Inventory of Potential Structural and Nonstructural Alternatives for Increasing Navigation Capacity of the Upper Mississippi River System

ANATOLY HOCHSTEIN, BRUCE BARKER, AND IVAN ZABALOIEFF

Innovative design, operational changes, or relatively low-cost structural modifications may eliminate constraints at existing locks and, as a result, lock replacement or other major capital investments to increase waterway carrying capacity can be significantly postponed while still providing adequate capacity. The relief of constraints to navigation and corresponding capacity improvements, however, represent a complex area of waterway analysis that requires combined analytic expertise in the disciplines of hydraulic, hydrologic, and structural engineering; operations research; naval architecture; and economics. The primary elements of water transportation, including lock facilities, channel design, and maintenance and tow fleet operations, are not isolated factors that can be treated separately but are integrated parts of a complex system. About 40 different improvement measures to improve waterway capacity have been analyzed. These measures are grouped as follows: scheduling of lock operations (assistance to multicut lockages), improvements to approaches, modification of tow configuration and operation pattern, and lock operating controls and minor structural actions to correct design deficiency. Each measure is evaluated based on its history of application, cost, and impact on capacity. The most promising measures were found to be lockage scheduling ("N-up/N-down" policy), the use of helper boats, the modification of tow haulage equipment, and the use of bow thrusters. As a result of the assessment of the impact of individual measures and combinations of measures (scenarios) on lock performance, specific input variables for capacity determinations are presented. These key input variables were used in the lock capacity model to simulate future transportation development of the Upper Mississippi waterway system.

This paper reports on a contract study of navigation capacity improvements completed in April 1981 for the Upper Mississippi River Basin Commission. The Commission had been directed by Congress to prepare a master management plan for the Upper Mississippi River System (UMRS) by January 1, 1982. The system consists of the Mississippi River between Cairo, Illinois, and St. Paul, Minnesota; the Illinois Waterway; and the navigable portions of the Minnesota, St. Croix, Black, and Kaskaskia Rivers (see Figure 1).

All master-plan studies pertaining to navigation capacity improvements on the system, economic evaluation of these improvements, and analysis of related transportation impacts were assigned to the Navigation-Transportation Work Team. The work-team members represented the U.S. Army Corps of Engineers, the U.S. Department of Transportation, the U.S. Maritime Administration, the departments of transportation of five states, and four public members.

This was the earliest contract study of the work team, since an inventory of structural and nonstructural capacity improvement measures would provide the essential building blocks for navigation capacity expansion plans. Beyond a few site-specific studies, conducted by the Corps of Engineers, no systemwide inventory existed.

Building additional locks is, of course, the best-known means for increasing the capacity of canalized waterways. But it is also the most expensive means. For this reason, the work team desired an imaginative and exhaustive search for less capital-intensive but effective measures. These are often styled "nonstructural" measures but really encompass structural modifications, equipment improvements, operational improvements, towing equipment improvements, and even increases in lock staffing and towboat crewing. The study scope also included anything that could reduce haulage cost and facilitate traffic movements, especially at congested locks. The contractor's proposal responded very well to this objective.

Of course, the study results would determine the success of the work team's navigation capacity expansion planning, or its failure if significantly effective measures were overlooked. In addition, the array of measures had to serve three planning objectives dictated by master-plan study requirements:

1. Full range of system capacities--A number of system capacity improvement schemes would be constructed to explore the full range of capacity up to "unconstrained" waterway traffic projections. It was hoped that this range would at least include one scheme yielding the greatest net economic benefits. It would provide a range of potential future traffic densities needed for impact studies to be done by the Environmental Studies Work Team. Finally, it would provide a range of traffic diversions needed for intermodal impact studies.
2. Primarily nonstructural scheme--Several system capacity improvement schemes would use only nonstructural measures--that is, no additional locks. The best of these would satisfy a Water Resources Council planning requirement for an alternative plan that makes maximum feasible use of nonstructural measures.
3. Second lock at Alton--Congress explicitly requested information on a second lock at the new Locks and Dam 26 under construction at Alton, Illinois. When is a second lock needed and economically justified? What size should it be--110x600 ft or 110x1200 ft?

