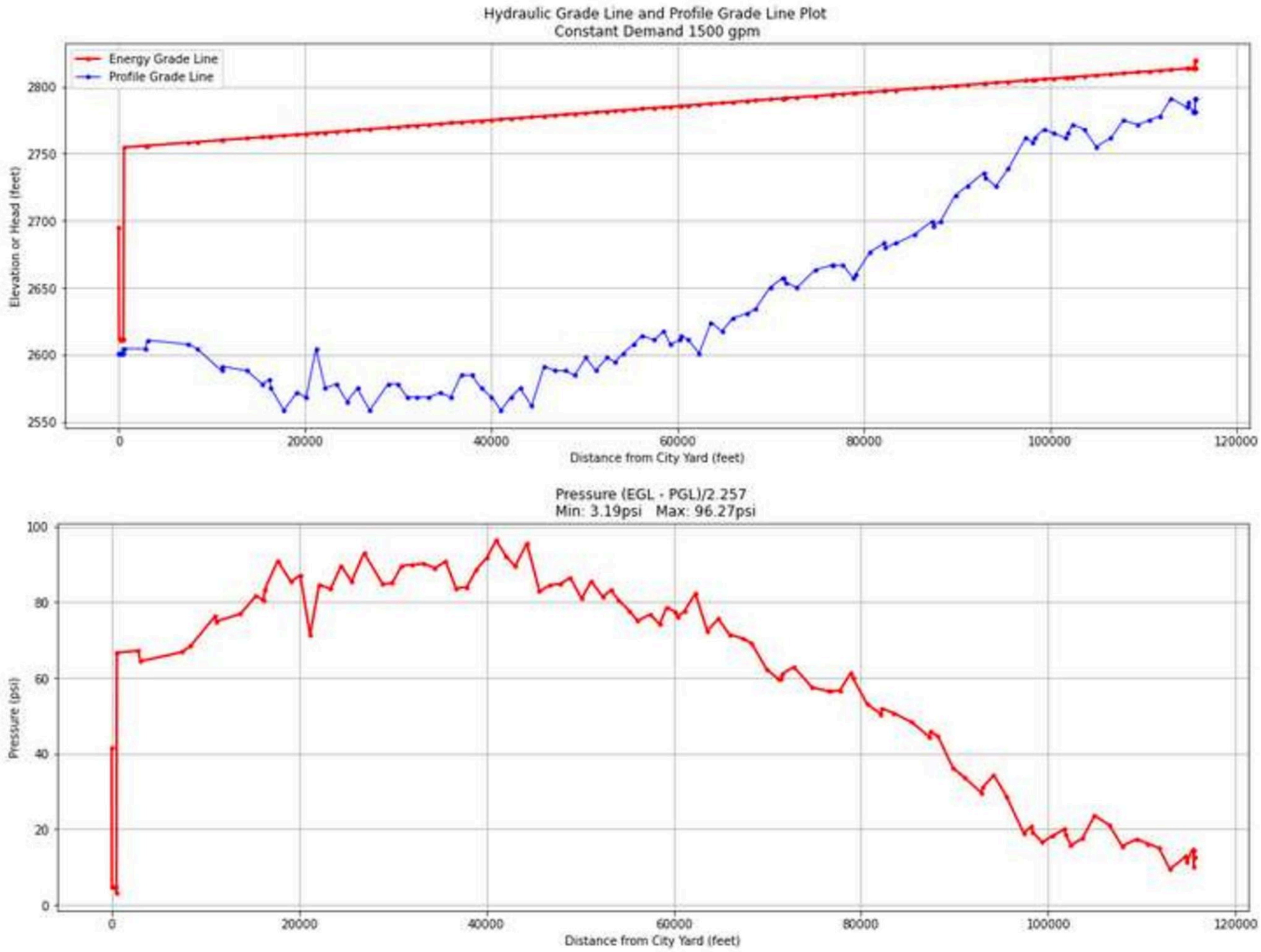

Figure 20. HGL and PGL at 1500 gpm (Sustained)

Step-Change Demand of 210/2100 gpm

Figure 21 is a plot of the system demand as a repeating pattern of 210 to 2100 gpm.

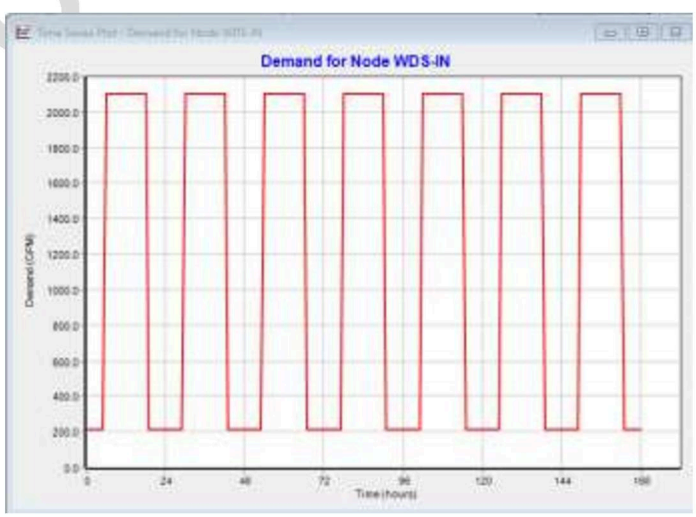

Figure 21. System Demand at Connection to Water Distribution System

The pattern has 12 hours of demand at 210 gpm and 12 hours of demand at 2100 gpm, so it represents a low (but non-zero) flow condition and a high (design flow from wellfield) flow condition. This simulation showed that the ISR tanks function under the simulation conditions as a tandem tank system. The TSR tanks also function in tandem (a desired behavior).

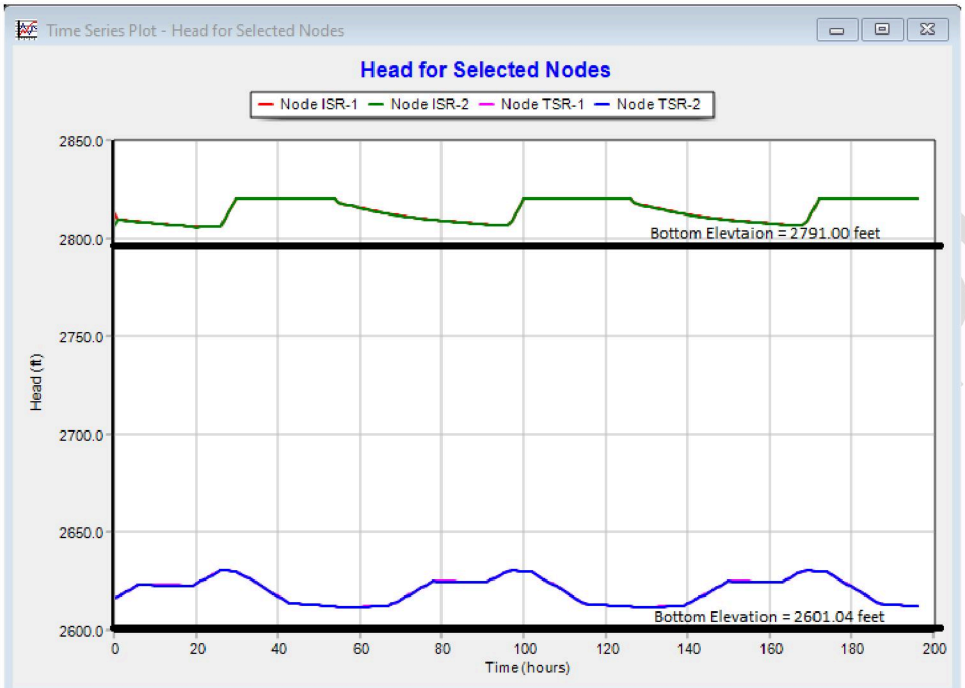

Figure 22. ISR/TSR Storage Tank Elevations.

Figure 22 is an annotated plot of the tank surface elevations, which also depicts the tank bottom elevations. The lowest water depth in the ISR tank pair (somewhere near hour 24 and again at hour 96) is 15.37 feet above the tank bottom. The target minimum depth was 15 feet for ISR_1. The upper trace is the ISR tank pair; the lower trace is the TSR tank pair. The four traces are hard to depict as the ISR and TSR tank pairs plot nearly on top of each other (anticipated for the TSR pair)

Figure 23 is a plot of the HGL and PGL at hour 18 of the simulation (demand 2100 gpm, just before the step change down to 210 gpm)

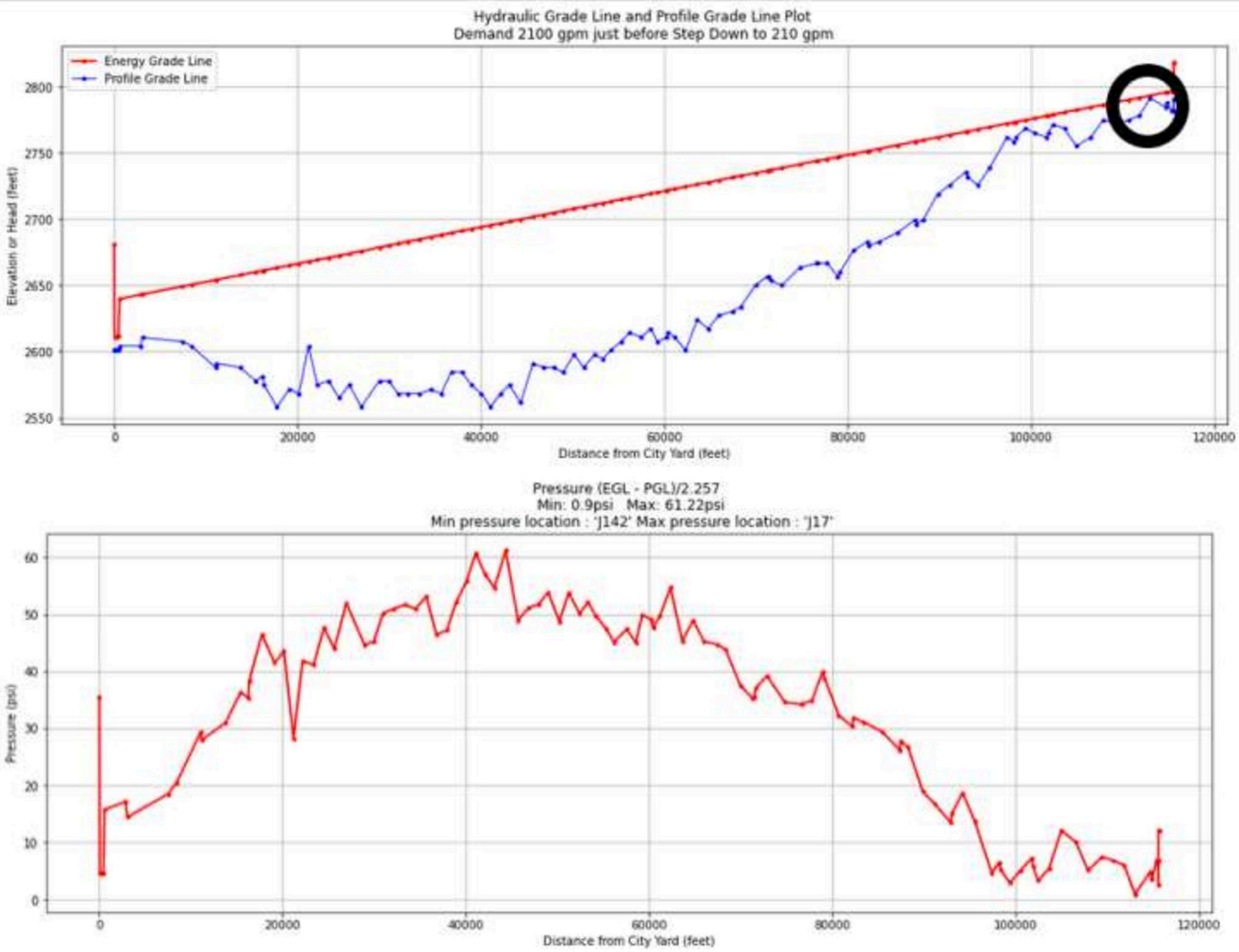

Figure 23. HGL and pressure along pipeline at hour 18 of varying step change scenario.

The black circle identifies the low pressure location a bit downstream of the ISR tanks, the next pair of plots show that the pressure would be negative at this location an hour later.

Figure 24 is a plot of the HGL and PGL at hour 19 of the simulation (demand 210 gpm, just after the step change down from 2100 gpm.)

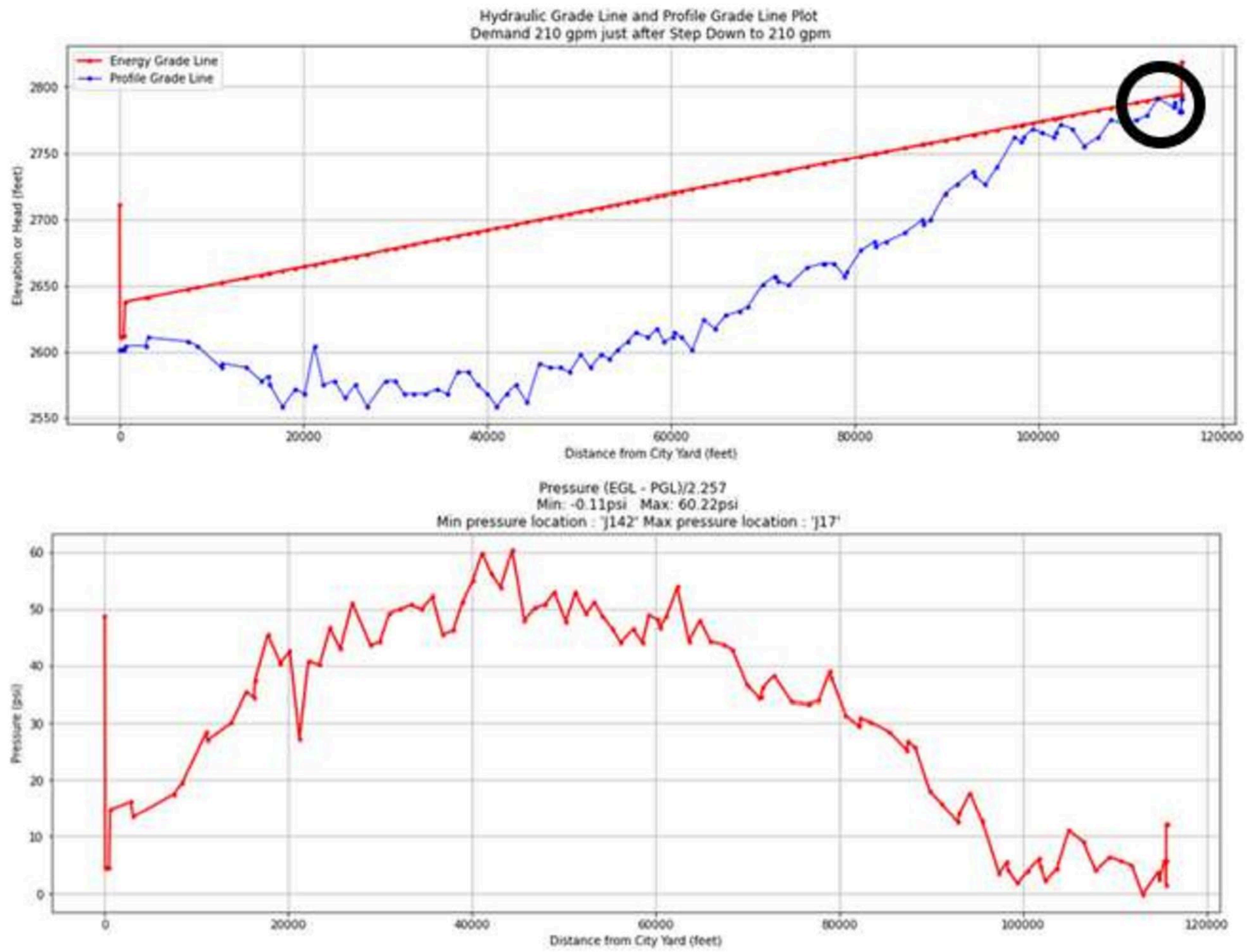

Figure 24. HGL and pressure along pipeline at hour 19 varying step change demand scenario

Indeed the pressure is negative (but recovers in an hour). The next two pairs of plots show the behavior when demand increases from 210 gpm to 2100 gpm. The simulation is allowed to continue (with negative pressure) and the pressure recovers after the low value that occurs after every instance of the step change down from 2100 gpm.[7]

Figure 25 is a plot of the HGL and PGL at hour 29 of the simulation (demand 210 gpm, just before the step change to 2100 gpm). The pipeline has recovered pressures to positive values (as anticipated at the lower demand).

[7] The step-change itself is not the cause, but rather the 2100 gpm supply for 12 hours, and the tank control rules. The modeler assumed that continuous operation of the wellfield is undesirable (if not impossible over long enough time), but that there would be a start/stop operation scheme, with the substantial tankage supplying raw water during the wellfield idle periods.

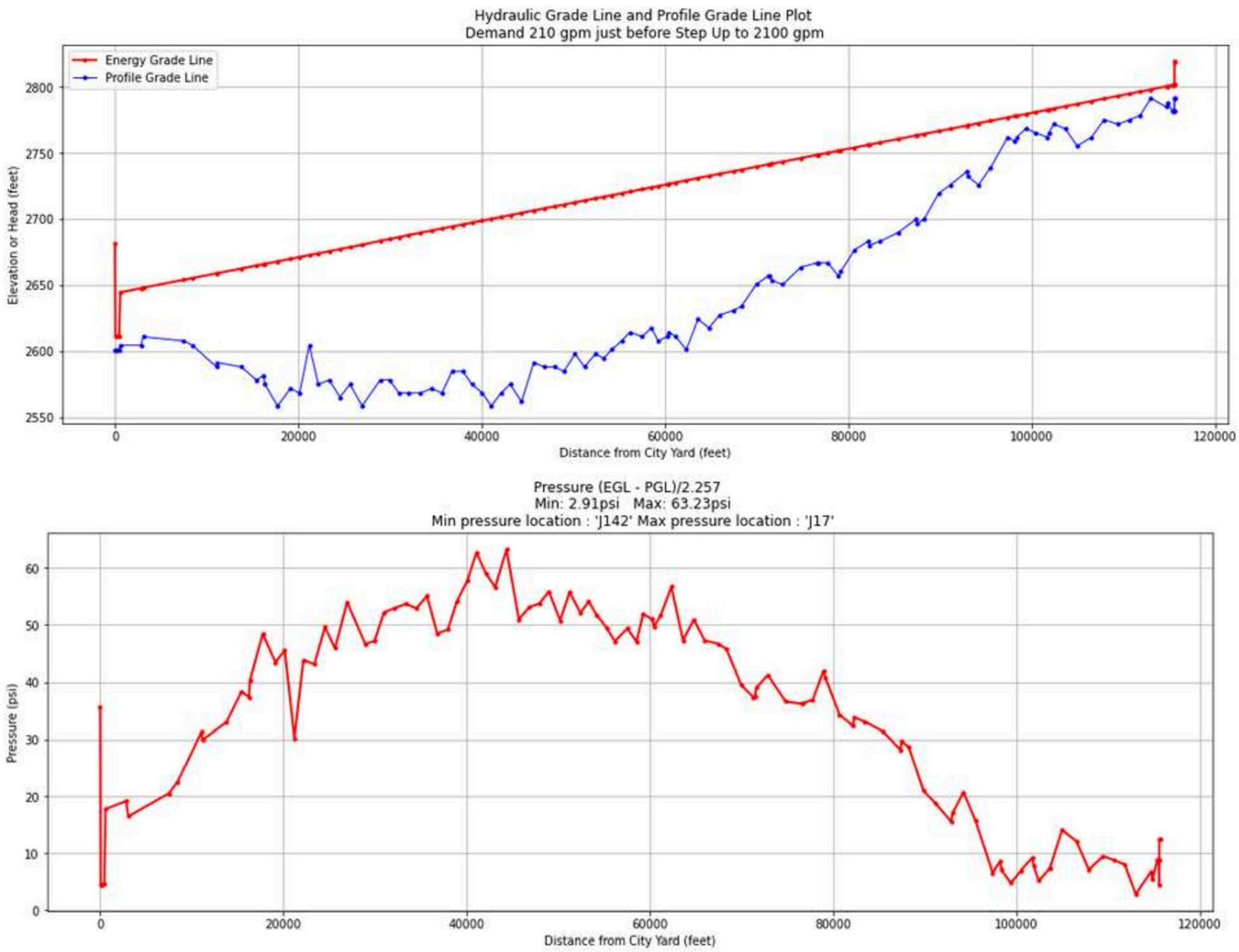

Figure 25. HGL and pressure plot along pipeline at hour 29 of varying step change scenario

Figure 26 is a plot of the HGL and PGL at hour 30 of the simulation (demand 2100 gpm, just after the step change to 2100 gpm)

