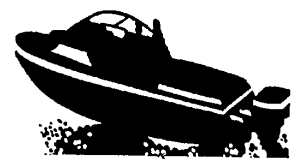
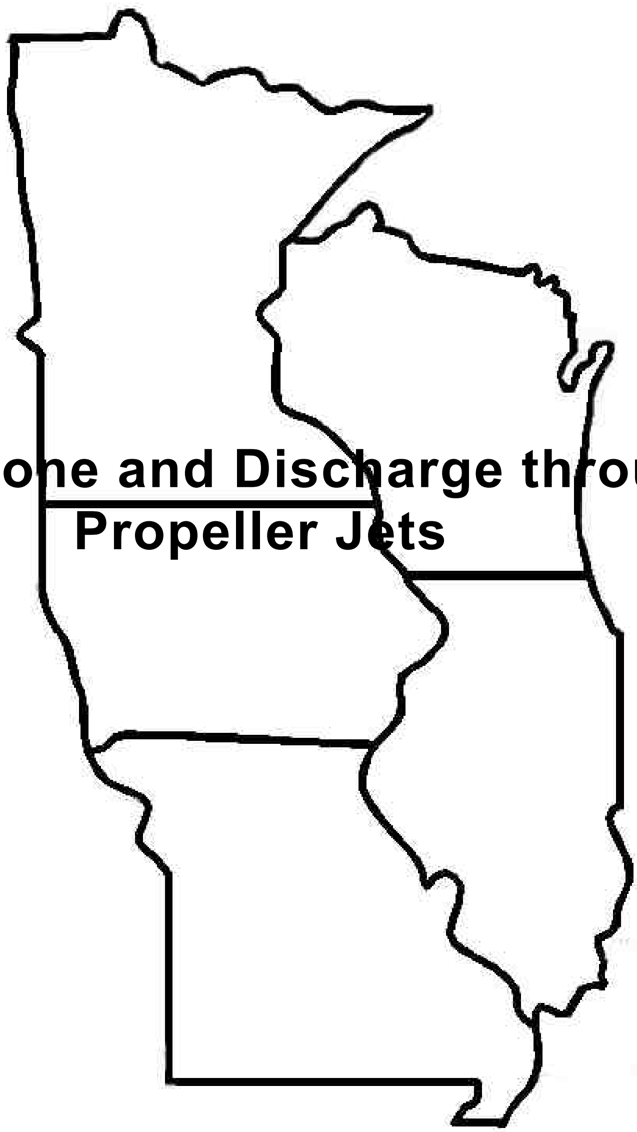
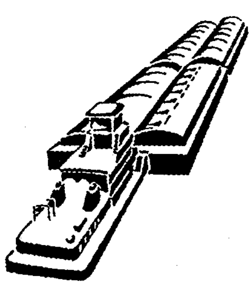
ENV Report 25

Interim Report For The Upper Mississippi River - Illinois Waterway System Navigation Study



Inflow Zone and Discharge through Propeller Jets





September 2000

US Army Corps
of Engineers

Rock Island District
St. Louis District
St. Paul District

Upper Mississippi River - Illinois Waterway System Navigation Study

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Inflow Zone and Discharge through Propeller Jets

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Contents

Preface

The work reported herein was conducted as part of the Upper Mississippi River - Illinois Waterway (UMR-IWW) System Navigation Study. The information generated for this interim effort will be considered as part of the plan formulation process for the System Navigation Study. Permission to publish this information was granted by Headquarters, U.S. Army Corps of Engineers.

The UMR-IWW System Navigation Study is being conducted by the U.S. Army Engineer Districts, Rock Island, St. Louis, and St. Paul, under the authority of Section 216 of the Flood Control Act of 1970. Commercial navigation traffic is increasing and, in consideration of existing system lock constraints, will result in traffic delays which will continue to grow into the future. The system navigation study scope is to examine the feasibility of navigation improvements to the Upper Mississippi River and Illinois Waterway to reduce delays to commercial navigation traffic. The study will determine the location and appropriate sequencing of potential navigation improvements on the system, prioritizing the improvements for the 50-year planning horizon from 2000 through 2050. The final product of the System Navigation Study is a Feasibility Report which is the decision document for processing to Congress.

