Evaluation of Lock and Dams 4 Through 8

Site, Flow, and Lock Operation Characteristics Related to Invasive Carp Passage

Prepared for
University of Minnesota

January 2021

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Evaluation of Lock and Dams 4 Through 8 – Site, Flow, and Lock Operation Characteristics Related to Invasive Carp Passage

January 2021

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Certifications

I hereby certify that this plan, specification, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Minnesota.

Brian Siljenberg
PE #: 50033

January 4, 2022
Date

Executive Summary

This report summarizes the findings of evaluations conducted on Mississippi River Lock and Dams 4 through 8 regarding the potential for invasive carp (carp) passage and deterrence. The site evaluation included a review of site features exhibiting the highest and lowest potential of invasive carp passage. Hydraulic evaluations included a review of river flows and gate operations from 2000 to 2020. The results were compared to published findings on similar data ranging from 1970 to 2000. A desktop study was completed to determine the feasibility to include a fish deterrence system, focusing on identifying locations where the deterrence system was only required at the lock.

The results of the hydraulic evaluation found that Lock and Dam 5 is the least likely to experience hydraulic conditions favorable for carp passage so it would be the favored site for carp deterrent system from that perspective. Additionally, only Lock and Dam 5 lacks both fixed crest spillways and submersible dams, avenues by which carp can pass during times of high water. Other site features such as lock width and availability of power were equal (or similar) and suitable to installing a carp deterrent such as a BAFF. Lock and Dam 4 located just short distance upstream of Lock and Dam 5 is the next most suitable site, suggesting the two sites could be used in tandem.

In sum, Lock and Dam 5 is recommended as the most promising site for implication of a barrier strategy because it: (1) is the least likely to experience conditions favorable for invasive carp passage; (2) lacks both fixed crest spillways and submersible dams, and (3) has a relatively small upstream pool with a relatively impassable Lock and Dam located upstream which could be used for monitoring and removal of invasive carp following rare flood events.

2 Site Evaluation

The primary purpose of lock and dams 4 through 8 is to maintain an upper pool upstream of the dam with sufficient depth to enable barge navigation. These locks and dams are called "run of the river" dams since all flow that approaches the dam must be passed in real time through the spillway features and any other ancillary conduits such as culverts or powerhouses. The location of these locks is shown in Figure 1.

The "dam" portion of the lock and dam is not designed to overtop and thus invasive carp passage is not possible. Several additional features (ex. fixed crest spillways) are considered sensitive to invasive carp passage and are also considered within this report.

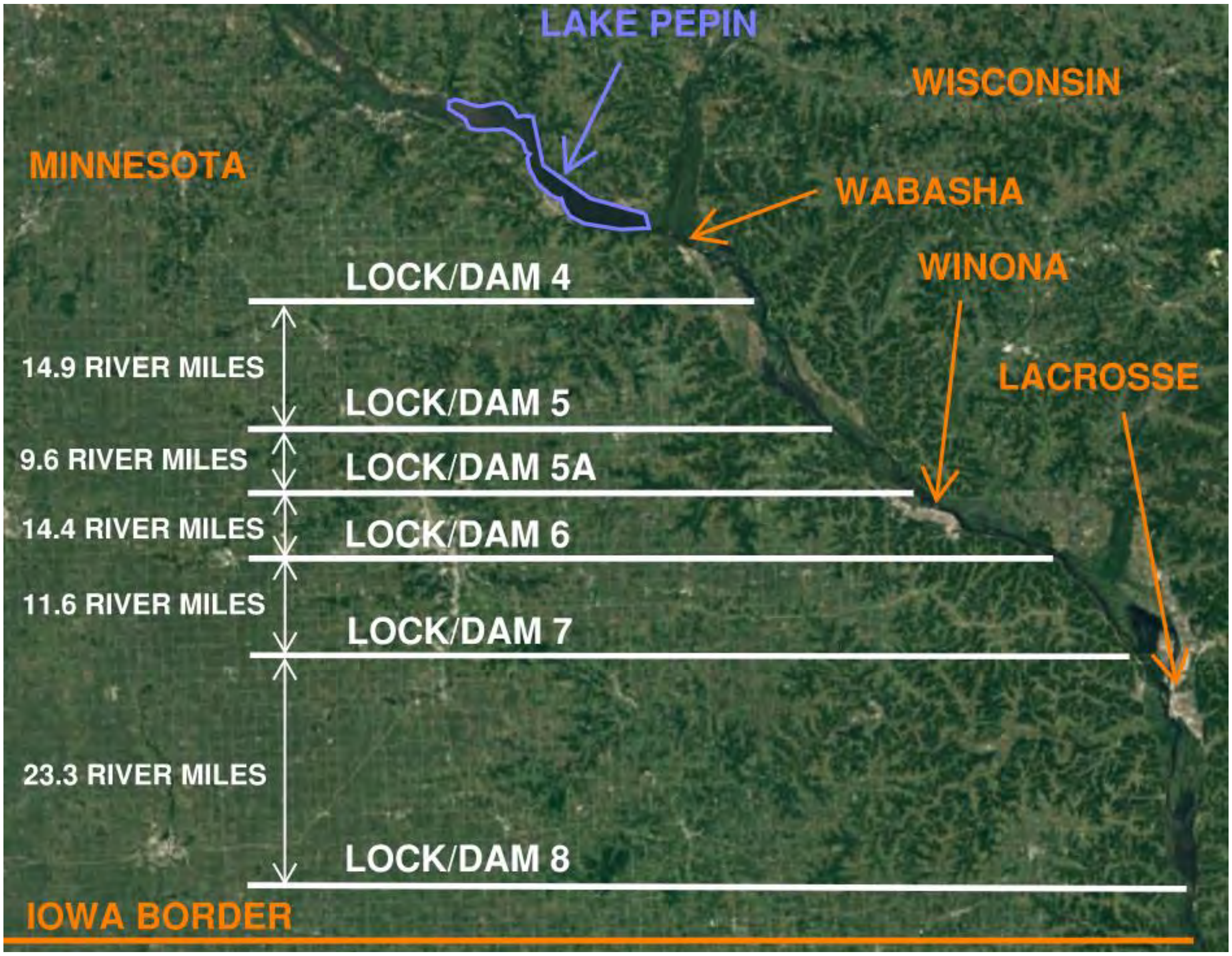


Figure 1 Lock and dam sites evaluated in scope of this study

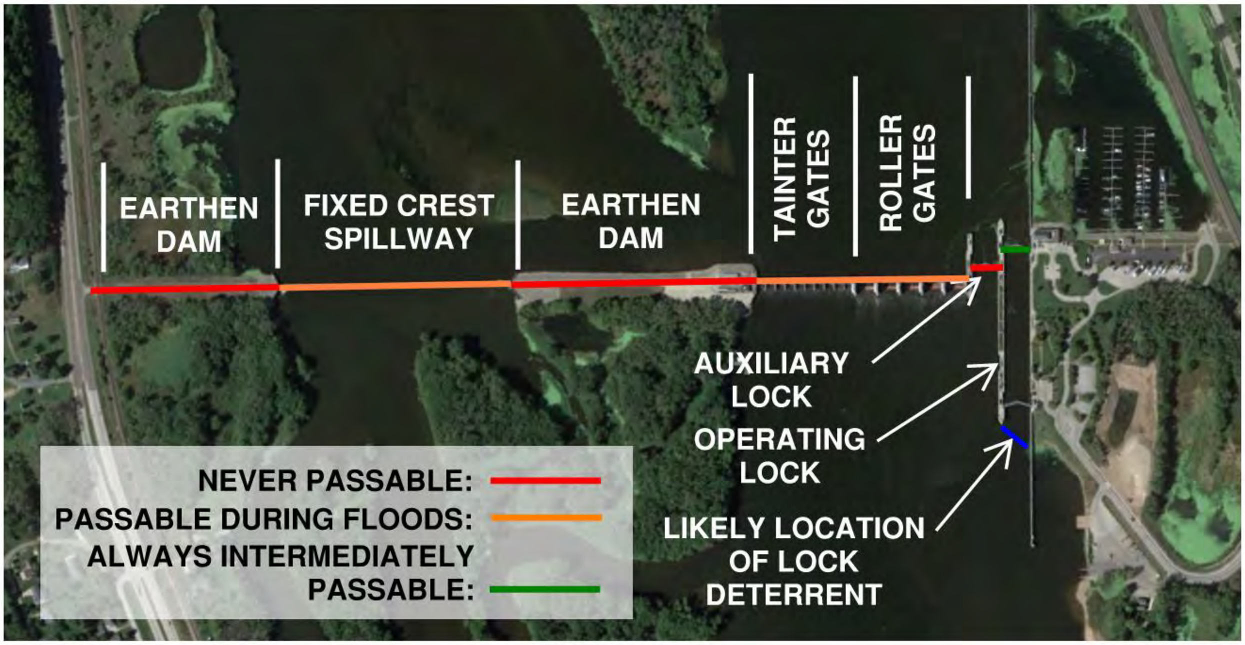


Figure 2 Typical lock and dam features

2.1 Lock and Dam Features Sensitive to Invasive Carp Passage

Lock and Dams are composed of several structural features that serve to create a headwater pool at a higher elevation than the tailwater pool. The structural features below all constituent a location where invasive carp could pass the dam alignment.

2.1.1 Lock

Description: Locks enable river traffic to pass the dam structure and manage the headwater and tailwater elevation differential as shown in Figure 3.

Sensitivity to invasive carp passage: Invasive carp can pass through the lock the same way river traffic does whereby one of the two sets of doors opens allowing traffic and fish inside the lock chamber. The most widely considered approach to minimize carp passage in a lock are submersed deterrent systems that employ sound and possible air (see below).

Potential mitigation of invasive carp passage: One type of deterrent system that has proven effective is a Bio-Acoustic Fish Fence (BAFF) that produces a combination of stimuli (light, sound, bubbles) the invasive carp find undesirable, yet river traffic can pass over.

2.1.2 Roller and tainter gates

Description: Roller and tainter gates are structurally different but functionally the same in that they constrict river flows through a gate that raises to open as shown in Figure 4. Their purpose is to maintain the upper pool elevation while allowing for the variable flow the river is subject to.