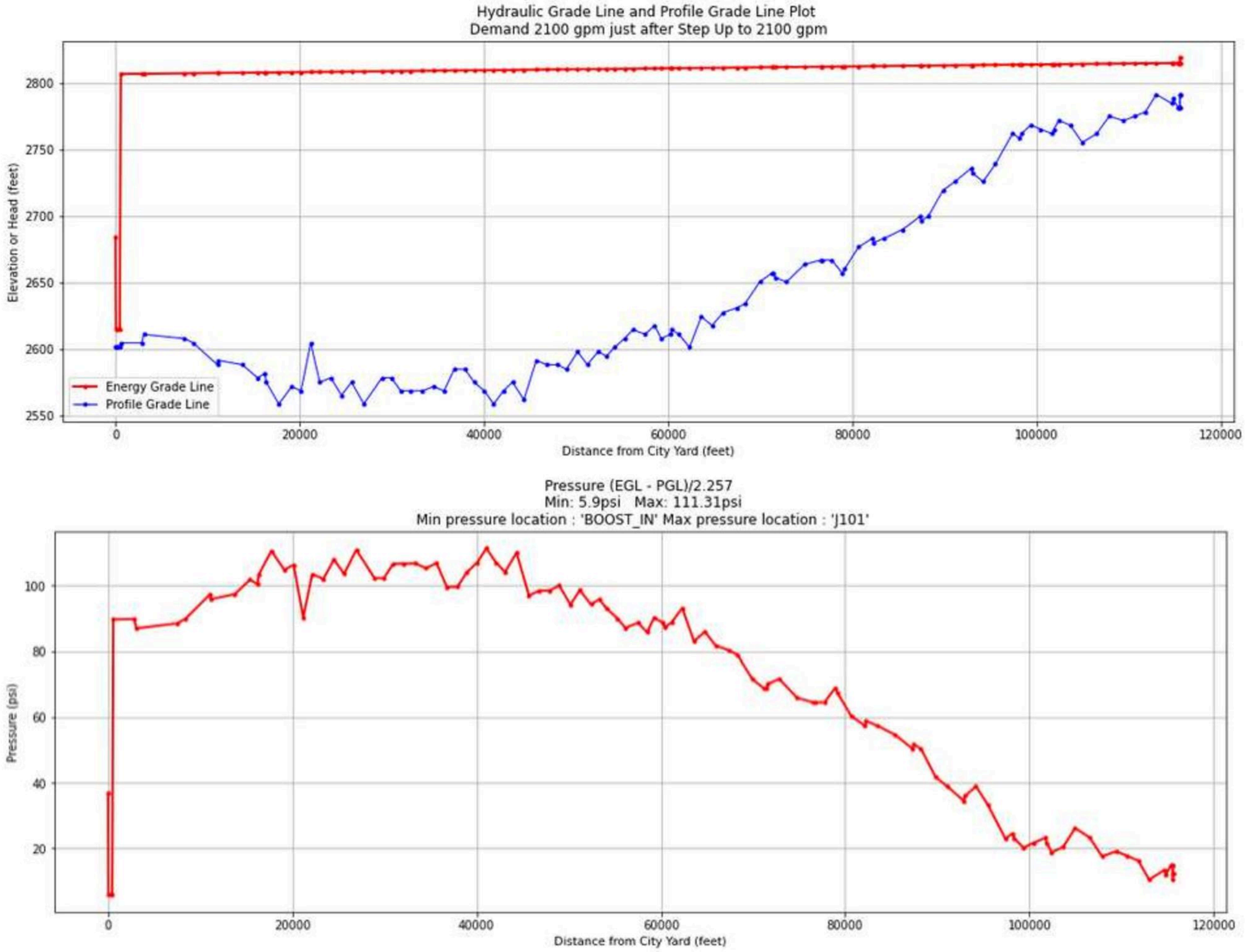

Figure 26. HGL and pressure plot along pipeline at hour 30 of varying step change scenario.

These three profiles provide useful guidance of where in the system minimum and maximum pressures are located. The last profile illustrates that when demand steps up, the system draws from the storage tanks before pipeline flow begins to resupply the tanks (evidence is the low HGL slope). At the end of this demand cycle the profiles should look like the first pair just before demand steps down again. The depicted behavior repeats on a 24-hour cycle. The simulations were run for over 180 hours to identify numerical instability.

Figure 27 is a screen capture from a GIS mapping of the system showing the location of the low pressure in the pipeline system. The location is at Node 141 and 142 of the model. [8]

A reasonable mitigation for the low pressure is to run the pipeline in these locations deeper (deeper trenching) to address the low pressure. A subsequent model was adjusted so that node J142 is 10 feet lower, and J141 is 6 feet lower.

[8] Approximate location is 103.37 degrees West, 31.15 degrees North.

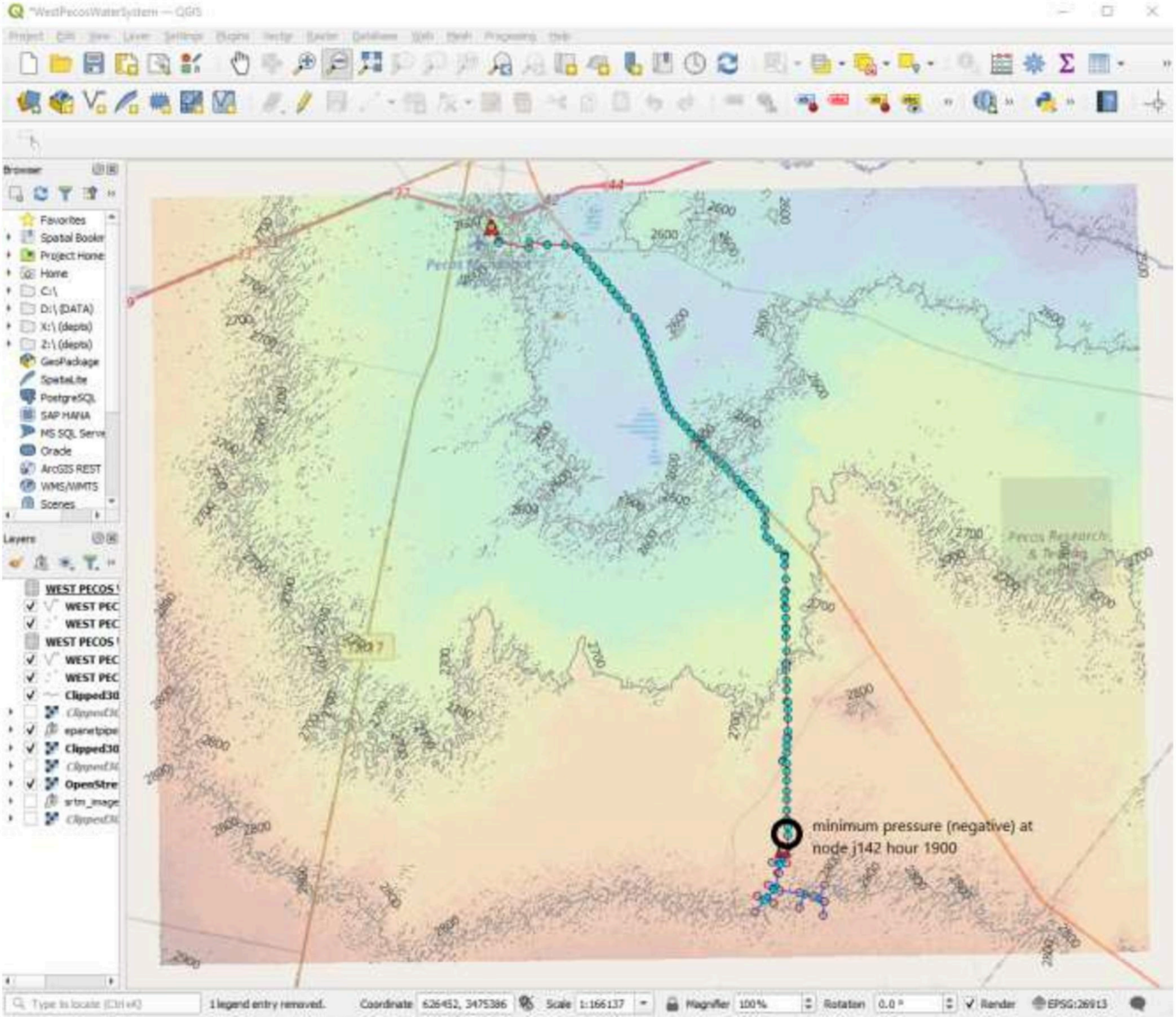

Figure 27. Location of low pressure in pipeline simulation.

Step-Change Demand of 210/2100 gpm (Nodes J141 and J142 lowered – deeper trench)

Figure 28 is a plot of the HGL and PGL at hour 19 of the simulation (demand 210 gpm, just after the step change down from 2100 gpm.) with the two nodes adjusted lowered (representing deeper trenching).

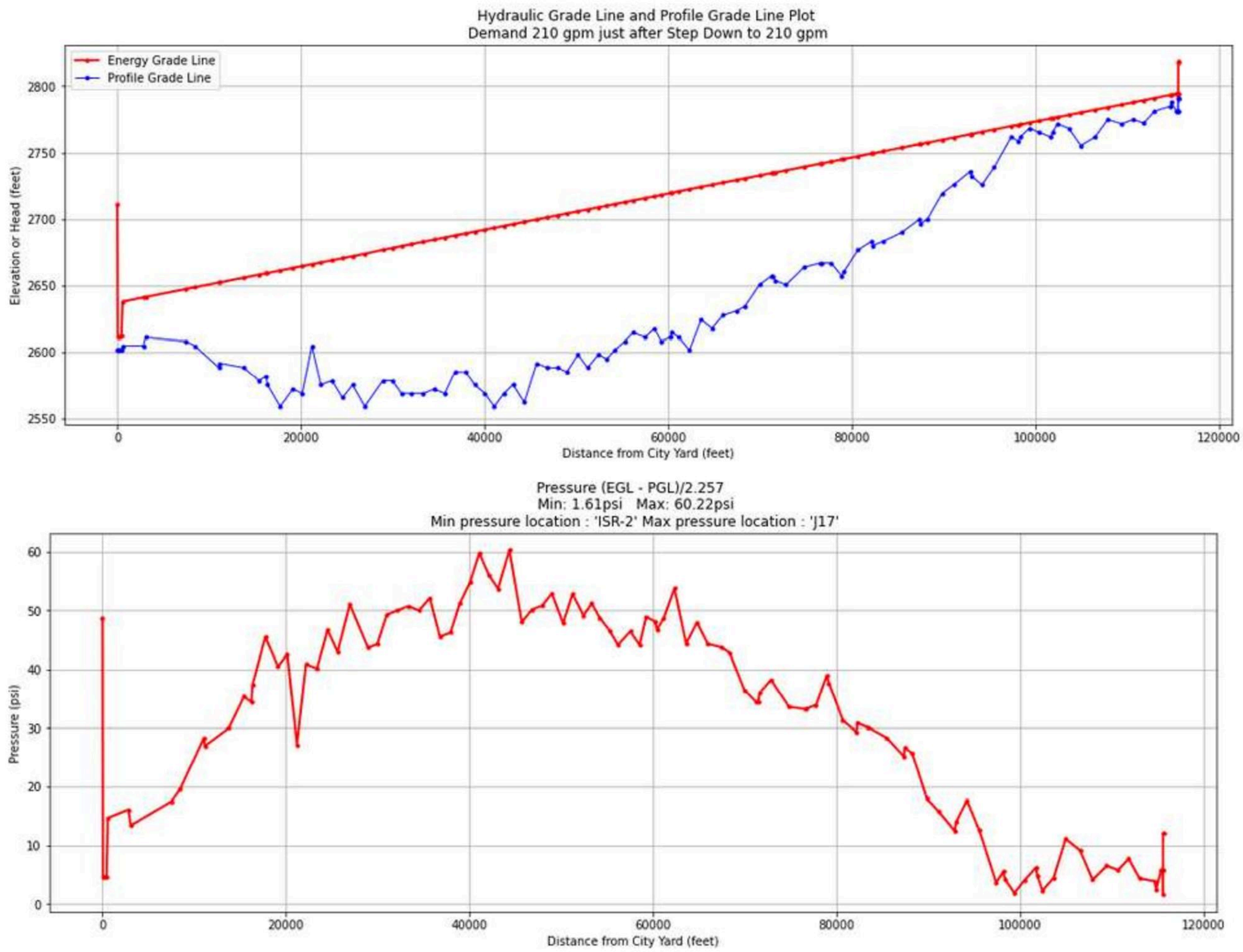

Figure 28. HGL and pressure plot along pipeline at hour 19 of varying step change scenario

After examination of this simulation nodes J36, J37,J39,J40,J134,J135,J138,J139, and J140 were lowered between 5 and 6 feet deeper than originally anticipated. The result of that change is shown in Figure 29 below.

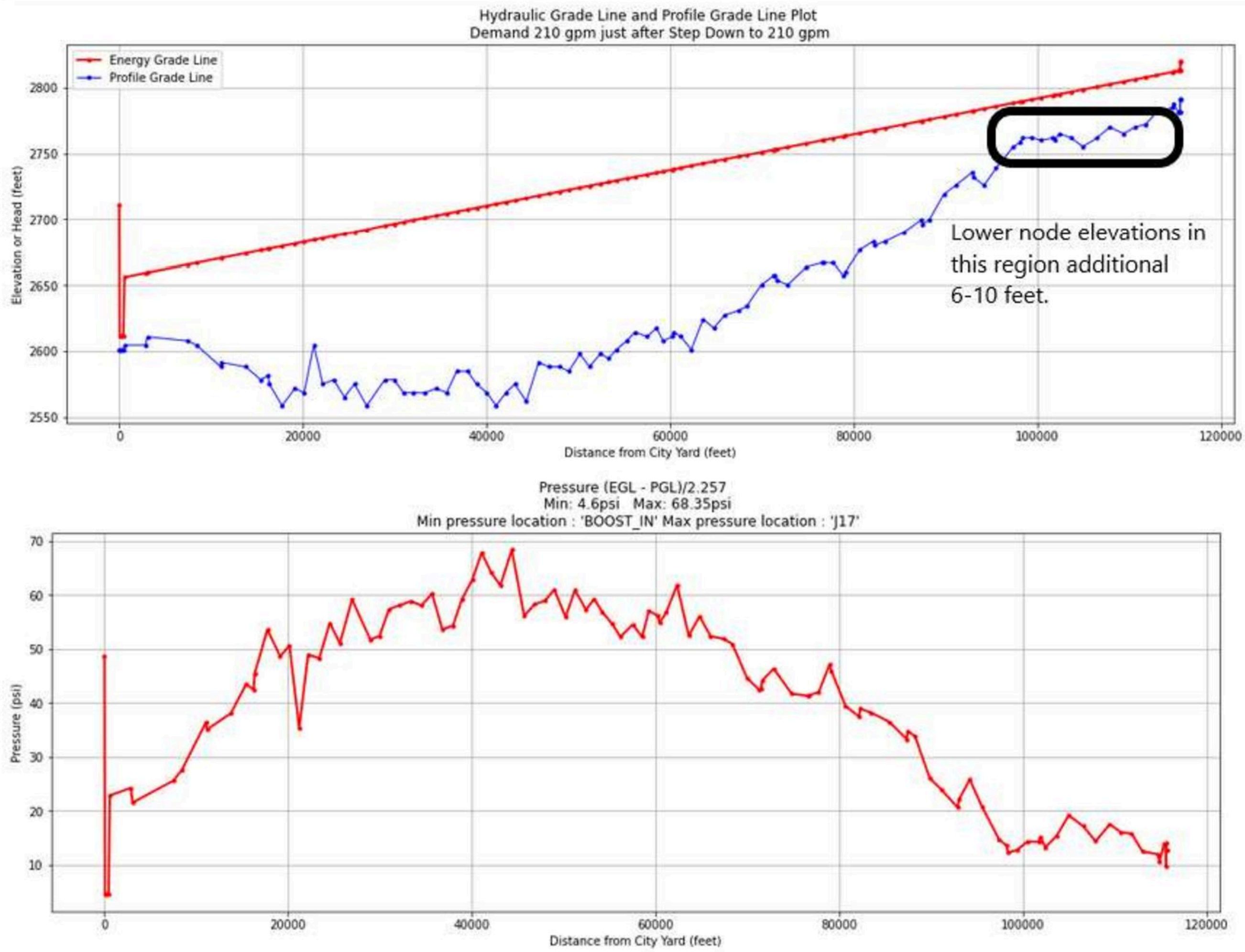

Figure 29. HGL and pressure plot along pipeline at hour 19 of varying step change scenario

After these changes, the minimum pressure occurs in the BOOST_IN node that boosts water into the existing water distribution system. This location is downstream of the TSR tank pair, which is a reasonable (and accessible location for the minimum).

Water Age for Step-Change Demand of 210/2100 gpm (Node modifications implemented)

Water age is a useful by-product of the simulation model; in these scenarios a tracer is assumed at all supply reservoirs (the wellfield) and the software reports average age at a node based on evolution of the tracer.

The greatest water age (magnitude and spatial distribution) in the system occurs at 176 hours of simulation is reported as 41.5 hours in TSR_2. Figure 30 is a plan view map with color coding to indicate water age in the different parts of the system. Magenta is the "oldest" water; Red is the "youngest." The red reservoirs in the wellfield represent water in the aquifer itself (by default age is zero).

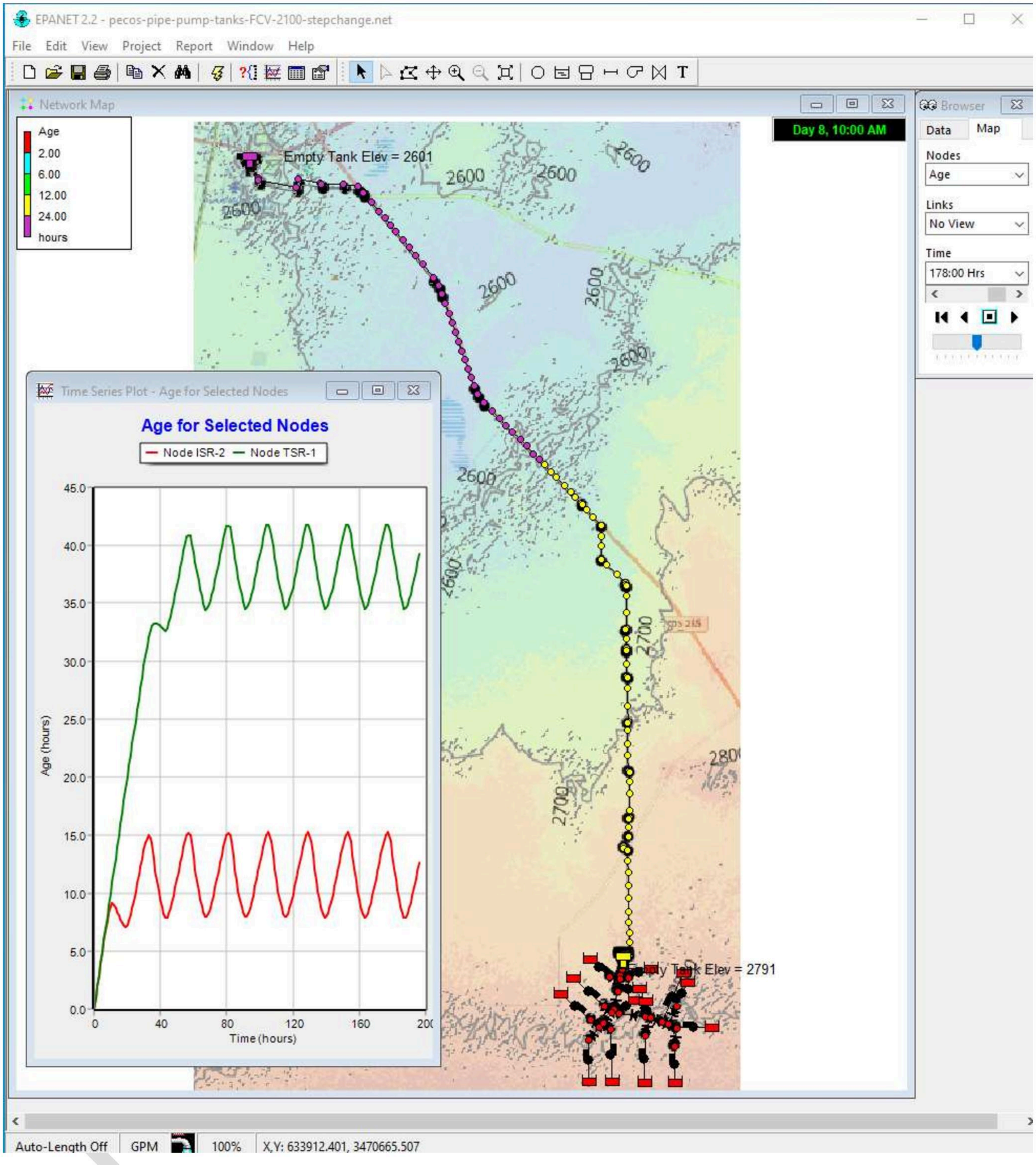

Figure 30. Water age in system at ISR tanks and TSR tanks.

