Appendix E

Overview of Numerical Modeling Effort for Assessment of Site-Specific Tailwater Impacts

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I. General

As part of the ongoing engineering effort in support of the Upper Mississippi River and Illinois Waterway System Navigation Study, two-dimensional numerical models were built to investigate the hydraulic impacts of new lock construction at 16 lock and dam sites on the Upper Mississippi River and Illinois Waterway. The concerns for hydraulic impacts included approach and exit conditions as well as changes in flow conditions both during and after construction.

The numerical modeling effort was designed to complement the navigation modeling effort conducted at the Waterways Experiment Station (WES) in assessment of large-scale improvement measures. While physical models are best suited for studying navigation conditions, they have a high cost and do not have the flexibility of numerical models for making quick changes in bank alignment and bathymetry. Therefore, the physical modeling effort was confined to two sites that exhibited generically representative characteristics and were used to aid in the creation and verification of the numerical models.

The purpose of this document is to provide an overview of the numerical modeling procedures and assumptions and to provide examples of the type of output the model is capable of providing. A complete description of the numerical modeling effort is contained in an interim report entitled “Hydraulic Impacts of New Lock Construction,” dated July 1996.

II. Terminology

As the terminology being used to describe the various lock locations, types, sites, and alternatives can be confusing, the following definitions are provided for clarity:

Lock *Location* – Refers to where a new lock would be located in the dam structure. A plan view of the lock locations is shown in Figure 1.

- Location 1 – Landward and adjacent to the existing lock structure
- Location 2 – Extension of the existing lock
- Location 3 – Auxiliary miter gate bay or lock chamber
- Location 4 – Gated portion of the dam
- Location 5 – Non-overflow or overflow section of the dam
- Location 6 – Landward of the lock and dam structure, located on the opposite bank from the exiting lock

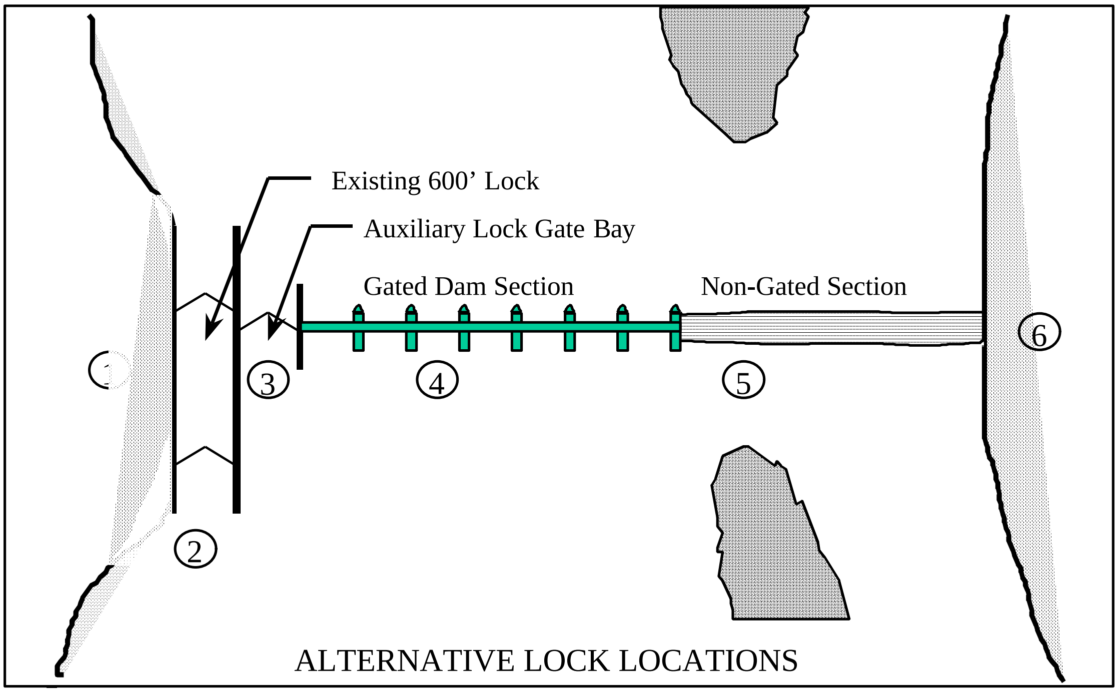


Figure 1 - Alternative New Lock Locations at a Typical Existing Lock and Dam Site.

Lock *Type* – Refers to the three conceptual lock designs being considered. Since from a river hydraulics standpoint the lock types are nearly identical, no attempt to differentiate between types was made in the modeling effort.

- Type A – Lock designed to current design standards and utilizing traditional construction techniques (i.e., a large, de-watered cofferdam).
- Type B – A lower cost lock using construction techniques proven in marine construction that previously have not commonly been used in lock construction.
- Type C – The lowest first cost design that is operationally safe with predictable performance. A "no frills" design utilizing innovative construction techniques.

Lock *Site* – Refers to a specific lock & dam (e.g., Lock & Dam 15, Lock & Dam 22, Peoria Lock & Dam, etc.)

Lock *Alternative* – Refers to a combination of lock site, location, and type.

Not all combinations of lock site, location and type are still under consideration. During the initial screening process, all Location 5, Location 6, and Type A locks were eliminated.

III. Scope of Modeling Effort

Numerical models were developed for Locks & Dams 20, 21, 22, 24, and 25 to assess navigation conditions for each large-scale improvement alternative under consideration. Unless prohibited by conditions at a specific site, lock Locations 1-4 were investigated for a variety of flows ranging from a 50% duration flow to the flow at which the lock goes out of operation. At each lock and dam site, the advantages and disadvantages for each of the lock locations were identified, and recommendations of channel improvements made. Results from the numerical and physical modeling were then used to assess plan alternatives for the remaining 11 unmodeled sites based on similarities with the modeled sites. All new locks modeled consisted of a 110-foot by 1,200-foot chamber, a 1,200-foot upstream guardwall, and a 1,200-foot downstream guidewall. Any refinements in the guardwall and guidewall lengths and configurations would be addressed during site-specific feasibility studies. Although 600-foot-long chambers were not separately modeled, the model results for the 1,200-foot locks would largely be applicable.