Sensitivity to invasive carp passage: The gates under normal flow operation result in high enough velocities that invasive carp cannot overcome the flow and thus cannot pass from downstream to upstream. However, higher flow events result in raising of the gates to adequately pass the flow. As the gates are raised, the flow velocity lowers. At some point, typically near the point of the gate being fully raised out of the water, velocities are sufficiently low to allow invasive carp passage. A more desirable site exhibits a smaller number of gates in their fully raised position a smaller percentage of time relative to the other sites. Gate count and size for each site is summarized in Table 2-3.

Potential mitigation of invasive carp passage: Operational changes can be considered to minimize the time in which gates are in the fully raised position permitting invasive carp passage. Individual gate settings can also often be adjusted within the scope of USACE control manuals to reduce passage by as much as 10-20%. However, this strategy is ultimately limited by the fact that once the gates are fully lifted (at times of flood), little additional benefit can be derived. Also, substantial modifications to gate operating schedules would have an impact on water management that the USACE would have to evaluate and approve. It is theoretically possible that mitigation of fish passage might be provided using an electric or bio-acoustic fish fence located upstream of these gates but this would almost certainly be prohibitively expensive because of the size of these structures. Another potential mitigation approach could be structural whereby a steel rack sized small enough to prevent invasive carp passage is positioned upstream of the gate. However, such a rack is not feasible as it would limit flow and collect debris requiring routine clearing by the USACE. A rack would also introduce a risk of flooding upstream should the rack plug during a flood event when the USACE could not clear the debris.

2.1.3 Fixed crest spillway and submersible dams

Description: Fixed crest spillways are concrete structures that are designed to routinely allow flow to pass over them, mostly only during flood events. A submersible dam is structurally different than a fixed crest spillway in that is made of an armored earthen embankment, yet it functions the same way although water typically rarely overtops these structures (which also vary in elevation). There is no way for operators to adjust or block flow, after the upstream pool exceeds the sill elevation the spillway or submersible dam, it will be overtopped.

Sensitivity to invasive carp passage: A fixed crest spillway or submersible dam exhibits a low risk of invasive carp passage until two conditions exist: (1) it is overtopped and (2) the tailwater is sufficiently high such that invasive carp on the downstream side can pass upstream. A more desirable site has smaller or no fixed crest spillway or submersible dam elements with lower elevations. Fixed crest element size and count for each site is summarized in Table 2-3.

Potential mitigation of invasive carp passage: Fixed crest spillways are especially vulnerable to carp passage. Nevertheless, both fixed crest spillways and submersible dams would require either a structural barrier such as a steel rack or an electric barrier to minimize this risk. A steel rack is not feasible for the same reasons outlined in Section 2.1.2. An electric barrier could be installed and would only need to function when water overtops the crest. However, electric barriers – especially of the length required these Mississippi Dam sites – would be expensive to install and maintain.

2.1.4 Culverts and sluiceways

Description: Culverts exist at all sites, either through the fixed crest spillway or submersible dam, or through the dam embankment. A majority of these culverts were added after the lock and dam's original construction as method to mitigate stagnant water in the sloughs downstream of the dam embankment. Sluiceways are notches in the crest of fixed crest spillways with the intent of permitting continuous flow at upper pool elevations below the main crest elevation. These sluiceways are several feet wide and exist at all spillways in this evaluation.

Sensitivity to invasive carp passage: Culverts and sluiceways can be a conduit for upstream moving invasive carp during high flow events when velocities are low and the tailwater exceeds the invert elevation of the culvert. Mitigation efforts are discussed in the site descriptions. The sensitivity of culverts to upstream invasive carp migration would also be a function of culvert slope and length, and water velocity. Steep and/or high-water velocities may exceed the invasive carp's ability to pass upstream. A more desirable site has fewer or no culverts and sluiceways. Culvert and sluiceway count for each site is summarized in Table 2-3.

Potential mitigation of invasive carp passage: Culverts and sluiceways are smaller in size than the other elements discussed above and thus could be mitigated through many different methods, including:

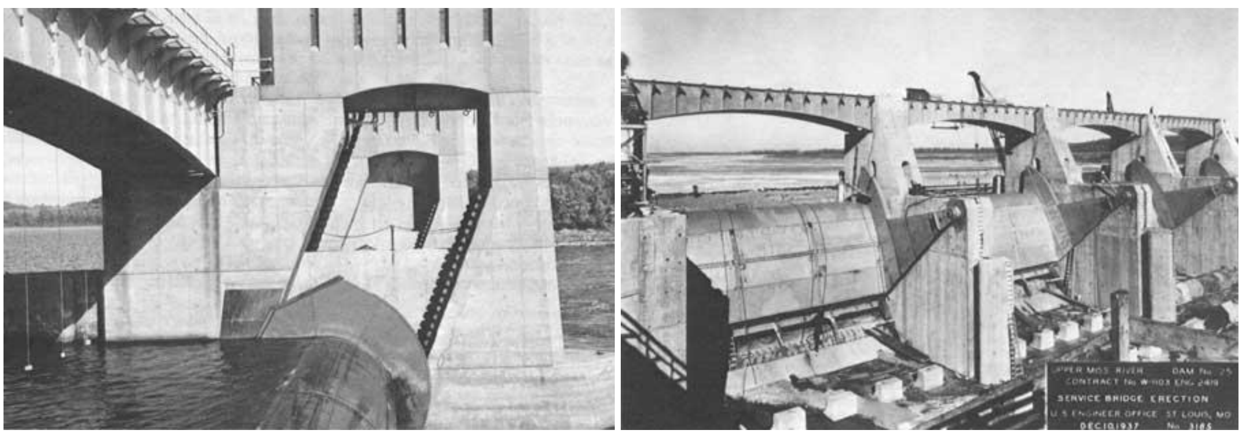
1. Remove the culvert or sluiceway
2. Install a grate over the culvert
3. Install an electric or bio-acoustic barrier downstream of the culvert/sluiceway
4. Monitor and selectively fish upstream pool following a flood

2.1.5 Upper Pool Size

Description: The purpose of the lock and dam system is to produce a series of deeper pools along the Mississippi to facilitate barge traffic where the river was historically not navigable part of the year. These pools create discrete sections of fish habitat. For the purposes of this study, the pool size is measured by its length along the centerline of the navigation channel and the lengths range from 43.9 miles upstream of LD 4 to 9.6 miles upstream of LD 5A.

Sensitivity to invasive carp passage: As described in Zielinski and Sorensen (2021) carp removal can be a mitigation approach for invasive carp. Therefore, pool size upstream of the lock and dam is a consideration in that a smaller pool is easier to monitor and remove invasive carp, thus making it more desirable. Smaller pools are also less likely to allow carp to reproduce.

Figure 3 Example of a Lock



(a) roller gate (National Park Service) (b) tainter gate (National Park Service)

Figure 4 Example of (a) a roller gate and (b) a tainter gate

2.2 Lock Fish Deterrent

For the purposes of this report, it is assumed that an underwater deterrent system would only be used at the lock where there is little (if any) flow velocity for invasive carp to overcome since deploying a system across all other features – while possible – would be fiscally prohibitive. The deterrent system would typically be located as shown in Figure 2. All lock chambers are 110-feet wide, and it can be assumed the angle of the system would be consistent throughout. The auxiliary lock chambers at all sites remains permanently closed. Therefore, there is no variability in these parameters to influence site selection.

Common fish deterrent systems need a power source which may include systems such as sound projectors, light arrays, and air compressors for bubbler systems. One commercially available system is called a Bio-Accoustic Fish Fence (BAFF). These utility supply systems would likely be housed on the nearby lock wall and powered from a local grid connection. There are two considerations that vary across sites related to the utility supply systems: (1) connection primary power to the utility supply systems and (2) the connection of the utility supply systems to the underwater barrier system.

2.2.1 Power Connection

Without a further detailed analysis of onsite power availability and consumption, it can conservatively be assumed for this study that additional power would be required from the nearby power grid. For the purposes of this evaluation, the distance from the likely utility location near the downstream end of the barrier system at the lock wall to the nearest observable power pole was measured and presented in Table 2-4.

2.2.2 Underwater Deterrent Connection

Common barrier systems may require the following utility connections from the utility supply system area:

1) Power for speakers and sound arrays
2) Low voltage communications for speakers and sound arrays
3) Compressed air for bubbler system

Given barge and other river traffic is common in the lock chamber, these connections require a safe route that does not hinder vessel passage. This can be achieved along the back side of the lock wall where accessible or down a ladder recess. The distance along the back side of a lock wall and within ladder recesses is relatively similar across all sites and therefore was not a major influence on site selection.

2.3 Lock and Dam Site Evaluations

The following sections outline site specific considerations extending from Lock and Dam 8 at the south (downstream) end of the study scope to Lock and Dam 4 on the north (upstream) end of the study scope as shown in Figure 1. This includes the existence of the lock and dam features sensitive to invasive carp passage listed above. Profiles illustrated to scale are shown in Figure 5 and itemized in Table 2-3.

2.3.1 Lock and Dam 8

Lock and dam 8 is located north of the Iowa-Minnesota border. The lock is located on the east bank of the river approximately 1,030-feet from the nearest power grid connection. There appears to be ample space near the downstream end of the lock to house barrier utility support systems. There are two submersible dams that combine for a total length of 2,275-feet. There are culverts in each submersible dam which provide continual flow to the Hastings Slough downstream of the dam along the west bank of the river.

2.3.2 Lock and Dam 7

Lock and dam 7 is located near LaCrosse, WI, just north of the I-90 river crossing. The lock is located on the west bank of the river approximately 630-feet from the nearest power grid connection. There appears to be ample space near the downstream end of the lock to house barrier utility support systems. There is a 1,000-foot fixed crest spillway that would likely require power from French Island. There are two sluiceways in this spillway that permit continuous flow to the slough directly downstream.

There is also an earthen dam and 670-foot submersible dam between French Island and the east bank of the river. Power would be required from the east bank of the river. There are two culverts in the 670-foot submersible dam that provide continuous flow to the east side of French Island.

Given invasive carp have been detected as far upstream as pool 8, it would be desirable to prevent their passage further upstream at Lock and Dam 7. However, the length of fixed crest spillway which would require a barrier combined with the culverts make this site very costly to implement a barrier.

2.3.3 Lock and Dam 6

Lock and dam 6 is located near Trempealeau, WI. The lock is located on the east bank of the river approximately 1,400-feet from the nearest power grid connection. There appears to be ample space near the downstream end of the lock to house barrier utility support systems. There is a 1,000-foot fixed crest spillway that would likely require power from east bank should a barrier system be installed. There are two sluice ways in the spillway that permit continuous flow to the slough directly downstream.

