Hydrodynamic Modeling of Marco Island Canals

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Project name: Hydrodynamic Modeling of Marco Island Canals

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1. Introduction and Objectives

The City of Marco Island is evaluating how to effectively improve water quality within the canals and waterways across Marco Island through modifications to the canal network to increase the exchange of gulf water. Tidal flushing between the north and south is now limited to a few small culverts under San Marco Road, which bisects Marco Island by hydrodynamically separating the northern and southern canal systems.

The City tasked Jacobs with performing a hydrodynamic modeling analysis to investigate the potential for improved tidal flushing in the dense network of dredged channels by means of installing new culverts and enlarging existing culvert connections across San Marco Road. Increasing the interconnectivity of the northern and southern canals could improve water exchange in throughout the island with surrounding gulf water. Improvements in flushing could be expected to reduce adverse environmental effects of stagnant water and loss of dissolved oxygen.

This technical memorandum documents the hydrodynamic modeling analysis, including data collection, model development, model simulations, and model results. Recommendations on how to move forward with modifications to interior channel connections are provided at the end of this technical memorandum.

2. Methodology

A dynamic numerical model is required to evaluate the tidal flushing across Marco Island; one that can simulate the change in pressures from the rising waters that change spatially around the island during tidal cycles. The hydrodynamic modeling approach was to construct a two-dimensional (depth-averaged) model of Marco Island (Figure 1) to quantify improvements in tidal flushing for alternative project scenarios in which culvert connections through San Marco Road are increased or enlarged. The modeling analysis was conducted with the US Army Corps of Engineers RMA2 and RMA4 models, run through the Surfacewater Modeling System (SMS) software version 13.3.3.

The RMA2 hydrodynamic model uses hydrographic survey data to assign channel depths on a cell-by-cell basis over a detailed model grid covering Marco Island. Tidal data was obtained from the National Gulf and Atmospheric Administration (NOAA) network of tidal gauges, namely stations at Caxambas Pass on the south side of the island and at Big Marco River on the north side of the island. The differences between the tidal elevations over time drive the hydrodynamics in the canals. The numerical model developed for this study solves for local stage and velocity every 15 minutes for a two-week tidal cycle at over 26,000 grid locations in the model domain. Model output can be used to quantify the net flow through the canals under existing conditions and proposed conditions with modified or new culverts. Comparison of the flows for proposed conditions to the existing conditions allows quantification of improvements in flushing.

Output from the hydrodynamic model was used as input into the RMA4 model, which simulates the transport of a conservative tracer into the interior channels, replacing the canal water as the simulation progresses. By comparing the increase in the tracer concentration in the interior canals overtime between the existing conditions simulations and proposed conditions simulations, one can determine the improvement in flushing.

Several assumptions were required in the development and application of the tidal hydrodynamic and flushing models of Marco Island. There are also several inherent limitations of the model. These assumptions and limitations are as follows:

- The model is based on canal depths provided by the City. The Consultant did not perform an independent bathymetric survey to confirm actual conditions. Although the data are dated and local depths could vary from those provided in the March 2005 survey, it is assumed that the survey provides a reasonable representation of the Island for the purposes of this modeling exercise.
- The modeling effort was limited to water movement, water age, and dilution effects. The modeling did not include water quality modeling of biological activity that may be occurring within the canals or associated canal bottoms. Therefore, projected improvements in dissolved oxygen can only be inferred.
- The Consultant has not assessed field conditions to determine the condition or extent of accumulated organic matter at the bottom of the canals that could contribute to the continued loss of dissolved oxygen even with promoting water exchange to reduce stagnant water conditions.
- The two-dimensional model assumes water is vertically mixed. This is not likely true near the bottom of the finger canals, but these canals are relatively shallow, and stratification would be small and not significantly affect the main issue of flushing. Salinity and temperature gradients could lead to reduced mixing in the bottom waters of the deeper canals relative to results presented herein. A more involved three-dimensional modeling analysis would be required to investigate sensitivity to vertical density differences.
- A typical tidal series was taken to represent a full 14-day tidal cycle. This same cycle was repeated to run longer than 14-day simulations. This is a simplification adopted to reduce model simulation run times (computational requirements) and is not expected to materially affect model results.
- Calibration of the hydrodynamic model was not conducted as there are no interior stage data to use and the current system is constrained (limited flow).
- The model does not include the influence of wind on local hydrodynamics. Wind is highly variable and will affect the flow in shallow coastal waters. By not including wind, the simulation results are a more direct evaluation of the potential effect of new culverts only.

2.1 Site Conditions

City staff provided hydrographic survey information from a survey conducted in March 2005. This was the latest available survey of the full island. City staff also provided information on the location, size, and invert elevations of existing culverts at San Marco Road. There are four existing culvert connections through San Marco Road. Figure 2 shows the location and diameter of 6 culverts, numbered sequentially from west to east. Culverts 2 and 3 are not currently connected all the way through San Marco Road.

Predicted tidal data was obtained from the NOAA website (tidesandcurrents.noaa.gov) for Caxambas Pass (Station 8724967) and Big Marco River (Station 8724991). NOAA publishes predicted tides based on harmonic constituents determined from historic records at a given location. The historic record appears to be limited to approximately 5 years at Caxambas Pass (1976 to 1981), while the gauge at Big Marco River has almost 60 years of historical data. Neither of these gauges are currently active. Figure 3 shows a 4-week sample of the predicted tides, showing the difference between spring tides (larger tidal range) and neap tides (smaller tidal range). Figure 4 shows a detail of two days’ worth of tides. Note the positive gradient from south to north, with tides at Caxambas Pass generally higher than those at Big Marco River. This stage differential is what drives the flushing across the island.

2.2 Hydrodynamic Model

The RMA2 hydrodynamic model was constructed in SMS using depth soundings provided by the City to set model geometry and NOAA predicted tides to drive the hydrodynamics. The model does not include any wind forcing. The model runs for a two-week period using 15-minute resolution water level predictions starting June 1, 2023. The two-week period accounts for the full spring-neap tidal cycle (Figure 3). The 26,000-element two-dimensional model grid is shown in Figure 5.

Model simulations were conducted for existing conditions and three potential future improvements that were developed in consultation with the City. The existing conditions simulation includes connections at Culverts 1, 4, 5, and 6. The connection at Culvert 4 was recently completed by the City. The Improvement 1 simulation increased the size of Culvert 1 from a 24-inch diameter pipe to a 60-inch diameter pipe. The Improvement 2 simulation increased the size of Culvert 5 to a 48-inch diameter pipe. The culvert is currently 30-inch diameter on the south side of San Marco Road and 24-inch diameter on the north side of the road. Improvement 2 also retained the improvement at Culvert 1. Improvement 3 connects Culvert 3 with a 30-inch diameter pipe. There is currently a 30-inch diameter pipe south of San Marco Road but no connection through to the north side of the road. Improvement. These scenarios are summarized in Table 1. The future changes were considered as potentially feasible, but no further engineering design or field investigations have been conducted.