For the purpose of the modeling effort, it was assumed that any loss in gated capacity due to construction of a Location 4 lock would be replaced by adding new gates on a one for one basis in the overflow section of the dam (if possible).

IV. Overview of Numerical Modeling System

The TABS-2 numerical modeling system was selected to assess flow conditions at the lock and dam sites for the various lock alternatives under consideration. The TABS-2 modeling system consists of several different component programs. A brief description of the key components, and their role in the overall modeling effort, follows.

A. FastTABS

FastTABS is used as both the pre- and post-processor for the computational element of the TABS-2 modeling system. It is used to aid in the creation of the finite element mesh, the specification of model boundary conditions and flow parameters, and for the graphical presentation of model output.

B. RMA-2 (River Management Associates, Inc.)

RMA-2 is the computational element of the TABS-2 system used in this effort. RMA-2 is a two-dimensional, depth-averaged, free surface, finite element program for solving hydrodynamic problems. Through the use of conservation of mass and momentum, RMA-2 computes water surface elevations and flow velocities at nodal points in a finite element mesh representing a body of water such as a river, harbor, or estuary. Both steady-state and transient (unsteady) solutions can be performed. The output from RMA-2 is written into both a binary and an ASCII solution file. The binary solution file can be read into FastTABS for graphical display of results or the ASCII output can be reduced to a series of XYZ data points for import into a GIS database or other application.

V. Modeling Process

The following is a brief discussion of the procedures used in the creation, verification and application of the numerical models. A more detailed description of the modeling process is contained in the aforementioned interim report entitled “Hydraulic Impacts of New Lock Construction.”

A. Numerical Model Creation

Model creation consists of the construction of a numerical, finite element mesh and the specification of model parameters and boundary conditions.

1. Mesh Creation

At each lock and dam site, finite element meshes were constructed which described the bathymetry (bottom surface geometry) and adjacent topography of the sections of river being modeled. The original goal of the modeling effort was to reproduce two miles of the river both upstream and downstream of the dam; however, the actual extent of the models was based on available bathymetric information, program constraints, and the presence of side channels. Two models were constructed for each lock and dam, one for the headwater and one for the tailwater. This is necessary as the flow through the dam structure could not be accurately represented within the numerical mesh and therefore was modeled as a known boundary condition. Hydrographic survey data in the form of XYZ coordinates were input into FastTABS as the basis for construction of the finite element mesh. The hydrographic surveys were augmented with detailed scour surveys, conducted in the vicinity of the dam, and digitized points taken from topographic maps.

Figure 2 shows a portion of the head and tailwater finite element meshes constructed for Lock & Dam 20, merged together for display purposes.

2. Boundary Conditions and Model Parameters

Once the mesh was constructed, boundary conditions were assigned to the mesh for each flow modeled. Boundary conditions were entered as an incoming (upstream) flow rate and a downstream water surface elevation. Also specified were roughness (Manning's n) and turbulent exchange parameters for each element in the geometric mesh.

B. Model Verification

The next step in the modeling process was the verification of model results in order to ensure that the model accurately reproduced conditions observed in the prototype. Through the model verification process, model parameters were adjusted to reproduce observed prototype velocities and water surface profiles. Verification of model results was accomplished through a combination of field measurements of velocity and depth, and measurements taken in the physical models of Lock & Dams 22 and 25, constructed at WES. Field measurements were used to verify the existing (or base condition) models at each site. Physical model results were used to verify the future (with project) conditions at Locks & Dams 22 and 25.

C. Application of Numerical Models

After verification of the existing condition models, adjustments were made to the finite element meshes to represent each proposed large-scale navigation improvement alternative (new lock construction at Locations 1-4). Each model was run for a variety of flow conditions representing average to maximum navigable discharges. The focus of this initial modeling effort was on higher discharges as this represents the worst conditions for navigation.