2.3.4 Lock and Dam 5A

Lock and dam 5A is located near the upstream edge of Winona, MN. The lock and spillway are located on the east side of the river with the lock on the west side of that complex residing on an island. High voltage power is evident crossing from the west bank of the river over a 1,000-foot fixed crest spillway. There are two sluice ways in the spillway that permit continuous flow to the slough directly downstream. There appears to be ample space near the downstream end of the lock to house barrier utility support systems.

2.3.5 Lock and Dam 5

Lock and dam 5 is located approximately 11 miles upstream of Winona, MN. The lock is located on the west bank of the river approximately 1,280-feet from the nearest power grid connection. There appears to be sufficient space near the downstream end of the lock to house barrier utility support systems, albeit not as much space as other locks. There are no fixed crest spillways or submersible dams at this site.

USACE documents indicate the presence of four culverts through the dam embankment which provide flow to the Indian Creek Slough on the east bank just upstream from the lock and spillway. If tailwater raises above the elevation of these culverts during flood events they could serve as a conduit for invasive carp passage. The water control manual states all culverts have stoplog slots where stoplogs are largely left out accept during floods.

Table 2-1 Aeration culverts listed in the water control manual for LD 5

Installation Year	Pipe	Flow
1956	36-inch CMP	70 CFS
1977	(3) 48-inch CMP	320 CFS

2.3.6 Lock and Dam 4

Lock and dam 4 is located approximately 7 miles downstream of Wabasha, MN. The lock is located on the west bank of the river approximately 1,280-feet from the nearest power grid connection. There appears to be sufficient space near the downstream end of the lock to house barrier utility support systems, albeit not as much space as other locks. There are no fixed crest spillways or submersible dams at this site.

USACE documents indicate the presence of six culverts as listed in Table 2-2 in the lock and dam 4 water control manual. Potential mitigation measures for these culverts are discussed in the previous section.

Table 2-2 Aeration culverts listed in the water control manual for LD 4

Site	Pipe
Clear lake	36-inch RCP
Lower Peterson Lake	48-inch CMP
3rd Lake	36-inch RCP
2nd and 1st Lake Single Intake	48-inch RCP
2nd Lake Outlet	48-inch RCP
1st Lake Outlet	48-inch RCP

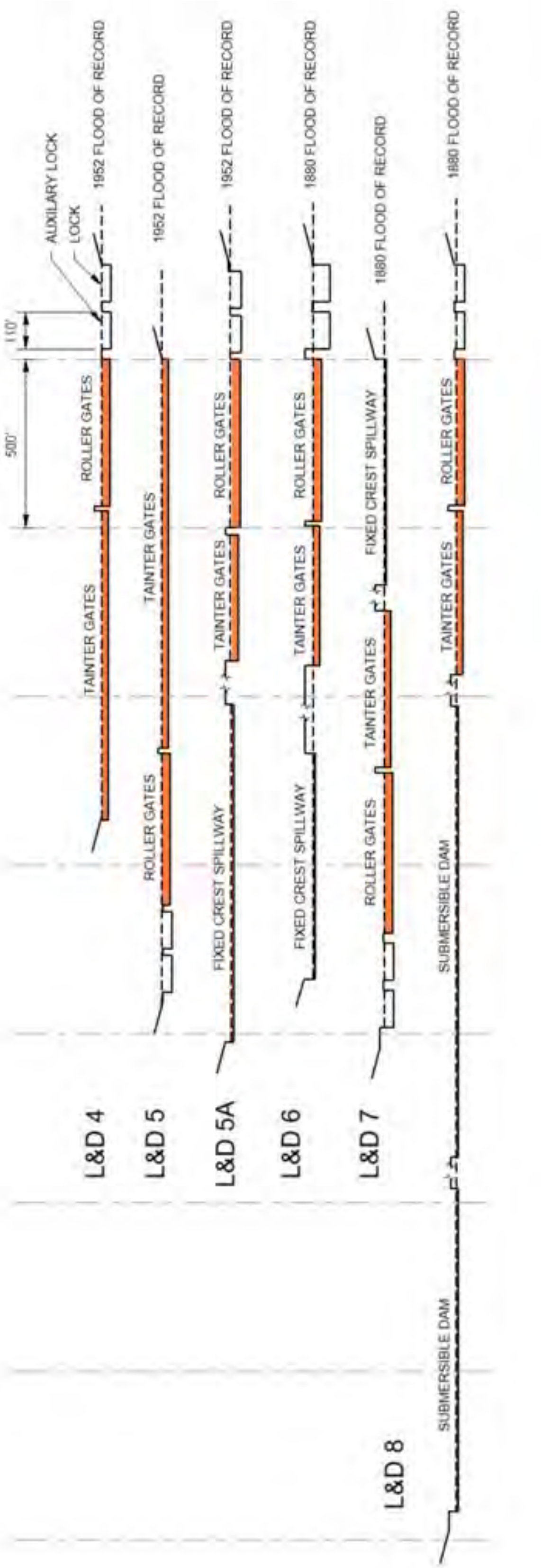


Figure 5 Profiles of spillways and locks for Lock and Dams 4 through 8

Table 2-3 Summary of site features relevant to invasive carp passage

Site	Roller Gates	Tainter Gates	Culverts or Sluices	Fixed Crest Spillway	Submersible Dam
Lock and Dam 8	5 Gates @ 80′ = 400′	10 Gates @ 35′ = 350′	2	NA	1 @ 937.5′ 1 @ 1337.5′
Lock and Dam 7	5 Gates @ 80′ = 400′	11 Gates @ 35′ = 385′	3	670′[1]	1,000′
Lock and Dam 6	5 Gates @ 80′ = 400′	10 Gates @ 35′ = 350′	4	1,000′	NA
Lock and Dam 5A	5 Gates @ 80′ = 400′	5 Gates @ 35′ = 105′	2	1,000′	NA
Lock and Dam 5	6 Gates @ 80′ = 480′	28 Gates @ 35′ = 980′	4	NA[3]	NA
Lock and Dam 4	6 Gates @ 80′ = 480′	22 Gates @ 35′ = 770′	5	NA[3]	NA

Note(s):

1) Each submersible dam at Lock and Dam 8 has a continuously flowing culvert feeding the Hastings Slough
2) Fixed crest spillway a sluice way, submerged culvert, and armored earthen section intended for overtopping during flood events.
3) There are four culverts through the dam embankment on the east side of the lock and spillway

Table 2-4 Estimated distance to local power grid connection

Site	Fixed crest spillway or submersible dam requiring a barrier	Estimated Distance to Nearest Power Pole for Local Power Grid Connection	Route Between Utility Supply Area and Underwater Barrier
Lock and Dam 8	2,275′	1,030′	Down Ladder Recess
Lock and Dam 7	670′	560′	Down Ladder Recess
Lock and Dam 6	1,000′	1,400′	Down Ladder Recess
Lock and Dam 5A	1,000′	0′[2]	Down Ladder Recess
Lock and Dam 5	NA	1,280′	Down Ladder Recess
Lock and Dam 4	NA	190′	Down Ladder Recess

Note(s):

1) Each submersible dam at Lock and Dam 8 has a continuously flowing culvert feeding the Hastings Slough
2) High voltage lines are evident crossing the fixed crest spillway from the west bank going to the powerhouse.

2.4 Site Evaluation Conclusions

The presence of a fixed crest spillway or submersible dam – which exists at Lock and Dam 5A through Lock and Dam 8 – was found to be a dominant site feature in that these elements would require a costly barrier over their length. Other site features such as lock width and availability of power were equal or similar across all sites. Based on site features alone, Lock and Dams 4 and 5 were found to be best suited for the implementation of an invasive carp barrier strategy.

3 Hydraulic Evaluation

The purpose of the hydraulic evaluation is to estimate the conditions under which invasive carp can pass through each lock and dam and the frequency at which these conditions are expected to occur. The result of this evaluation will identify which lock and dam(s) is the least favorable to invasive carp passage.

3.1 Hydraulic Evaluation Methods

The ability for carp to pass through a given Lock and Dam depends on the configuration of the structure as well as the flow through those structures over the course of a given year. These values change daily so an assessment of lock and dam permeability must consider conditions over the course of a year. Previously, most research on invasive carp passage has assumed that invasive carp passage occurs when a lock and dam raises its tainter gates and roller gates completely out of the water during times of high discharge. At these times, water velocities in the resulting flow fields are minimal. This condition is known as "open-river" because it resembles the conditions prior to the construction of the lock and dam when the river was fully open to flows. However, the exact conditions that determine open-river conditions at each lock and dam are complex and include discharge, upper pool height, and hydraulic head, all of which are estimates and not precise descriptors. Recent studies (Zielinski et al. 2018) show that the frequency of "open-river" conditions reported by USACE records are good, albeit imperfect, correlates of carp passage which vary with parameter used, dam structure, spillway gate operations, and local hydraulic conditions. USACE water control manuals provide guidance on how individual locks and dams should be operated by USACE engineers relative to discharge and pool height, and also when open-river conditions are expected. In this study we used 4 methods to estimate the actual amount of time that Locks and Dams 4-8 experience hydraulic conditions that likely permit invasive carp passage. The first 3 of these reflect different ways of estimating time in open-river, while the fourth uses carp passage data collected by Sorensen from Lock and Dam 8. We used the hydraulic conditions we measured to be present in the Mississippi River between 2000-2020.

3.1.1 Method 1: HW – TW < 1'

The first method assumes that invasive carp are only able to pass through a dam when the gates are lifted out of the water, also known as open river conditions. Under these conditions, the difference between the water surface elevation upstream and downstream of the dam (hydraulic head) is very small. Using daily measurements for water surface elevation at the headwater (upstream) and tailwater (downstream) of each Lock and Dam, the open river condition was assumed to be in effect for the following condition:

$$HW - TW < 1\,foot$$

The percentage of time for which this criteria was met is shown in Table 5.