Table 1. Summary of Scenarios Evaluated

Scenario	Culvert Location Diameter (inches, N/S)					
	1	2	3	4	5	6
Existing Conditions	24/24	X/36	x/30	24/24	24/30	30/36
Improvement 1	60/60	nc	nc	nc	nc	nc
Improvement 2	60/60	nc	nc	nc	48/48	nc
Improvement 3	60/60	nc	30/30	nc	48/48	nc

N/S means the north or south side of San Marco Road; X means not connected; nc means no change from existing conditions.

2.3 Flushing Model

The RMA4 model was used to simulate transport (advection and dispersion) of a conservative tracer under tidal action. Results from the 14-day hydrodynamic model simulation were used as inputs to the water quality model. Since the hydrodynamic model duration includes the full spring-neap tidal cycle, the water quality model was run for extended periods by repeating the hydrodynamics on a 14-day loop. This allowed for 8-week simulation periods to track the longer-term performance potential of modifications to the existing culverts. Flushing model simulations were conducted for each of the four hydrodynamic model simulations presented above. Simulation durations were set for a total of 56 days. The model domain was started with a tracer concentration of 0 (consider as mg/l for simplicity) while gulf boundaries were set at 100 (mg/l). By using this approach, the change in concentrations is also a measure on the amount of gulf water that is exchanged in the canals over a period of time. The concentration at any point in time at a given location can be interpreted as the fraction of ocean water at that point in the simulation.

The flushing model results can be sensitive to the dispersion coefficients used in the model. The model uses estimates of the dispersion coefficient but has not been calibrated. Calibration of the dispersion coefficient in the model would require a physical dye study in the interior canals of Marco Island. Also, wind conditions could alter results.

3. Results

3.1 Hydrodynamic Model of Flows

Model results are presented as tables of average net flows and time series plots of flows at select locations. Plots were generated at select locations to visually present the results.

Figure 6 presents a time series of flow through Culvert 1 for existing conditions and the enlarged 60-inch diameter culvert modelled in the Improvement 1 simulation. The average flow through Culvert 1 in the existing conditions simulation is 2.2 cfs. Figure 6 shows that flows though the existing culvert are generally symmetrical around the zero flow line, with maximum flows to the north of about 14 cfs and similar flows to the south. The larger 60-inch diameter culvert shows not only significantly larger peak flows exceeding 50 cfs, but also a marked asymmetry about the zero line with flows to the north occurring over about three-quarters of the tidal cycle, which yields a stronger net flow to the north. When averaged over the 14-day simulation, the flows to the north through Culvert 1 are 20.8 cfs, an almost ten-fold increase from existing conditions. The difference in cross section area of the culvert increased from 3.1 square feet to 19.6 square feet in this simulation.

Figure 7 presents a time series of flow through Culvert 5 for existing conditions and the enlarged 48-inch diameter culvert modelled in the Improvement 2 simulation. The average flow through Culvert 5 increases from 0.9 cfs in existing conditions to 14.1 cfs with the enlarged culvert. The increased asymmetry in tidal flows favoring flows to the north is visible in Figure 8 with the larger pipe diameter.

Table 2 presents a summary of the net flow at select locations averaged over the 14-day hydrodynamic model simulation period. Net flows are positive to the north, indicating flow from south to north through San Marco Road. Flow at the southern boundary measures the total net flow through the system. Flow here is found to increase from 11 cfs to 29.5 cfs in Improvement 1 and 54.7 cfs in Improvement 3.

Table 2. Average Flows (in cfs) for 14-day Hydrodynamic Simulations

Location	Existing Conditions	Potential Future Conditions		
		Improvement 1	Improvement 2	Improvement 3
Culvert 1	2.2	20.8	20.8	20.8
Culvert 2 and 3 (combined)	0.2	0.1	0.1	1.4
Culvert 4	2.2	2.2	2.2	2.2
Culvert 5	0.9	0.9	14.1	22.4
Culvert 6	4.1	4.1	4.1	4.1
Northeast Boundary	6.1	6.1	19.3	27.5
Northwest Boundary	7.4	25.9	25.9	29.6
South Boundary	11.0	29.5	42.7	54.7

Note: All flows for all simulations are positive to the north, indicating net flow through the island from south to north

3.2 Flushing Model

Flushing model results are presented as time series plots of tracer concentrations and snapshots of tracer concentration contour maps in the model domain after an 8-week simulation. The tracer concentration increases over time as gulf water flows through the island (south to north) under tidal action. A concentration between 0 and 100 is an indicator on the amount of gulf water exchanged at the cell in the model. For example, a concentration of 80 mg/L means that 80 percent of the water in the cell is gulf and 20 percent was the original canal water at that time. A concentration of zero means no gulf water has arrived at that point.

Figure 8 shows a time series of tracer concentration on the north side of Culvert 1 for the existing conditions and Improvement 1 scenarios. Increasing the size of the connections improves the net flow as discussed above which improves the rate of flushing as evidenced by the tracer concentration plots. The lack of flushing in Landmark Canal, which is prominent in the observed decline of local water quality, is easily seen in Figure 8. There is no gulf water at the north end of Landmark Canal after 56 days of tidal flushing.

Figure 9 presents the flushing model results on the north side of Culvert 5 for the existing conditions and Improvement 2 scenarios. Culvert 5 is closer to the outer boundaries of the model domain, and thus the gulf water reaches the crossing after 3.5 weeks. At the end of the 8-week simulation with the enlarged culvert, the tracer concentration at Culvert 5 is about three times higher than the existing conditions results.

Figures 10 through 12 compare contours of tracer concentration over the full model domain for existing conditions and each of the three potential improvement simulations. The existing conditions tracer contours are shown on the left in each figure, with contours between 0 (canal water) and 100 (gulf water). The improved conditions are shown on the right in each figure. The culverts active in the existing conditions simulation are noted (1, 4, 5, and 6). Results in all three figures are shows after 8 weeks of simulation time. The gulf water flows into the canal system from the north and south, mixing with the canal water and carrying some of the initial canal water out of the system on each falling (ebb) tide. The net flow from south to north and the tidal flushing on individual ebb tides both serve to increase the tracer concentrations in the interior canals.

Figure 10 shows the general improvement in water exchange in the Landmark Canal seen when Culvert 1 is enlarged from a 24-inch diameter pipe to a 60-inch diameter pipe. Tracer concentrations at the north end of Landmark Canal show almost 70% of the original water has been replaced by ocean water in the 8-week simulation period. There are no changes to conditions on the eastern side of the island between the existing conditions simulation and the Improvement-1 simulation.

Figure 11 compares tracer concentrations between the existing conditions simulation and the Improvement 2 simulation, which enlarged Culvert 5 to 48 inches in diameter and retained the enlarged Culvert 1 from the previous simulation. Tracer concentrations show 80% ocean water after 8 weeks with the enlarged culvert, a significant improvement to the 28% ocean water seen in the existing conditions simulation..