Repeating Hourly Variation Demand

This scenario uses the repeating hourly pattern described above. The pattern has two peak demand times one at 0800 and another at 1900. These are intended to represent morning peak demand and evening peak demand. This particular pattern is used with a low base demand (300 gpm) and the pattern adjusts each hour as dictated by the pattern.

The control rules are unchanged; there is a flow control valve to throttle flow into the TSR tank pair (controls the pipeline) and a flow control valve to throttle flow into ISR_2 to keep it from emptying. The wellfield is controlled by ISR_1 (the sand-trap tank) water levels.

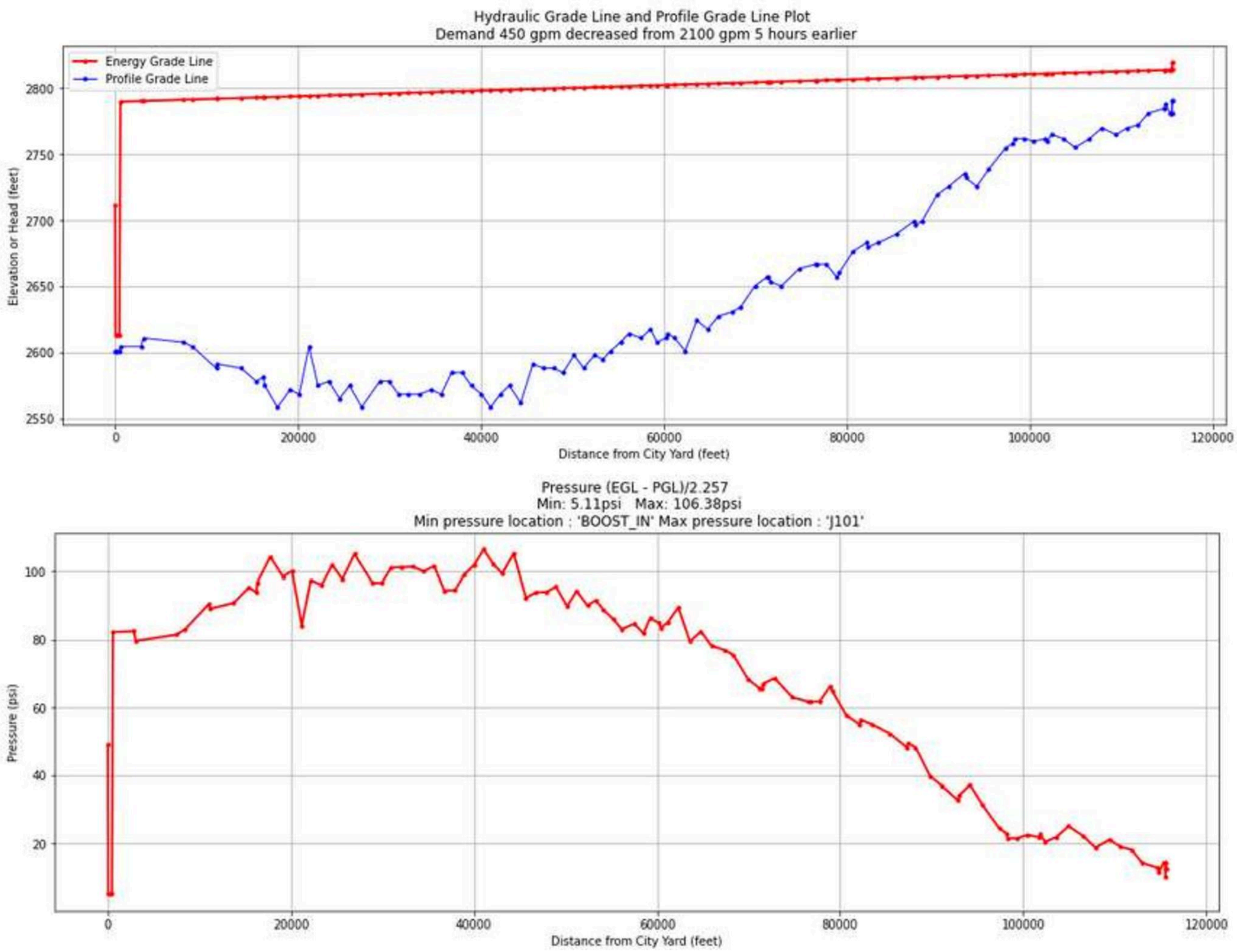

Figure 31. HGL and pressures at hour 36 of diurnal scenario

Figure 31 is the profile plots at hour 36 of the simulation which is the maximum pressure situation.

Figure 32 shows the pressure variation at the J101 node. The pressure ranges from 94 to about 109 psi and repeats every 24 hours. The cause of the peak is the control valve throttling flow into TSR_2. This modeled value of peak pressure under periodic conditions is below the nominal pressure rating for the HDPE pipe (DR 13.5). The pressure is also below the surge and cyclic maxima pressures as recommended by AWWA C906.

Figure 33 shows the flow through the flow control valve at TSR_2 the peak pressures are directly related to the drop in flow in the flow control valve (to keep from tank overfilling).

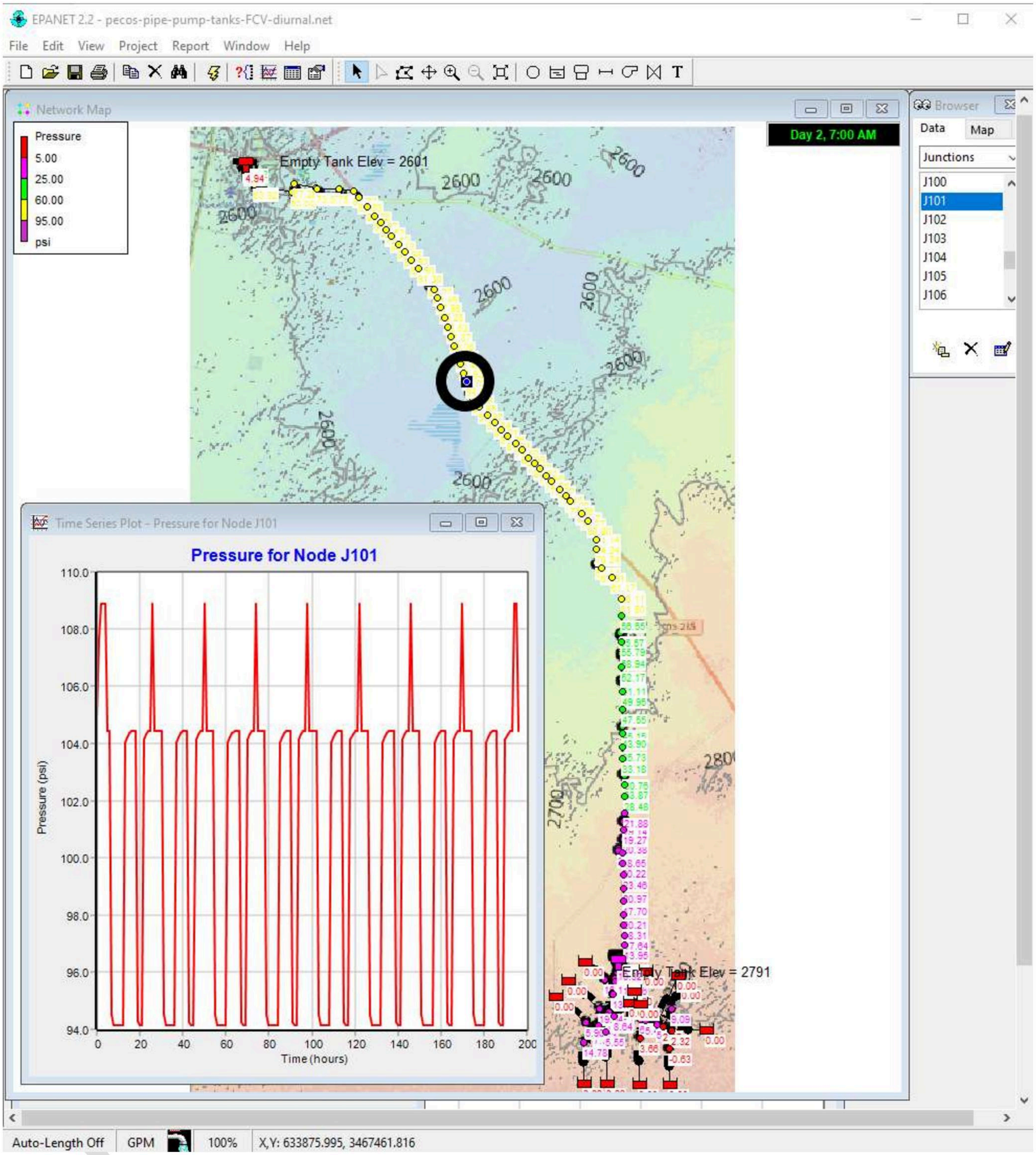

Figure 32. Pressure variation at Node J101

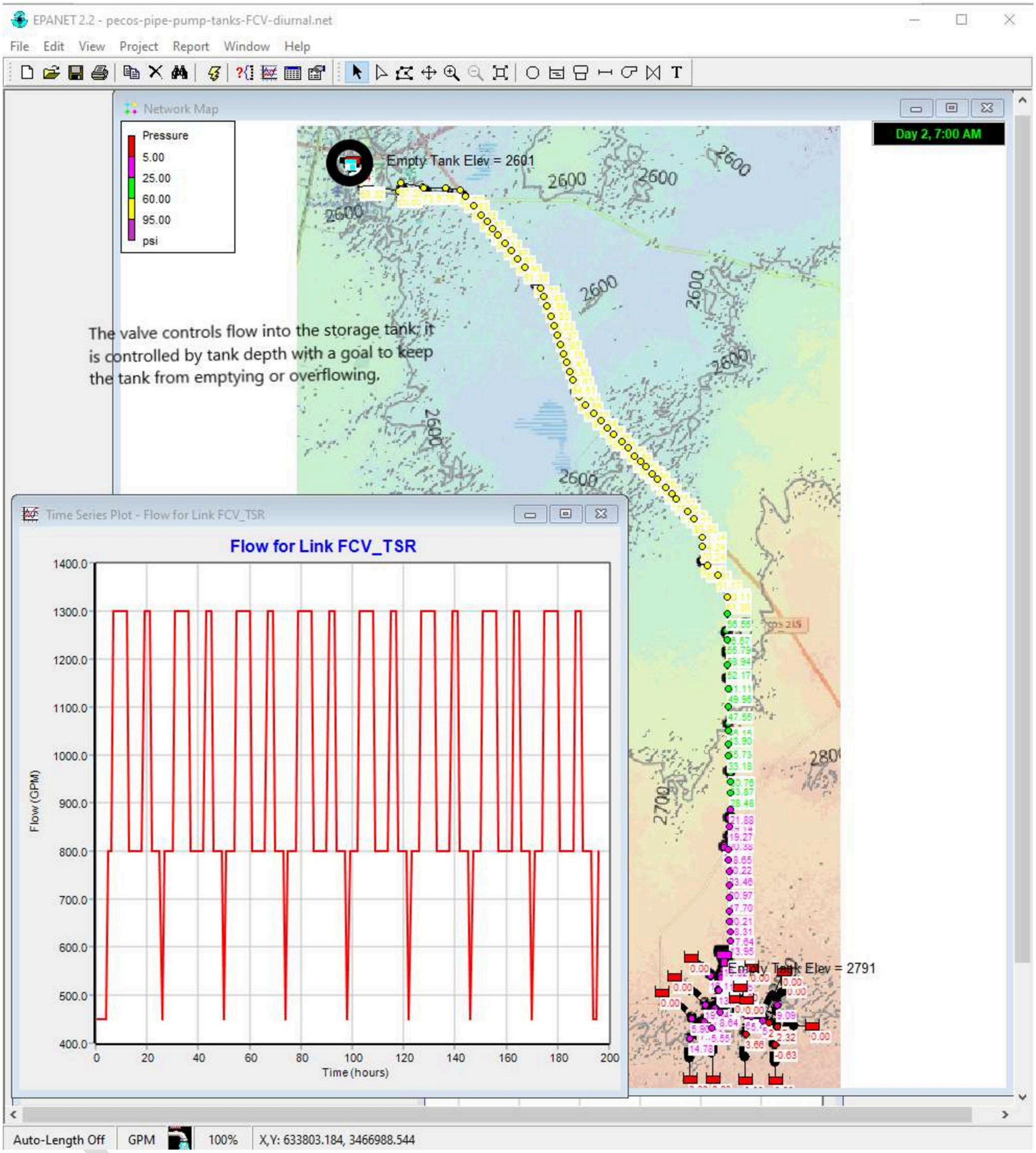

Figure 33. Flow variation in Flow Control Valve into TSR Tank Pair (pipeline control)

Water Age for Repeating Daily Demand Scenario (Node modifications implemented)

The greatest water age (magnitude and spatial distribution) in the system occurs at 80 hours of simulation is reported as 53.5 hours in TSR_2. Figure 30 is a plan view map with color coding to indicate water age in the different parts of the system. Magenta is the "oldest" water; Red is the "youngest." The red reservoirs in the wellfield represent water in the aquifer itself (by default age is zero).

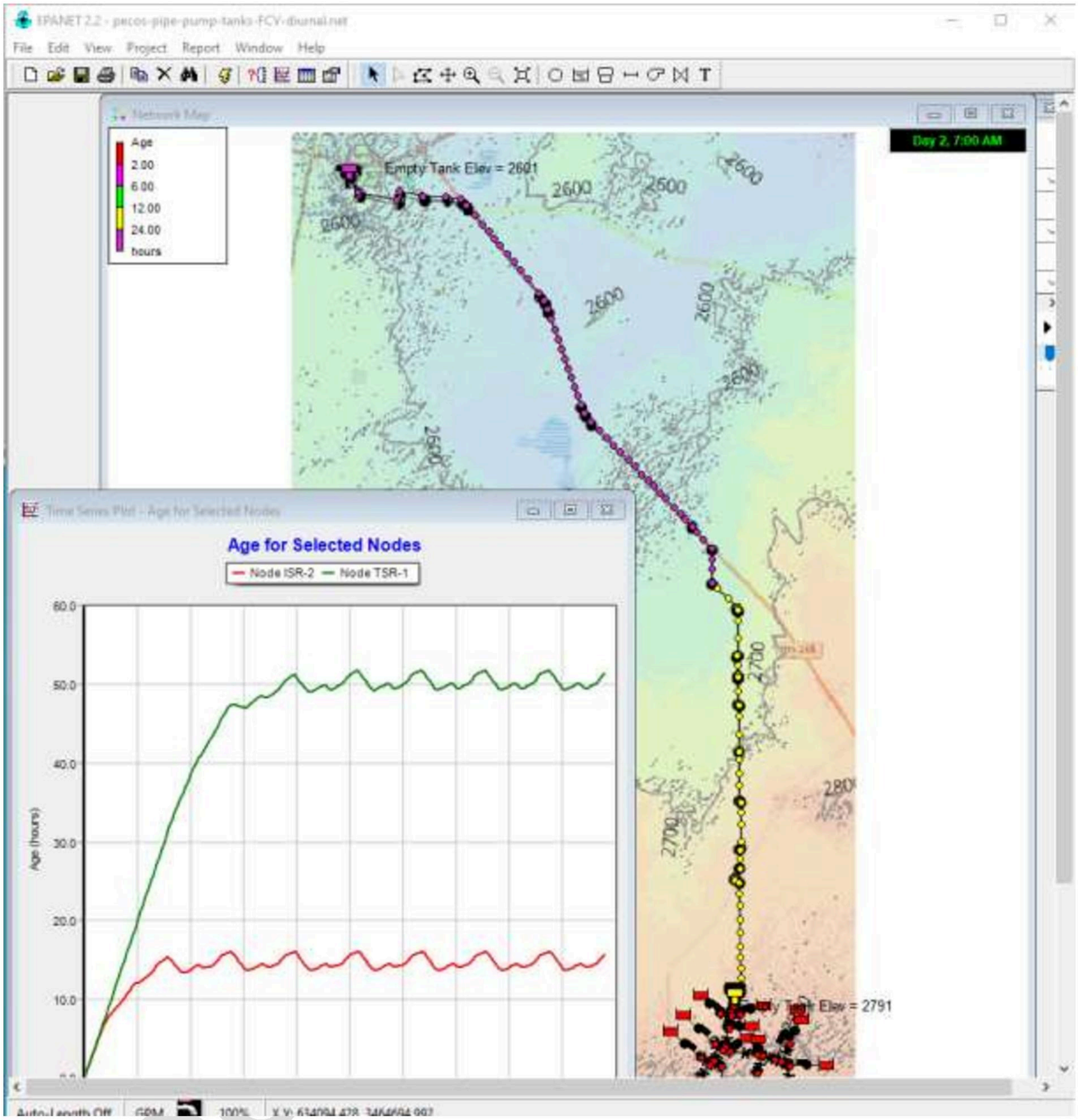

Figure 34. Water Age in ISR and TSR tank pairs.

The difference in age suggests a pipeline mean travel time of about 35 hours, which corresponds to an average velocity of almost 1 foot/second. The peak velocity in these simulations (daily varying) was 1.8 ft/sec, the lowest was 0.6 ft/sec. The computed average velocity was 1.3 ft/sec. The difference demonstrates that the storage elements are substantial contributors to system behavior.

Water Hammer Analysis

A simplified water hammer analysis was performed on the pipeline to estimate valve closure speeds. A manual analysis using guidance in Gupta (1989) resulted in estimated pressure changes in the table below.

The following material parameters were used:

ID = 18 inches (~ DR 13.5 20" OD specification)
ε= 1.481 inches (wall thickness for 20" DR 13.5)
E = 0.5 GPa for HDPE
ν = 0.45 (Poisson's ratio for HDPE)

Pressure Wave Travel Time (seconds)	Celerity (feet/sec)	Valve Closure Time (Seconds)	Maximum Pressure Change (psi)	Remarks
62.6	1854	~0	73.16	"Fast" closure equation
62.6	1854	120	38.2	"Very Slow" closure equation, at minimum closure time for elastic theory to apply

A numerical simulator model was used to explore different valve closure times using HDPE material properties; the manual calculations were used to guide simulation parameters, with the inclusion of friction terms.

Case 1. 0-second shutoff, frictionless pipe

This case assumes a sudden shutdown, the valve pressure ranges from -11 psi to 75 psi using the material properties for DR-13.5 HDPE, roughly in agreement with the "Fast" closure results above. The pressure wave travel time is on the order of 300 seconds to traverse the 21 mile pipeline.

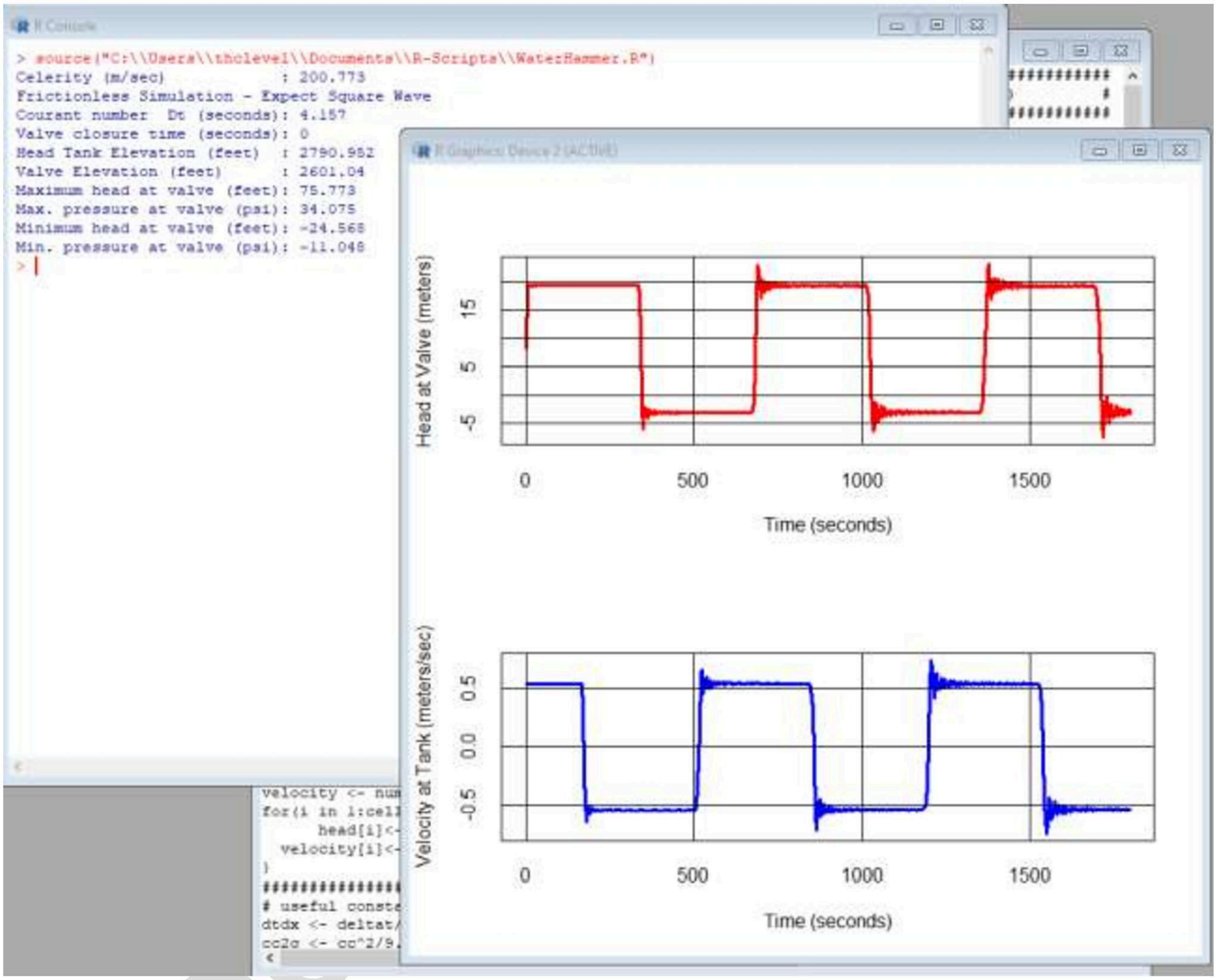

Figure 35. Water Hammer; 0-second shutdown; no damping

Case 2. 63-second shutoff, frictionless

This case assumes a linear shutdown over 63-seconds (about the time of the computed wave speed as per elastic theory) , the valve pressure ranges from -4 psi to 64 psi using the material properties for DR-13.5 HDPE.