3.1.2 Method 2: TW > 2nd Control

The second method also assumes that invasive carp are only able to pass through the dam under open river conditions. However, it differs from the first method is that this method assumes that the open river conditions were in effect only when the tailwater elevation was above the secondary control elevation (the elevation of the primary spillway and secondary spillway, if present).

$$TW > Secondary\ Control\ Elevation$$

This method was primarily used to quantify the lower limit for which open river conditions would occur. In other words, this condition is only met when the flow moving through the dam is so high that the tailwater is above the crest of the spillway. The percentage of time for which this criteria was met is shown in Table 5

3.1.3 Method 3: Q > Control

The third method also assumes that invasive carp are only able to pass through the dam under open river conditions. This method is different from the previous method in that it relies on the definition of open river conditions from the gate operations manual for each Lock and Dam. Daily flow (Q) measurements at each Lock and Dam were used, along with the control flow at which gates should be lifted out of the water, to check the following condition:

$$Q > control\ flow$$

Open river conditions are assumed to be met for any day when the flow exceeds the control flow specified for lifting the gates out of the water. Flow data was not available for Lock and Dam 6, so no evaluation was performed at this location. The percentage of time for which this criterion was met is shown in Table 5.

3.1.4 **Method 4: Tainters > 10'**

The final method does not rely on that assumption that invasive carp passage only occurs during open river conditions. Instead, this method is based on common carp passage data collected from 2019 – 2020 at Lock and Dam 8 and the actual conditions carp were noted to pass under. This data, summarized in Figure 6, shows that during 2019 common carp were observed passing through the gates when the flow in the river required that individual tainter gates were opened 10 feet according to the water control manual. During high, variable flow conditions at Lock and Dam 8, the tainter gates were moved between open river conditions and 10 feet open. This observation from the detailed Lock and Dam operations provided by the USACE was matched by the water control manual recommendations. The operations manual states that above the control flow, the gates should remain out of the water until flows drop below that control flow at which point they should be closed to 10 feet.

The dam operations data at Lock and Dam 8 indicates that the tainter gates are not opened more than 10 feet unless the control flow is exceeded. We found that the tainter gate height to put the gates back in the water following a period where the gates are out of the water is similar for each of the 6 Lock and Dams (i.e. for Lock and Dam 4 the height is 8 feet, for 5 it is 10 feet, for 5A it is 9 feet, and for 6 through 8 it is 10 feet). The flow at each Lock and Dam corresponding to these tainter gate heights was identified and compared to the daily flow. Any day when this flow was exceeded was assumed to be a passage day for invasive carp. The percentage of time for which this criteria was met is shown in Table 5

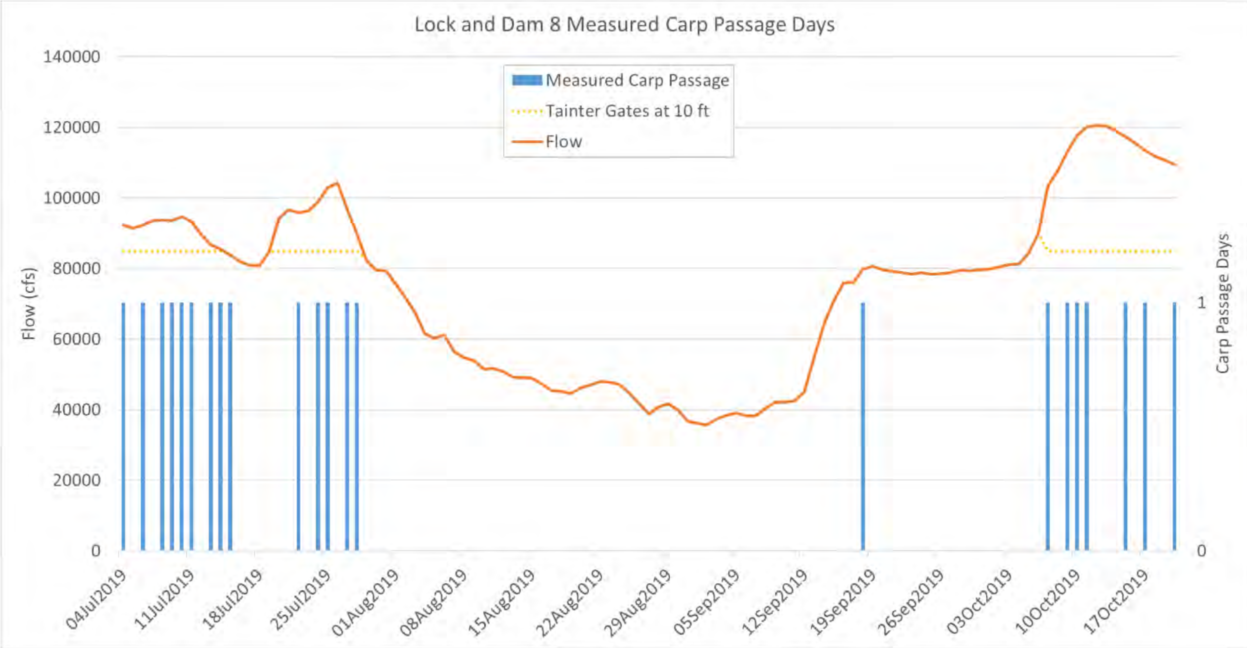


Figure 6 Invasive carp passage days at Lock and Dam 8 (Sorensen Lab, University of Minnesota)

Table 5 Estimates for percentage of time passable for invasive carp from 2000 - 2020

Location	Method 1: HW – TW < 1′	Method 2 TW > 2nd Control	Method 3 Q > Control	Method 4 Tainters > 10′
Lock and Dam 4	6.2%	3.4%	5.6%	7.8%
Lock and Dam 5	2.3%	1.1%	2.2%	2.5%
Lock and Dam 5A	19.2%	9.6%	16.2%	18.5%
Lock and Dam 6	12.4%	4.5%	NA	12.7%
Lock and Dam 7	6.6%	1.4%	6.0%	8.0%
Lock and Dam 8	6.9%	2.3%	6.4%	8.8%

3.2 Hydraulic Evaluation Results

The results of the hydraulic evaluation show that for each criterion considered, Lock and Dam 5 is the least likely to experience conditions favorable for invasive carp passage. While methods 1 through 3 are useful for understanding how often gates are lifted out of the water, invasive carp passage data at Lock and Dam 8 indicates that invasive carp can pass while the gates are still in the water (i.e. tainter gates are at 10ft). Using this data, a flow was identified at each lock and dam at which invasive carp are likely to be able to pass. This flow corresponds to the highest gate opening before and immediately after the gates are lifted out of the water.

3.3 Overtopping of Site Features

As discussed in Chapter 2, there are site features that may be subject to overtopping during certain flood events. These features are presented in Table 3-6 and include the embankment dam crest, fixed crest spillway, and submersible dam. The flood of records at each site show that the flood of record elevations are below the lowest embankment dam elevation in each case.

Table 3-6 Summary of site features relevant to invasive carp passage

Site	Lowest Embankment Dam Elevation	Fixed Crest Spillway or Submersible Dam	Flood of Record
Lock and Dam 8	639.5′	West Submersible Dam: 631.0′ East Submersible Dam: 631.0′	639.18′ (1965)
Lock and Dam 7	649.0′	Spillway: 639.0′ Onalaska Dam: 639.0′	648.18′ (1965)
Lock and Dam 6	654.5′	645.5′	654.65′ (1965)[1]
Lock and Dam 5A	664.0′	651.0′	663.74′ (1965)
Lock and Dam 5	670.0′	NA	668.73′ (1965)
Lock and Dam 4	677.0′	NA	676.45′ (1965)

Note(s):

1) Embankment raised 3′ during flood event

4 Conclusions

Although many site features are similar across the 6 locks and dams (ex. availability of power, lock width), the frequency that each lock and dam was susceptible to invasive carp passage via its spillway gates, and their vulnerability to passage via fixed crest spillways and submersible dams differed greatly. Upper pool size also varied. Based on the later features, Lock and Dam 5 is recommended as the most promising site for installing a carp deterrent system. This site is unique because only it: (1) lacks a fixed crest spillway or submersible dam, (2) has a relatively small upstream pool to facilitate monitoring and removal of invasive carp following a flood event, and (3) is the least likely to experience conditions favorable for invasive carp passage.

Table 4-1 Lengths of site features sensitive to invasive carp passage

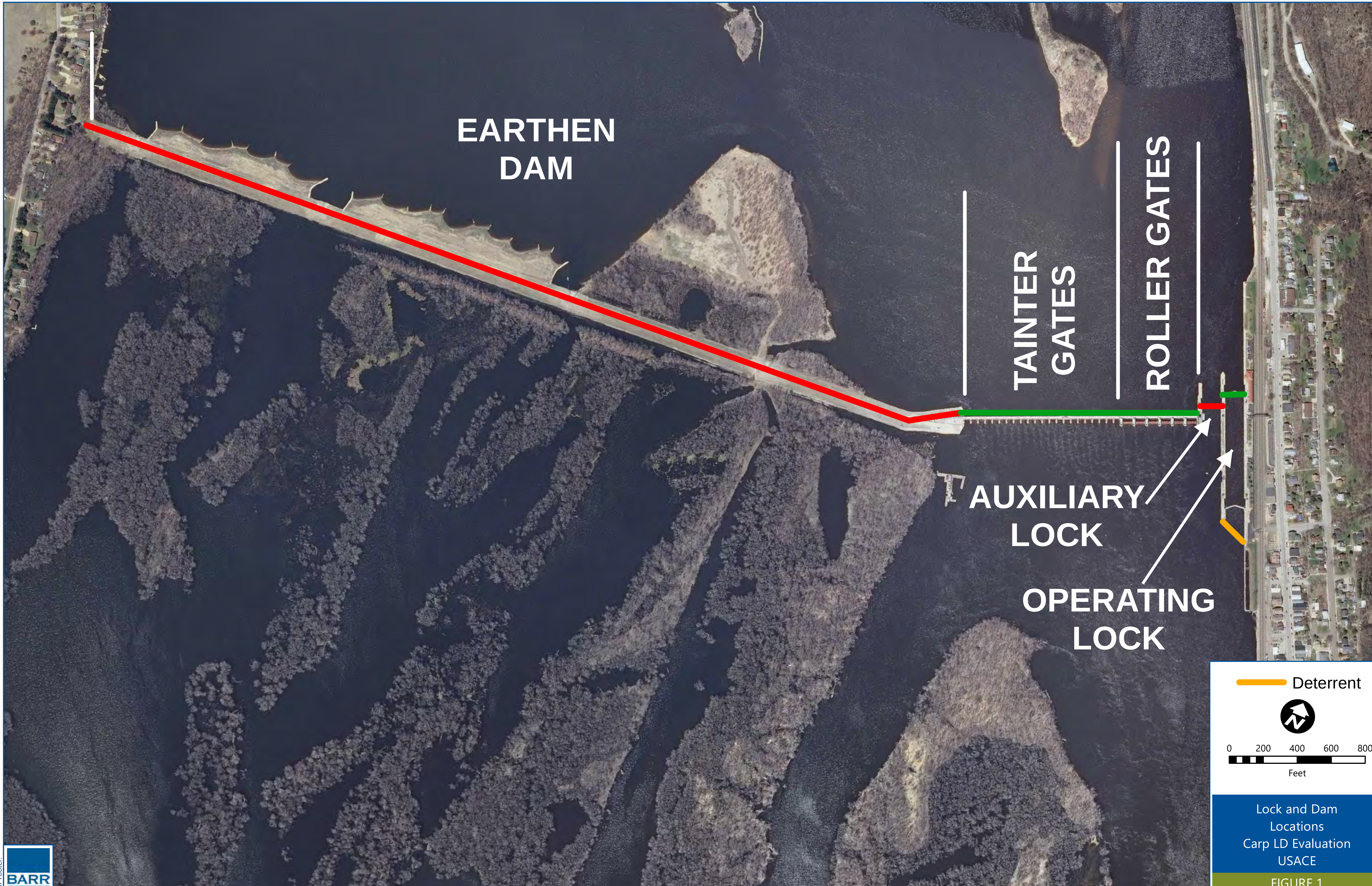
Site	Roller Gates	Tainter Gates	Culverts or Sluices	Fixed Crest Spillway	% Passable
Lock and Dam 8	5 Gates @ 80′ = 400′	10 Gates @ 35′ = 350′	2	1 @ 937.5′ 1 @ 1337.5′	8.8%
Lock and Dam 7	5 Gates @ 80′ = 400′	11 Gates @ 35′ = 385′	3	1 @ 670′[1] 1 @ 1,000′	8.0%
Lock and Dam 6	5 Gates @ 80′ = 400′	10 Gates @ 35′ = 350′	4	1,000′	12.7%
Lock and Dam 5A	5 Gates @ 80′ = 400′	5 Gates @ 35′ = 105′	2	1,000′	18.5%
Lock and Dam 5	**6 Gates @ 80′ = 480′**	**28 Gates @ 35′ = 980′**	4	**NA**	**2.5%**
Lock and Dam 4	6 Gates @ 80′ = 480′	22 Gates @ 35′ = 770′	5	NA	7.8%