Figure 12 compares the tracer concentrations after 8 weeks of tidal flushing for the Improvement 3 simulation. There are minor incremental improvements in water exchange in the canals near Culverts 3 and 4 with the additional connection of Culvert 3 through San Marco Road.

4. Summary, Conclusions, and Recommendations

Only a complex hydrodynamic model, like the one developed here, could characterize the flow and flushing across the island. The hydrodynamic modeling analysis clearly demonstrates the potential for improved water exchange between the canals and waterways across Marco Island with water surrounding Marco Island by increasing the number and size of culverts across San Marco Road. The minor asymmetry in tides between the Caxambas Pass gauge in the south and the Big Marco River gauge in the north is enough to promote a net flow from south to north through the island. Flushing is evident from the time series plots of tracer concentration near the culverts and from the plan view contour plots of the whole island. Significant changes in the simulated concentrations occurred with the potential improvement scenarios.

Existing culverts provide a net flow from south to north of about 2 cfs each averaged over the 14-day tidal cycle. Enlarged culverts can get over ten times the net flow seen in the existing conditions simulations. The flushing time of the system, quantified as the volume of the system divided by the net inflow, can be reduced by up to a factor of five for the improvements analyzed in this study.

The improvement scenarios included here were potential project combinations provided by the City and it may choose to phase implementation. As projects move forward with design there may be other challenges that will alter results provided here. These results demonstrate that adding more culvert capacity should increase flushing from south to north. The increase in flushing will depend on the ability to increase the total size of all culverts under San Marco Road. However, there will be a maximum flow capacity that could be attained given the size of the island (upstream versus downstream gradient) and canal system size.

5. References

City of Marco Island, 2005. Hydrographic survey information of Marco Island. March 2005.

NOAA, 2023. NOAA Tides and Currents website for local tide predictions. at Big Marco River and Caxambas Pass.

Big Marco River (https://tidesandcurrents.noaa.gov/stationhome.html?id=8724991)

Caxambas Pass (https://tidesandcurrents.noaa.gov/stationhome.html?id=8724967)