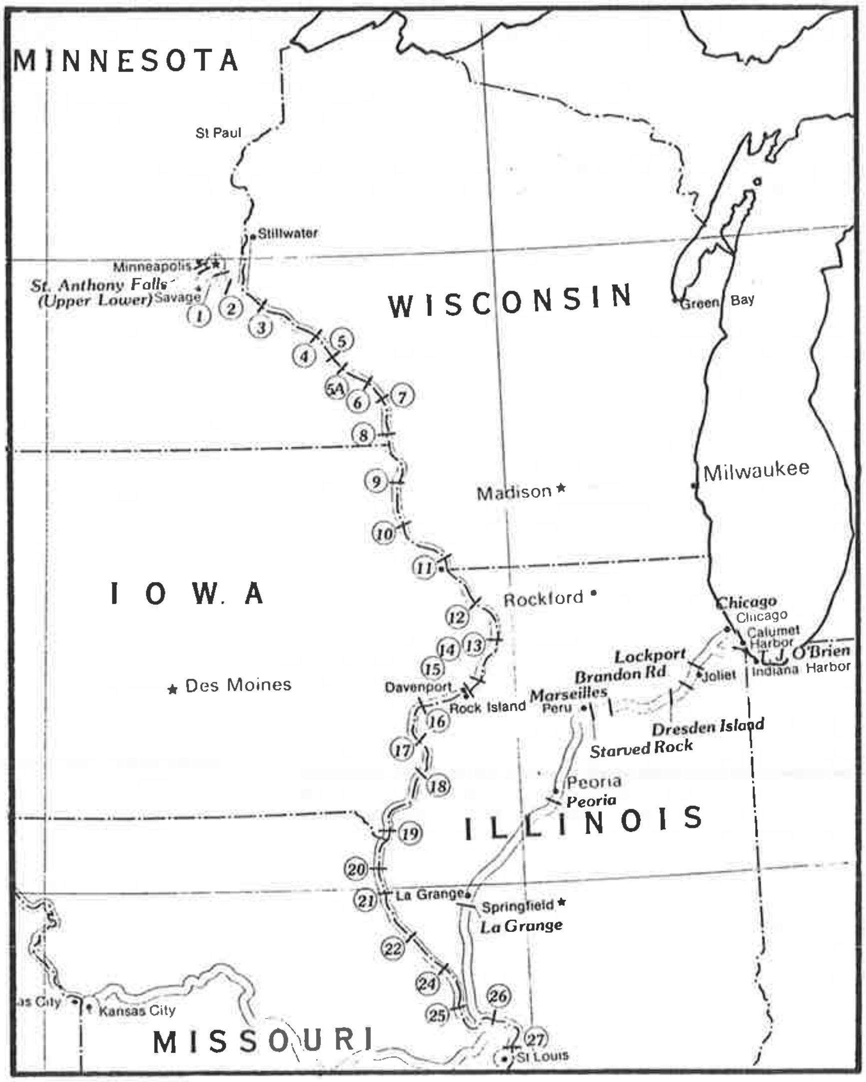
Finally, study results had to be organized and presented to immediately serve as input to the work team's planning and evaluation studies. Narrative, tabular, and map presentations were required to describe where a measure could be used--for example, at which locks, how it works, and how it is implemented. Capital, operation, maintenance, repair, and annualized costs were required for economic evaluation. Performance data on lock processes and component lockage times had to be presented in the exact form required for data input to a lock simulation model.

MEASUREMENT OF CAPACITY AND PERFORMANCE

The capacity of a canalized waterway system is essentially limited by locks, especially the most congested locks. For this reason and other study constraints, the work team decided not to develop a model capable of simulating tow movements throughout the system. Instead, it concentrated on improving a lockage simulation model, which became LOKSIM2.

Model development proceeded concurrently with this contract study and was completed at the same time. Then the performance data for measures selected by the work team were analyzed with the model to produce lockage delay functions. This unfortu-

Figure 1. Upper Mississippi River Basin system.



nate but unavoidable timing of work created special difficulties for the contractor and the work team:

1. The contractor had to evaluate the capacity effectiveness of measures and combinations of measures without benefit of the most sophisticated tool, the LOKSIM2 model.
2. The work team had to screen, discard, and select measures to a large degree before they were fully evaluated.

The solution was to quantify the effectiveness of measures, for interim purposes, by calculating the change in lock tonnage capacity. This was done by using a lock capacity formula the contractor had developed for the National Waterways Study that consists of the following equations for capacity (C) and service time (T):

$$C = \left(\prod_{i=1}^{3} Ki \right) NLT_s/T \quad (1)$$

and

$$T = T_f + f_d (T_t + D) + f_s S \quad (2)$$

where

Ki = three reduction coefficients for empty back-haul, recreation or downtime, and seasonality;
N = time frame under consideration (month or year);
L = barge lading (tons/barge);
T_s = tow size (barges);
T_f = fly/exchange lockage time;
T_t = turnback lockage time;
D = extra time for double lockages;
S = extra time for setover lockages;
f_d = frequency of double lockages; and
f_s = frequency of setover lockages.

This formula estimates one point, very high, on the lockage delay function. Cargo throughput at this point is called "capacity". As can be seen from the formula, this calculated capacity is directly proportional to tons per tow and inversely proportional to average lockage time. The lock processes and process time components are closely related to those used in the LOKSIM2 model and the Performance Monitoring System (PMS) data base.