5 References

Zielinski, D.P.; Sorensen, P.W. Numeric Simulation Demonstrates That the Upstream Movement of Invasive Bigheaded Carp Can Be Blocked at Sets of Mississippi River Locks-and-Dams Using a Combination of Optimized Spillway Gate Operations, Lock Deterrents, and Carp Removal. *Fishes* **2021**, 6, 10. https://doi.org/10.3390/fishes6020010

Appendix A

Site Maps


EARTHEN DAM
TAINTER GATES
ROLLER GATES
AUXILIARY LOCK
OPERATING LOCK
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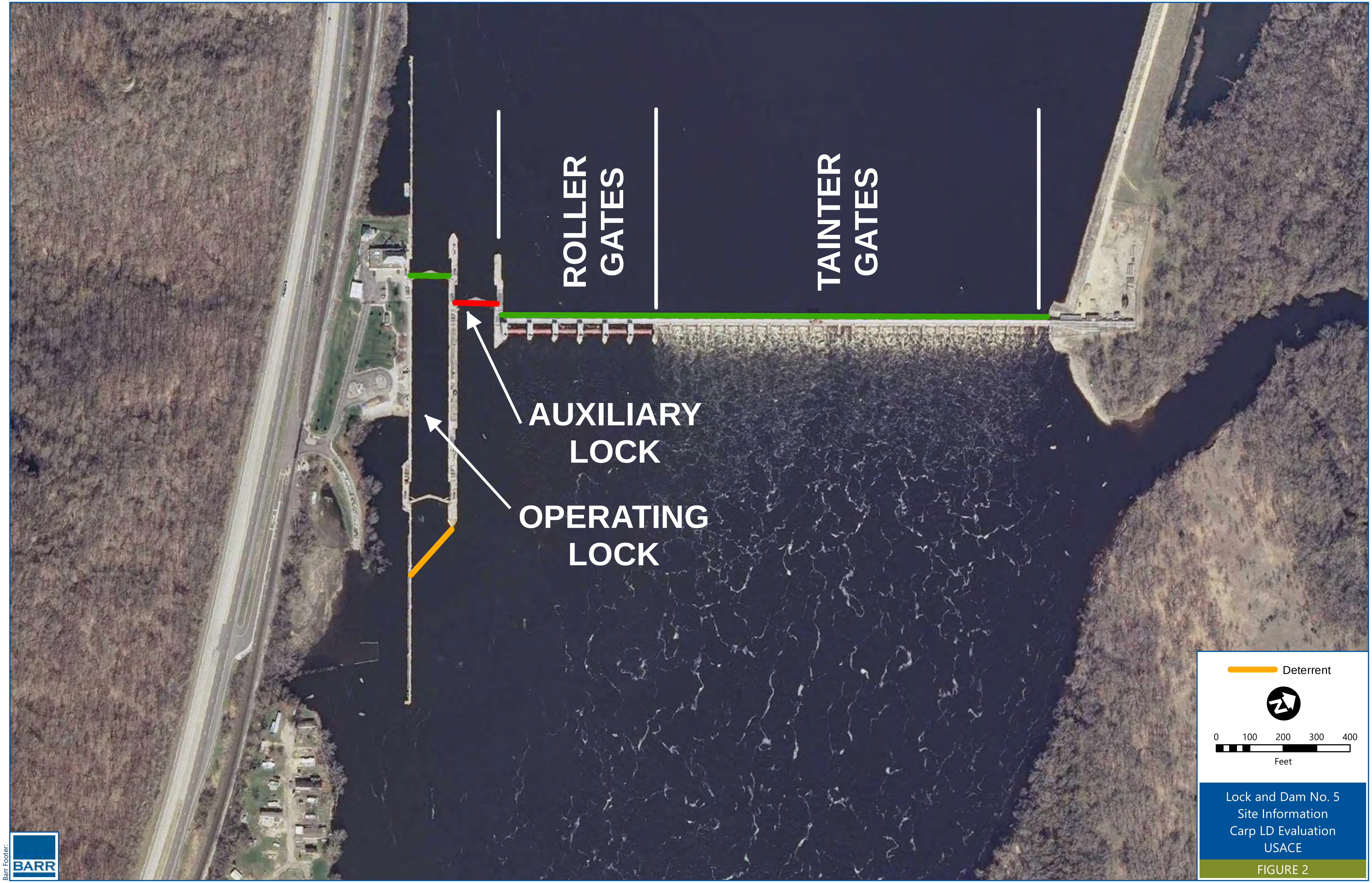
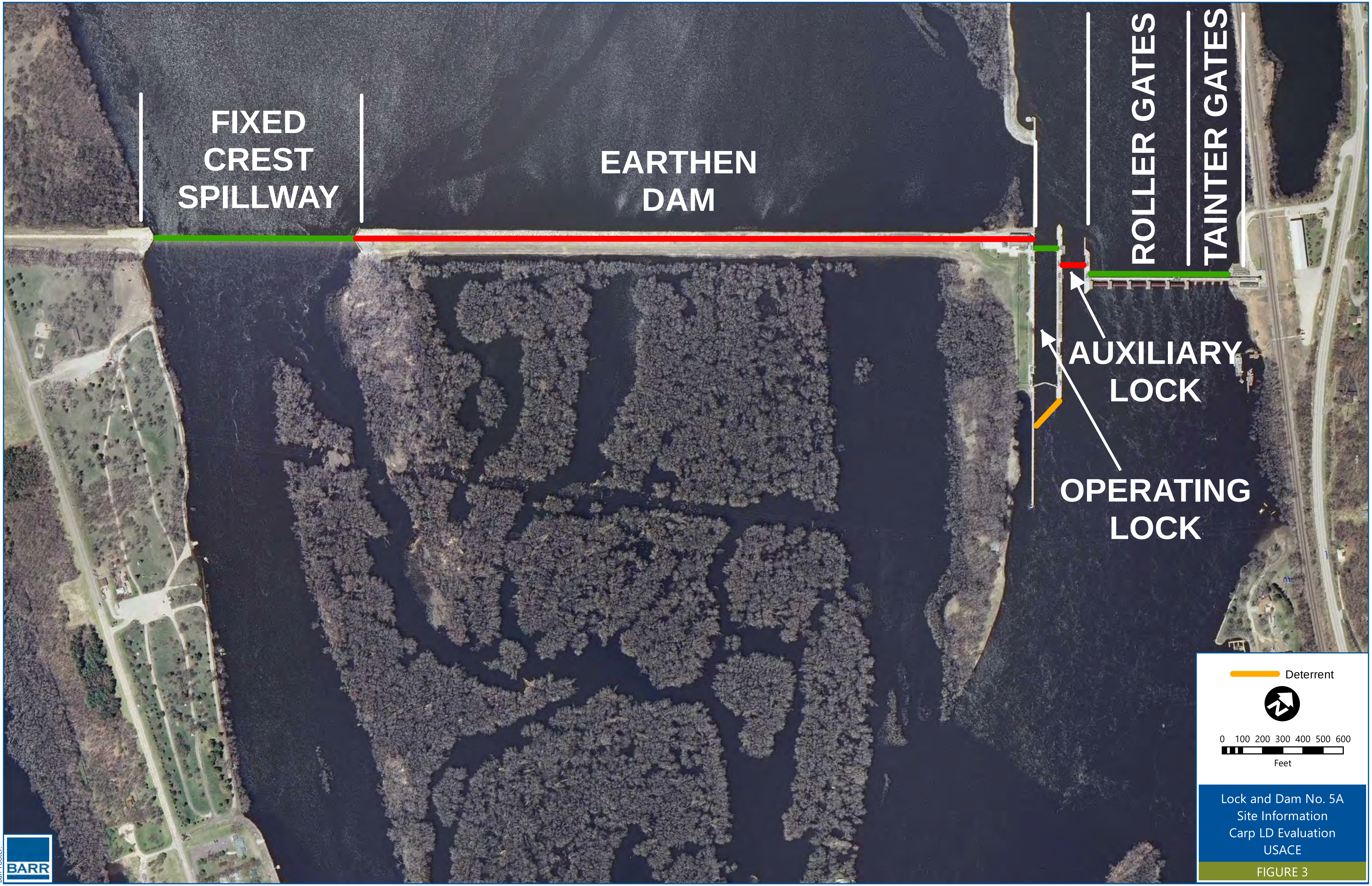
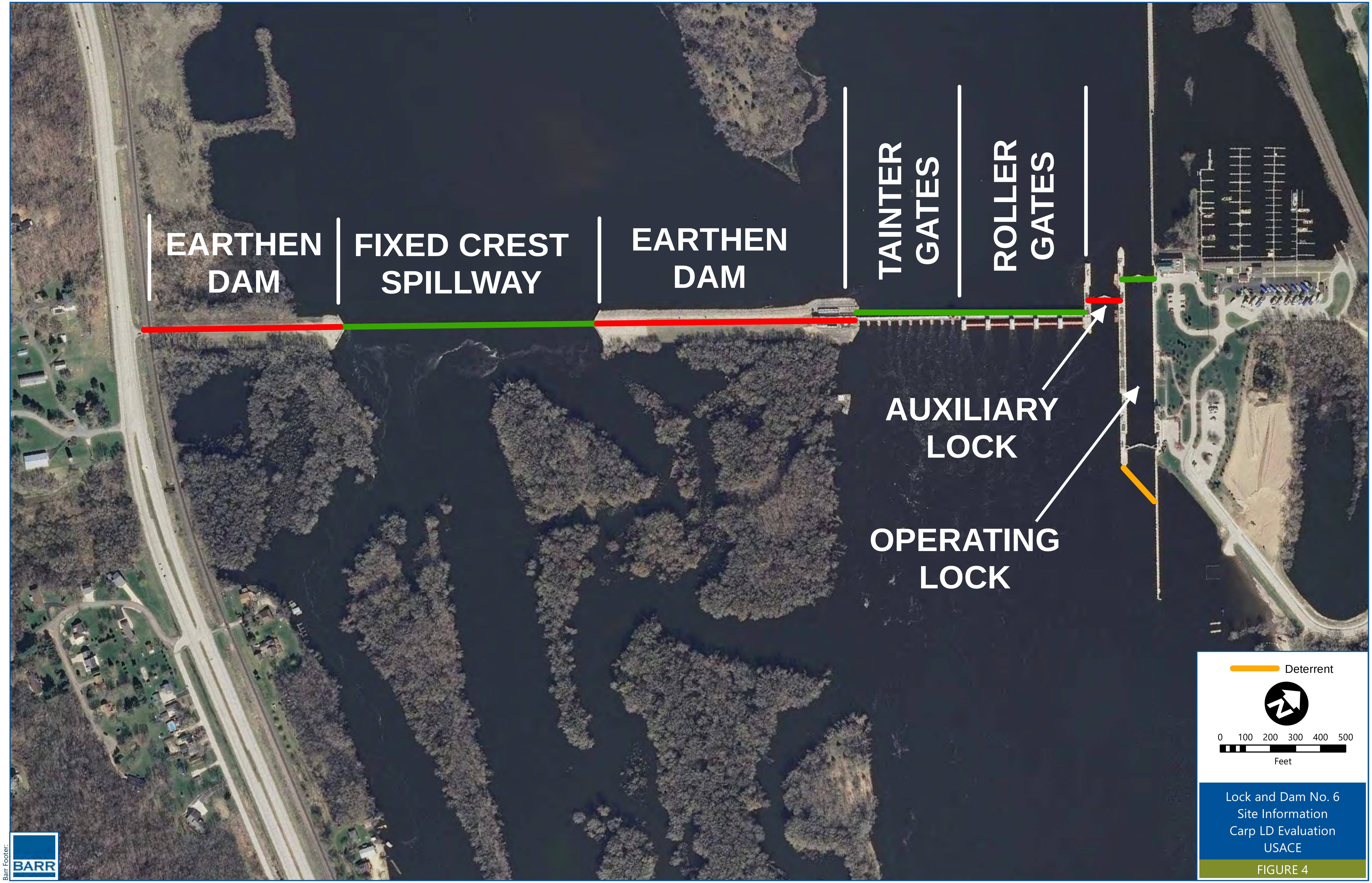
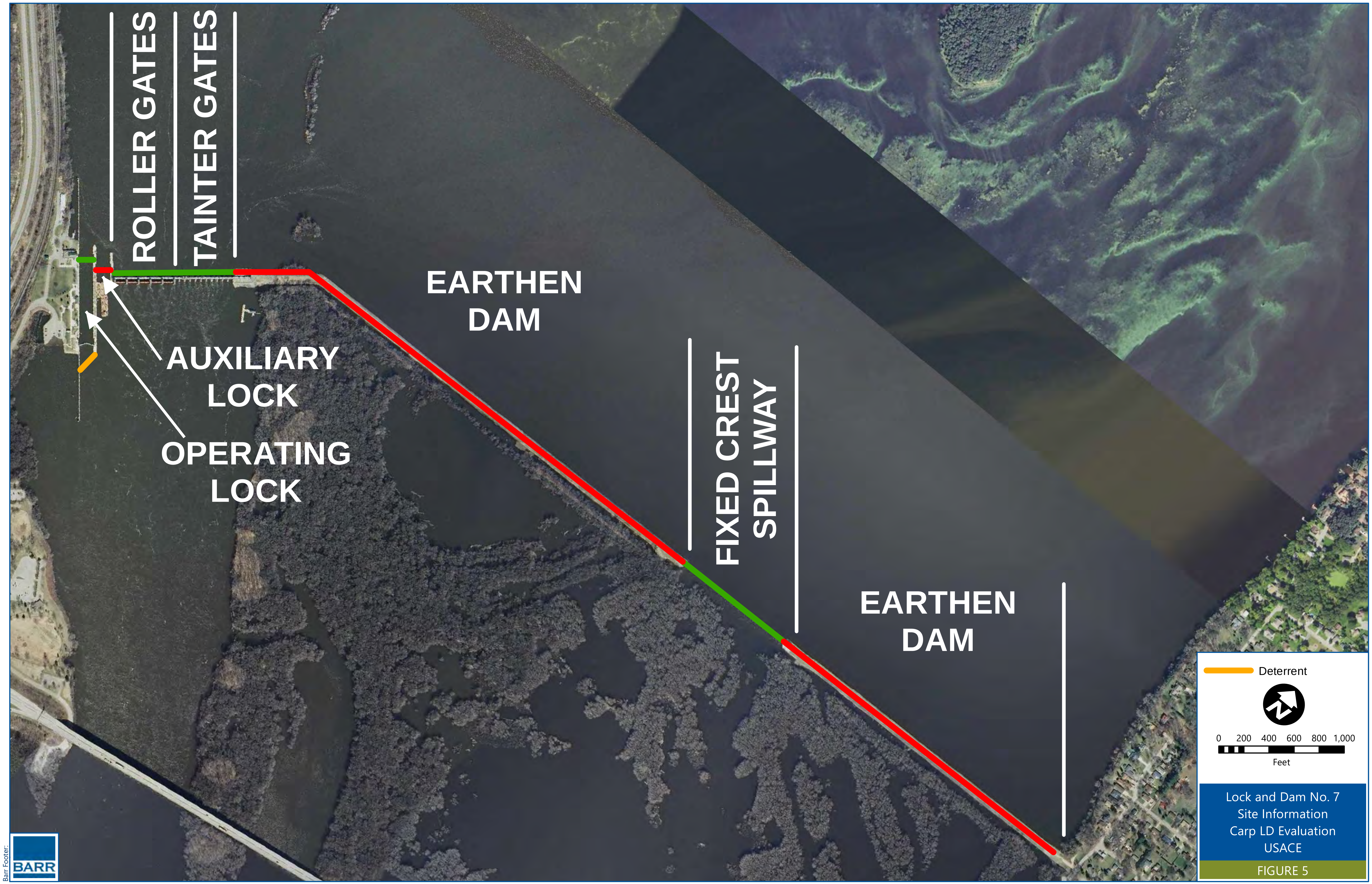
0 200 400 600 800
Feet
Lock and Dam Locations
Carp LD Evaluation
USACE
FIGURE 1
BARR
Barr Footer:

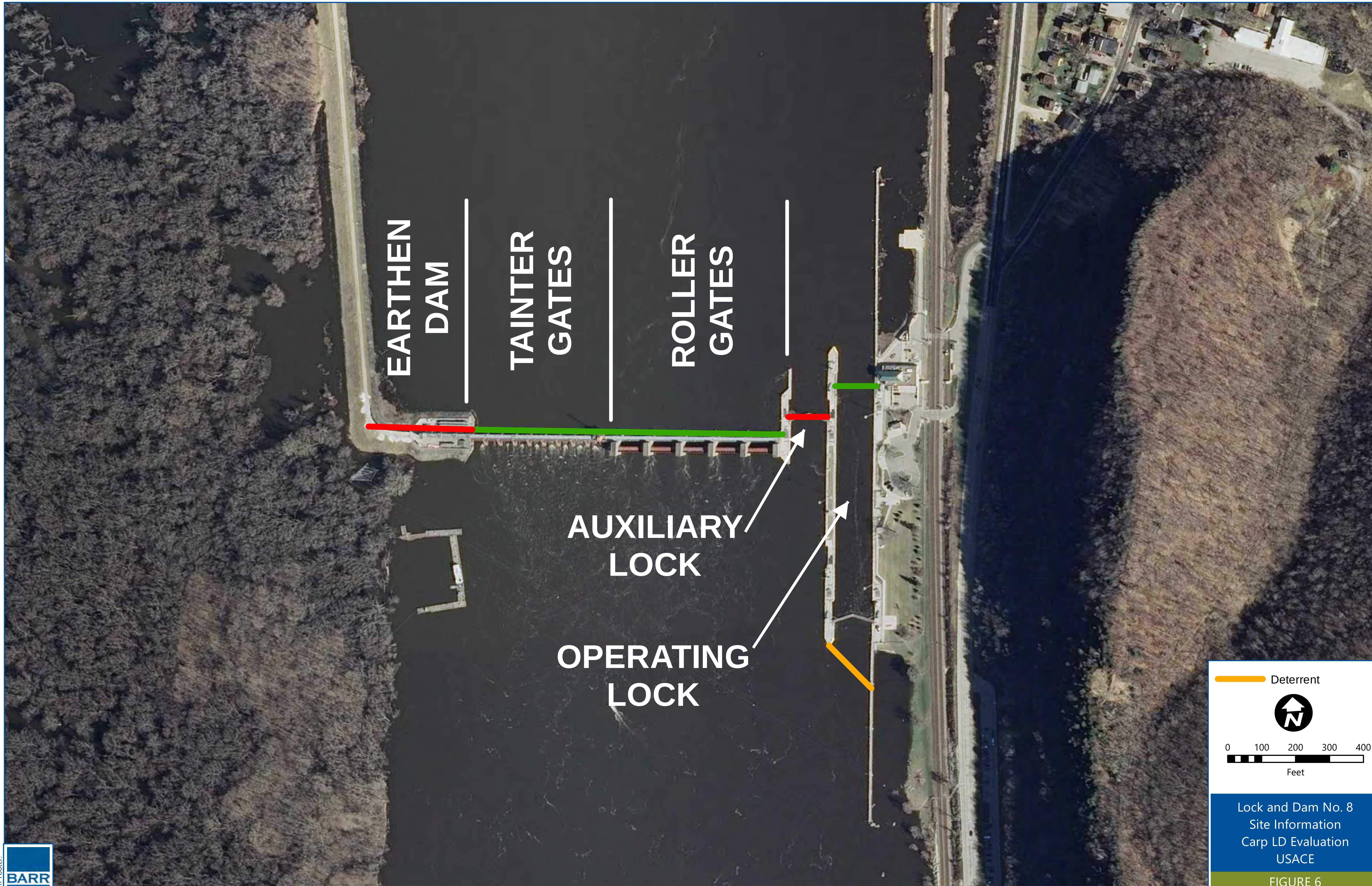

ROLLER GATES
TAINTER GATES
AUXILIARY LOCK
OPERATING LOCK
Deterrent
0 100 200 300 400
Feet
Lock and Dam No. 5
Site Information
Carp LD Evaluation
USACE
FIGURE 2
BARR
Barr Footer:



Lock and Dam No. 5A
Site Information
Carp LD Evaluation
USACE
FIGURE 3

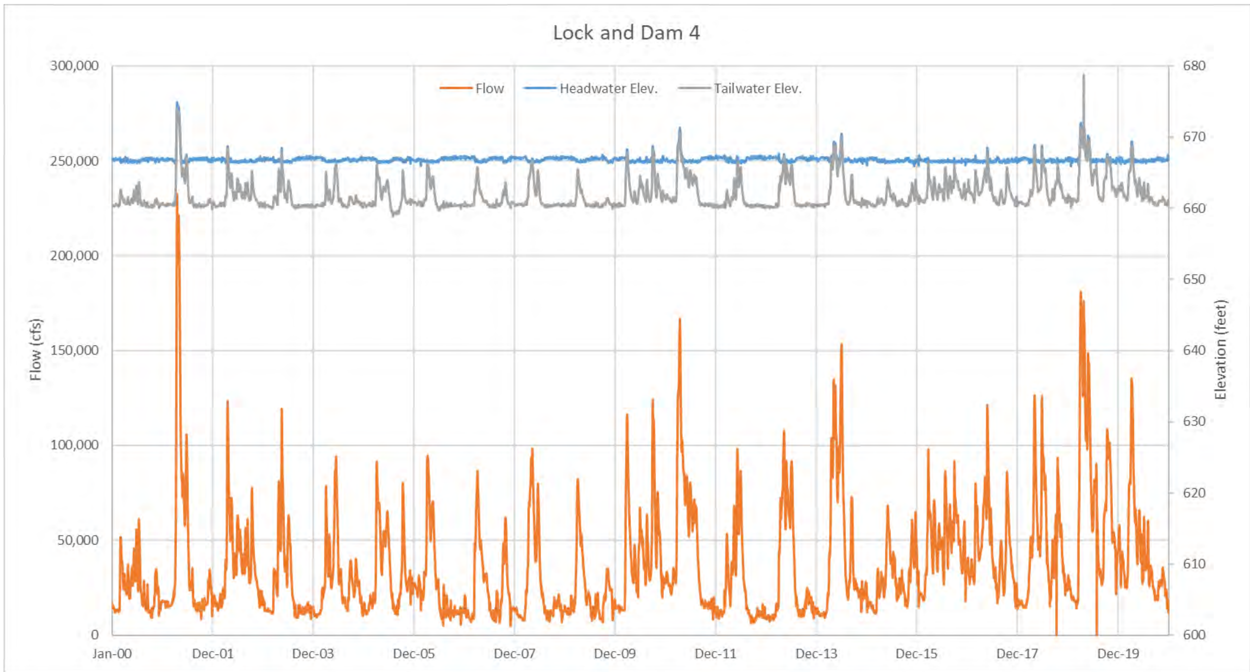

EARTHEN DAM
FIXED CREST SPILLWAY
EARTHEN DAM
TAINTER GATES
ROLLER GATES
AUXILIARY LOCK
OPERATING LOCK
Deterrent
0 100 200 300 400 500
Feet
Lock and Dam No. 6
Site Information
Carp LD Evaluation
USACE
FIGURE 4
BARR
Barr Footer:

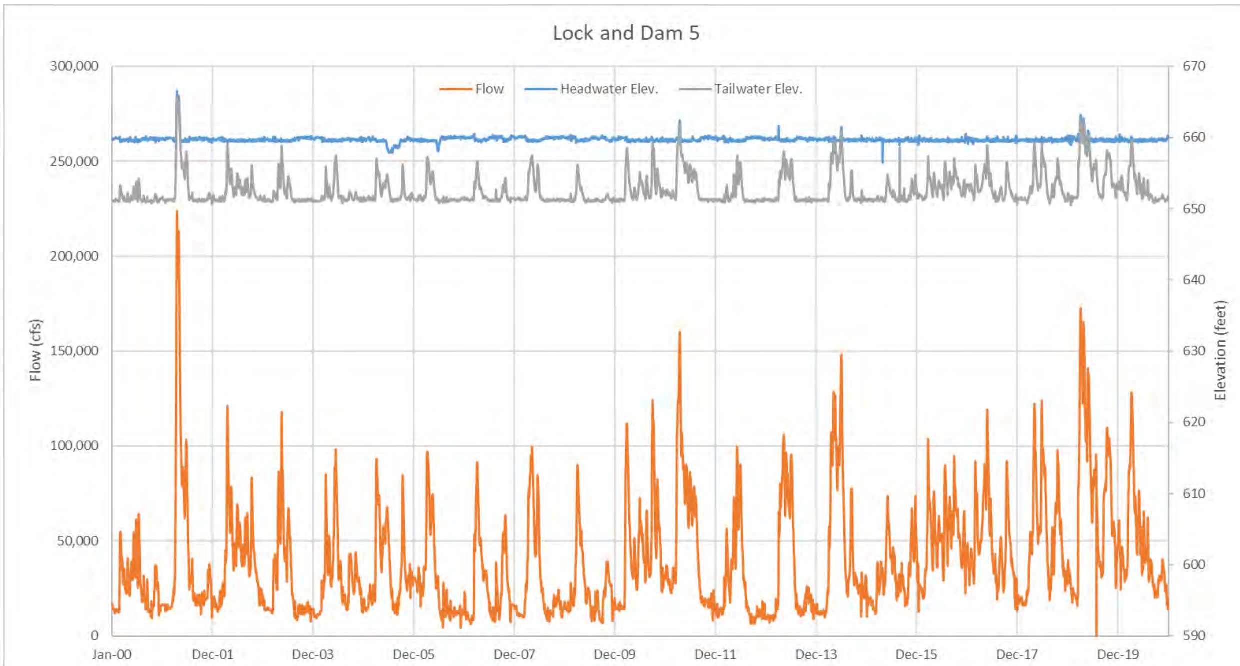

ROLLER GATES
TAINTER GATES
EARTHEN DAM
AUXILIARY LOCK
OPERATING LOCK
FIXED CREST SPILLWAY
EARTHEN DAM
Deterrent
0 200 400 600 800 1,000
Feet
Lock and Dam No. 7
Site Information
Carp LD Evaluation
USACE
FIGURE 5
BARR
Barr Footer:

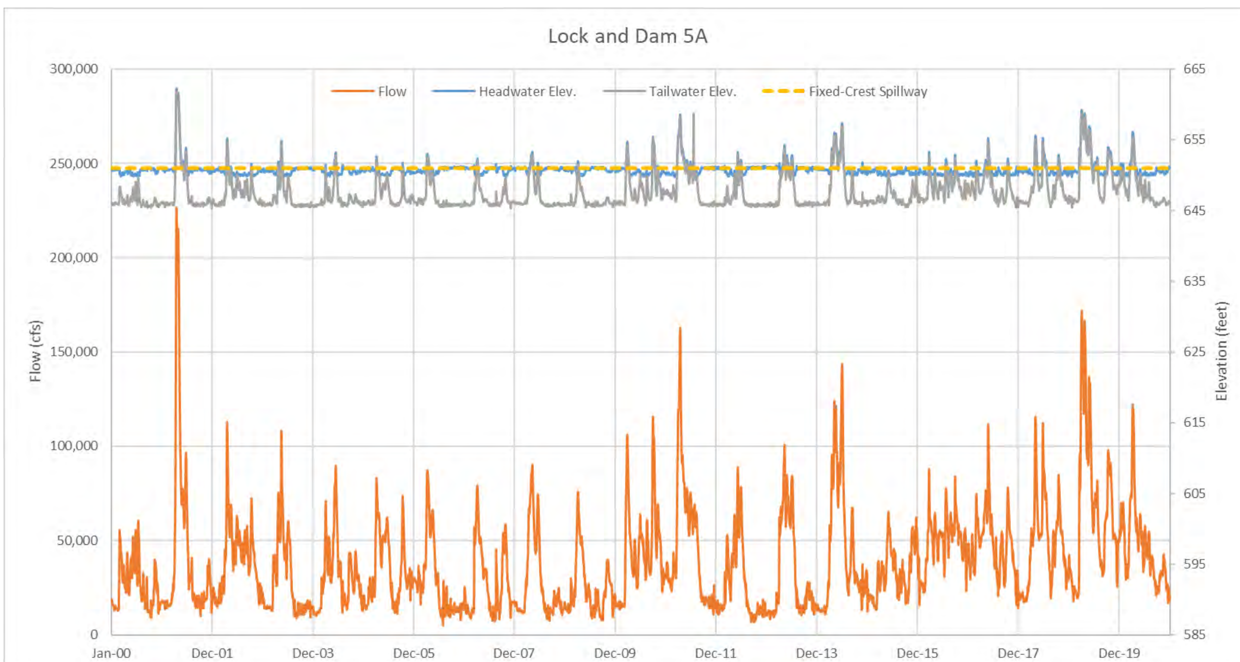

EARTHEN DAM
TAINTER GATES
ROLLER GATES
AUXILIARY LOCK
OPERATING LOCK
Deterrent
N
0 100 200 300 400
Feet
Lock and Dam No. 8
Site Information
Carp LD Evaluation
USACE
FIGURE 6
Barr Footer:
BARR