Aquaveo, 2023. Surfacewater Modeling System, version 13.3. www.Aquaveo.com

Figures


Big Marco River
Caxambas Pass
Feet (U.S. Survey)
0
2500
5000

Figure 1. Marco Island Overview with Model Domain

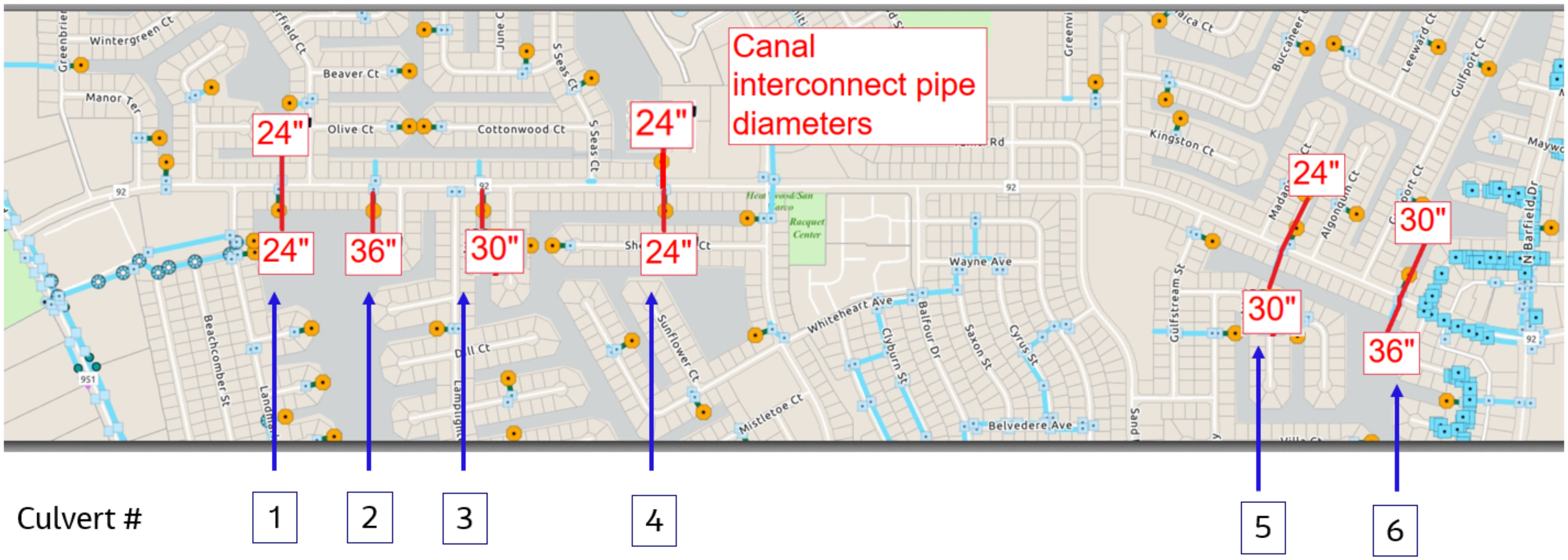

Figure 2. Existing Conditions: 4 Active Connections through San Marco Road

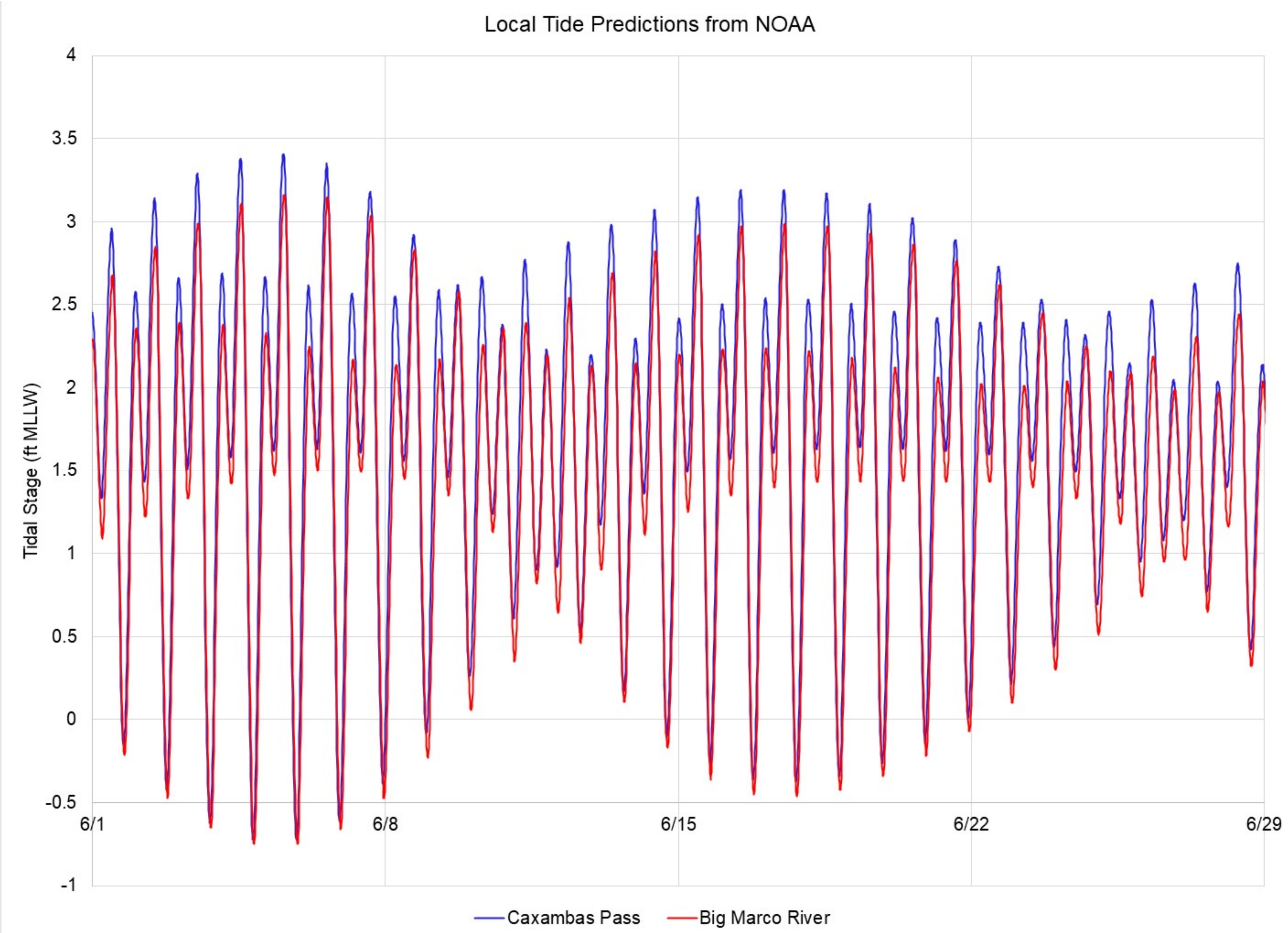

Figure 3. June 2023 Tides at Caxambas Pass and Big Marco River (NOAA)

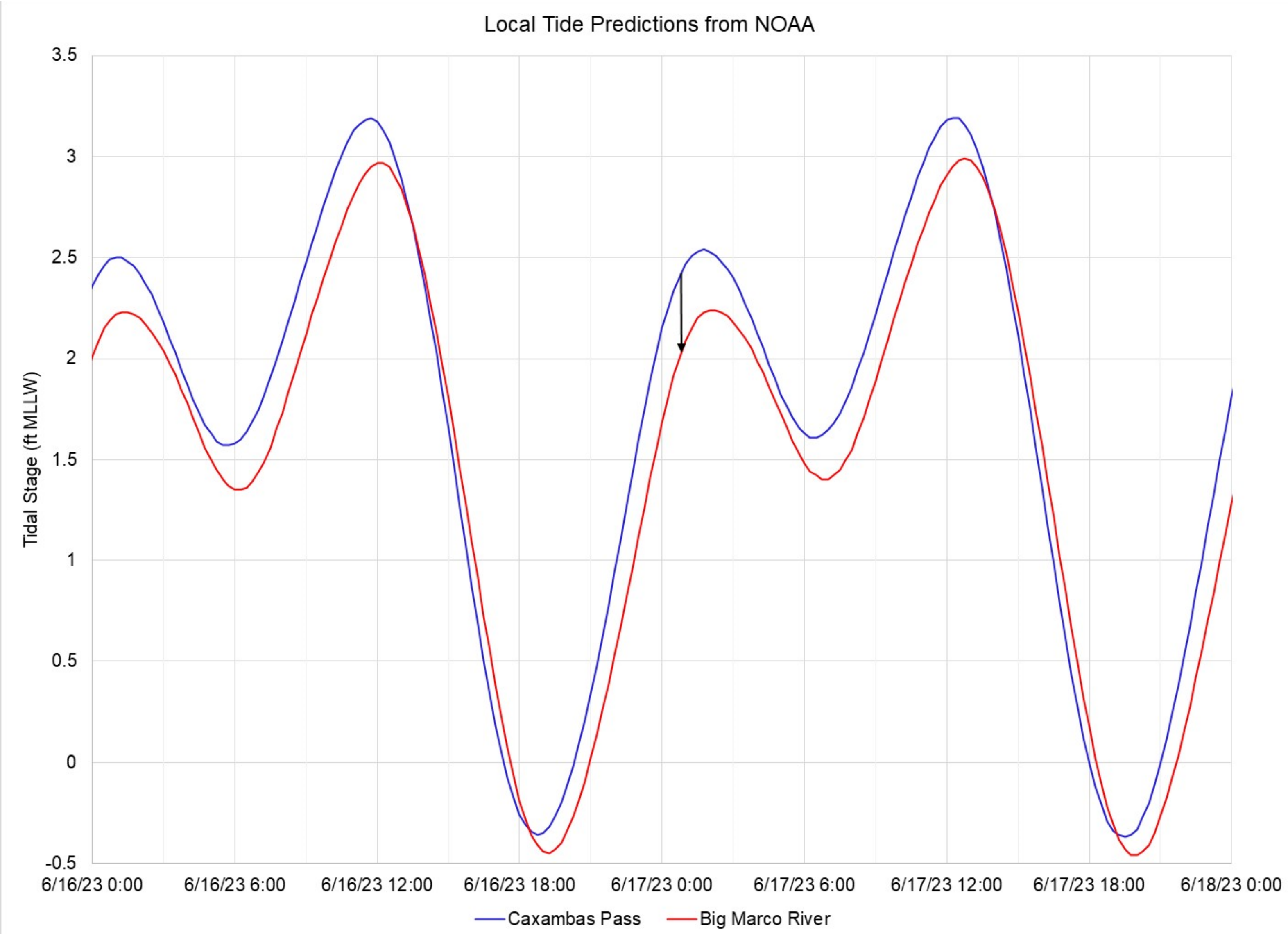

Figure 4. Tide Detail at Caxambas Pass and Big Marco River (NOAA)