Since neither the calculated capacity nor the absolute value of change in capacity was particularly useful to the work team, the formula was used to calculate an index. The chosen index was percentage increase in capacity (PIC), which could readily separate measures with great effect from those with little effect.

Table 1. Average 1976 PMS data.

	Lockage										Fleet			
	Time (min)													
	Approach				Exit		Frequency		Extra Time					
Lock	Fly/ Exchange	Turnback	Entry	Chambering	Fly/ Exchange	Turnback	Setovers	Doubles	Setovers	Doubles	Avg Tow Size (no. of barges)	Barge Lading (tons)	Frequency of Loaded Barges	Seasonal Factor
Upper Saint Anthony	3.5	3.0	4.0	9.0	3.5	3.5	0.65	-	5.0	-	1.67	1337	0.50	0.52
Lower Saint Anthony	5.0	5.0	4.5	12.0	2.0	2.5	0.69	-	7.0	-	1.79	1252	0.50	0.56
1	4.5	3.5	5.0	14.0	4.5	4.5	0.66	0.03	6.5	15.5	1.81	1271	0.50	0.56
2	13.0	7.0	6.5	10.5	4.5	5.5	0.14	0.41	23.0	20.5	6.97	1488	0.60	0.70
3	10.5	5.5	5.0	7.0	5.0	5.5	0.15	0.52	23.0	20.5	7.66	1502	0.64	0.65
4	12.5	4.5	5.5	7.0	5.0	5.0	0.13	0.53	23.0	20.5	8.08	1523	0.65	0.66
5	12.0	4.0	5.5	8.0	5.0	5.0	0.14	0.54	23.0	20.5	8.09	1502	0.67	0.67
5A	10.5	3.5	5.0	7.5	6.0	5.5	0.15	0.58	23.0	20.5	8.09	1513	0.67	0.67
6	14.0	4.0	5.5	7.0	4.5	6.5	0.13	0.56	23.0	20.5	8.30	1507	0.67	0.67
7	12.5	4.5	6.5	6.5	5.5	5.5	0.11	0.58	23.0	20.5	8.28	1504	0.67	0.65
8	12.0	5.0	5.5	9.0	7.5	6.5	0.14	0.57	23.0	20.5	8.35	1505	0.67	0.66
9	12.0	4.5	6.0	7.5	6.0	6.0	0.15	0.59	23.0	20.5	8.52	1499	0.70	0.66
10	11.0	4.0	5.5	8.0	5.0	5.5	0.10	0.58	23.0	20.5	8.30	1497	0.70	0.66
11	14.5	4.0	5.0	10.5	6.0	5.0	0.11	0.58	23.0	20.5	8.35	1487	0.70	0.66
12	16.0	6.5	5.0	7.5	5.5	5.5	0.13	0.60	23.0	20.5	8.83	1480	0.71	0.65
13	10.5	3.0	5.5	9.0	6.0	6.0	0.13	0.60	23.0	20.5	8.78	1482	0.71	0.66
14	9.0	4.5	4.0	8.5	4.5	4.5	0.09	0.45	23.0	20.5	7.52	1391	0.69	0.68
15	13.5	5.0	4.5	11.5	7.0	6.5	0.14	0.49	23.0	20.5	7.57	1495	0.71	0.67
16	9.0	3.0	4.5	9.0	10.0	4.5	0.14	0.48	23.0	20.5	7.39	1494	0.70	0.68
17	20.0	6.0	5.0	8.0	8.0	5.0	0.14	0.54	23.0	20.5	8.12	1487	0.69	0.67
18	13.5	4.0	6.0	9.0	5.0	5.0	0.15	0.56	23.0	20.5	8.30	1465	0.69	0.67
19	19.0	9.0	8.0	21.0	11.5	9.5	-	-	-	-	8.81	1479	0.68	0.69
20	15.0	4.0	5.0	8.0	7.0	5.5	0.14	0.62	23.0	20.5	9.08	1475	0.68	0.69
21	18.5	6.5	5.0	8.0	6.0	5.0	0.14	0.61	23.0	20.5	9.17	1475	0.68	0.69
22	26.5	9.0	6.0	8.5	13.0	5.5	0.15	0.62	23.0	20.5	9.21	1478	0.68	0.71
24	18.5	5.0	5.0	10.5	7.0	6.0	0.18	0.58	23.0	20.5	8.86	1487	0.66	0.72
25	20.0	5.0	4.5	10.0	3.5	3.5	0.17	0.58	23.0	20.5	8.91	1489	0.66	0.72
26														
Main chamber	24.0	2.0	6.5	14.0	9.0	7.0	0.16	0.72	23.0	20.5	10.40	1457	0.65	0.85
Auxiliary chamber	18.0	5.5	2.0	13.5	4.0	3.0	0.15	0.48	23.0	20.5	3.53	1329	0.52	0.85
27														
Main chamber	14.5	4.0	8.5	12.0	8.5	7.5	-	-	-	-	8.62	1513	0.69	0.85
Auxiliary chamber	13.5	3.0	5.0	9.5	4.5	4.0	0.17/0.05	0.53/0.28	23.0	20.5	2.91/ 6.5	1480	0.46	0.85
T. J. O'Brien	3.0	2.5	3.0	11.5	3.0	3.0	-	-	-	-	2.19	1212	0.61	0.82
Lockport	10.0	4.5	5.0	21.0	7.0	4.0	0.51	0.10	23.0	20.5	5.24	1511	0.59	0.77
Brandon Road	15.5	7.0	5.0	19.0	8.0	5.0	0.36	0.26	23.0	20.5	5.99	1449	0.60	0.80
Dresden Island	12.5	5.0	4.5	16.5	5.0	4.0	0.32	0.28	23.0	20.5	6.04	1527	0.61	0.87
Marseilles	13.5	5.5	5.5	20.0	9.0	4.0	0.30	0.29	23.0	20.5	5.87	1543	0.61	0.83
Starved Rock	13.0	7.0	5.0	13.5	6.5	4.0	0.30	0.32	23.0	20.5	6.18	1532	0.61	0.91
Peoria	13.5	5.0	6.5	11.0	7.5	6.0	0.29	0.41	23.0	20.5	6.95	1507	0.61	0.91
LaGrange	17.5	7.0	6.5	8.0	6.0	6.0	0.24	0.53	23.0	20.5	7.95	1455	0.63	0.91