The study was performed during 1995 through 1998 by personnel of the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS. The study was under the direction of Dr. James R. Houston, Director, CHL; Mr. Charles C. Calhoun, Jr., Assistant Director, CHL; and Mr. C. E. Chatham, Jr., Chief, Navigation and Harbors Division (NHD), CHL. The study was conducted by Dr. S. T. Maynord, Navigation Branch, NHD.

At the time of publication of this report, Director of ERDC was Dr. James R. Houston, and Commander was COL James S. Weller, EN.

1 Inflow Zone to Propellers

Introduction

The inflow zone and discharge through propeller jets is primarily of interest in addressing environmental effects of navigation. Studies on the Upper Mississippi River System (UMRS) outlined in U.S. Army Corps of Engineers (USACE) (1994) are evaluating the significant environmental resources on the UMRS and probable impacts in terms of threatened and endangered species, water quality, recreational resources, fisheries, mussels and other macroinvertebrates, waterfowl, aquatic and terrestrial macrophytes, and historic properties. The purpose of the study reported herein is to assist in the evaluation of the effects of navigation on fisheries by defining the quantity of water passing through the propellers and the inflow zone of the waterway that passes through the propellers.

General

Which zone of the waterway is passing through the propeller jet? This author has occasionally heard the comment that "the propellers draw the water off the bank," implying that a significant portion of the flow through the propellers comes from the bank region. This comment is likely the result of the observed drawdown alongside the vessel. The observed drawdown is primarily a function of the vessel cross-sectional area, A_s, the channel cross-sectional area, A_c, and the vessel speed. The drawdown occurs whether the vessel is self-propelled or pulled with a rope from the bank. Experiments have shown this by running comparative experiments with a tow having operating propellers and the same tow pulled at the same speed but without the propellers operating. Only in highly confined channels where A_c / A_s is small, does the propeller make a discernable contribution to the drawdown in the nearshore region.

In addressing which part of the waterway goes through the propellers, the distinction must be made between mixing in the river by ambient currents and mixing by the tow. If dye is injected into the river far ahead of the tow, it is likely that ambient currents would mix the waterway to such an extent that dye injected in the near bank zone would find their way to the area where the tows operate. The intent of this study is to focus on the inflow zone immediately in front of the vessel and how that zone is affected by mixing by the tow. While the inflow zone defines the region that can go through the propellers, not all water in this zone will go through the propellers. This study will define whether the inflow zone extends from bank to bank or if the inflow zone is only a portion of the total width. A separate portion of the study is addressing long distance mixing by ambient flows. The intended use of this inflow zone is to allow biologist to determine where in the cross section they must determine the concentration of organisms (such as fish, fish larvae, fish eggs) that are subject to passage through the propeller jet.

To determine the inflow zone for typical UMRS vessels, this study used both physical and numerical models.

Physical Model Experiments

Physical model experiments were conducted at a 1:25-scale ratio with both a stationary tow with water moving past the tow and a tow moving relative to earth. Details of the model basin, scaling relations for transference from model to prototype, and comparison of model and prototype return velocity and drawdown for the 1:25-scale model are given by Maynord and Martin (1997). The cross section used in the stationary and moving tow experiments was an asymmetric section having a scaled width of 520 m (all quantities are in the equivalent prototype value). All studies were conducted with the tow near the thalweg which was located near the center of the cross section.