Figure 5. RMA2 and RMA4 Model Grid of Marco Island

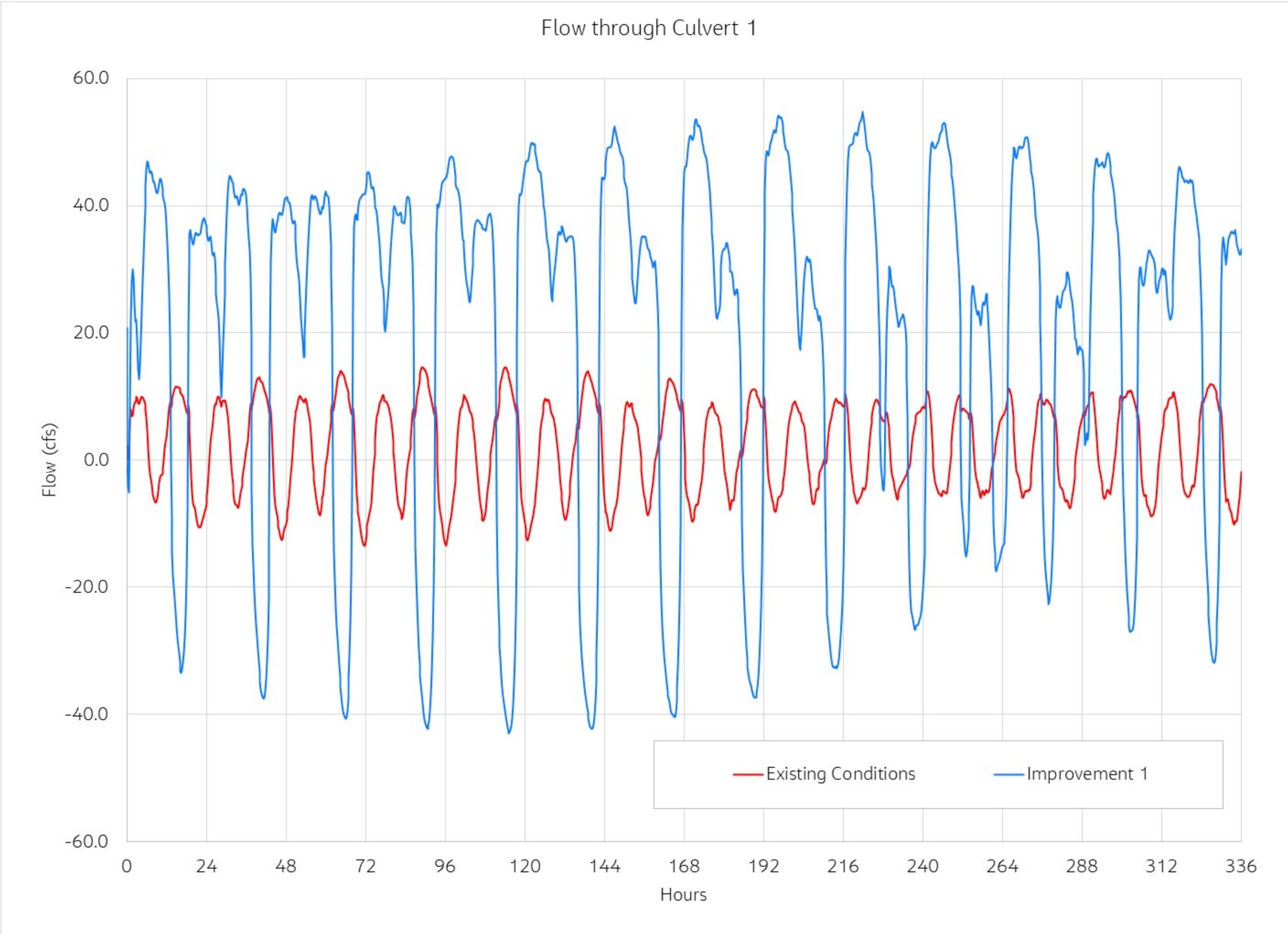

Figure 6. Existing and Improvement 1: Tracer Concentration at the end of 56-day simulation

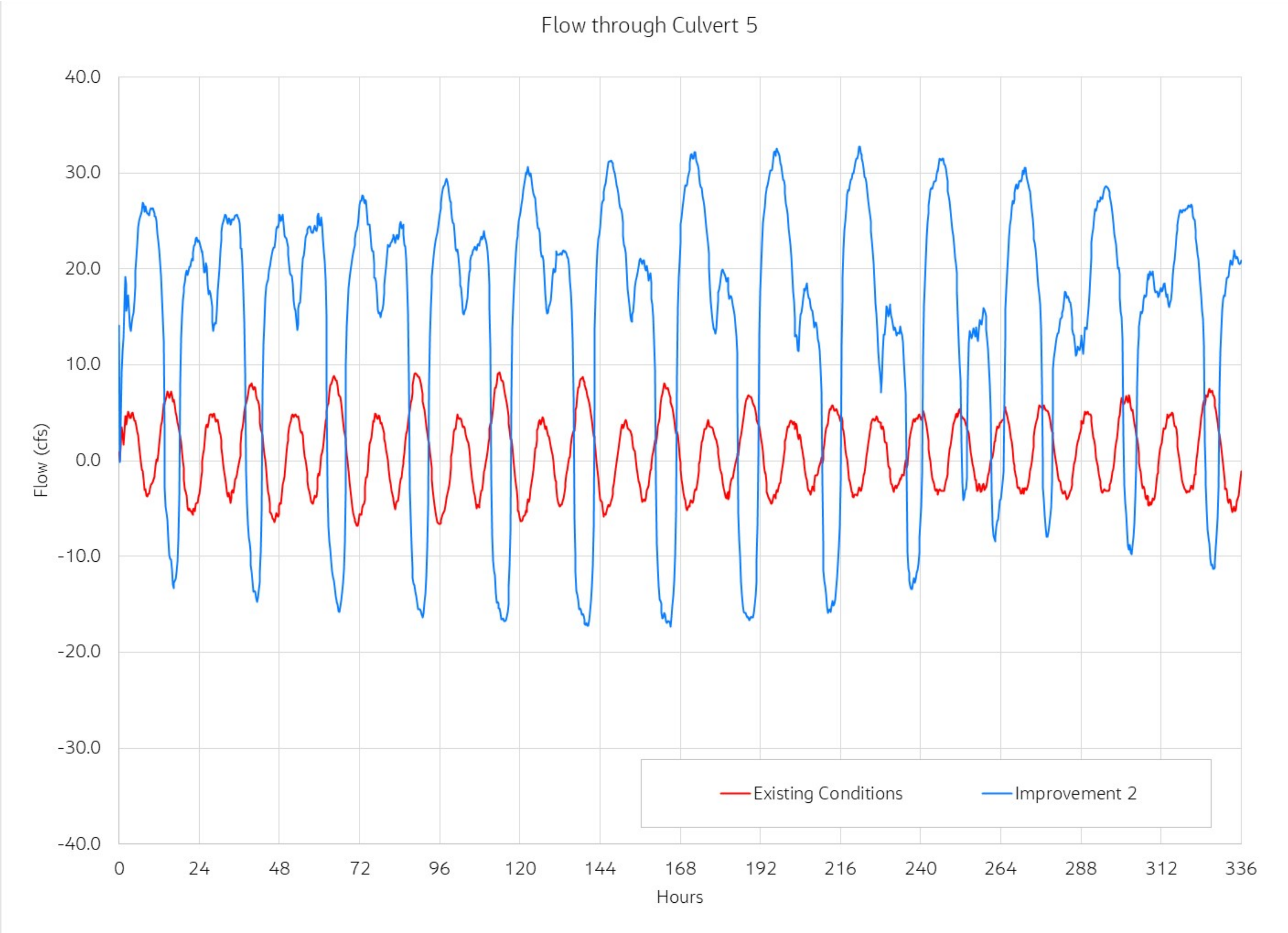

Figure 3. Existing and Improvement 1: Tracer Concentration at the end of 56-day simulation