A cost-effectiveness index was then derived by dividing PIC by the annualized cost in thousands of dollars. The highest values of this index were associated with very inexpensive measures that produced some, albeit small, increase in capacity. As expected, high-capacity locks were observed to have moderately low cost-effectiveness indices.

Hindsight gained from the LOKSIM2 evaluations can be summarized as follows:

1. The indices are generally reliable in showing the preference or rank order of closely competing and mutually exclusive measures.
2. The indices are not very reliable in ordering nonexclusive and essentially unrelated measures.
3. The indices tend to exaggerate the utility of measures that are only effective at a very high rate of use.
4. The indices tend to underrate the utility of measures that are effective at a moderate to high rate of use.

Calculated capacities and derived indices are not the best means for measuring the performance of capacity expansion measures. Performance is ultimately measured in economic terms: the transportation cost savings resulting from a measure versus the annual cost of implementing a measure.

Transportation savings for locks result primarily from increasing the service rate of lockages by adding lock chambers, reducing component lockage times, and improving lockage processes (for example, by eliminating double and setover lockages). Other savings could result from reducing recreational lockages by a restrictive policy or eliminating such lockages with a separate recreational lock.

The basic cost reduction information for economic analysis is the shifted delay function that results from a measure or a combination of measures. The delay function is calculated by a lock simulation model. Consequently, the performance of a lock improvement measure must be described quantitatively and accurately in the exact lock processing terms and component lockage times used in the simulation model.

The lock processing terms and component times used in this study are given below:

T_s = average tow size (barges),
L = average barge lading (tons),
$K1$ = frequency of loaded barges,
$K2$ = availability factor = 1 - frequency of downtime and recreation,
$K3$ = seasonality factor = average seasonal tonnage/peak seasonal tonnage,
A_f = fly/exchange approach (min),

Table 2. Selected measures to increase system capacity.