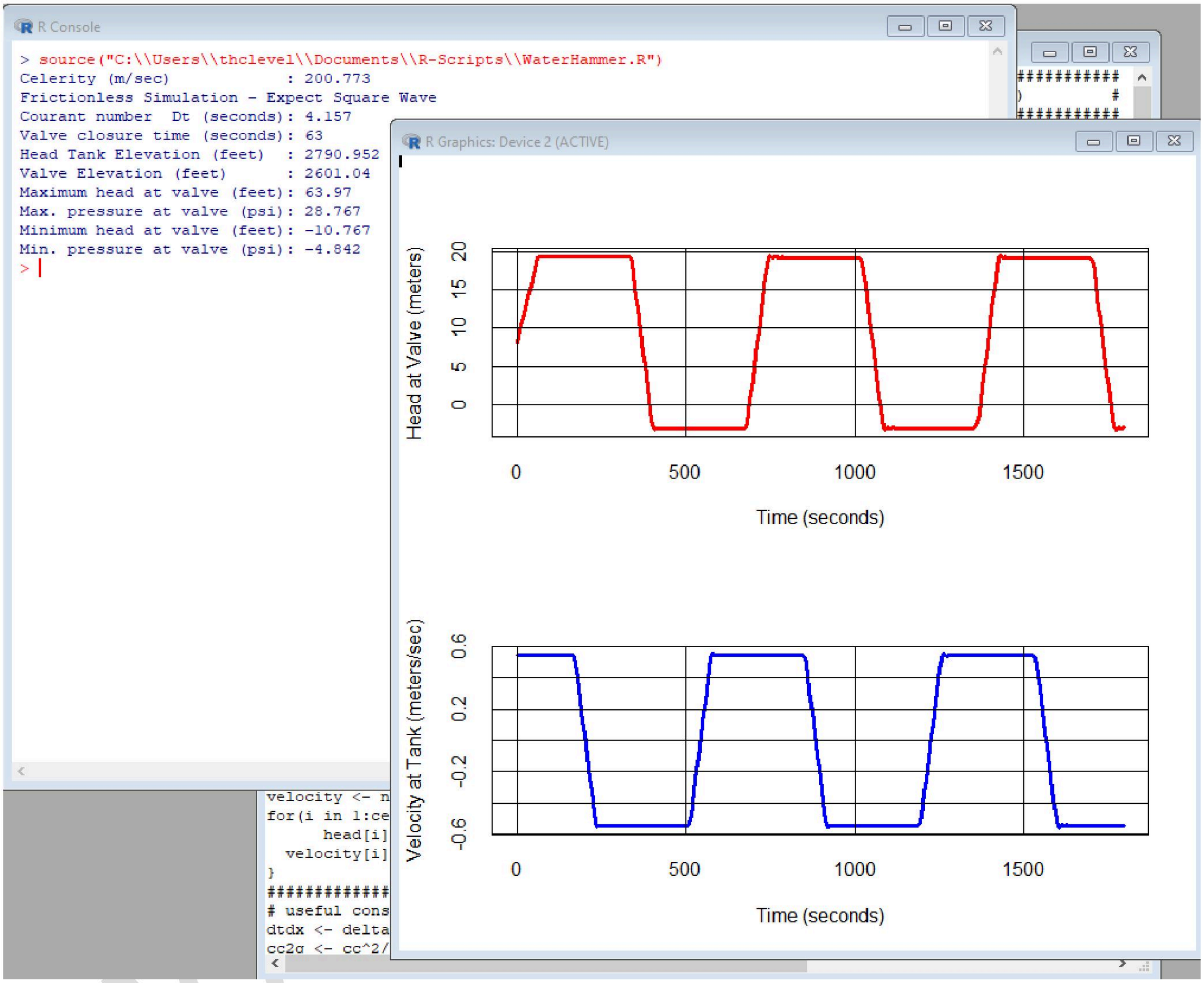

Figure 36. Water Hammer; 63-second shutdown; frictionless

Case 3. 63-second shutoff, smooth pipe friction factor

This case assumes a linear shutdown over 63 seconds with a smooth pipe friction factor for a Reynolds number of 50,000. The valve pressure ranges from 7.5 psi to 23 psi using the material properties for DR-17 HDPE. The pressure wave travel time is on the order of 250 seconds to traverse the 21 mile pipeline; the wave is damped by friction considerably.

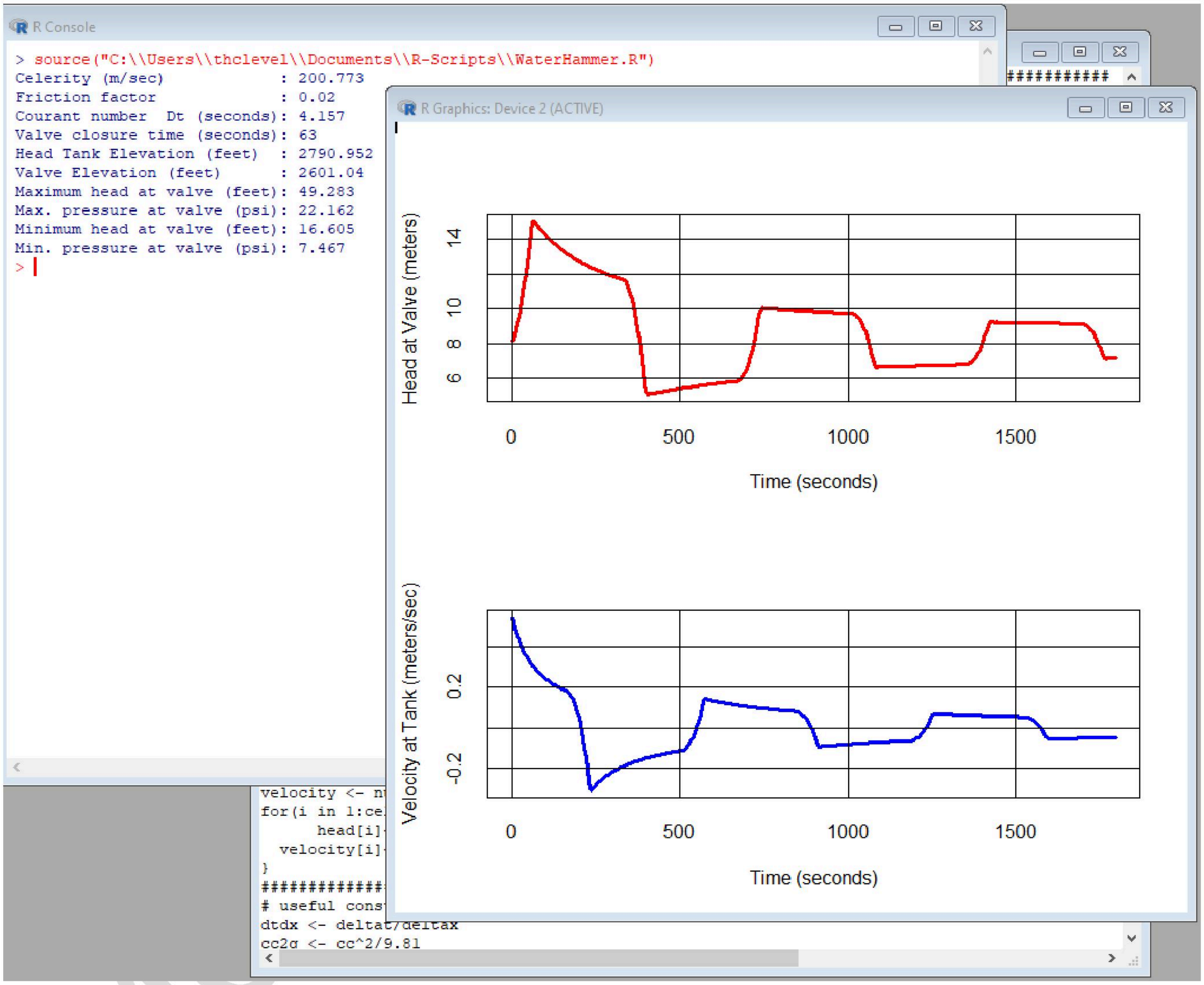

Figure 37. Water Hammer; 63-second shutdown; frictional damping

Case 4. 130-second shutoff, smooth pipe friction factor

This case assumes a linear shutdown over 130 seconds, roughly the recommended speed for elastic wave theory to be applied., the valve pressure ranges from 8 psi to 43 psi using the material properties for DR-17 HDPE. The pressure wave is damped by friction (as expected) and the peak pressures are reduced by the longer closure time.

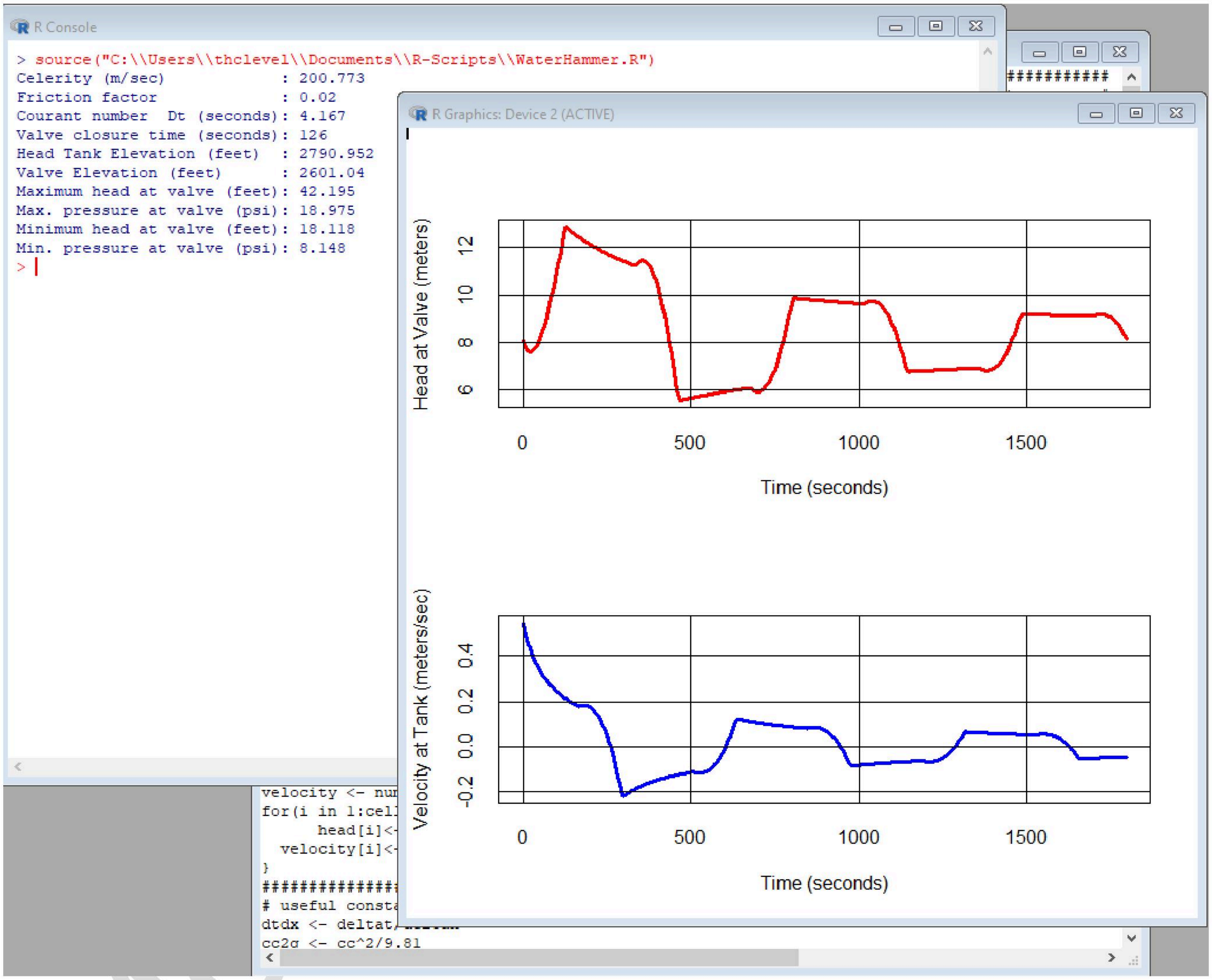

Figure 38. Water Hammer; 130-second shutdown; frictional damping

Case 5. 130-second shutoff, smooth pipe friction factor

This case assumes a linear shutdown over 130 seconds, roughly the recommended speed for elastic wave theory to be applied., the valve pressure ranges from 8 psi to 53 psi using the material properties for DR-17 HDPE, in this case the upper bound of pipe Elasticity is applied (1.45 GPa) which is a value approaching mild steel (hence a stiffer pipe). The effect of a stiffer pipe is apparent in the reduced travel times (as compared to the previous trace).

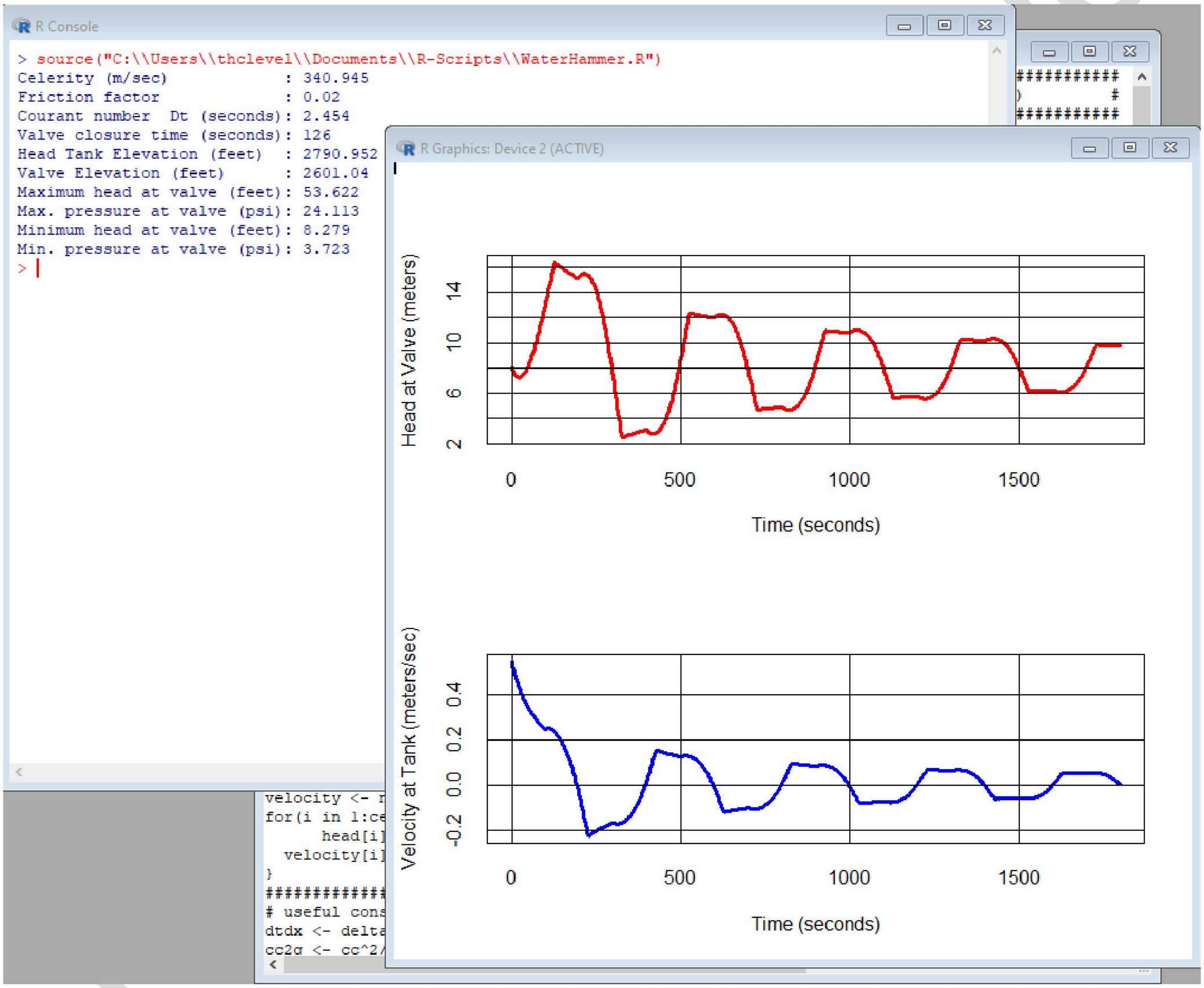

Figure 39. Water Hammer; 130-second shutdown; frictional damping (stiff plastic)

These results collectively suggest that the pipeline can withstand velocity changes induced by the flow control valves. In all the cases the expected pressure change is less than the nominal pressure rating of the pipe.[9]

[9] If there is a sudden closure (unlikely) at the peak pressure condition (at node J101) the combined pressure would be on the order of 185 psi. This value is above the nominal pressure rating, but is below the cyclic pressure guidance in AWWA C906 for repeated surge as well as below the pressure for an occasional surge.

Conclusions

The hydraulic system simulated contains two flow control valves (FCV); one at the intermediate storage tanks (adjacent to the wellfield) and another at the terminal storage tanks (adjacent to the booster pumps into the existing system). Modeling indicated that a portion of the pipeline will benefit from deeper trenching in the portion near the upstream ISR tanks (wellfield end of the pipeline), the increased depths seem within the structural capability of HDPE (20" pipe can be buried 16-53 feet below grade depending on backfill; the deeper number is for compacted backfill). These locations are detailed in Figure 40 below.