Stationary tow experiments

The advantage of the stationary tow experiments with water moving past the vessel at a velocity equal to the vessel speed is that a dynamic event is changed to a steady event and measurements are much easier. The primary disadvantage is that the channel bottom is not moving relative to the tow which affects the vertical velocity profile. This dissimilarity does not have a major influence on the experiments to determine the zone of inflow to the propellers, because the primary influence is on the vertical velocity profile rather than the lateral velocity profile which defines the inflow zone to the propellers. In the stationary tow experiments, depth at the vessel was 4.8 m, average depth-averaged velocity in the path of the tow was 2.0 m/s, vessel draft was 2.7 m, barges formed a 32-m-wide by 258-m-long tow plus the towboat. The total propeller thrust for bollard pull conditions (thrust for stationary tow) was 382,500 N, which was 80 percent of full power from a 4,176-kW open wheel towboat based on the Toutant (1982) equation presented later in this report. The 2.0-m/s velocity was the equivalent vessel speed relative to the water. A relatively low tow speed was used, because it should result in the largest inflow zone for a given propeller speed. Three lateral positions were used to inject the dye as shown on Figure 1. A dye trace line shows the position of the center of the dye cloud along the length of the tow. Note how the dye cloud moves away from the tow at the bow and then toward the tow at the stern. This movement pattern has been observed in model tows that are propelled by a towboat or propelled by a towing carriage without a

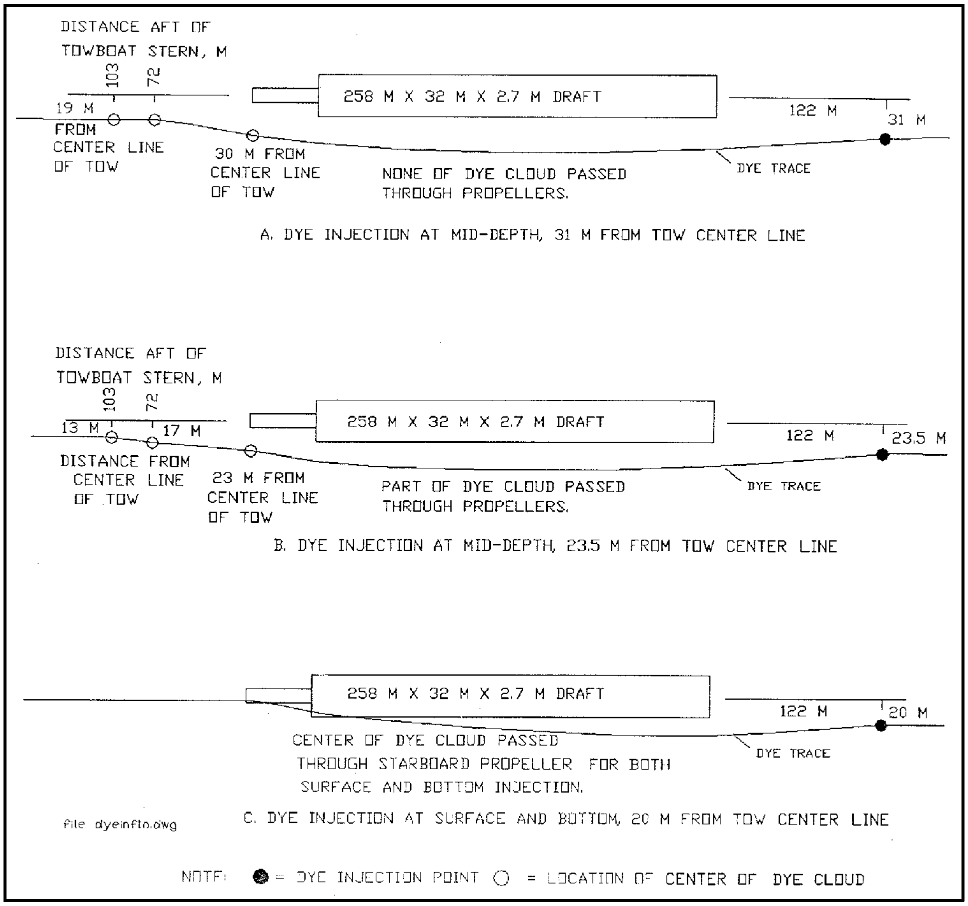

Figure 1. Inflow zone, physical model experiments using stationary vessel, equivalent tow speed = 2 m/sec relative to water, depth = 4.8 m, thrust = 382,500 N

towboat. Based on the stationary barge experiments for 4.8-m depth, the dividing point between no passage through the propellers and some passage through the propellers is between 31 and 23.5 m from the tow center line which is 15 to 7.5 m from the edge of the barges.