Measure	Quantitative			Qualitative			
	Annualized Cost ($000s)	Cost/PIC ($000s)	PIC[a]	Safety	Operation Versus Investment	General Use	Applicability
Scheduling of lock operations, assistance to multicut lockages							
Institute N-up/N-down policy	0	0	-13 to 16	High	-	Common	Moderate
Provide helper boats	964	60	16	Moderate	Operation	Rare	Wide
Provide switchboats	1420	89	16	Low	Operation	Rare	Limited
Institute ready to serve policy	2092	63	33	Low	Operation	Proposed	Limited
Improve tow haulage equipment	751	27	28	Low	Investment	Proposed	Wide
Increase lock staffing	52	39	1-2	High	Operation	Proposed	Moderate
Institute lock scheduling	9	3	3	High	Operation	Rare	Moderate
Improvements to approaches							
Improvements to approaches	116	39	3	High	Investment	Common	Moderate
Provide adjacent mooring cells	18	14	1-2	High	Investment	Common	Limited
Provide funnel-shaped guidewalls	U	U	U	High	Investment	Proposed	Limited
Install wind deflectors	2-20	25-200	0-0.1	High	Investment	Proposed	Limited
Tow configuration and operations							
Use of regular bow thrusters	U	U	4	High	Investment	Rare	Wide
Use of bowboats	U	U	21	High	Investment	Proposed	Wide
Tow-size standardization	U	U	17	Moderate	Operation	Proposed	Wide
Cooperative scheduling	U	U	13	Moderate	Operation	Proposed	Wide
Waterway traffic management	5-15	3	4	High	Operation	Proposed	Wide
Expand fleeting areas	200	U	U	Moderate	Investment	Common	Limited
Bridge maintenance and operation	U	U	0-5	High	Operation	Common	Wide
Lock operating controls							
Modify intake-outlet structures	70	16	4	Moderate	Investment	Rare	Limited
Install trash racks	29	7	4	Moderate	Investment	Common	Limited
Expedite operations in ice conditions	23	12	2	Moderate	Investment	Common	Wide
Install air bubbler system	38	-	0	High	Operation	Common	Limited
Install floating mooring bitts	14	-	0	High	Operation	Common	Limited
Improve lock operating equipment	191	-	0	High	Investment	Rare	Limited
Install gate wickets	High	-	0-3	Low	Investment	Proposed	Limited
Provide operating guides	Moderate	-	0-3	High	Operation	Proposed	Wide
Centralize controls	104	104	1	High	Investment	Rare	Wide
Provide replaceable fenders	Low	-	0-1	Low	Investment	Proposed	Wide
Clear vessel from filling-emptying system	Low	-	0	High	Investment	Common	Wide
Structural actions							
Reduce interference from recreation	419	65	6	Moderate	Investment	Common	Wide
Improve use of auxiliary chamber	U	U	10-50	Moderate	Operation	Common	Limited
Enlarge locks to 1200 ft	4575	95	48	Low	Investment	Rare	Wide
Physical lock replacement	8950	61	148	High	Investment	Common	Wide

Note: U = unavailable.

[a]Typical range.

A_t = turnback approach (min),
X_f = fly/exchange exit time (min),
X_t = turnback exit time (min),
E = entry time (min),
F = chambering time (min),
$X_{t,1}$ = turnback exit time for first cut (min),
F' = chambering time between cuts (min),
$A_{t,2}$ = turnback approach time (min),
E2 = entry time (min),
F2 = chambering time (min),
Δ = variation due to impact of a given measure.

Entry time (E) includes breakup time for doubles (7.0 min) and reconfiguration time for setovers (10.0 min); exit time (X_{tf}) includes makeup time for doubles (13.5 min) and reconfiguration time for setovers (13.0 min). Terms A_f through F are used in their given form when the impact in the variables is the same for single, setovers, or doubles. Terms $A_{t,2}$ through F2 are used for the second cut of a double lockage.

A large amount of data on lock processes and component times has been collected by the Corps of Engineers and was compiled for this study. In 1975, as part of a PMS, the Corps instituted a special lockage log form. The Corps has now collected thousands of measured observations of the most common lockage process and component times at locks in the UMRS. Table 1 gives a compilation of some of the data.

ASSESSMENT OF CAPACITY PROBLEMS AND POTENTIAL MEASURES

The development of capacity improvement measures requires an exact understanding of congestion problems in operations and time component terms. The design problem is then to develop a measure that will improve the operations or times. The solution can be approached from either direction.

For example, the work team and the contractor had available numerous proposals for capacity improvements from the National Waterways Study and project- or site-specific studies of Corps of Engineers districts. There is also some literature on European experience. These measures could be costed and analyzed in terms of operations and component times.

The work team provided the contractor the results of a lockmaster survey. Along with technical data on lock design, equipment, and operations, the survey provided opinions on problems at each site. These opinions provided clues to the causes of abnormal time components shown in PMS data. Additional sources of problems and potential solutions included (a) the opinions of masters and pilots and work-team members, (b) interviews with Corps division and district operations personnel, and (c) field reconnaissance of each lock site.

The search produced 43 measures that have some potential for improving the navigational capacity of the system.

Table 3. Helper-boat alternative with N-up/N-down policy.