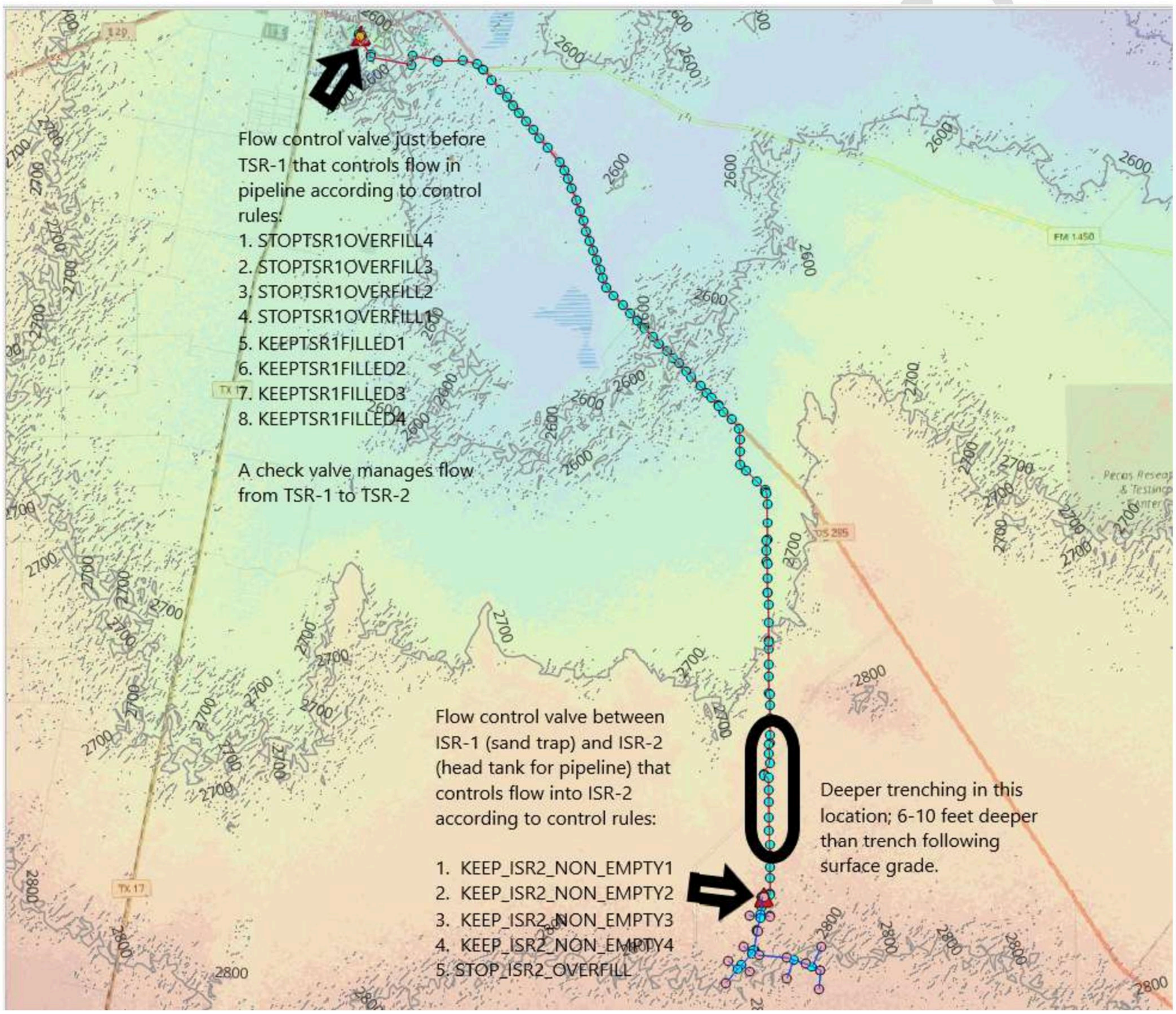

Figure 40. Locations of Flow Control Valves, and region where pipeline should be 6-10 feet deeper to adjust vertical curvature enough to manage low-pressure region.

These simulations indicate that the pipeline will experience operational pressure variations between 5 psi and 110 psi depending on location. The low pressures occur after sustained delivery at the highest nominal (design) discharges; high pressures occur predictably at the topographic low points when discharge is being throttled because the downstream tanks are approaching full.

Figure 41 is a profile (elevation) plot with potential air relief valves (blue) located at local elevation maxima. Annotations on the figure identify specific locations where valves are redundant.

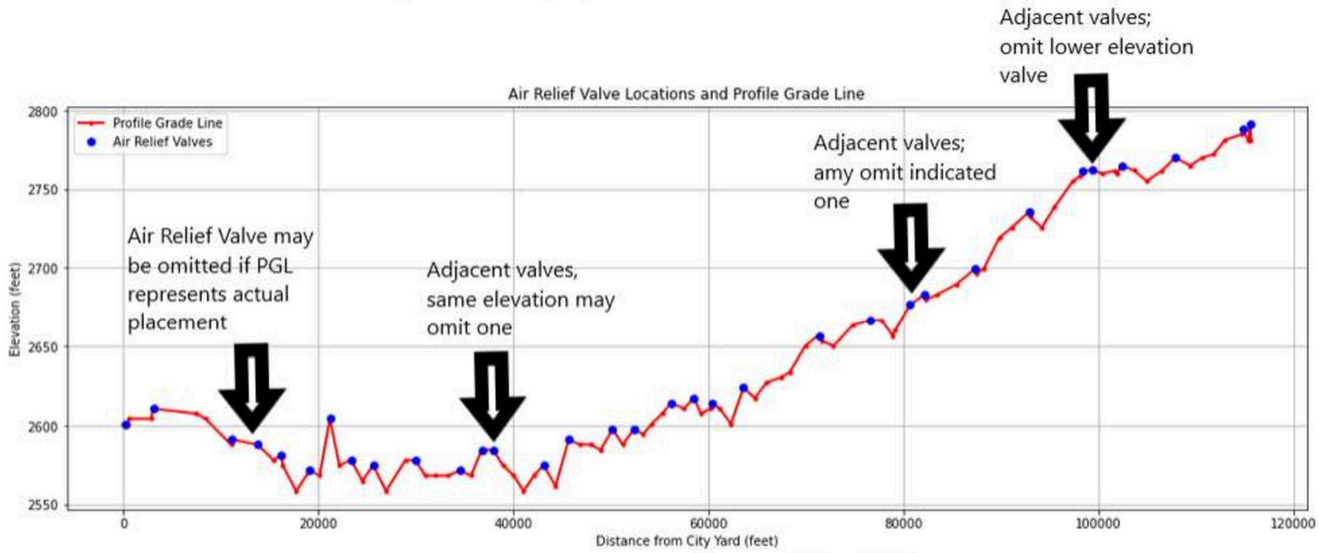

Figure 41. Profile grade line and suggested air relief valve locations.

Figures 42-48 indicate locations on the plan-view base map for air relief valves (to let vapor out of the system) based on the profile above. The quantity depicted (31 air release valves) are based on the alignment and localized topographic highs and lows. A valve at J89 is likely necessary as it is a local high point in the system.

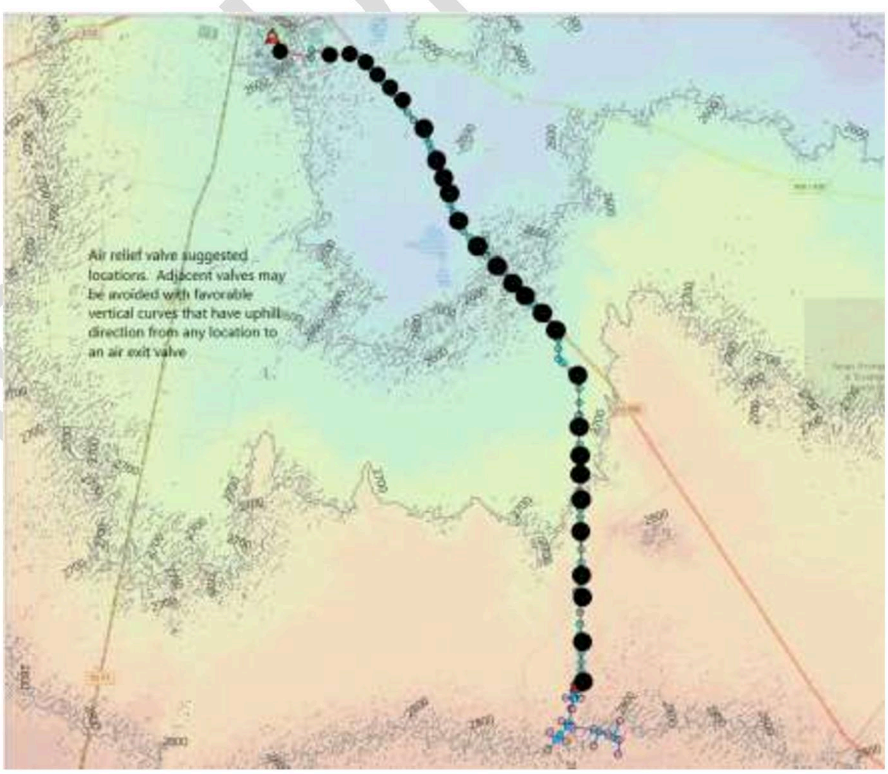

Figure 42. Air Relief Valve Locations (over view). Detail in following figures.

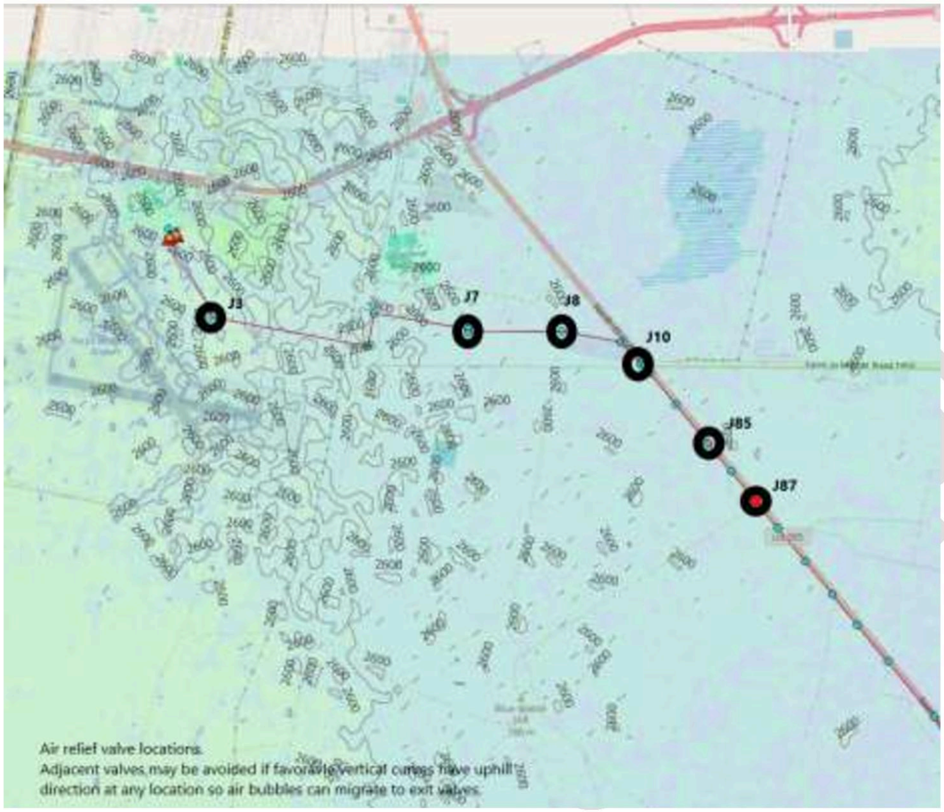

Figure 43. Air Relief Valve Locations (Panel 1 of 6)

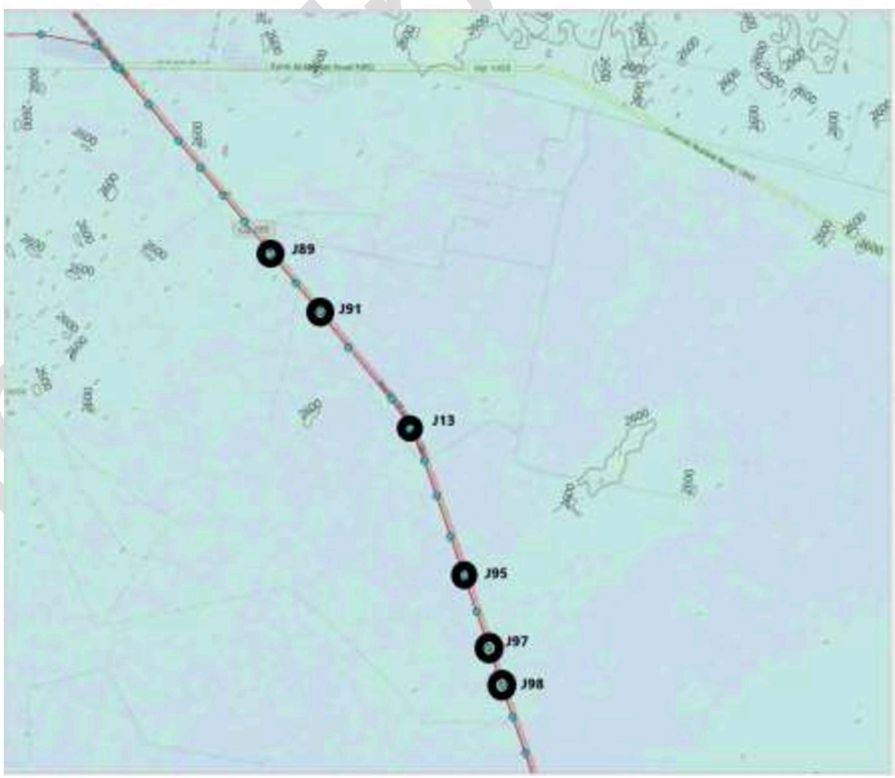

Figure 44. Air Relief Valve Locations (Panel 2 of 6)

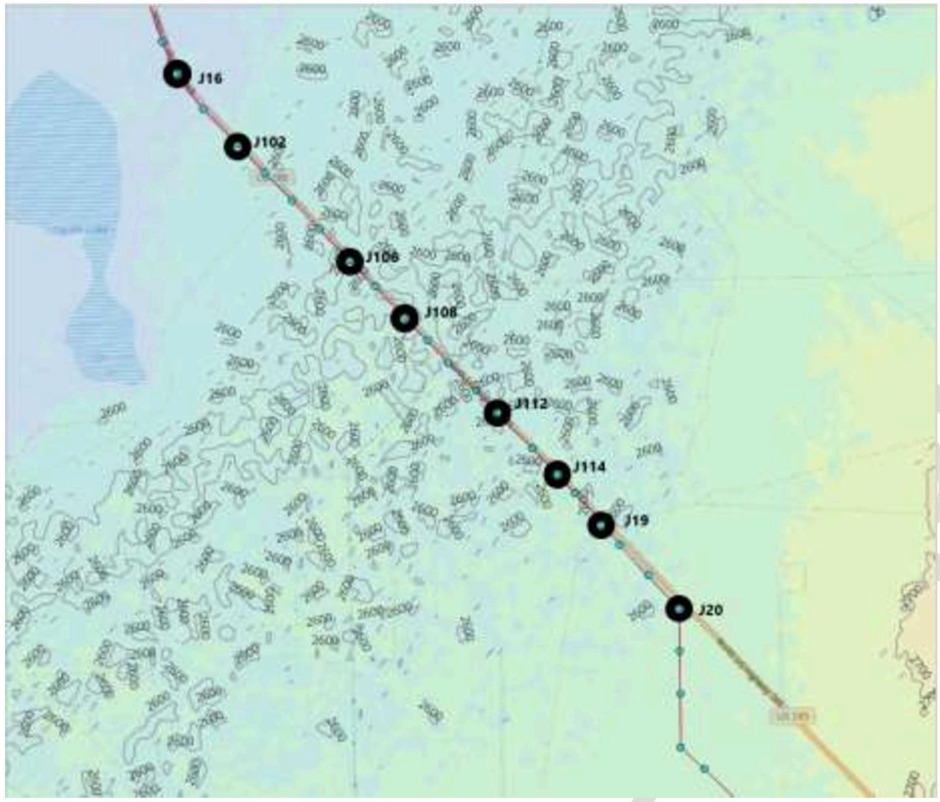

Figure 45. Air Relief Valve Locations (Panel 3 of 6)

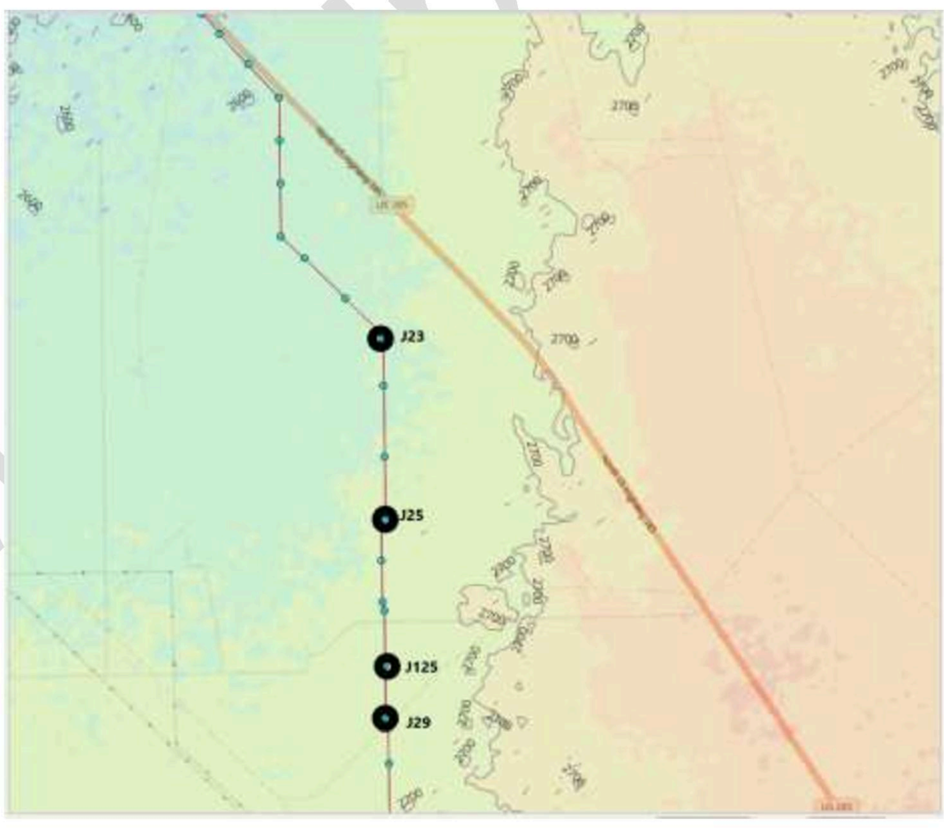

Figure 46. Air Relief Valve Locations (Panel 4 of 6)

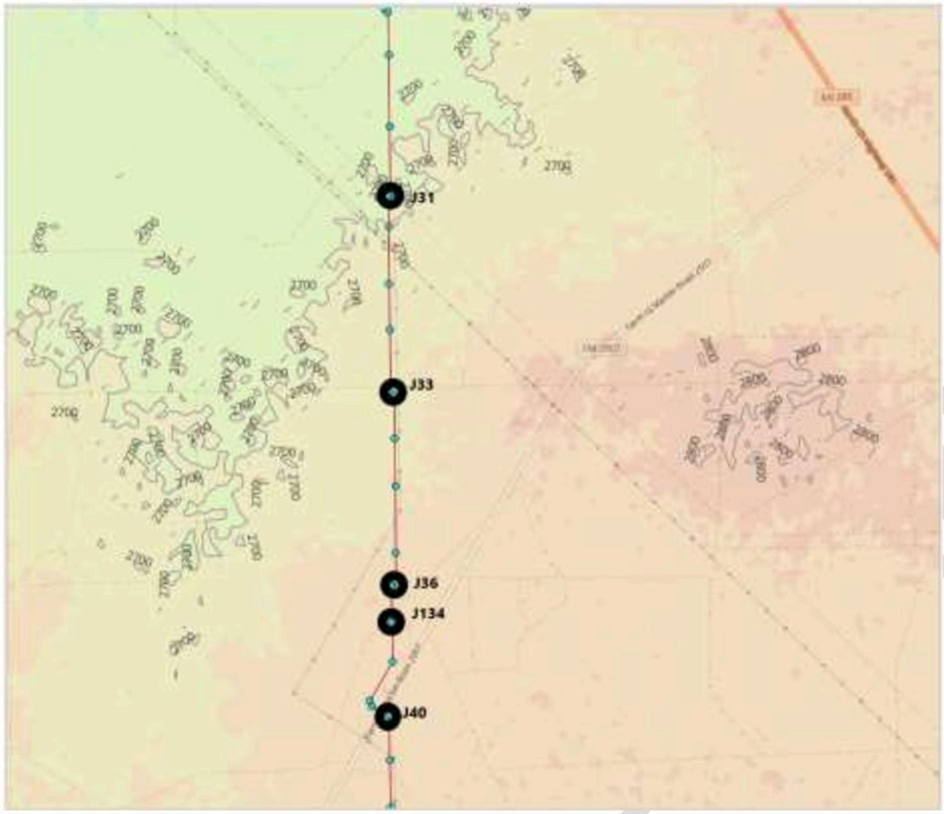

Figure 47. Air Relief Valve Locations (Panel 5 of 6)

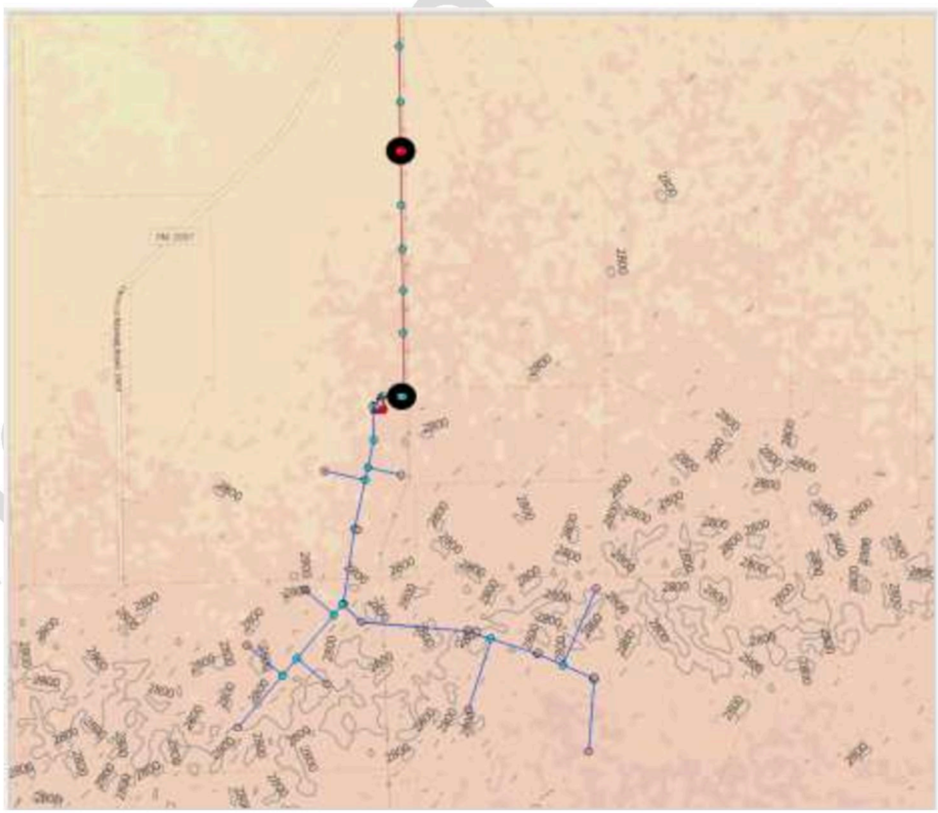

Figure 48. Air Relief Valves (Panel 6 of 6)

Figure 50 is a profile (elevation) plot with suggested pressure release valves located at local elevation minima. The four valves from the left edge are in the authors opinion necessary to protect the pipeline in the event of over pressure (say the flow control valve fails and rapidly shuts for some reason).