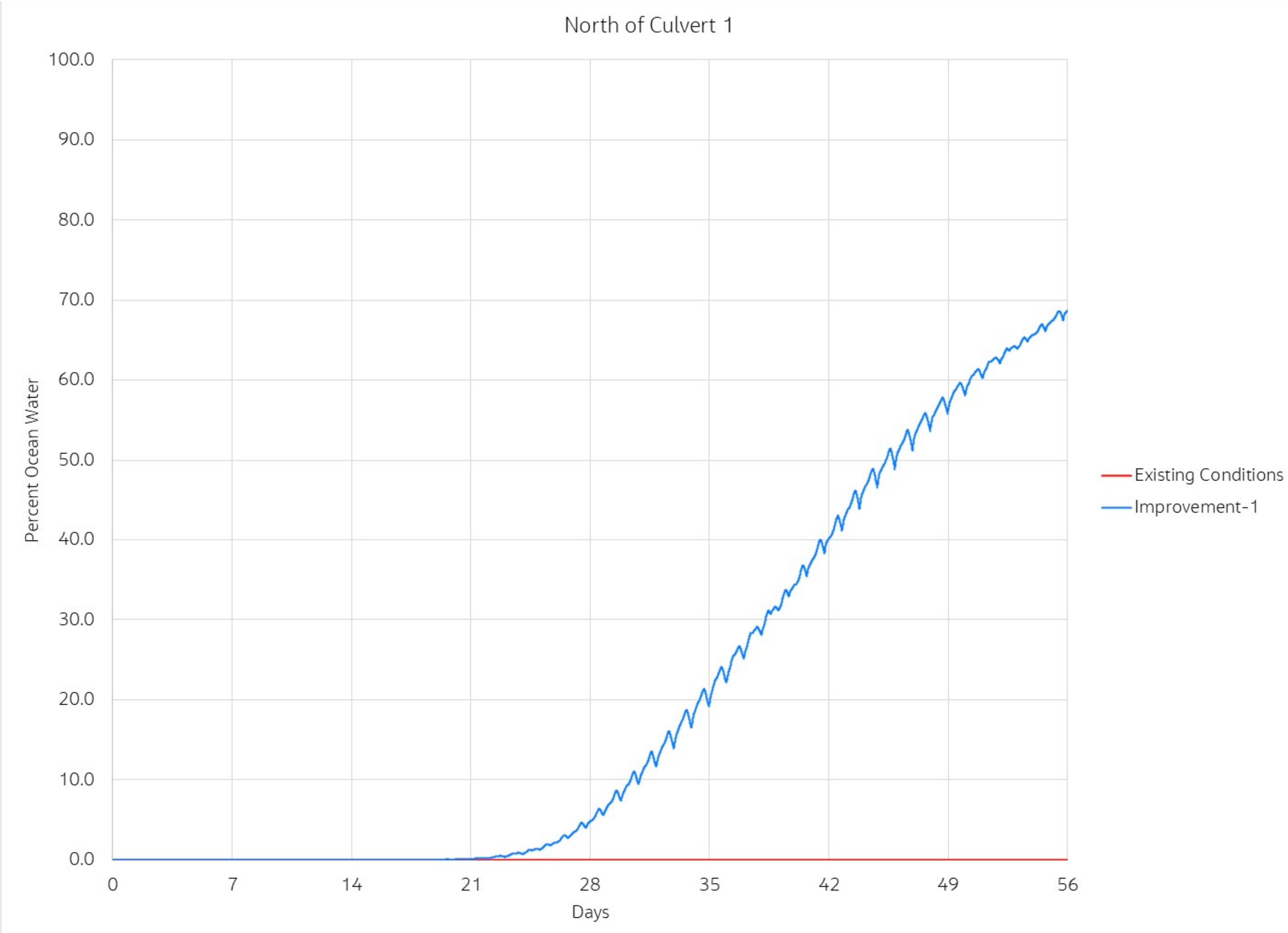

Figure 8. Existing and Improvement 1: Tracer Concentration at the end of 56-day simulation