Lock	Time Reduction: Doubles ΔX_t	Setovers ΔE	Setovers ΔX_t	PIC	Annualized Cost ($000s)	Cost/PIC ($000s)
Upper Saint Anthony	-	-	-	-	-	-
Lower Saint Anthony	-	-	-	-	-	-
1	-	-	-	-	-	-
2	13.5	10	13	10.6	991	93
3	13.5	10	13	21.4	966	45
4	13.5	10	13	22.8	960	42
5	13.5	10	13	23.0	976	42
5A	13.5	10	13	26.7	1002	38
6	13.5	10	13	23.1	996	43
7	13.5	10	13	22.7	990	44
8	13.5	10	13	20.0	952	48
9	13.5	10	13	20.5	960	47
10	13.5	10	13	16.8	989	59
11	13.5	10	13	19.9	991	47
12	13.5	10	13	21.2	981	46
13	13.5	10	13	19.9	984	49
14	13.5	10	13	14.9	484	32
15	13.5	10	13	16.2	484	30
16	13.5	10	13	22.2	957	43
17	13.5	10	13	22.0	952	43
18	13.5	10	13	21.5	973	45
19	-	-	-	-	-	-
20	13.5	10	13	21.7	945	44
21	13.5	10	13	20.4	1019	50
22	13.5	10	13	18.2	1047	58
24	13.5	10	13	20.0	1037	52
25	13.5	10	13	21.1	1009	48
26						
Main chamber	13.5	10	13	17.4	1112	64
Auxiliary chamber	13.5	10	13	21.2	1112	53
27						
Main chamber	-	-	-	-	-	-
Auxiliary chamber	13.5	10	13	14.2	1050	74
T. J. O'Brien	-	-	-	-	-	-
Lockport	13.5	10	13	6.4	1030	161
Brandon Road	13.5	10	13	8.9	979	110
Dresden Island	13.5	10	13	8.5	1003	118
Marseilles	13.5	10	13	7.7	975	127
Starved Rock	13.5	10	13	12.6	1010	80
Peoria	13.5	10	13	19.5	942	48
LaGrange	13.5	10	13	23.4	945	40

Screening Measures

The ultimate objective of screening the list of measures was to identify those that are widely applicable and potent in improving system capacity. But most measures required developmental work to perfect performance and cost data. There was a need to concentrate efforts on measures that were judged to have the greatest payoff potential.

Quantitative screening criteria were the capacity and cost-effectiveness indices previously discussed. Qualitative measures included (a) safety effects, rated from low to high; (b) nature of costs, whether capital or operational; (c) use, rated as rare, common, or proposed; and (d) applicability, rated as limited, moderate, or wide.

The criteria were applied to all measures based on available information and were provided to the work team. Using its collective judgment, the work team grouped the measures into three study priorities and one group not to be studied.

Following development work, all of the refined performance and cost data were presented for further screening. This information is presented in Table 2.

Development and Evaluation of Measures

The development and evaluation of measures represented the major work effort of the study. Prior to this stage, many measures were no more than ideas and needed considerable original evaluation for further screening.

Development included the design of features needed to make the measure operational and to adapt it to lock and dam sites. Measure operations were perfected to best enhance overall lockage operations. Specific sites were identified where the measure was applicable as well as potentially useful. Cost estimates (investment, operation, and annualized) were prepared for each measure on a site-specific basis.

The performance data needed for the lock simulation model were then estimated for each site in terms of time reductions from the PMS average times. Table 3 gives an example of how performance, cost, and capacity indices were compiled.

Applicability and Compatibility of Measures

Additional locks can usually be sited to minimize interference with existing locks. Consequently, they are always a compatible measure making a great, net contribution to capacity. But this is not the case with the so-called nonstructural measures.

Some nonstructural measures are mutually exclusive. The prime example is four potent measures to expedite double lockages: bowboats, helper boats, switchboats, and powered traveling kevels. Some measures can worsen performance at certain sites. For example, an "N-up/N-down" service order is only productive where chambering time is low relative to approach times. But hydraulic improvements that reduce chambering time enhance N-up/N-down.

The important point is that the merits of a particular measure are not properly seen when it is used alone. Rather, good combinations must be found. One good combination (or order of improvement) is to reduce chambering time, which enhances the impact of N-up/N-down service order, which finally enhances the impact of helper boats or traveling kevels. A poor combination is to improve approach times where these are already low relative to chambering time. This tends to preclude the use of helper boats or traveling kevels and to encourage the use of switchboats, which constitute the most expensive and least effective double lockage measure. Moreover, the approach improvements do not help a switchboat operation very much.

The importance of combining measures had not been fully recognized in the past. So the proper combinations found in the study process were extremely valuable. Figure 2 shows the results of testing combinations at an Illinois Waterway lock.

COMPOSITION OF CAPACITY IMPROVEMENT SCHEMES

The next task was to compose capacity improvement schemes by using the developed capacity improvement measures. These schemes were called "scenarios", and several objectives to be served by the scenarios were described earlier.

The remaining work was to assemble proper combinations of measures, or actions, by using the knowledge that had been gained. These combinations are presented in Table 4.

Scenario 1 was intended to be a base, or "without project", condition. Therefore, it only includes simple, inexpensive improvements. Scenarios 2 and 3 are alternative candidates for a primarily nonstructural scenario. Scenario 2 uses bowboats, systemwide, as the double lockage measure; scenario 3 uses helper boats, switchboats, or kevels where appropriate. Scenario 4 adds additional locks to scenario 3 to provide a combined structural-nonstructural scheme. Scenario 5 is primarily a structural scheme, since the potent double lockage measures are eliminated.