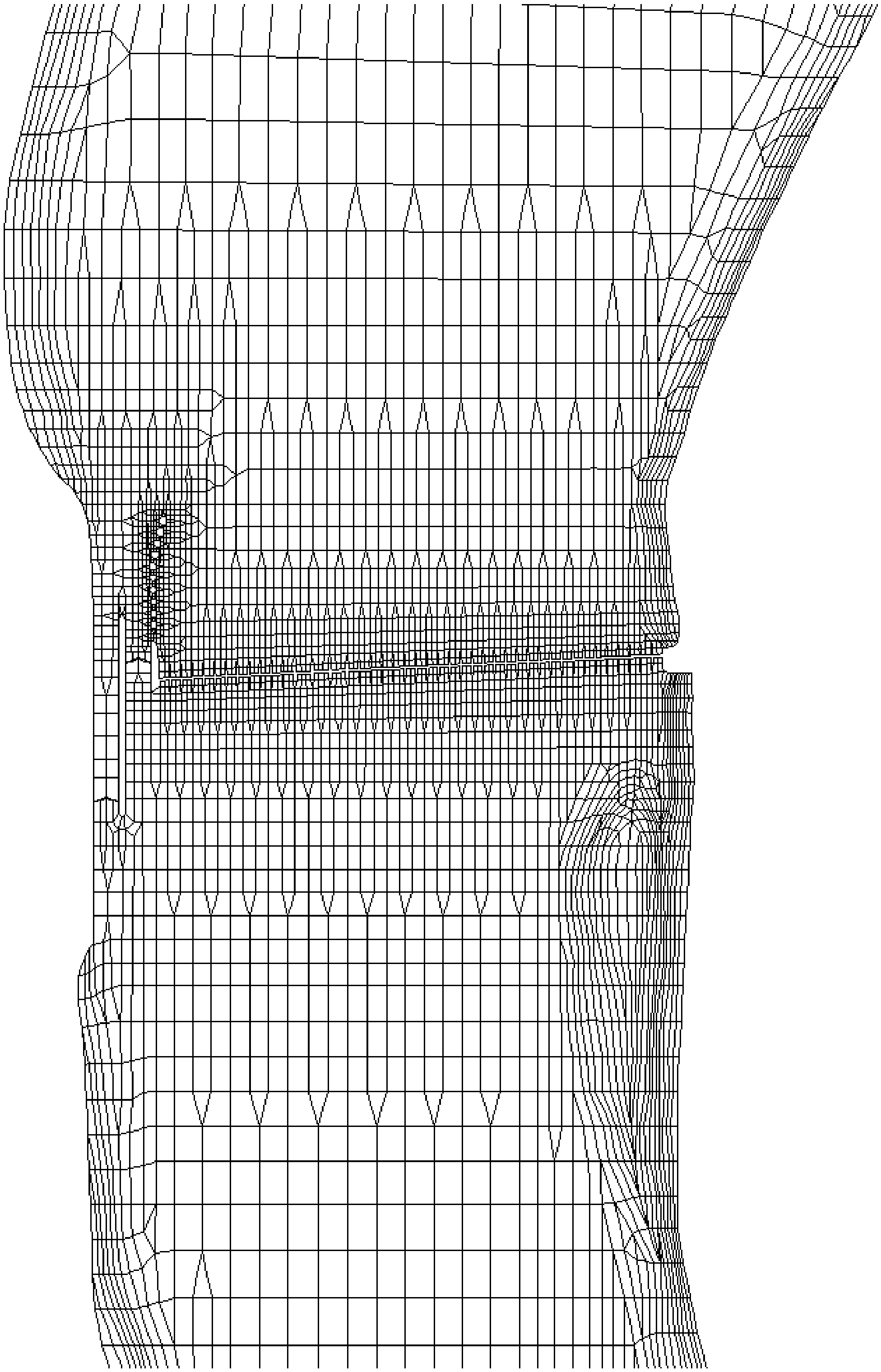


Figure 2 - Portions of the Head and Tailwater Finite Element Meshes for Lock and Dam 20, Base Conditions.

VI. Model Limitations and Assumptions

There are a number of limitations and assumptions inherent to the use of numerical models. These limitations and assumptions are not unique to this modeling effort, but rather are present in just about every application of this type of model. It is, however, important to understand these limitations and assumptions when interpreting and applying model results. The limitations and assumptions, described below, are divided into those associated with the model itself and those associated with the modeling process.

A. Numerical Model Assumptions and Limitations

As stated earlier, RMA-2 is a two-dimensional model; therefore, areas where three-dimensional flow conditions exist (such as flow through the submerged ports of the guardwall or in the immediate vicinity of the dam gates) can not be accurately represented in the model. However, if the model is capable of reproducing observed velocities and depths in these areas, it can be assumed that the three-dimensional flow conditions can be adequately represented two-dimensionally. It was on this premise that verification of the model was conducted. As with most hydraulic models, RMA-2 invokes the hydrostatic assumption, that is, the model assumes that vertical accelerations are negligible and that velocity vectors point in generally the same direction over the entire depth of the water column at any instant in time.

Second, RMA-2 is a fixed bed model. Therefore, it does not compute scour or deposition of sediments, nor does it account for any change in substrate composition or bedforms that may result from changes in the flow distribution associated with a given alternative.

As mentioned previously, the dam gates can not be accurately represented within the numerical mesh and must be modeled as a boundary condition. In the headwater model, the dam was specified as a constant water surface boundary. This resulted in a relatively uniform distribution of flow across the dam gates. At higher flows, and when the dam is out of operation, this uniform distribution of flow is appropriate. However, at low flows the majority of the flow is typically passed through the dam gates immediately adjacent to the auxiliary gate bay, not uniformly across the dam. This can be corrected for by limiting the number of gates that flow is allowed to pass through in the model at lower flows. This was not critical in the navigation modeling as the focus of the effort was on higher flows, when navigation conditions are at their worst, but would be important when modeling lower flows such as those representing overwintering conditions.

B. Assumptions and Limitations Associated with the Modeling Process

Data collection for the modeling effort extended over several seasons with bathymetric information collected first (to facilitate model creation) and prototype measurements of velocity and depth (used in the verification process) taken last. This made comparison of model and prototype velocities difficult as bathymetric changes were noted between the two surveys.

The minimum sounding increment of the hydrographic and scour surveys was 50 feet, with variable transect spacing. This makes detection of small-scale flow features impossible. While further data collection and refinement of the numerical grid sounds attractive, it would not necessarily produce a more accurate solution due to the other assumptions and limitations of the model.

Comparison of velocity measurements taken in the WES physical models to those computed in the numerical model was difficult due to the different methods of velocity measurement used in the two models. In the physical models, the velocity in the top 9 feet of the water column was measured, whereas the numerical models computed a depth-averaged velocity. This can result in large discrepancies in the tailwater region where the presence of deep scour holes results in model velocities significantly lower than those measured in the physical model.

VII. Description of Model Output

Output from the model consists of two-dimensional velocity components and water depths at each node of the finite element mesh. Contours and velocity vectors plots can be generated directly using FastTABS. Example bathymetric and velocity vector plots are shown in Figures 3 and 4. Direct comparison of alternatives is not possible in FastTABS unless the numbering and location of all nodes within the models remains the same. This is not the case between models of differing lock location, since the finite element mesh was adjusted to accommodate the new lock structure, guidewalls and guardwalls, and any channel improvements included in the model. Therefore, comparison of velocities between alternatives was accomplished through the use of GIS, described below.

VIII. Integration of Model Results with GIS Database

ArcInfo was utilized for the plotting of velocity contours and comparison of alternatives. Model input was imported into ArcInfo as XYZ coordinates with the other information (velocity, depth, etc.) input as attributes to the points. Using these points, a TIN (triangulated irregular network) was created for each alternative and velocity contours developed. In order to map the increase/decrease in velocity associated with a given alternative, the TINs had to first be converted to a lattice-grid (a 10-meter spacing was used) then subtracted from one another.

Contour diagrams, using depth-averaged data at two representative flows, 50,000 CFS and 120,000 CFS, were created for the base condition and for new lock Location 4. As described earlier, this location entails replacement of lost flow with a new gate, and thus has the most potential to induce changes in velocity magnitude or direction. Though

Figure 3 - Example Contour Plot Showing Existing Tailwater Bathymetry at Lock and Dam 20.