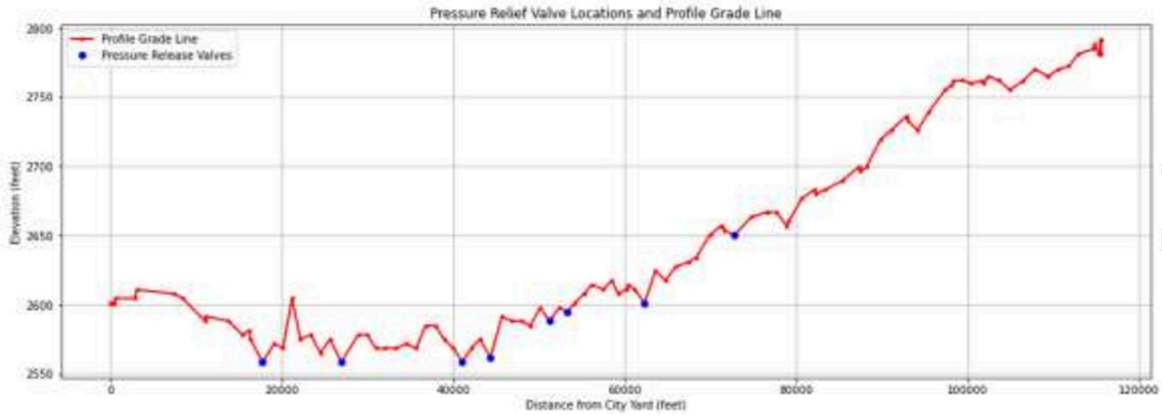

Figure 49. Profile plot showing elevation along alignment and suggested pressure release valve locations.

Figures 50-52 indicate locations on the plan-view base map for pressure relief valves (to release excessive water pressure from the system) based on the profile above. The quantity depicted are based on the alignment and topographic highs and lows.

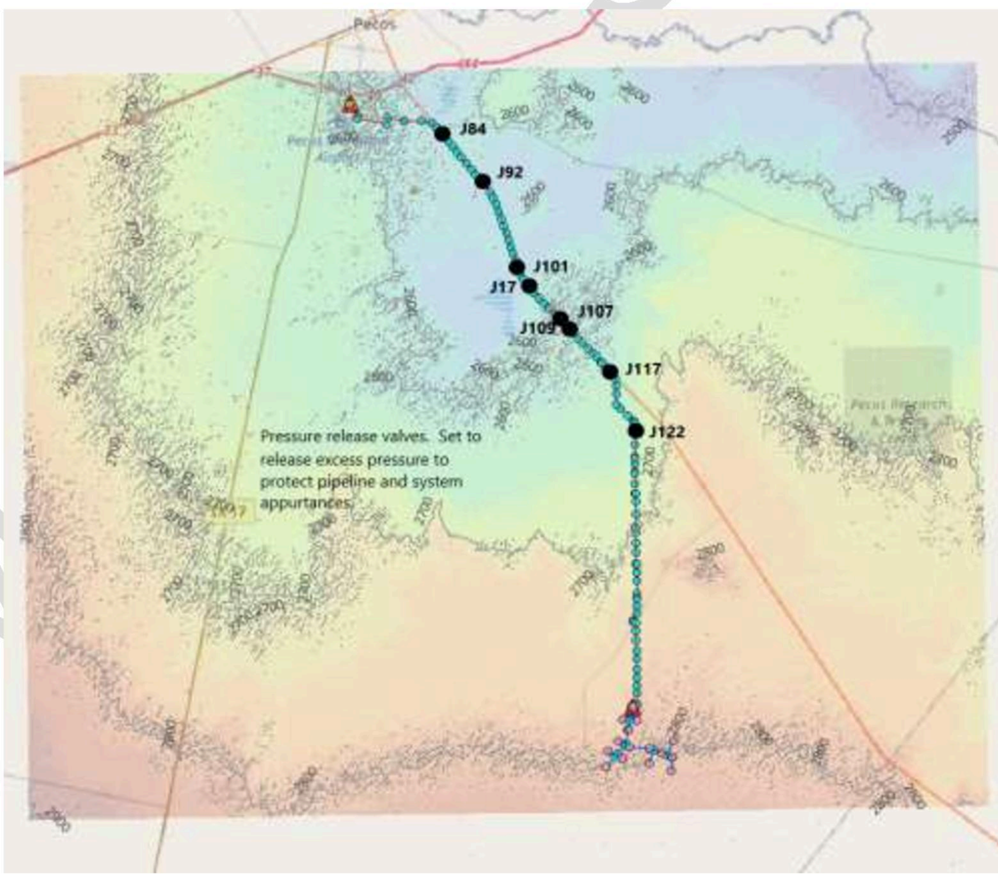

Figure 50. Pressure Release Valve Locations (overview – details in subsequent panels)

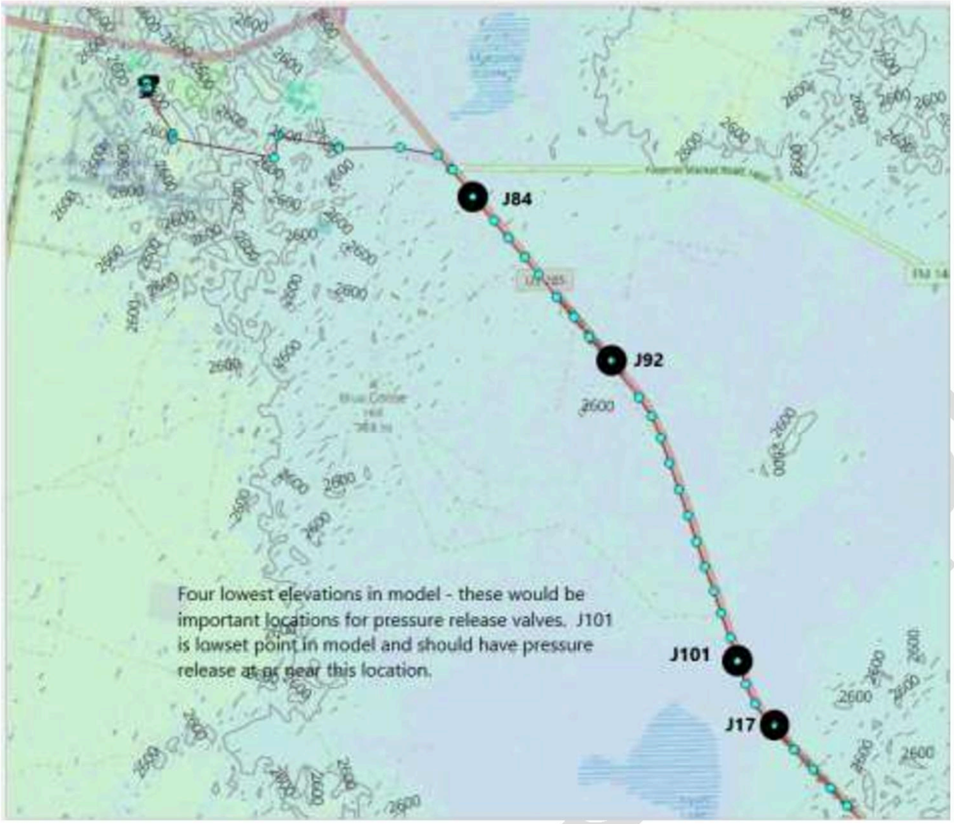

Figure 51. Pressure Release Valves. (Panel 1 of 2) Location J101 is lowest point in pipeline.

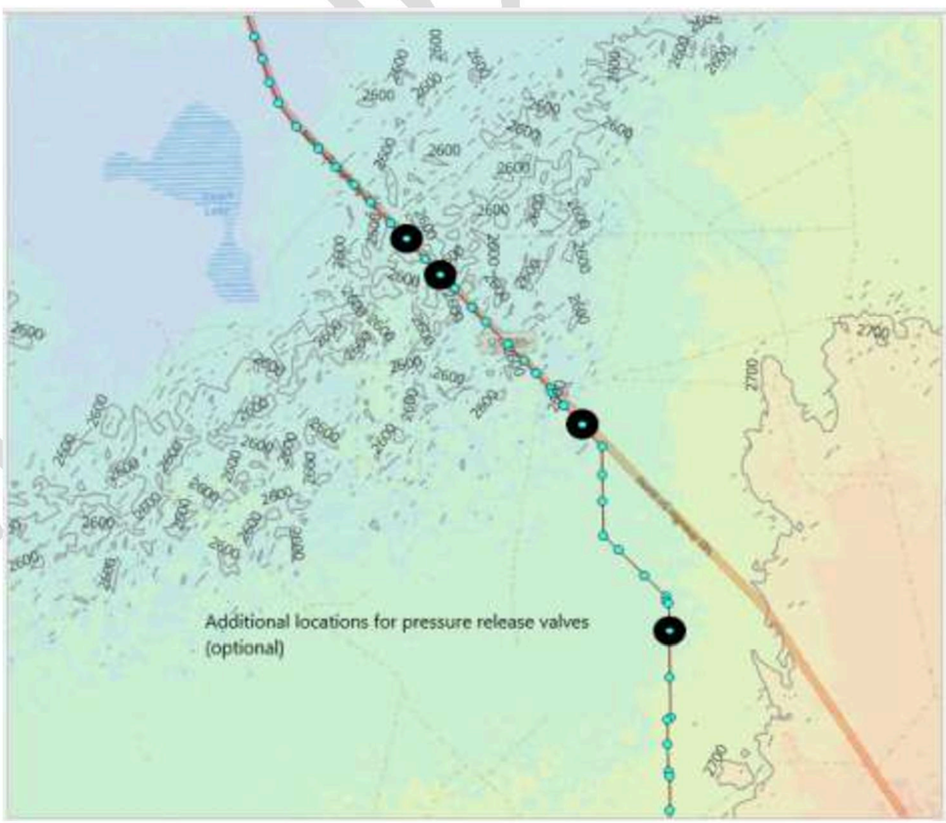

Figure 52. Pressure Release Valves (Panel 2 of 2) (additional locations)

A simple water hammer analysis suggests that the flow valve control speeds should be programmed such that a flow change is effected over a period of 2 minutes.

The water age in the system during daily variation is less than 52 hours, and retains this age over 190+ simulation hours.

The models herein are all stored at http://freeswmm.ddns.net a semi-public website[10]; access credentials are in appendix V. A video linked at LINKHERE demonstrates how to run the models and make exploratory changes on the web implementation if desired.

[10] Semi-public means that the website is publicly accessible, but user credentials are required to access the back-end models. It is primarily intended for training but is a convenient way to share the model datasets. This report is housed there as well.

References

Cleveland, T. G. (2018) "Pipeline Transients — Water Hammer" pp. 141-148 in *Fluid Mechanics Computations in R: A Toolkit to Accompany CE 3305 at TTU*. Department of Civil, Environmental, and Construction Engineering. http://54.243.252.9/ce-3372-webroot/3-Readings/CFMinR/CFMinR.pdf

Gupta (1989). Hydrology and Hydraulic Systems, Prentice Hall, NJ (pp 571-580)

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J.M. Eagle (2012). "MINIMUM AND MAXIMUM BURIAL DEPTH RECOMMENDATIONS FOR EAGLE CORR PE™" https://www.jmeagle.com/sites/default/files/MaximumBurialDepthEagleCorr.pdf

Appendix – I Loss Coefficients for Different Materials

Various references were consulted to determine a useful value for HDPE roughness parameter in EPANET including Figure 53, Figure 54, and Figure 55.

APPENDIX

A

Friction Losses for Water Flow Through Pipe*

Accurate prediction of friction losses in pipe is a complex matter involving many variables. In Civil Engineering applications, the Hazen Williams formula is typically used to calculate friction losses through water conveying pipe. The formulae are as follows:

$$h_{ft/100\,ft} = \frac{1044}{d_{inches}^{4.8655}} \times \left(\frac{Q_{gpm}}{C}\right)^{1.85} \text{ (U.S.)}$$

$$h_{f(m/100\,m)} = \frac{608{,}704{,}451}{d_{mm}^{4.8655}} \times \left(\frac{Q_{L/min}}{C}\right)^{1.85} \text{ (metric)}$$

where h_f = friction head loss in feet per 100 ft (or meters per 100 m) of water pipe
C = roughness coefficient
Q = flow in gpm (or liters per minute)
d = inside diameter in inches (or millimeters)

Roughness coefficient is based on the material of the pipe. For PVC pipe, the standard C value is 150. New steel pipe uses a C value of 140, but with use and corrosion a lower value is typically used. For HDPE pipe, a range of C values between 150 and 160 is typical.

Tables A.1 and A.2 show friction loss data calculated by the Hazen Williams formula for the most commonly used steel and PVC pipe diameters, based on C values of 140 and 150, respectively. It should be noted that steel and PVC pipe are manufactured to different sizing specifications and therefore do not have the same inside diameters (Chapter 15). The inside diameter of HDPE pipe can vary significantly for any nominal diameter and a calculation of pipe friction using the true inside diameter is recommended.

A graphical depiction of friction loss through PVC pipe developed from the PVC table is presented to provide a quick reference. A table is also included showing the friction loss through various fittings as an equivalent length of pipe.

*Standards and practices for metric pipe manufacturing vary from country to country. It is therefore not practical to attempt to address international variances within this Appendix. Accordingly, discussion is confined to current practice in the United States. International readers are advised to consult their local regulating agency or manufacturer.

Figure 53. Hazen-Williams Friction Factor for HDPE
(from https://onlinelibrary.wiley.com/doi/pdf/10.1002/9780470168103.app1)

TABLE 25.12 Relative Roughness and Hazen-Williams Constants for Various Pipe Materials

Type of Pipe or Surface	ε(FT) Range	ε(FT) Design	C Range	C Clean	C Design
STEEL					
welded and seamless	0.0001–0.0003	0.0002	150–80	140	100
interior riveted, no projecting rivets				139	100
projecting girth rivets				130	100
projecting girth and horizontal rivets				115	100
vitrified, spiral-riveted, flow with lap				110	100
vitrified, spiral-riveted, flow against lap				100	90
corrugated				60	60
MINERAL					
concrete	0.001–0.01	0.004	152–85	120	100
cement-asbestos			160–140	150	140
vitrified clays					110
brick sewer					100
IRON					
cast, plain	0.0004–0.002	0.0008	150–80	130	100
cast, tar (asphalt) coated	0.0002–0.0006	0.0004	145–50	130	100
cast, cement-lined	0.000008	0.000008		150	140
cast, bituminous-lined	0.000008	0.000008	160–130	148	140
cast, centrifugally spun	0.00001	0.00001			
galvanized, plain	0.0002–0.0008	0.0005			
wrought, plain	0.0001–0.0003	0.0002	150–80	130	100
MISCELLANEOUS					
fiber				150	140
copper and brass	0.000005	0.000005	150–120	140	130
wood stave	0.0006–0.003	0.002	145–110	120	110
transite	0.000008	0.00008			
lead, tin, glass		0.000005	150–120	140	130
plastic (PVC and ABS)		0.000005	150–120	140	130

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Figure 54. C Values for various materials from: "Water Distribution Systems" in Land Development Handbook, Ed. S.O. Dewberry, Dewberry Inc., McGraw-Hill

Table 3: Hazen-Williams Coefficients for Different Materials.

Material	C_h	Material	C_h
ABS - Acrylonite Butadiene Styrene	130	Aluminum	130 - 150
Asbestos Cement	140	Asphalt Lining	130 - 140
Brass	130 - 140	Brick sewer	90 - 100
Cast-Iron - new unlined (CIP)	130	Cast-Iron 10 years old	107 - 113
Cast-Iron 20 years old	89 - 100	Cast-Iron 30 years old	75 - 90
Cast-Iron 40 years old	64-83	Cast-Iron, asphalt coated	100
Cast-Iron, cement lined	140	Cast-Iron, bituminous lined	140
Cast-Iron, wrought plain	100	Cast-Iron, seal-coated	120
Cement lining	130 - 140	Concrete	100 - 140
Concrete lined, steel forms	140	Concrete lined, wooden forms	120
Concrete, old	100 - 110	Copper	130 - 140
Corrugated Metal	60	Ductile Iron Pipe (DIP)	140
Ductile Iron, cement lined	120	Fiber	140
Fiber Glass Pipe - FRP	150	Galvanized iron	120
Glass	130	Lead	130 - 140
Metal Pipes - Very to extremely smooth	130 - 140	Plastic	130 - 150
Polyethylene, PE, PEH	140	Polyvinyl chloride, PVC, CPVC	150
Smooth Pipes	140	Steel new unlined	140 - 150
Steel, corrugated	60	Steel, welded and seamless	100
Steel, interior riveted, no projecting rivets	110	Steel, projecting girth and horizontal rivets	100
Steel, vitrified, spiral-riveted	90 - 110	Steel, welded and seamless	100
Tin	130	Vitrified Clay	110
Wrought iron, plain	100	Wooden or Masonry Pipe - Smooth	120
Wood Stave	110 - 120		

Example Estimate the head loss in a 72-inch, 10,000-foot steel pipe carrying water at 200 CFS using the Hazen-Williams formula.

Solution Using Table 3 an estimate of the C_h is 100. Next substitute into the HW formula as

$$h_f = 3.02\ (10,000ft)\ (6ft)^{-1.167}(\frac{4(200cfs)}{\pi(6ft)^2 100})^{1.85} \approx 28ft \tag{23}$$

[9]Adapted from `http://www.engineeringtoolbox.com/hazen-williams-coefficients-d_798.html`.

Figure 55. Values of C for various materials from:
(http://54.243.252.9/ce-3372-webroot/3-Readings/HydraulicsNotes/hydraulics-notes-tgc.pdf)

Appendix II- Burst Pressure Guidance for HDPE

PERFORMANCE PIPE
A DIVISION OF CHEVRON PHILLIPS CHEMICAL COMPANY LP

www.performancepipe.com

M-55 states that "No allowance for corrosion and therefore, no subsequent lowering of the flow capacity need be considered when using PE pipe."

D3 What is the maximum flow velocity for HDPE?

1. *In a pumped system the maximum operating velocity is limited by the surge pressure capacity of the pipe. The Plastics Pipe Institute's Handbook of Polyethylene Pipe states that "if surge is not a consideration, water flow velocities exceeding 25 feet per second may be acceptable."*

D4 Does the fusion bead affect flow?

1. *No. The Hazen Williams C factor of 155 was determined with pipe that was fused together and thus contained inner fusion beads.*

D5 What is the safe peak pressure (surge plus pumping) for HDPE?