Any scheme can be improved through repetitive

Figure 2. Sequencing of actions and alternative scenarios for Marseilles Lock (Illinois River).

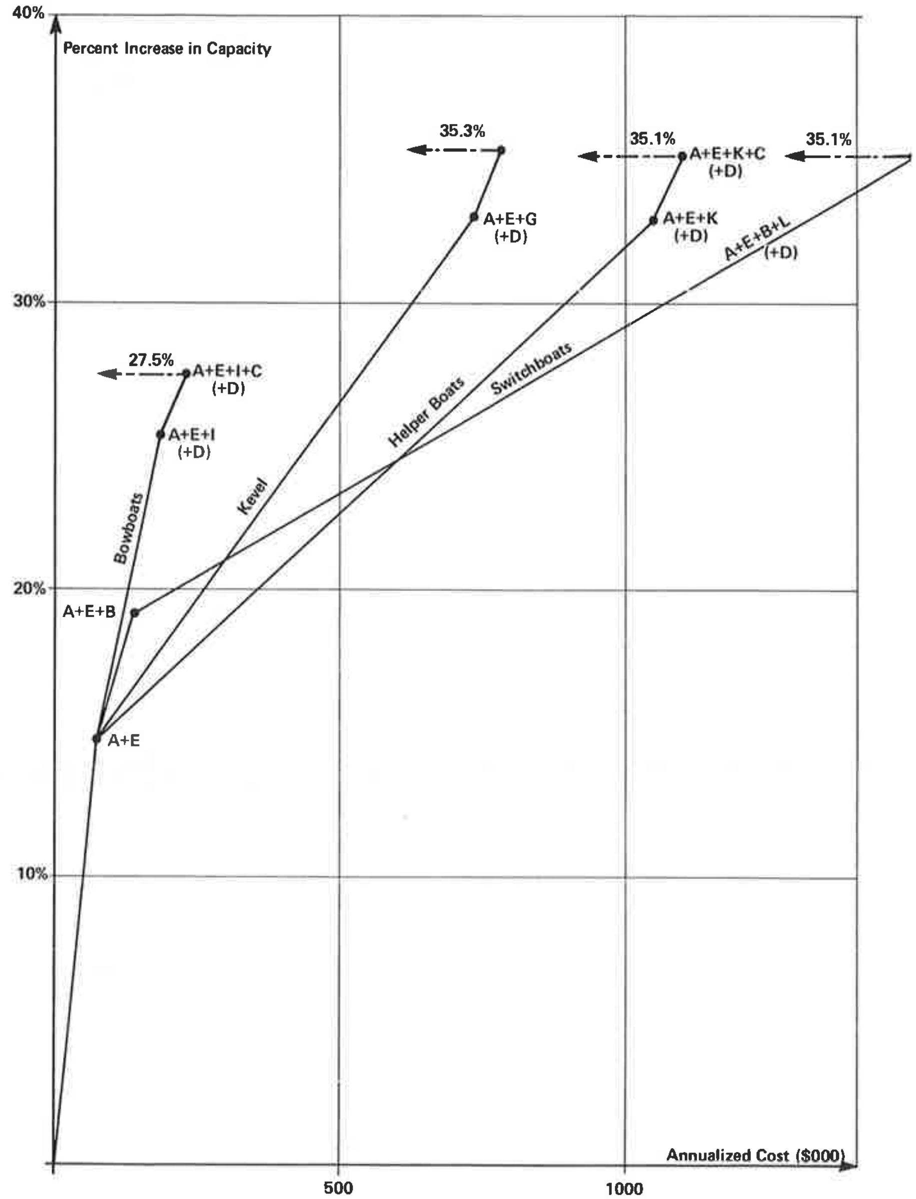


Table 4. Action scenarios.

Action	Description	Scenario 1	2	3A	3B	4A	4B	5
	Government							
A	Correct design deficiencies							
1	< $20 000/PIC	•	•					
2	< $50 000/PIC			•	•	•	•	•
B	Improve approaches							
1	< $20 000/PIC		•					
2	< $50 000/PIC			•	•	•	•	•
C	Increase lock staffing							
1	< $20 000/PIC		•					
2	< $50 000/PIC			•	•	•	•	•
D	Institute N-up/N-down where appropriate	•	•	•	•	•	•	•
E	Expedite operations in ice conditions			•	•	•	•	•
F	Recreational locks, locks 2-11			•	•	•	•	•
G	Traveling kevel as alternative to helper boats				•		•	
H	Build locks							
1	Maximum of one 1200-ft lock/year					•	•	
2	Build 1200-ft locks							•
	Industry							
I	Mandate bowboats for large tows		•					
J	Mandate minimum crew on deck		•					
K	Helper boats where appropriate			•		•		
L	Switchboats where appropriate			•	•	•	•	

trials and economic evaluations. Unfortunately, the deadline for the UMRS master plan did not permit this. Once the scenarios were prepared, there was just enough time to evaluate them.