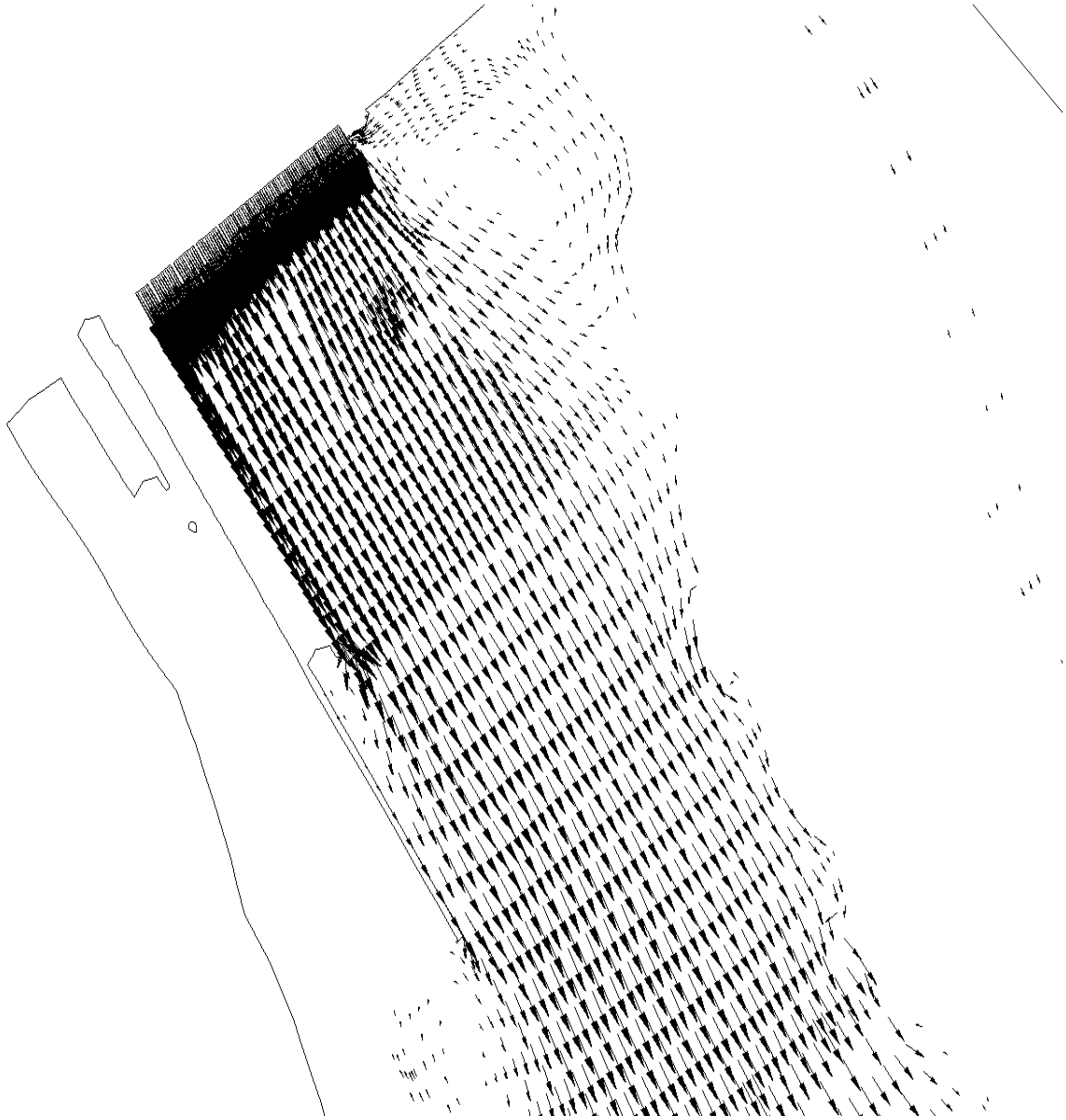


Figure 4 - Example Velocity Vector Plot Showing Flow Through a Location 4 Ported Guardwall at Lock and Dam 22.

changes (in the area of the dam) with other lock locations are not foreseen at this time, similar diagrams could be created if deemed necessary. These diagrams are intended to portray the areal extent and magnitudinal change in velocity in areas approximately 2 miles upstream and downstream of the dam, with the primary focus being downstream.

IX. Conversion from Depth-Averaged Velocity to Vertical Profile

At the November 13, 1996, NECC meeting, resource agency representatives inquired whether the depth-averaged velocities could be converted to a velocity one or two feet off the channel bottom. One way this could be done is through the use of a standard turbulent velocity profile. Knowing the depth, channel geometry, bed roughness (or representative grain size) and the computed depth-averaged velocity at each node, the velocity at any depth can be estimated using one of a number of turbulent velocity profiles that have been proposed. An example of such a profile, proposed by Vanoni (1967), is as follows:

$$v = V + \frac{1}{K}\sqrt{gdS}\left(1 + \ln\frac{y}{d}\right)$$

Where:
y = depth at which to compute velocity
v = velocity at depth y
V = depth-averaged velocity
d = channel depth
g = acceleration due to gravity
S = channel slope
K = Von Karmon constant ≈ 0.4

This type of approach would work in a fairly uniform portion of the channel, but would not be appropriate immediately upstream or downstream of the dam, near structures (e.g., ported guardwalls, dikes, etc.), or in areas downstream of the dam where significant scour holes have developed.

Glossary

Boundary Conditions: Water levels, flows, concentrations, stage/discharge relationships, etc., which are specified at the boundaries of the area being modeled. Unspecified boundaries are considered "no-flow" boundaries by the model.

Finite Element: A method of solving the basic governing equations of a numerical model. The spatial domain is divided into geometric elements in which the solution of the governing equations is approximated by a continuous function. This method lends itself well to the river environment because of its diversity in computational mesh (element size, shape, and orientation), flexibility of boundary conditions, and continuity of the solution over the area.