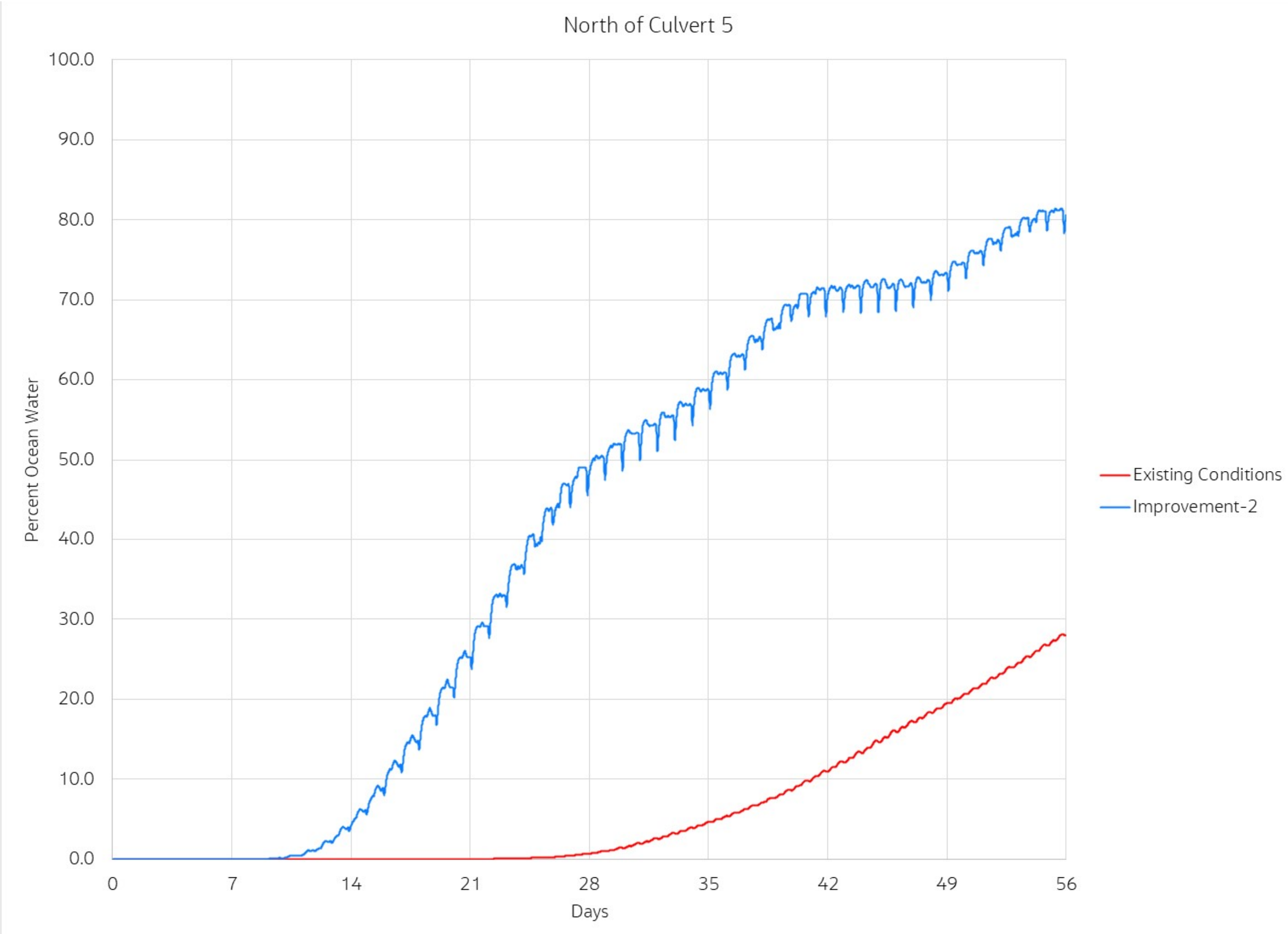

Figure 9. Existing and Improvement 2: Tracer Concentration at the end of 56-day simulation

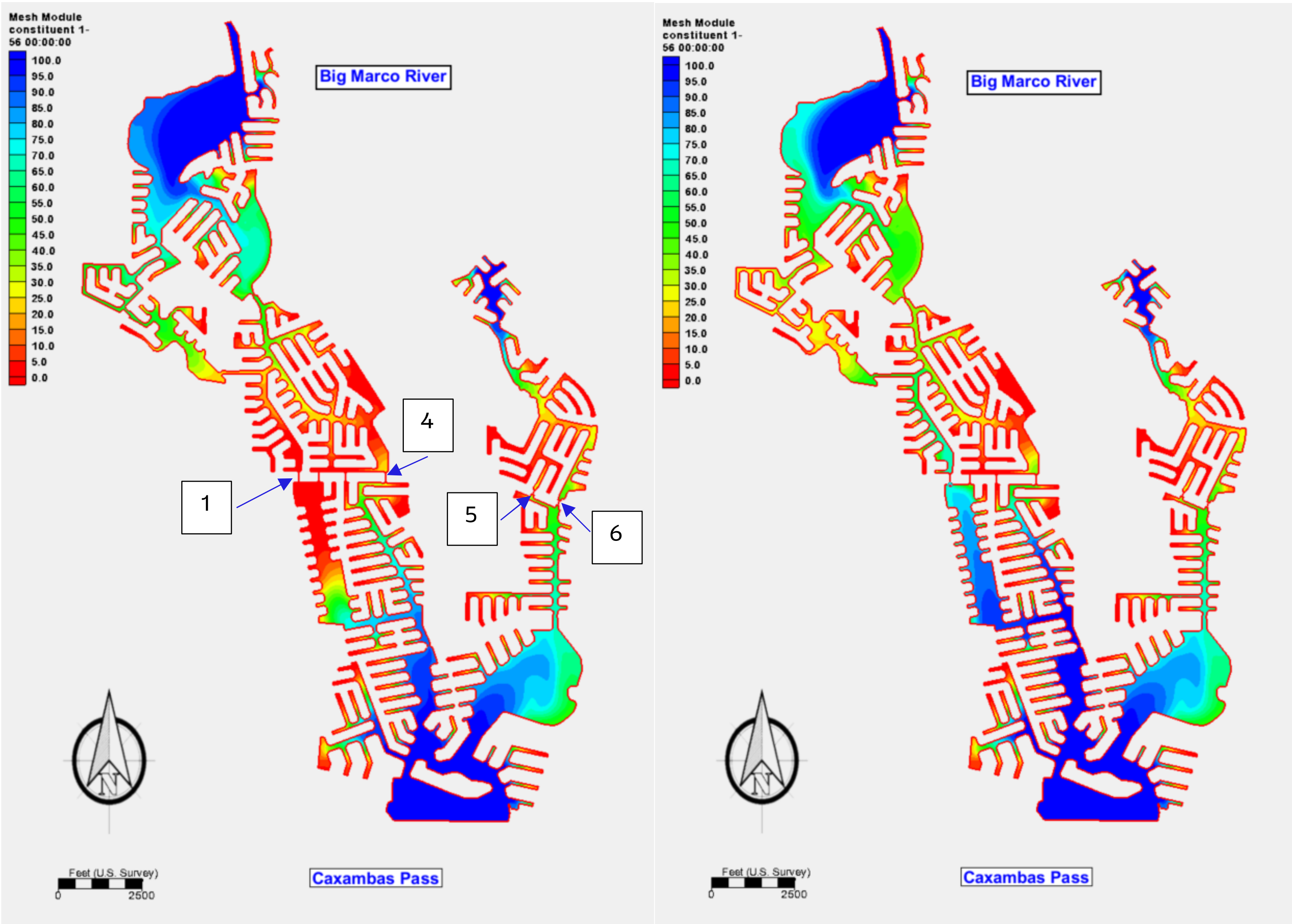

Figure 10. Existing and Improvement 1: Tracer Concentration at the end of 56-day simulation