CONCLUSIONS

This study provided the imaginative and exhaustive search for improvement measures desired. Knowledge of useful nonstructural measures has been expanded. Certainly these measures should be considered in future navigation planning studies, but planners should be cautious in generalizing the results.

One should not assume hydraulic inefficiencies or approach problems where none exist. Double lockage measures are useless where there are no double-lockage-sized tows. There is no substitute for starting with reliable, quantitative data on performance: PMS, surveys, interviews, and on-site investigations. Solutions must be tailored to the problems. Good combinations of measures must be found. The greatest time and effort should go into developing the best ideas.

Publication of this paper sponsored by Committee on Inland Water Transportation.

Analysis of Lock Capacity by Simulation

MICHAEL S. BRONZINI AND RICHARD A. MARGIOTTA

LOKSIM2 is a discrete event simulation model developed to analyze the capacity and delay characteristics of single locks on the U.S. inland waterways. Extending previous single-lock simulation techniques, LOKSIM2 features a highly detailed representation of the components of the locking cycle. The model is directly compatible with data provided by the U.S. Army Corps of Engineers Performance Monitoring System. A preprocessor model, TOWLST1, generates tow traffic inputs so as to match distributions of underlying tow characteristics. The output from LOKSIM2 is used to estimate the parameters of a lock delay function. Delay functions obtained for various lock physical and operating conditions can be used to analyze proposed lock improvements.

This paper describes the development and application of a single-lock simulation model, LOKSIM2, used for lock capacity analysis as part of the Upper Mississippi River Master Plan Study. The LOKSIM2 model was developed in response to the need for a method of analysis that could estimate the physical capacity of a single lock under a variety of structural and nonstructural improvement scenarios. Previous single-lock simulators, including LOKSIM (1), LOCALC (2), the lockage routines in the Waterway Analysis Model (3), and SNGLOK (U.S. Army Corps of Engineers, North Central Division), either could not provide the required level of detail or were too cumbersome to use. They did, however, provide the basis for the LOKSIM2 model, which is basically an extension and refinement of these prior modeling efforts. LOKSIM2 is the most detailed model yet created to simulate the operation of a single lock. All input data can be obtained readily from the U.S. Army Corps of Engineers Performance Monitoring System (PMS). The model was programmed in FORTRAN and GASP, a series of FORTRAN-based subroutines that greatly facilitate programming of simulation models (4).

This paper explains the operation of the model, including the structure of inputs and output, and shows how model results are used to estimate lock capacity.

OPERATION OF MODEL

Overview of Lock Operations

Before a process can be simulated, it is necessary to become acquainted with the details of that process. If more details are accounted for in the simulation, there is a greater likelihood that the results will be realistic. There is, however, a direct relation between amount of detail and cost in terms of development, computer time, and data requirements. Since the objective of this research was to simulate the operation of a single lock, a great degree of complexity could be incorporated into the model. If the purpose had been to simulate an entire system of locks, a less detailed model of lock operations might have been adequate.

Essentially, a lock is a chamber located in or near a dam that can be sealed off and within which the water level can be raised or lowered to meet the water level above or below the dam so that vessels can pass through the dam. Vessels that use locks fall into three categories: (a) commercial tows, which are made up of one or more barges propelled by a towboat; (b) recreational craft, which are noncommercial pleasure boats; (c) light boats, which are towboats traveling without barges. Most lock time is normally devoted to servicing commercial tows.

Because lock chambers and tows come in various sizes and configurations, there are several types of lockages that may occur. A single lockage takes place if the entire tow can fit into the lock as is. A setover lockage occurs if the configuration of a tow must be changed to fit the chamber size but all of it fits into the chamber when it is reassembled (thus, single and setover lockages require only one flooding or evacuation of the chamber). Double lockages occur when the tow is too large to be locked through on one pass; in such a case, some barges go through, the chamber is returned to the starting level, and the remaining barges and towboat are locked through. Recreational craft and light boats (referred to henceforth as RLBs) can be locked through with a tow if there is room left in the chamber, or they can be locked through by themselves or with more RLBs. It is also possible to subdivide single, setover, and double lockages into more specific types if necessary. In addition, on some of the less active waterways, locks can be so limited in size that only a small number of barges (sometimes only one) can be locked through at a time so that triple, quadruple, or quintuple lockages are required. Because this study covered only the Upper Mississippi River system, where all locks (except one) are at least 110 ft wide and 600 ft long, these latter types of lockages did not have to be considered.

The operation of locks is governed by a set of