1. *AWWA C906 defines two types of surge pressure, recurring and occasional. The safe peak pressure or allowed total pressure for HDPE pipe is 1.5 times the pipe's pressure rating for recurring surge and 2.0 times the pipe's pressure rating for occasional surge. For instance a DR17 pipe which has a pressure rating of 100 psi can safely handle total pressure during recurring surge of 150 psi and total pressure during an occasional surge of 200 psi.*

Figure 56. Burst-Pressure Guidance (and another C value) from https://hdpe.ca/assets/data/technical-data/performance-pipe/FAQ-Municipal-water.pdf

HDPE IRON PIPE SIZE (IPS) PRESSURE PIPE PE4710

		DR 7 (333 psi)			DR 7.3 (318 psi)			DR 9 (250 psi)			DR 9.3 (241 psi)			DR 11 (200 psi)			DR 13.5 (160 psi)		
Pipe Size	Avg OD	Min Wall	Avg ID	Weight lb/ft	Min Wall	Avg ID	Weight lb/ft	Min Wall	Avg ID	Weight lb/ft	Min Wall	Avg ID	Weight lb/ft	Min Wall	Avg ID	Weight lb/ft	Min Wall	Avg ID	Weight lb/ft
1/2	0.840	0.120	0.59	0.12	0.115	0.60	0.11	0.093	0.64	0.10	0.090	0.65	0.09	0.076	0.68	0.08	0.062	0.71	0.07
3/4	1.050	0.150	0.73	0.19	0.144	0.75	0.18	0.117	0.80	0.15	0.113	0.81	0.15	0.095	0.85	0.12	0.078	0.88	0.10
1	1.315	0.188	0.92	0.29	0.180	0.93	0.28	0.146	1.01	0.23	0.141	1.02	0.23	0.120	1.06	0.20	0.097	1.11	0.16
2	2.375	0.339	1.66	0.95	0.325	1.69	0.91	0.264	1.82	0.77	0.255	1.83	0.74	0.216	1.92	0.64	0.176	2.00	0.53
3	3.500	0.500	2.44	2.06	0.479	2.48	1.98	0.389	2.68	1.66	0.376	2.70	1.61	0.318	2.83	1.39	0.259	2.95	1.16
4	4.500	0.643	3.14	3.40	0.616	3.19	3.28	0.500	3.44	2.75	0.484	3.47	2.67	0.409	3.63	2.30	0.333	3.79	1.91
5 3/8	5.375	0.768	3.75	4.85	0.736	3.81	4.68	0.597	4.11	3.92	0.578	4.15	3.81	0.489	4.34	3.29	0.398	4.53	2.73
5	5.563	0.795	3.88	5.20	0.762	3.95	5.02	0.618	4.25	4.20	0.598	4.29	4.08	0.506	4.49	3.52	0.412	4.69	2.92
6	6.625	0.946	4.62	7.36	0.908	4.70	7.12	0.736	5.06	5.96	0.712	5.11	5.79	0.602	5.35	4.99	0.491	5.58	4.15
7	7.125	0.976	5.06	8.23	0.976	5.06	8.23	0.792	5.45	6.89	0.766	5.50	6.70	0.648	5.75	5.78	0.528	6.01	4.80
8	8.625	1.232	6.01	12.48	1.182	6.12	12.06	0.958	6.59	10.09	0.927	6.66	9.81	0.784	6.96	8.46	0.639	7.27	7.03
10	10.750	1.536	7.49	19.40	1.473	7.63	18.74	1.194	8.22	15.68	1.156	8.30	15.24	0.977	8.68	13.14	0.796	9.06	10.92
12	12.750	1.821	8.89	27.28	1.747	9.05	26.36	1.417	9.75	22.07	1.371	9.84	21.44	1.159	10.29	18.49	0.944	10.75	15.36
14	14.000	2.000	9.76	32.90	1.918	9.93	31.78	1.556	10.70	26.61	1.505	10.81	25.85	1.273	11.30	22.30	1.037	11.80	18.52
16	16.000	2.286	11.15	42.97	2.192	11.35	41.51	1.778	12.23	34.75	1.720	12.35	33.76	1.455	12.92	29.12	[illegible]	[illegible]	[illegible]
18	18.000	2.571	12.55	54.37	2.466	12.77	52.53	2.000	13.76	43.97	1.935	13.90	42.73	1.636	14.53	36.84	1.333	15.17	30.61
20	20.000	2.857	13.94	67.13	2.740	14.19	64.85	2.222	15.29	54.28	2.151	15.44	52.77	1.818	16.15	45.49	1.481	16.86	37.79
24	24.000	3.429	16.73	96.68	3.288	17.03	93.39	2.667	18.35	78.18	2.581	18.53	75.98	2.182	19.37	65.52	1.778	20.23	54.44
26	26.000							2.889	19.88	91.75	2.796	20.07	89.17	2.364	20.99	76.89	1.926	21.92	63.89
28	28.000							3.111	21.40	106.40	3.011	21.62	103.42	2.545	22.60	89.15	2.074	23.60	74.09
30	30.000							3.333	22.93	122.13	3.226	23.16	118.72	2.727	24.22	102.35	2.222	25.29	85.04
32	32.000													2.909	25.83	116.46	2.370	26.98	96.76
34	34.000													3.091	27.45	131.48	2.519	28.66	109.26
36	36.000													3.273	29.06	147.41	2.667	30.35	122.49

DR 13.5 has 15-inch ID. Model used 17.43 inch ID; Closest is 20 inch in the Table, so used those values for water hammer. Maximum model pressure is below nominal 160 psi

Figure 57. Tabulated HDPE Pressure ratings from https://www.jmeagle.com/sites/default/files/HDPESpecSheet4710%20.pdf

Appendix III – EPANET Input File

Representative input file. All the models are stored at the FreeSWMM website (described in Appendix VI)

```
[TITLE]


[JUNCTIONS]
;ID              Elev            Demand          Pattern
 J1              2604.32         0.00000                          ;
 J2              2604.32         0.00000                          ;
 J3              2620.72         0.00000                          ;
 J4              2607.60         0.00000                          ;
 J5              2604.32         0.00000                          ;
 J6              2587.92         0.00000                          ;
 J7              2591.20         0.00000                          ;
 J8              2587.92         0.00000                          ;
 J9              2578.08         0.00000                          ;
 J10             2581.36         0.00000                          ;
 J11             2574.80         0.00000                          ;
 J12             2578.08         0.00000                          ;
 J13             2578.08         0.00000                          ;
 J14             2568.24         0.00000                          ;
 J15             2568.24         0.00000                          ;
 J16             2574.80         0.00000                          ;
 J17             2561.68         0.00000                          ;
 J18             2610.88         0.00000                          ;
 J19             2614.16         0.00000                          ;
 J20             2624.00         0.00000                          ;
 J21             2630.56         0.00000                          ;
 J22             2656.80         0.00000                          ;
 J23             2656.80         0.00000                          ;
 J24             2653.52         0.00000                          ;
 J25             2666.64         0.00000                          ;
 J26             2666.64         0.00000                          ;
 J27             2656.80         0.00000                          ;
 J28             2660.08         0.00000                          ;
 J29             2683.04         0.00000                          ;
 J30             2679.76         0.00000                          ;
 J31             2699.44         0.00000                          ;
 J32             2696.16         0.00000                          ;
 J33             2735.52         0.00000                          ;
 J34             2732.24         0.00000                          ;
 J35             2758.48         0.00000                          ;
 J36             2761.76         0.00000                          ;
 J37             2765.04         0.00000                          ;
 J38             2761.76         0.00000                          ;
 J39             2765.04         0.00000                          ;
 J40             2771.60         0.00000                          ;
 J41             2784.72         0.00000                          ;
 J42             2788.00         0.00000                          ;
 J43             2781.44         0.00000                          ;
 J44             2781.44         0.00000                          ;
 J45             2781.44         0.00000                          ;
 J46             2781.44         0                                ;
 J47             2781.44         0                                ;
 J48             2778.16         0                                ;
```

```
 J49             2774.88         0                                        ;
 J50             2774.88         0                                        ;
 J51             2781.44         0                                        ;
 J52             2791.28         0                                        ;
 J53             2791.28         0                                        ;
 J54             2774.88         0                                        ;
 J55             2784.72         0                                        ;
 J56             2784.72         0                                        ;
 J57             2788            0                                        ;
 J58             2784.72         0                                        ;
 J59             2784.72         0                                        ;
 J60             2781.44         0                                        ;
 J61             2781.44         0                                        ;
 J62             2791.28         0                                        ;
 J63             2774.88         0                                        ;
 J64             2791.28         0                                        ;
 J65             2784.72         0                                        ;
 J66             2797.84         0                                        ;
 J67             2784.72         0                                        ;
 J68             2791.28         0                                        ;
 J69             2791.28         0                                        ;
 J70             2788            0                                        ;
 J71             2797.84         0                                        ;
 J72             2797.84         0                                        ;
 J73             2804.4          0                                        ;
 J74             2801.12         0                                        ;
 J75             2804.4          0                                        ;
 J76             2814.24         0                                        ;
 J77             2797.84         0                                        ;
 J78             2810.96         0                                        ;
 J79             2814.24         0                                        ;
 J80             2810.96         0                                        ;
 J81             2814.24         0                                        ;
 J82             2824.08         0                                        ;
 J83             2781.44         0                                        ;
 WDS-IN          2601.00         2100             2                       ;
 BOOST_IN        2601            0                                        ;
 1               2604.32         0                                        ;
 TCVTSR1         2601            0                                        ;

[RESERVOIRS]
;ID              Head            Pattern
 R25W3           2330                             ;
 R25W5           2330                             ;
 R25W2           2330                             ;
 R24W2           2330                             ;
 R24W3           2330                             ;
 R24W1           2330                             ;
 R25W1           2330                             ;
 R30W1           2330                             ;
 R30W4           2330                             ;
 R30W5           2330                             ;
 R30W6           2330                             ;
 R30W3           2330                             ;
 R30W2           2330                             ;
 R25W4           2330                             ;

[TANKS]
```

```
;ID                 Elevation           InitLevel           MinLevel            MaxLevel
      Diameter            MinVol              VolCurve            Overflow
 TSR-1              2601                15                  0.0000              30
      92                  0.0000                                  ;Terminal Storage
(Z=2601.04)
 TSR-2              2601                15                  0.0000              30
      92                  0.0000                                  ;Terminal Storage 2
(Z=2607.6)
 ISR-1              2791.00             22.5                15                  30
      52.0                0.0000                                  ;Grade 2791
 ISR-2              2791.00             15                  0                   30
      52                  0.0000                                  ;

[PIPES]
;ID                 Node1               Node2               Length              Diameter
      Roughness           MinorLoss           Status
 1                  J45                 J44                 103.75              17.43
      150                 0.00                OPEN                ;
 2                  J44                 J43                 63.44               17.43
      150                 0.00                OPEN                ;
 3                  J43                 J42                 543.04              17.43
      150                 0.00                OPEN                ;
 4                  J42                 J41                 141.37              17.43
      150                 0.00                OPEN                ;
 5                  J41                 J40                 12253.62            17.43
      150                 0.00                OPEN                ;
 6                  J40                 J39                 555.50              17.43
      150                 0.00                OPEN                ;
 7                  J39                 J38                 158.26              17.43
      150                 0.00                OPEN                ;
 8                  J38                 J37                 1255.29             17.43
      150                 0.00                OPEN                ;
 9                  J37                 J36                 2098.64             17.43
      150                 0.00                OPEN                ;
 10                 J36                 J35                 180.96              17.43
      150                 0.00                OPEN                ;
 11                 J35                 J34                 5143.43             17.43
      130                 0.00                OPEN                ;
 12                 J34                 J33                 154.09              17.43
      130                 0.00                OPEN                ;
 13                 J33                 J32                 5444.28             17.43
      130                 0.00                OPEN                ;
 14                 J32                 J31                 86.43               17.43
      130                 0.00                OPEN                ;
 15                 J31                 J30                 5079.74             17.43
      130                 0.00                OPEN                ;
 16                 J30                 J29                 95.38               17.43
      130                 0.00                OPEN                ;
 17                 J29                 J28                 3006.91             17.43
      130                 0.00                OPEN                ;
 18                 J28                 J27                 235.90              17.43
      130                 0.00                OPEN                ;
 19                 J27                 J26                 2175.36             17.43
      130                 0.00                OPEN                ;
 20                 J26                 J25                 172.13              17.43
      130                 0.00                OPEN                ;
 21                 J25                 J24                 4964.61             17.43
      130                 0.00                OPEN                ;
```

22		J24		J23		154.06	17.43
	130		0.00		OPEN	;	
23		J23		J22		204.70	17.43
	130		0.00		OPEN	;	
24		J22		J21		3800.44	17.43
	130		0.00		OPEN	;	
25		J21		J20		3851.41	17.43
	130		0.00		OPEN	;	
26		J20		J19		3178.39	17.43
	130		0.00		OPEN	;	
27		J19		J18		190.21	17.43
	130		0.00		OPEN	;	
28		J18		J17		15888.45	17.43
	130		0.00		OPEN	;	
29		J17		J16		1243.64	17.43
	130		0.00		OPEN	;	
30		J16		J15		984.75	17.43
	130		0.00		OPEN	;	
31		J15		J14		11142.98	17.43
	130		0.00		OPEN	;	
32		J14		J13		1028.97	17.43
	130		0.00		OPEN	;	
33		J13		J12		1006.01	17.43
	130		0.00		OPEN	;	
34		J12		J11		12584.41	17.43
	130		0.00		OPEN	;	
35		J11		J10		110.04	17.43
	130		0.00		OPEN	;	
36		J10		J9		822.89	17.43
	130		0.00		OPEN	;	
37		J9		J8		1643.15	17.43
	130		0.00		OPEN	;	
38		J8		J7		2617.41	17.43
	130		0.00		OPEN	;	
39		J7		J6		96.86	17.43
	130		0.00		OPEN	;	
40		J6		J5		2621.34	17.43
	130		0.00		OPEN	;	
41		J5		J4		933.52	17.43
	130		0.00		OPEN	;	
42		J4		J3		4425.24	17.43
	130		0.00		OPEN	;	
43		J3		J2		245.25	17.43
	130		0.00		OPEN	;	
44		J2		J1		2258.84	18.00
	135.0000		0.00		OPEN	;	
82		J67		J65		1938.8408	6
	150		0		CV	;	
83		J65		J64		624.5776	12
	150		0		CV	;	
84		J64		J62		1602.3456	6
	150		0		CV	;	
85		J62		J61		359.9144	8
	150		0		CV	;	
86		J61		J60		34.5056	12
	150		0		Open	;	
87		J60		J59		6.8552	12
	150		0		Open	;	

88	J59	J58	9.4136	12	150	0	Open	;
89	J58	J56	2110.2208	12	150	0	CV	;
90	J56	J55	10.2664	12	150	0	Open	;
91	J55	J53	1402.036	12	150	0	CV	;
92	J53	J52	348.992	12	150	0	Open	;
93	J52	J51	795.8264	12	150	0	CV	;
94	J51	J50	949.7568	14	150	0	Open	;
95	J82	J81	2047.1136	6	150	0	CV	;
96	J81	J80	14.7272	12	150	0	Open	;
97	J80	J78	19.2864	12	150	0	Open	;
98	J79	J78	28.8312	6	150	0	Open	;
99	J78	J76	936.9976	6	150	0	CV	;
100	J76	J74	770.7672	6	150	0	CV	;
101	J74	J72	1367.7928	8	150	0	CV	;
102	J72	J71	696.18	8	150	0	CV	;
103	J71	J69	2981.2576	8	150	0	CV	;
104	J69	J61	716.1552	12	150	0	CV	;
105	J77	J76	2322.8632	12	150	0	CV	;
106	J73	J72	2085.5552	6	150	0	CV	;
107	J66	J65	1302.1928	6	150	0	CV	;
108	J68	J64	1108.4432	6	150	0	CV	;
109	J63	J62	1094.4048	6	150	0	CV	;
110	J83	J52	951.9872	12	150	0	CV	;
111	J54	J53	1159.2832	12	150	0	CV	;
112	J57	J56	92.824	12	150	0	Open	;
113	J70	J71	27.6504	12	150	0	Open	;
45	J75	J74	25.68	12	150	0	Open	;
52	J50	J49	13.67	14	150	0	Open	;
53	J49	J48	16.695	14	150	0	Open	;

```
 54                J48                J47                114.70             14
      150                0                  Open         ;
 V2ISR1            J47                ISR-1              27.24              14
      150                0                  CV           ;
 ISR2_PL           ISR-2              J46                20.172             17.43
      150                0                  CV           ;
 56                J46                J45                22.96              17.43
      150                0                  Open         ;
 ISR_1_2           ISR-1              ISR-2              87.32              17.43
      150                0                  CV           ;
 TSR_OUT           TSR-2              BOOST_IN           77.61              17.43
      130                0                  Open         ;Connector to Existing System
 TSR_INPUT         1                  TSR-1              20.00              17.43
      130                0                  Open         ;
 TSR_TRAN          TCVTSR1            TSR-2              60.37              17.43
      130                0                  Open         ;
 FCV_TSR           J1                 1                  1000               18
      100                0                  Open         ;
 48                TSR-1              TCVTSR1            10                 18
      100                0                  CV           ;

[PUMPS]
;ID                Node1              Node2              Parameters
 P-24W2            R24W2              J54                HEAD 8FAHC  ;
 P-25W2            R25W2              J63                HEAD 8FAHC  ;
 P-25W5            R25W5              J66                HEAD 8FAHC  ;
 P-25W3            R25W3              J67                HEAD 8FAHC  ;
 P-25W4            R25W4              J68                HEAD 8FAHC  ;
 P-30W2            R30W2              J73                HEAD 8FAHC  ;
 P-30W3            R30W3              J75                HEAD 8FAHC  ;
 P-30W6            R30W6              J82                HEAD 8FAHC  ;
 P-30W5            R30W5              J78                HEAD 8FAHC  ;
 P-30W4            R30W4              J77                HEAD 8FAHC  ;
 P-30W1            R30W1              J70                HEAD 8FAHC  ;
 P-25W1            R25W1              J69                HEAD 8FAHC  ;
 P-24W1            R24W1              J57                HEAD 8FAHC  ;
 P-24W3            R24W3              J83                HEAD 8FAHC  ;
 49                BOOST_IN           WDS-IN             HEAD BOOST_TSR     SPEED 1.0
      ;

[VALVES]
;ID                Node1              Node2              Diameter           Type  Set-
ting         MinorLoss

[TAGS]

[DEMANDS]
;Junction          Demand             Pattern            Category

[STATUS]
;ID                Status/Setting
 P-24W2            Closed
 P-25W2            Closed
 P-25W5            Closed
 P-25W3            Closed
 P-25W4            Closed
 P-30W2            Closed
 P-30W3            Closed
 P-30W6            Closed
```

```
 P-30W5           Closed
 P-30W4           Closed
 P-30W1           Closed
 P-25W1           Closed
 P-24W1           Closed
 P-24W3           Closed

[PATTERNS]
;ID               Multipliers
;12-hour step demand changes
 2                0.1               0.1               0.1               0.1
      0.1               0.1
 2                1.0               1.0               1.0               1.0
      1.0               1.0
 2                1.0               1.0               1.0               1.0
      1.0               1.0
 2                1.0               0.1               0.1               0.1
      0.1               0.1
;Constant Pattern (Same as Steady Flow Model)
 1                1                 1                 1                 1
      1                 1
 1                1                 1                 1                 1
      1                 1
 1                1                 1                 1                 1
      1                 1
 1                1                 1                 1                 1
      1                 1
;Generic Pattern Max Well Flow at Hour 0800 - Use 300 gpm as base
 4                1                 1                 2                 2.5
      3.5               4.5
 4                6                 7                 6                 4.5
      3.5               2.5
 4                1.5               1                 1.5               2.5
      3.5               4
 4                5                 4                 3.5               2.5
      1.5               0.9

[CURVES]
;ID               X-Value           Y-Value
;PUMP: PUMP: 8FAHC 17-stage turbine lift pump (at wellhead)
 8FAHC            0                 652
 8FAHC            60                648
 8FAHC            90                632
 8FAHC            120               606
 8FAHC            150               557
 8FAHC            180               484
 8FAHC            220               404
;PUMP: PUMP: Booster Station TSR into WDS
 BOOST_TSR        0                 100
 BOOST_TSR        2100              70
 BOOST_TSR        4000              6
;PUMP: PUMP: Wellhead Booster
 WB               0                 812
 WB               112               717
 WB               168               485
;PUMP: PUMP: BoosterStationISRExit
 BOOST_ISR        0                 120
 BOOST_ISR        2100              114
 BOOST_ISR        4200              99
```

```
;PUMP: PUMP: BoosterStation-Intermediate
 BOOST_JP16       0                 55
 BOOST_JP16       2100              52
 BOOST_JP16       4200              42

[CONTROLS]





[RULES]
RULE KEEPISR1FULL
IF TANK ISR-1 LEVEL < 27
THEN PUMP P-24W2 STATUS IS OPEN
AND PUMP P-24W3 STATUS IS OPEN
AND PUMP P-24W1 STATUS IS OPEN
AND PUMP P-25W2 STATUS IS OPEN
AND PUMP P-25W5 STATUS IS OPEN
AND PUMP P-30W3 STATUS IS OPEN
AND PUMP P-30W4 STATUS IS OPEN
AND PUMP P-30W5 STATUS IS OPEN
AND PUMP P-25W1 STATUS IS OPEN
AND PUMP P-30W6 STATUS IS OPEN
AND PUMP P-30W2 STATUS IS OPEN
AND PUMP P-25W4 STATUS IS OPEN
AND PUMP P-25W3 STATUS IS OPEN
AND PUMP P-30W1 STATUS IS OPEN

RULE STOPISR1FILL
IF TANK ISR-1 LEVEL > 29
THEN PUMP P-24W2 STATUS IS CLOSED
AND PUMP P-24W3 STATUS IS CLOSED
AND PUMP P-24W1 STATUS IS CLOSED
AND PUMP P-25W2 STATUS IS CLOSED
AND PUMP P-25W5 STATUS IS CLOSED
AND PUMP P-30W3 STATUS IS CLOSED
AND PUMP P-30W4 STATUS IS CLOSED
AND PUMP P-30W5 STATUS IS CLOSED
AND PUMP P-25W1 STATUS IS CLOSED
AND PUMP P-30W6 STATUS IS CLOSED
AND PUMP P-30W2 STATUS IS CLOSED
AND PUMP P-25W4 STATUS IS CLOSED
AND PUMP P-25W3 STATUS IS CLOSED
AND PUMP P-30W1 STATUS IS CLOSED

RULE STOPTSR2OVERFILL
IF TANK TSR-2 LEVEL > 29.5
THEN CV TSR_TRAN STATUS IS CLOSED

RULE KEEPTSR2FILLED
IF TANK TSR-2 LEVEL < 10.0
THEN CV TSR_TRAN STATUS IS OPEN

RULE STOPTSR1OVERFILL
IF TANK TSR-1 LEVEL > 29.5
THEN PIPE TSR_INPUT STATUS IS CLOSED
```

```
RULE KEEPTSR1FILLED
IF TANK TSR-1 LEVEL < 10.5
THEN PIPE TSR_INPUT STATUS IS OPEN



[ENERGY]
 Global Efficiency      75
 Global Price           0
 Demand Charge          0

[EMITTERS]
;Junction          Coefficient
 J1                0.00
 J2                0.00
 J3                0.00
 J4                0.00
 J5                0.00
 J6                0.00
 J7                0.00
 J8                0.00
 J9                0.00
 J10               0.00
 J11               0.00
 J12               0.00
 J13               0.00
 J14               0.00
 J15               0.00
 J16               0.00
 J17               0.00
 J18               0.00
 J19               0.00
 J20               0.00
 J21               0.00
 J22               0.00
 J23               0.00
 J24               0.00
 J25               0.00
 J26               0.00
 J27               0.00
 J28               0.00
 J29               0.00
 J30               0.00
 J31               0.00
 J32               0.00
 J33               0.00
 J34               0.00
 J35               0.00
 J36               0.00
 J37               0.00
 J38               0.00
 J39               0.00
 J40               0.00
 J41               0.00
 J42               0.00
 J43               0.00
 J44               0.00
```

```
 J45               0.00
 J46               0.00
 J47               0.00
 J48               0.00
 J49               0.00
 J50               0.00
 J51               0.00
 J52               0.00
 J53               0.00
 J54               0.00
 J55               0.00
 J56               0.00
 J57               0.00
 J58               0.00
 J59               0.00
 J60               0.00
 J61               0.00
 J62               0.00
 J63               0.00
 J64               0.00
 J65               0.00
 J66               0.00
 J67               0.00
 J68               0.00
 J69               0.00
 J70               0.00
 J71               0.00
 J72               0.00
 J73               0.00
 J74               0.00
 J75               0.00
 J76               0.00
 J77               0.00
 J78               0.00
 J79               0.00
 J80               0.00
 J81               0.00
 J82               0.00
 J83               0.00

[QUALITY]
;Node              InitQual

[SOURCES]
;Node              Type                Quality             Pattern
 R30W5             CONCEN              1000                1

[REACTIONS]
;Type        Pipe/Tank          Coefficient


[REACTIONS]
 Order Bulk              1
 Order Tank              1
 Order Wall              1
 Global Bulk             0
 Global Wall             0
 Limiting Potential      0
 Roughness Correlation   0
```

```
[MIXING]
;Tank              Model

[TIMES]
 Duration                196:00
 Hydraulic Timestep      0:01
 Quality Timestep        0:05
 Pattern Timestep        1:00
 Pattern Start           0:00
 Report Timestep         1:00
 Report Start            0:00
 Start ClockTime         00:00
 Statistic               NONE

[REPORT]
 Status                  Full
 Summary                 No
 Page                    0

[OPTIONS]
 Units                   GPM
 Headloss                H-W
 Specific Gravity        1.0
 Viscosity               1.0
 Trials                  40
 Accuracy                0.001
 CHECKFREQ               2
 MAXCHECK                10
 DAMPLIMIT               0
 Unbalanced              Continue 10
 Pattern                 1
 Demand Multiplier       1.0
 Emitter Exponent        0.5
 Quality                 None mg/L
 Diffusivity             1.0
 Tolerance               0.01

[COORDINATES]
;Node              X-Coord                Y-Coord
J1                 641814.170             3474046.260
J2                 642174.170             3473459.180
J3                 642174.170             3473384.410
J4                 643500.630             3473137.950
J5                 643553.250             3473417.650
J6                 644341.480             3473285.740
J7                 644342.700             3473256.240
J8                 645140.640             3473265.010
J9                 645633.590             3473175.790
J10                645803.270             3472990.990
J11                645830.570             3472971.490
J12                648271.440             3470011.340
J13                648441.120             3469755.840
J14                648563.990             3469467.190
J15                649669.840             3466254.960
J16                649794.670             3465981.910
J17                650020.910             3465677.650
J18                653391.120             3462198.220
J19                653410.620             3462143.610
J20                654065.940             3461429.780
```