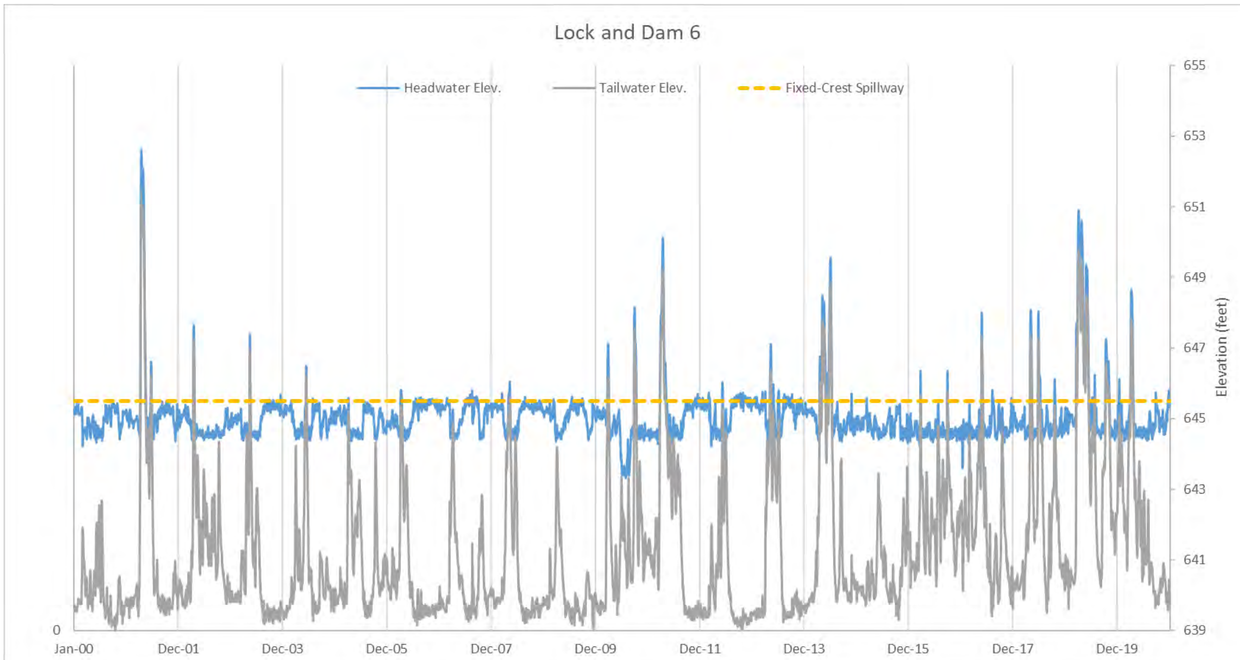
Appendix B

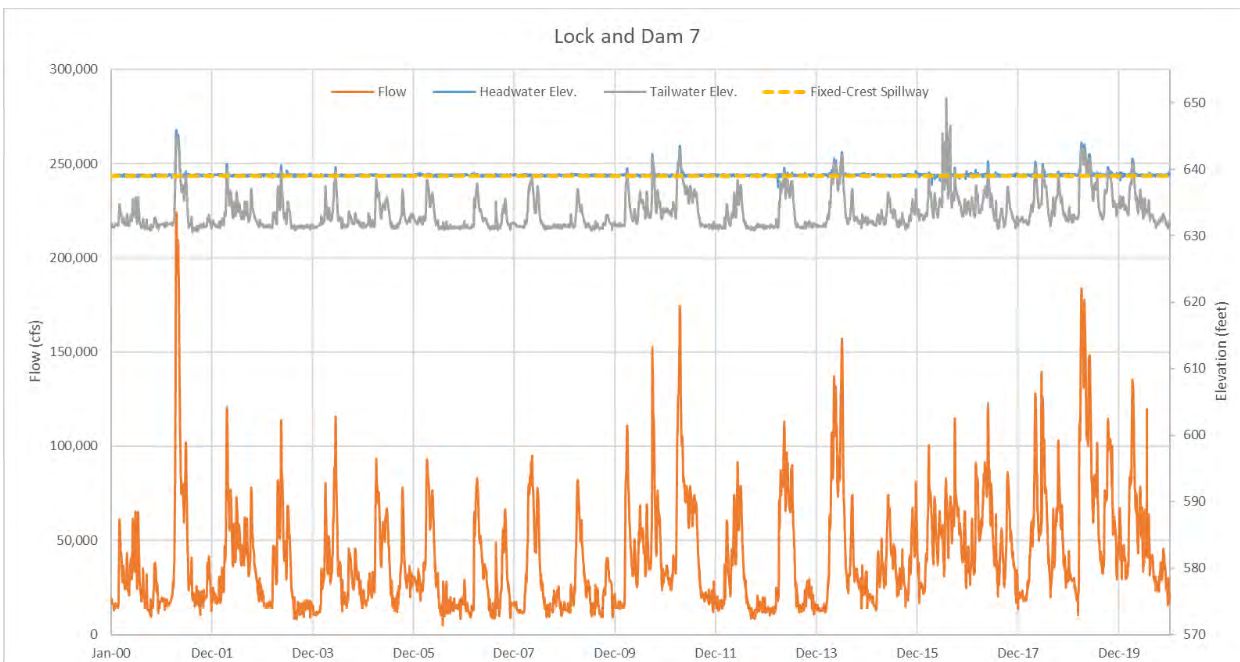
Hydraulic Data

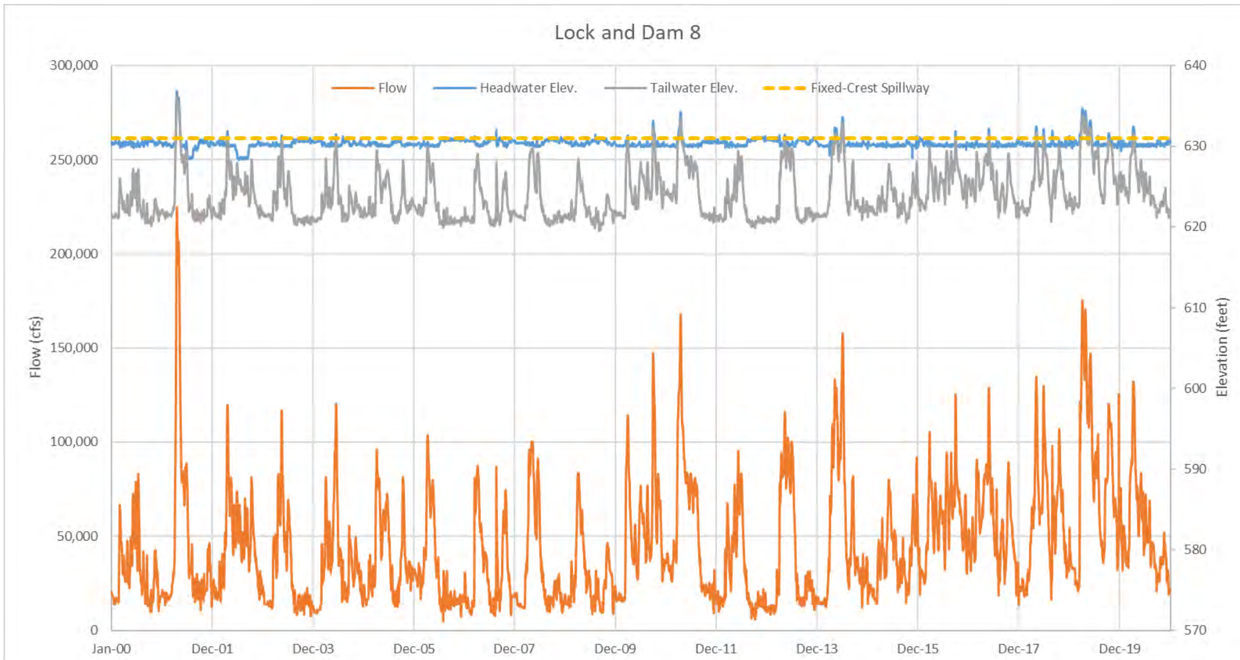



Lock and Dam 5
Flow
Headwater Elev.
Tailwater Elev.
Flow (cfs)
Elevation (feet)
300,000
250,000
200,000
150,000
100,000
50,000
0
670
660
650
640
630
620
610
600
590
Jan-00
Dec-01
Dec-03
Dec-05
Dec-07
Dec-09
Dec-11
Dec-13
Dec-15
Dec-17
Dec-19


Lock and Dam 5A
Flow
Headwater Elev.
Tailwater Elev.
Fixed-Crest Spillway
Flow (cfs)
Elevation (feet)
300,000
250,000
200,000
150,000
100,000
50,000
0
665
655
645
635
625
615
605
595
585
Jan-00
Dec-01
Dec-03
Dec-05
Dec-07
Dec-09
Dec-11
Dec-13
Dec-15
Dec-17
Dec-19


Lock and Dam 6
Headwater Elev.
Tailwater Elev.
Fixed-Crest Spillway
Elevation (feet)
655
653
651
649
647
645
643
641
639
0
Jan-00
Dec-01
Dec-03
Dec-05
Dec-07
Dec-09
Dec-11
Dec-13
Dec-15
Dec-17
Dec-19


Lock and Dam 7
Flow
Headwater Elev.
Tailwater Elev.
Fixed-Crest Spillway
Flow (cfs)
Elevation (feet)
300,000
250,000
200,000
150,000
100,000
50,000
0
650
640
630
620
610
600
590
580
570
Jan-00
Dec-01
Dec-03
Dec-05
Dec-07
Dec-09
Dec-11
Dec-13
Dec-15
Dec-17
Dec-19



Lock and Dam 8
Flow
Headwater Elev.
Tailwater Elev.
Fixed-Crest Spillway
Flow (cfs)
Elevation (feet)
300,000
250,000
200,000
150,000
100,000
50,000
0
640
630
620
610
600
590
580
570
Jan-00
Dec-01
Dec-03
Dec-05
Dec-07
Dec-09
Dec-11
Dec-13
Dec-15
Dec-17
Dec-19