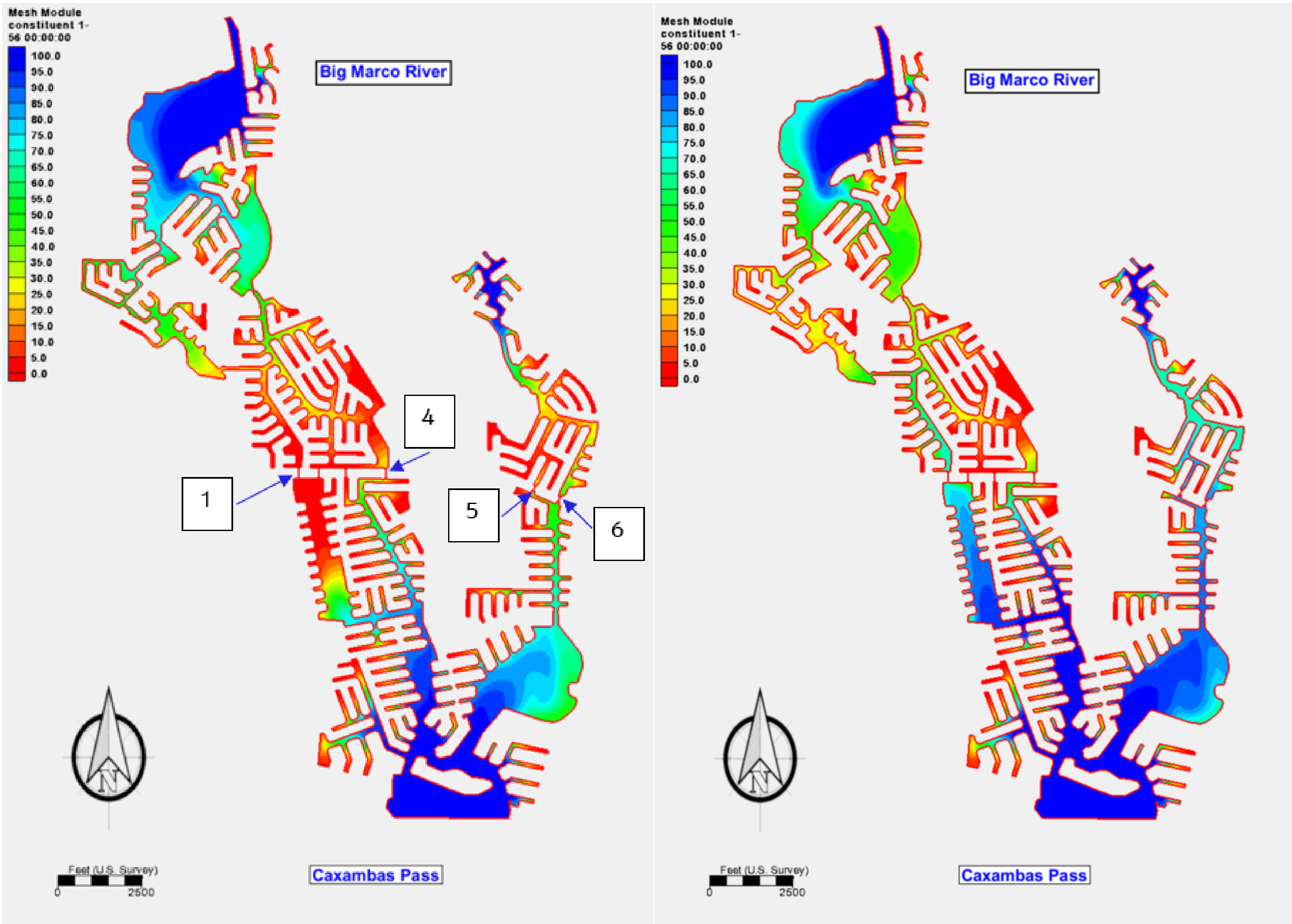

Figure 11. Existing and Improvement 2: Tracer Concentration at the end of 56-day simulation

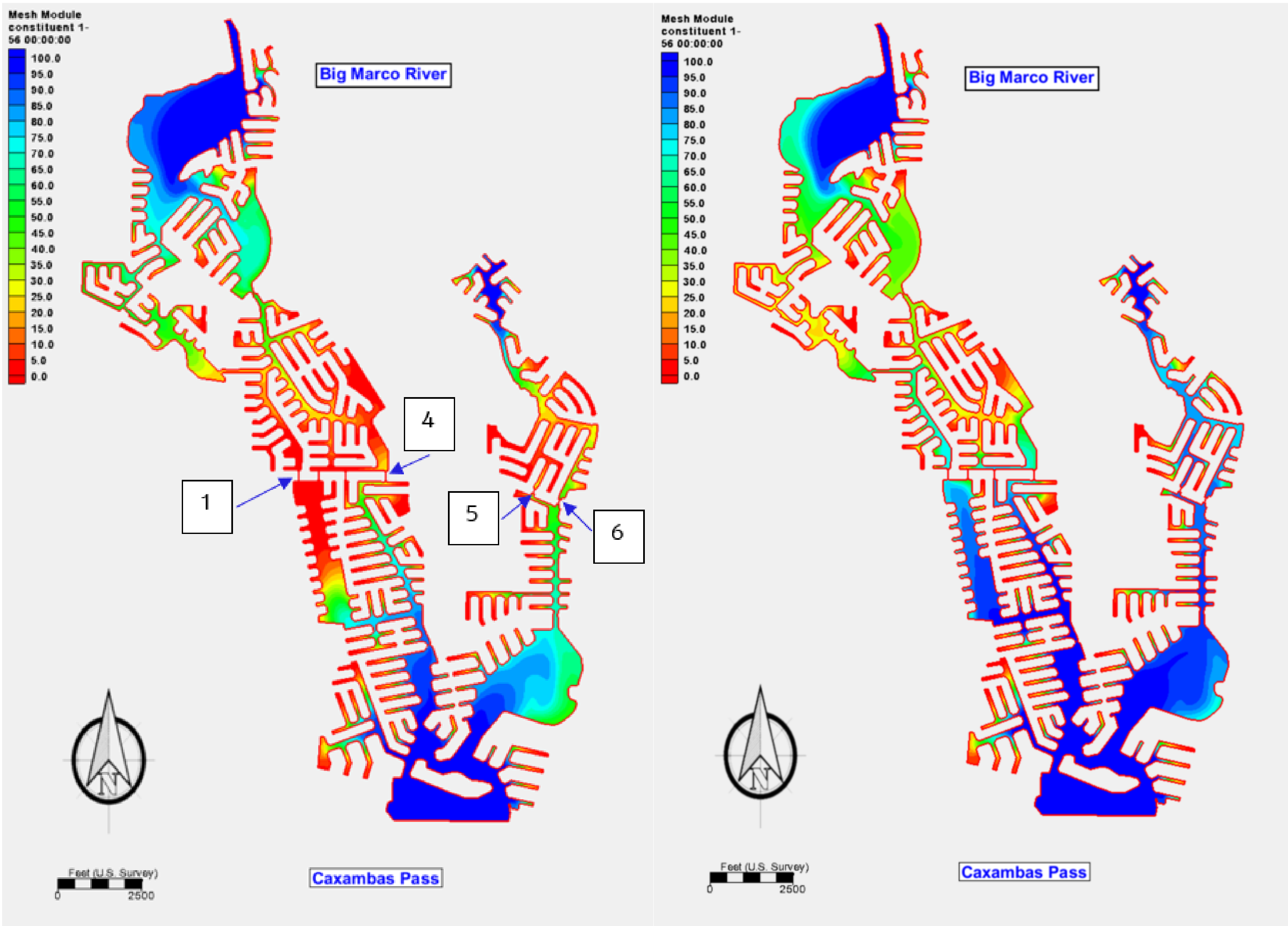

Figure 12. Existing and Improvement 3: Tracer Concentration at the end of 56-day simulation