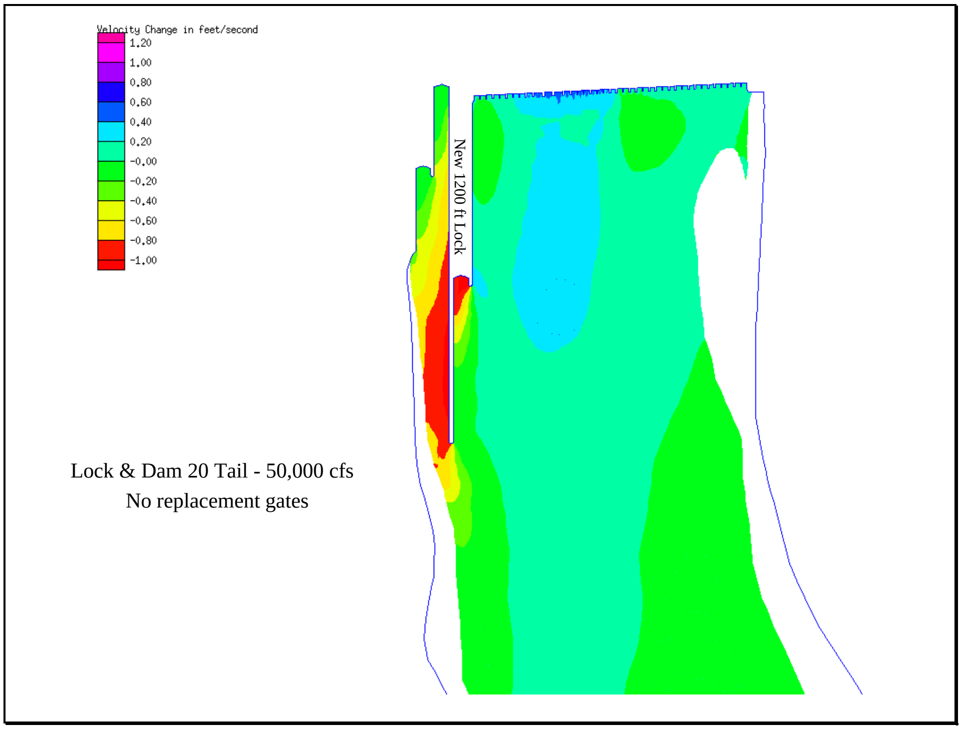
Manning's n: A channel roughness parameter attributed to R. Manning (1889), which is widely used in hydraulic calculations involving free-surface (open channel) flow.

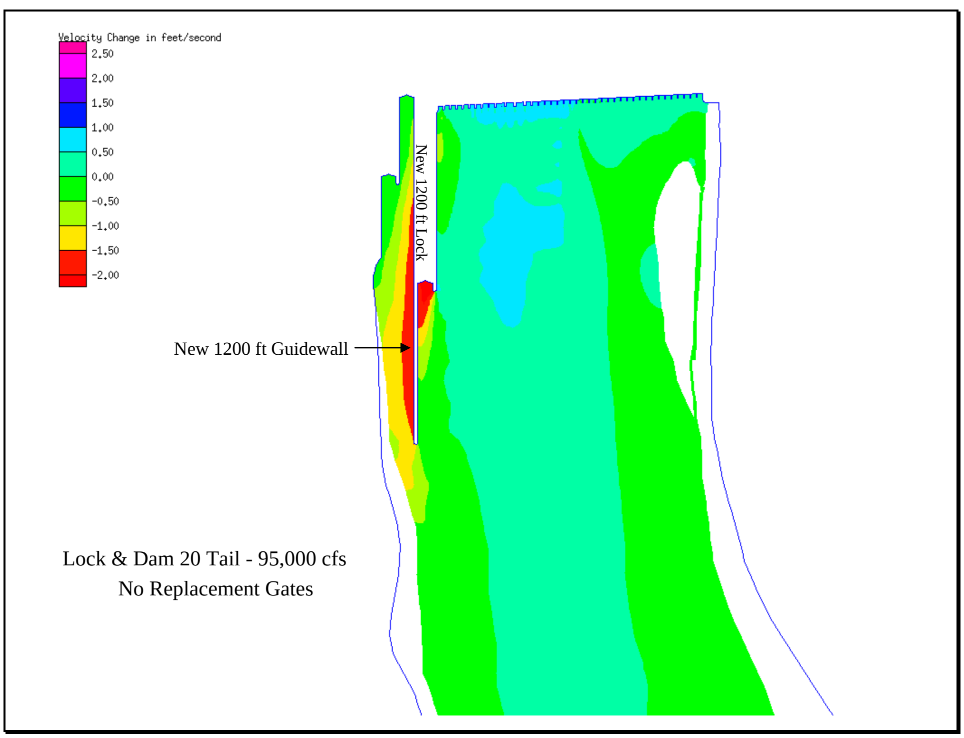
Roughness: In a river or stream bed, the material on the side slopes or the bottom that inhibits the flow.

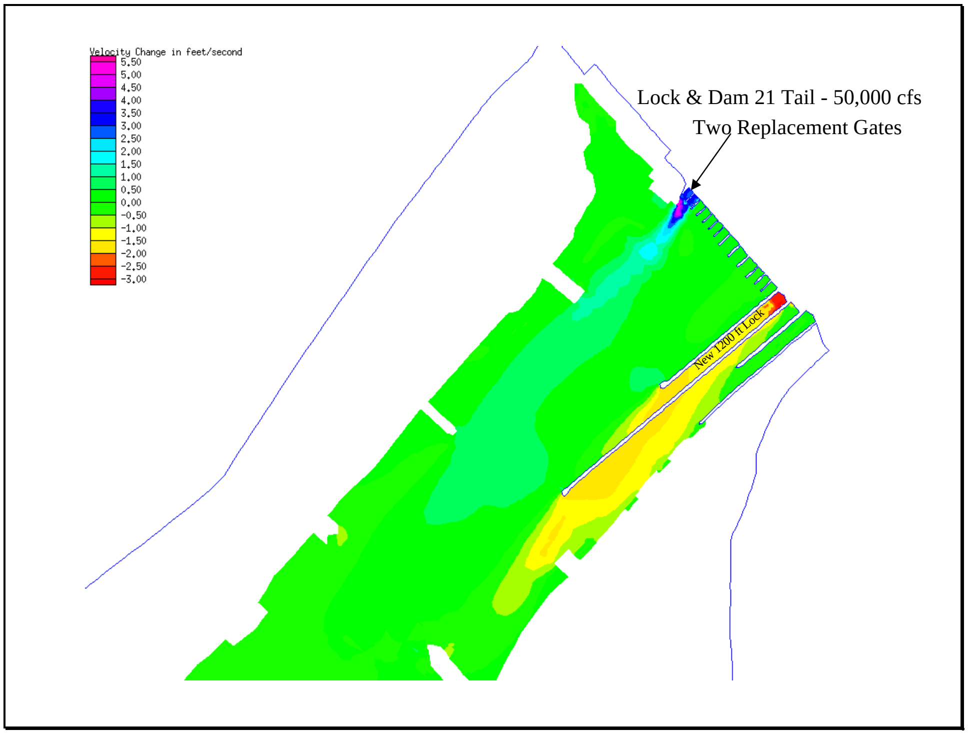
Steady-State: A simulation in which the boundary conditions are static. The variables being investigated (flow, depth, velocity) do not change with time.