J21	654081.540	3460255.670
J22	654916.300	3459452.120
J23	654916.300	3459389.710
J24	654951.400	3459358.500
J25	654970.910	3457845.030
J26	654931.900	3457809.920
J27	654943.600	3457146.800
J28	654959.200	3457076.590
J29	654970.910	3456159.920
J30	654993.330	3456141.400
J31	655012.840	3454592.820
J32	654996.260	3454572.340
J33	655013.810	3452912.590
J34	655048.920	3452881.380
J35	655060.620	3451313.300
J36	655021.610	3451274.290
J37	655033.320	3450634.570
J38	654842.180	3450303.010
J39	654853.880	3450256.200
J40	655002.110	3450174.290
J41	655061.050	3446438.890
J42	655033.460	3446405.780
J43	654867.920	3446403.020
J44	654854.390	3446389.200
J45	654856.490	3446357.640
J46	654856.060	3446350.650
J47	654834.150	3446326.550
J48	654799.220	3446324.930
J49	654794.740	3446322.510
J50	654792.930	3446318.750
J51	654800.190	3446033.000
J52	654748.750	3445795.890
J53	654726.120	3445691.920
J54	654380.690	3445766.720
J55	654635.590	3445274.170
J56	654635.150	3445271.070
J57	654663.140	3445266.870
J58	654539.420	3444634.870
J59	654538.650	3444632.110
J60	654537.540	3444630.340
J61	654530.680	3444622.370
J62	654459.410	3444538.930
J63	654205.780	3444755.720
J64	654142.030	3444167.550
J65	654018.310	3444022.800
J66	653716.430	3444280.640
J67	653634.310	3443573.400
J68	654399.140	3443948.240
J69	654697.400	3444481.380
J70	655604.610	3444406.810
J71	655602.550	3444398.640
J72	655804.400	3444333.010
J73	655608.480	3443728.110
J74	656201.180	3444204.710
J75	656204.150	3444211.960
J76	656416.550	3444110.710
J77	656700.530	3444759.470
J78	656678.430	3443996.590
J79	656685.690	3444001.540

```
J80                 656683.050              3443992.960
J81                 656684.370              3443988.670
J82                 656637.860              3443366.290
J83                 655032.550              3445735.080
WDS-IN              641822.894              3474128.901
BOOST_IN            641833.841              3474121.635
1                   641812.268              3474061.294
TCVTSR1             641842.722              3474060.143
R25W3               653629.234              3442168.042
R25W5               652658.601              3445169.196
R25W2               653116.026              3445738.188
R24W2               653673.861              3446385.277
R24W3               655793.635              3446061.733
R24W1               655403.151              3445381.173
R25W1               655235.800              3444968.375
R30W1               655603.971              3444934.905
R30W4               657054.343              3445570.837
R30W5               657902.253              3444008.898
R30W6               656630.388              3442123.415
R30W3               656920.463              3445916.695
R30W2               655559.345              3442112.258
R25W4               654443.674              3442156.885
TSR-1               641832.240              3474054.830
TSR-2               641885.570              3474083.130
ISR-1               654842.390              3446327.570
ISR-2               654857.987              3446348.849

[VERTICES]
;Link               X-Coord                 Y-Coord
ISR_1_2             654850.419              3446328.391
ISR_1_2             654856.065              3446333.768

[LABELS]
;X-Coord                Y-Coord            Label & Anchor Node
654988.295                 3446320.946            "Empty Tank Elev = 2791"
643070.753                 3474498.797            "Empty Tank Elev = 2601"

[BACKDROP]
  DIMENSIONS        641069.852              3441832.292              657444.848
      3475580.259
 UNITS              None
 FILE
 OFFSET             0.00              0.00

[END]
```

Appendix IV - Water Hammer R Script

The script below is adapted from:

Cleveland, T. G. (2018) "Pipeline Transients — Water Hammer" pp. 141-148 in *Fluid Mechanics Computations in R: A Toolkit to Accompany CE 3305 at TTU*. Department of Civil, Environmental, and Construction Engineering. http://54.243.252.9/ce-3372-webroot/3-Readings/CFMinR/CFMinR.pdf

It is intended to be run in an ordinary R environment. It was developed for pedagogical purposes, and at best is an approximation of general characteristics of system behavior.

```
#####################################################################################
#Pipeline Transients using Explicit Finite Differences (linearized formulation)   #
#####################################################################################
rm(list=ls()) # deallocate memory
######## prototype functions ###############
celerity <- function(density,elasticity_fluid,elasticity_solid,diameter,thickness){
  temp1<- 1.0/elasticity_fluid
  temp2<- diameter/(elasticity_solid*thickness)
  temp3<- temp1 + temp2
  temp4<- density*temp3
  celerity <- sqrt(1.0/temp4)
  return(celerity)
}
### Simulator Code ###############################
# Simulation Conditions (this section could be replaced with an input file)
# fluid properties
density <- 1000  #kg/m^3
elasticity_fluid <- 2.0e09 #Pa (2.0 GPa)
elasticity_solid <- 1.5e09 #Pa (1.5 GPa)
diameter <-  0.4572 #m (18 inches nominal for DR17 spec)
thickness <- 0.02689 #m (1.059 inhces for DR17 spec)
cc <- celerity(density,elasticity_fluid,elasticity_solid,diameter,thickness)
message("Celerity (m/sec) : ",round(cc,3))
# simulation properties
deltax <- 845.125 #meters (60 elements)
courantRatio <- 0.9876 #select courant ratio to set time step.  If bigger than 1
unstable
deltat <- courantRatio*(deltax/cc) # force to be courant number for stability
# allocate head and velocity vectors, assign initial values
elevValve = 793 #meters
elevTank = 850.9 #meters
```

```
startHead <- 859-elevTank #total head meters above tank bottom 8.84=(2820-2791)/3.28 from EPANET at ISR_2
startVelo <- 0.92 #meters/second 3.02/3.28 from EPANET at ISR2_PL
pipeLength <- 33805 #meters 21*5280/3.28 from manual calculation
closeTime <- 0 #seconds
simulationDuration <- 1800 #seconds
frictionFactor <- 0.02 #Moody Chart smooth pipe should be OK for HDPE; Re = 50,000
cellCount <- as.integer((pipeLength/deltax)+1)
head <- numeric(0)
velocity <- numeric(0)
for(i in 1:cellCount){
      head[i]<-startHead
  velocity[i]<-startVelo
}
####################################################################################
# useful constants
dtdx <- deltat/deltax
cc2g <- cc^2/9.81
do2 <- 1.0/(diameter*2) #used when friction included
#### force full-open velocity to agree with startVelo #######
c_factor = sqrt(2*9.8*(head[1]))/startVelo # used to simulate valve closure over finite time.
#c_factor = 1.0
###############################################
# allocate some output vectors
etime<-numeric(0)
headvalve<-numeric(0)
velocitytank<-numeric(0)
# simulation values
etime[1] <- 0
headvalve[1] <- head[cellCount]
velocitytank[1] <-velocity[1]
######################
# Time Stepping Loop #
######################
maxiter <- 1+simulationDuration/deltat
for(itime in 2:maxiter){
  etime[itime]<-etime[itime-1]+deltat
###### valve closure model ##############
  closeRatio <- 1-(etime[itime]/closeTime)
```

```
  if(closeRatio >= 0.0){
  velocity[cellCount] <- closeRatio*sqrt(2*9.8*(head[1]))/c_factor
  }
  else{
  velocity[cellCount] <- 0
  }
####### update velocity #########
for(i in 1:(cellCount-1)){
  friction <- frictionFactor*velocity[i]*abs(velocity[i])*do2
  velocity[i]=velocity[i]-9.81*dtdx*(head[i+1]-head[i])-deltat*friction
}
####### update head #########
for(i in 2:(cellCount)){
  head[i]=head[i]-cc2g*dtdx*(velocity[i]-velocity[i-1])
}
headvalve[itime]<-head[cellCount]
velocitytank[itime] <-velocity[1]
}
# report results
if(frictionFactor <= 0.0001){
   message("Frictionless Simulation - Expect Square Wave")
} else{
   message("Friction factor             : ",round(frictionFactor,3))
}
########################
message("Courant number  Dt (seconds): ",round(deltat,3))
message("Valve closure time (seconds): ",round(closeTime,3))
message("Maximum head at valve (feet): ",round(3.28*(max(headvalve)),3))
message("Max. pressure at valve (psi): ",round(14.75*(max(headvalve))/10,3))
message("Minimum head at valve (feet): ",round(3.28*(min(headvalve)),3))
message("Min. pressure at valve (psi): ",round(14.75*(min(headvalve))/10,3))
# plot results
par(mfrow=c(2,1))
plot(etime,headvalve,type="l",pch=19,lwd=3,tck=1,xlab="Time   (seconds)",ylab="Head
at Valve (meters)",col="red")
plot(etime,velocitytank,type="l",pch=19,lwd=3,tck=1,xlab="Time
(seconds)",ylab="Velocity at Tank (meters/sec)",col="blue")
#
###########
```

Appendix V- EGL Plotting Script (Python)

The script below is intended to run in a Jupyter notebook using the iPython kernel. It should run in ordinary python if the requisite packages are installed (into the kernel)

```
# Produce Plot of HGL and PGL from EPANET Network Node
import matplotlib.pyplot as plt

id_lat_lon = []
externalfile = open("NodesInOrder.txt",'r') # create connection to file, set to
read (r), file must exist
for line in externalfile:
    id_lat_lon.append([str(n) for n in line.strip().split()])
externalfile.close()
# type cast head columns
for i in range(len(id_lat_lon)):
    id_lat_lon[i][1]=float(id_lat_lon[i][1])
    id_lat_lon[i][2]=float(id_lat_lon[i][2])
#id_lat_lon

# distance function x is northing, y is easting
# origin is TSR_2: 641885.570,3474083.130
x_origin = 641885.57
y_origin = 3474083.13
#
def distanceXY(xpoint,ypoint,x_origin,y_origin):
    import math
    dsq = ((xpoint-x_origin)**2)+((ypoint-y_origin)**2)
    distanceXY = math.sqrt(dsq)
    return(distanceXY)

# build a related list - ID and distance from TSR1
id_dist_raw = [] # null list, will use append
id_dist_raw.append([id_lat_lon[0][0],distanceXY(id_lat_lon[0][1],id_lat_lon[0][2],i
d_lat_lon[0][1],id_lat_lon[0][2])])
for i in range(1,len(id_lat_lon)):

id_dist_raw.append([id_lat_lon[i][0],3.28*distanceXY(id_lat_lon[i][1],id_lat_lon[i]
[2],id_lat_lon[i-1][1],id_lat_lon[i-1][2])+id_dist_raw[i-1][1]])
#id_dist_raw

id_heads = []
externalfile = open("heads-p2-h30-q2100.txt",'r') # create connection to file, set
to read (r), file must exist
for line in externalfile:
    id_heads.append([str(n) for n in line.strip().split()])
externalfile.close()
# retype head columns
for i in range(len(id_heads)):
    id_heads[i][1]=float(id_heads[i][1])
    id_heads[i][2]=float(id_heads[i][2])

id_excludes = []
externalfile = open("NodesToExclude.txt",'r') # create connection to file, set to
read (r), file must exist
for line in externalfile:
    id_excludes.append([str(n) for n in line.strip().split()])
externalfile.close()
```

```
# retype head columns
for i in range(len(id_excludes)):
    id_excludes[i][1]=float(id_excludes[i][1])
    id_excludes[i][2]=float(id_excludes[i][2])

#print(id_heads)
#id_excludes

# naive join
# want a list ID,dist,head1,head2 - but it should be sorted on dist, remove RXXX
locations
len1 = len(id_dist_raw)
len2 = len(id_heads)
len3 = len(id_excludes)
pdataframe = []
for irow in range(len1):
    drop = 0
    for jrow in range(len3):
        if(id_dist_raw[irow][0] == id_excludes[jrow][0]):
            #print("skip this row")
            drop = 1
    if(drop == 1):
        continue
# scan and skip RW rows
#    if("R" in id_dist_raw[irow][0] and "W" in id_dist_raw[irow][0]):
#            continue
# build the dataframe
    else:
        for jrow in range(len2):
            if(id_dist_raw[irow][0] == id_heads[jrow][0]):

pdataframe.append([id_heads[jrow][0],id_dist_raw[irow][1],id_heads[jrow][1],id_head
s[jrow][2]])
            else:
                continue


#pdataframe

## Build Plotting lists
list1 = []
list2 = []
list3 = []
list4 = []
delta_h = []
p_psi = []
for i in range(len(pdataframe)):
    list1.append(pdataframe[i][1]) # distance
    list2.append(pdataframe[i][2]) # elevation
    list3.append(pdataframe[i][1]) # distance
    list4.append(pdataframe[i][3]) # total head
    delta_h.append(pdataframe[i][3]-pdataframe[i][2]) # pressure head
    p_psi.append(delta_h[i]/2.257) # pressure

xlabel = 'Distance from City Yard (feet)'
ylabel = 'Elevation or Head (feet)'
legend1 = 'Energy Grade Line'
legend2 = 'Profile Grade Line'
ptitle = 'Energy Grade and Profile Grade Line Plot \n P2-H30-Q2100'
```

```
cline1 = 'red'
cline2 = 'blue'

def
Plot2Lines(list1,list2,list3,list4,ptitle,xlabel,ylabel,legend1,legend2,cline1,clin
e2):
# Create a line chart of speed on y axis and time on x axis
    mydata = plt.figure(figsize = (18,5)) # build a drawing canvass from figure
class; aspect ratio 4x3
    plt.plot(list1, list2, c=cline1, marker='.',linewidth=2) # basic line plot
    plt.plot(list3, list4, c=cline2, marker='.',linewidth=1) # basic line plot
    plt.xlabel(xlabel) # label the x-axis
    plt.ylabel(ylabel) # label the y-axis, notice the LaTex markup
    plt.legend([legend1,legend2]) # legend for each series
    plt.title(ptitle) # make a plot title
    plt.xlim(0, 120000)
#    plt.ylim(2700, 2850)
    plt.grid() # display a grid
    plt.show() # display the plot
    return()

def PlotALine(list1,list2,ptitle,xlabel,ylabel):
# Create a line chart of speed on y axis and time on x axis
    mydata = plt.figure(figsize = (20,5)) # build a drawing canvass from figure
class; aspect ratio 4x3
    plt.plot(list1, list2, c='red', marker='.',linewidth=2) # basic line plot
#    plt.plot(list3, list2, c='blue', marker='.',linewidth=1) # basic line plot
    plt.xlabel(xlabel) # label the x-axis
    plt.ylabel(ylabel) # label the y-axis, notice the LaTex markup
#    plt.legend([legend1,legend2]) # legend for each series
    plt.title(ptitle) # make a plot title
    plt.xlim(0, 120000)
#    plt.ylim(2700, 2850)
    plt.grid() # display a grid
    plt.show() # display the plot
    return()



Plot2Lines(list1,list4,list3,list2,ptitle,xlabel,ylabel,legend1,legend2,cline1,clin
e2);
# Find location in EPANET of min pressure
minpos = p_psi.index(min(p_psi))
minloc = str(pdataframe[minpos][0])
# Find location on EPANET of max pressure
maxpos = p_psi.index(max(p_psi))
maxloc = str(pdataframe[maxpos][0])
ylabel = 'Pressure (psi) or Pressure Head (feet)'
ptitle = 'Pressure (EGL - PGL)/2.257 \n Min: ' + repr(round(min(p_psi),2)) + 'psi
Max: ' + repr(round(max(p_psi),2)) + 'psi ' \
+ '\n Min location : ' + minloc + ' Max location : ' + maxloc
legend1 = 'Pressure Head (feet)'
cline1 = 'black'
legend2 = 'Pressure (psi)'
cline2 = 'red'
Plot2Lines(list1,delta_h,list3,p_psi,ptitle,xlabel,ylabel,legend1,legend2,cline1,cl
ine2);
#PlotALine(list1,p_psi,ptitle,xlabel,ylabel);
```

Appendix VI – Accessing FREESWMM

The simulation input files, supporting data, a working implementation for this project are located at http://freeswmm.ddns.net/

A video showing how to access FreeSWMM is located at https://youtu.be/yjfJt-sMdBk