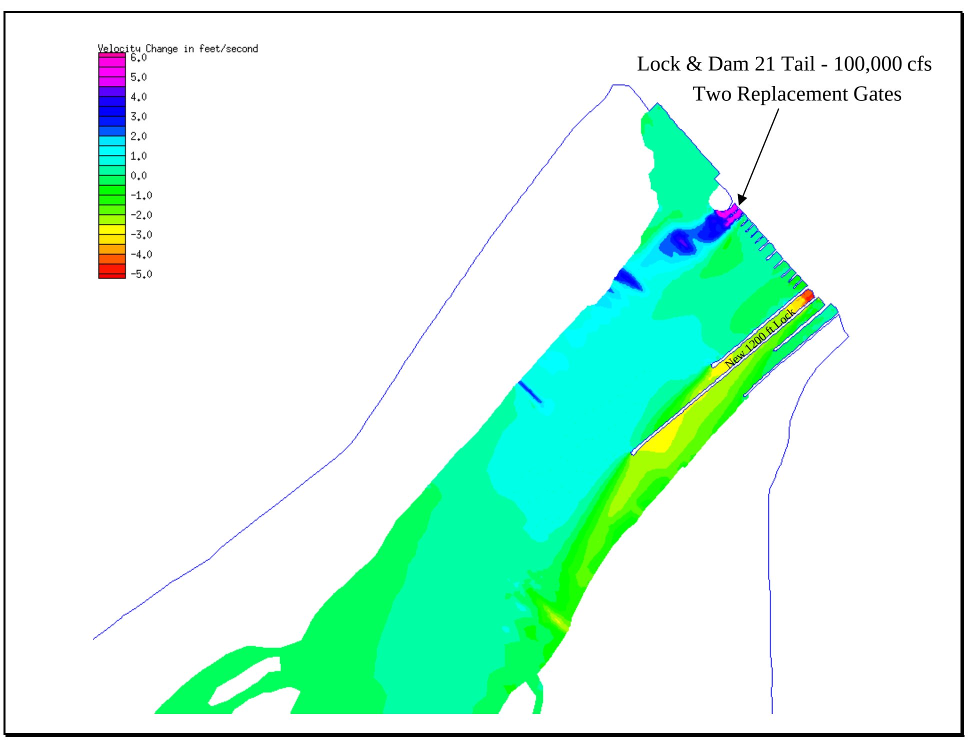
Transient: Opposite of steady-state. Boundary conditions and variables being investigated change with time. Used when modeling a specific event (e.g., the flood of 1993) or hypothetical hydrograph.

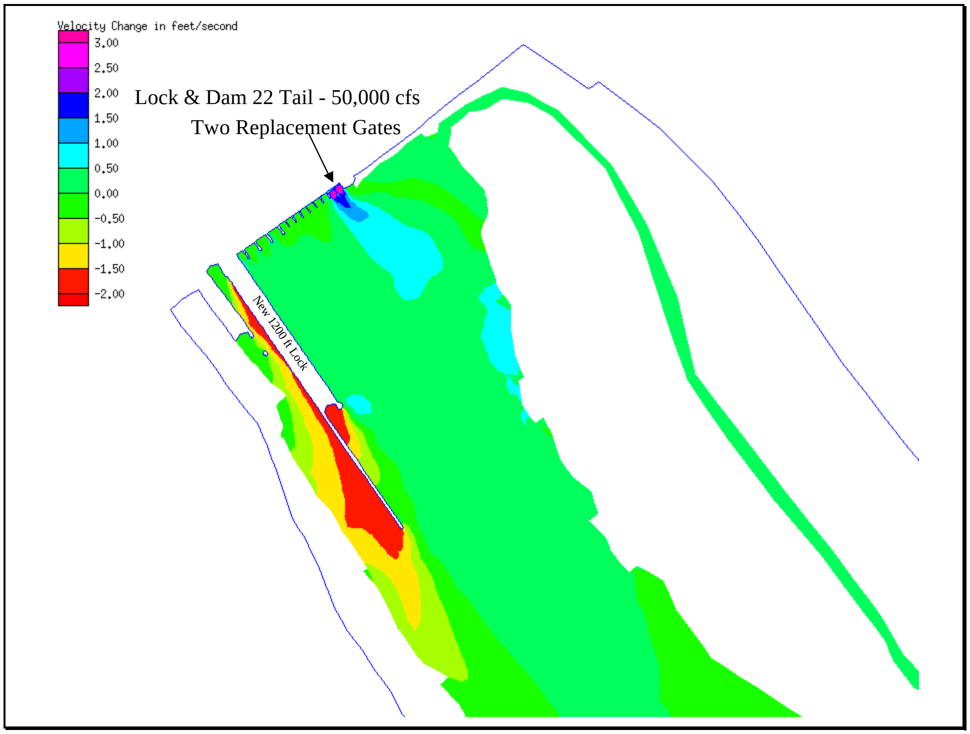
Example TABS Outputs at Each Lock Modeled

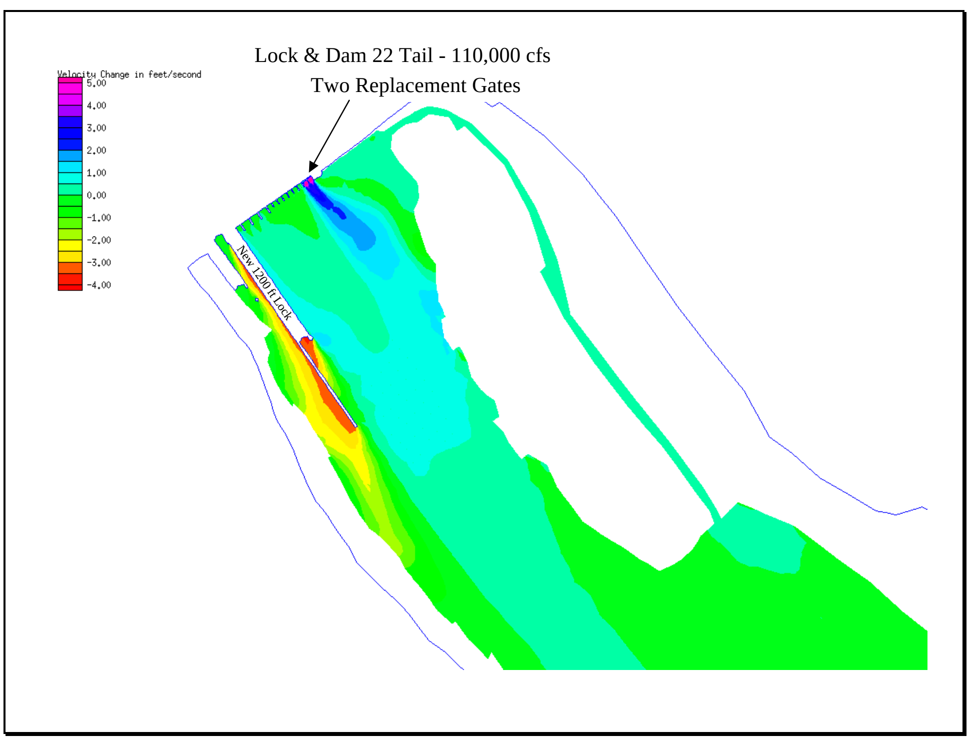

Velocity Change in feet/second
1.20
1.00
0.80
0.60
0.40
0.20
-0.00
-0.20
-0.40
-0.60
-0.80
-1.00
New 1200 ft Lock
Lock & Dam 20 Tail - 50,000 cfs
No replacement gates

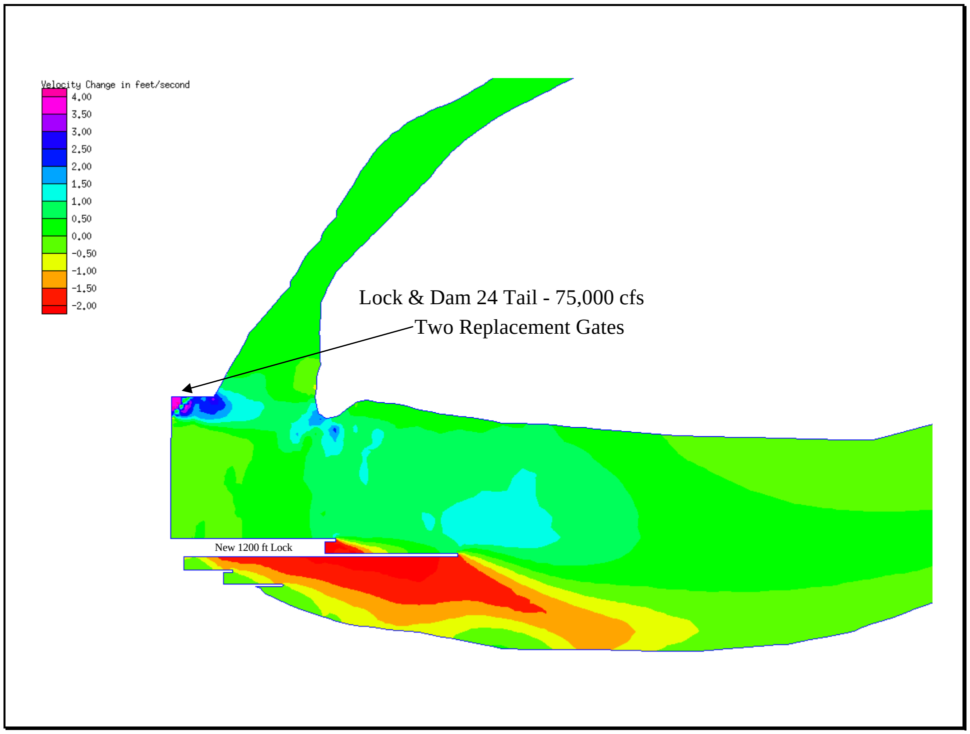

Velocity Change in feet/second
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
New 1200 ft Lock
New 1200 ft Guidewall
Lock & Dam 20 Tail - 95,000 cfs
No Replacement Gates

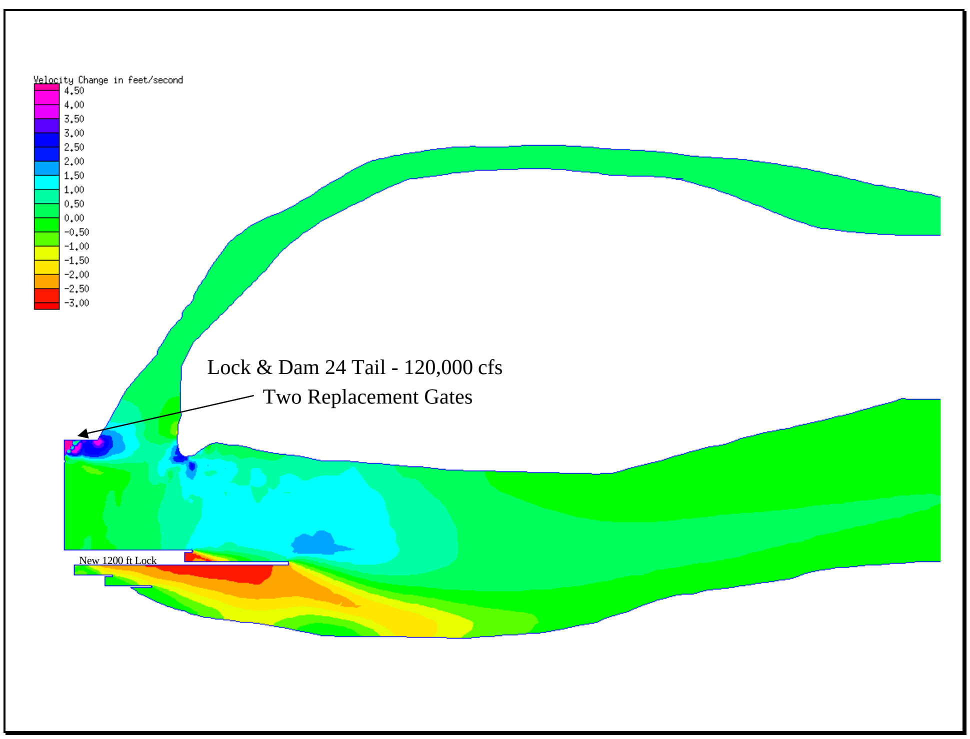

Velocity Change in feet/second
5.50
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
Lock & Dam 21 Tail - 50,000 cfs
Two Replacement Gates
New 1200 ft Lock

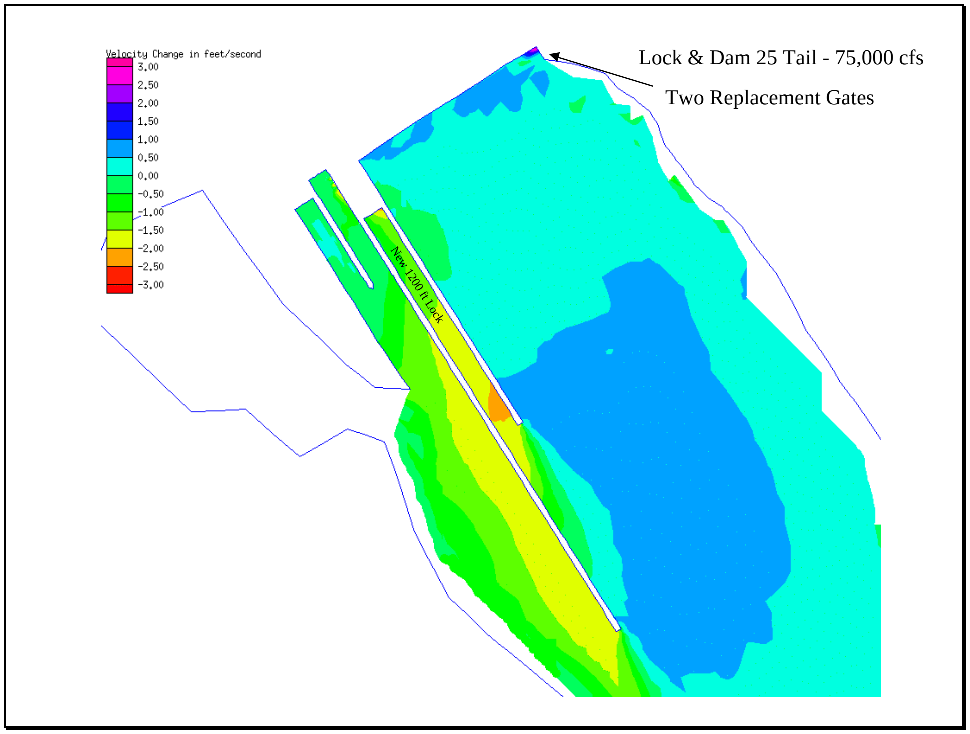

Velocity Change in feet/second
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
Lock & Dam 21 Tail - 100,000 cfs
Two Replacement Gates
New 1200 ft Lock

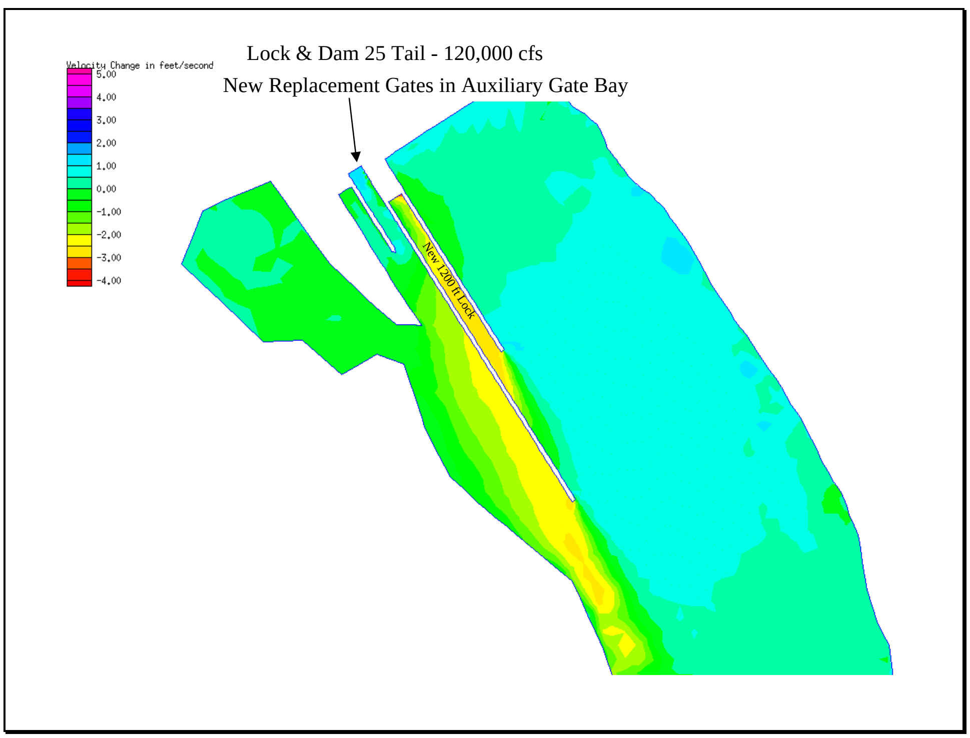

Velocity Change in feet/second
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
Lock & Dam 22 Tail - 50,000 cfs
Two Replacement Gates
New 1200 ft Lock


Lock & Dam 22 Tail - 110,000 cfs
Two Replacement Gates
Velocity Change in feet/second
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
New 1200 ft Lock


Velocity Change in feet/second
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
Lock & Dam 24 Tail - 75,000 cfs
Two Replacement Gates
New 1200 ft Lock


Velocity Change in feet/second
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
Lock & Dam 24 Tail - 120,000 cfs
Two Replacement Gates
New 1200 ft Lock


Velocity Change in feet/second
3.00
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
Lock & Dam 25 Tail - 75,000 cfs
Two Replacement Gates
New 1200 ft Lock


Lock & Dam 25 Tail - 120,000 cfs
New Replacement Gates in Auxiliary Gate Bay
Velocity Change in feet/second
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
New 1200 ft Lock