Moving tow experiments

The moving tow experiments were conducted with water depths of 4.3, 5.6, 9.8, and 12.2 m with respective ambient depth averaged velocities of 0.8, 0.9, 1.0, and 0.9 m/s near the vessel path. Dye was injected at the bed at various lateral distances measured perpendicular from the tow center line. All experiments were conducted with 382,500 N (86,000 lb) thrust under bollard pull conditions.

For the 4.3-m water depth, the upbound vessel traveled at 1.5 m/s (relative to earth) or 2.3 m/s (relative to water). The downbound vessel traveled at 3.1 m/s (earth) or 2.3 m/s (water). Observations are based on what happened to the dye near to the injection point. For both tow directions, some of the dye passed through the propellers when injected 23.5 m from the tow center line. None of the dye passed through propellers when placed 27.5 m away from the tow center line.

For the 5.6-m depth, two upbound and one downbound speeds were used. Observations are based on what happened to the dye near to the injection point. For the upbound vessel at 2.1 m/s (earth) or 3.0 m/s (water), dye positioned at 20 m from the tow center line did not pass through the propellers. However, dye injected 16 m from the tow center line (equal to edge of barges) had a portion of the dye pass through the propellers. For the upbound vessel at 1.1 m/s (earth) or 2.0 m/s (water), dye positioned at 24.5 m from the tow center line did not pass through the propellers. Dye injected 20 m from the tow center line had a portion of the dye pass through the propellers. For the downbound vessel at 4 m/s (earth) or 3.1 m/s (water), dye positioned at 24.5 m from the tow center line did not pass through the propellers. Dye injected 20 m from the tow center line had a portion of the dye pass through the propellers.

In the 4.3- and 5.6-m depth experiments, the conclusions were based on observing what happened to the dye near to the injection point, thus eliminating the mixing by the vessel. In the 9.8- and 12.2-m depth experiments, the observations of dye were made at the injection point and at a point 244 m downstream of the injection point which was about one tow length. For a 9.8-m depth with an upbound tow traveling at 2.8 m/s (earth) or 3.8 m/s (water), dye injected 24 m from the tow center line did not go through the propellers when viewed 244 m downstream of the injection point. When viewed at the injection point, dye 20 m from the tow center line did not go through the propellers. Results for a 12.2-m depth for an upbound tow traveling at 2.75 m/s (earth) and 3.6 m/s (water) were the same as the 9.8-m depth experiments. Several dye experiments were conducted to see if the dye was not pulled up into the propellers for the larger depths. For both 9.8- and 12.2-m depths, dye injected at the channel bottom was not pulled into the propellers when viewing at the injection point. For both 9.8- and 12.2-m depths, dye injected at the channel bottom was pulled into the propellers when viewing at 244 m downstream of the injection point. Significant mixing was observed beneath the model barge. The clearance between hull and channel bottom is analogous to the flow depth in an open channel. Almost complete vertical mixing will occur in an open channel having a length of about 50 channel depths. For the typical UMRS, three-barge-wide by five-barge-long by 2.74-m-draft vessel having total barge length of 297 m, near complete vertical mixing will have occurred at or before the stern for all underkeel clearances of 6 m or less, which represents the majority of UMRS tows.

Based on the physical model for depths from 4.3 to 12.2 m, the inflow zone to the propellers is about 50 m wide for the 32-m-wide tow that is typical for the UMRS. Lesser tow widths or unloaded barges will have narrower inflow zone widths, but a 50-m width for all tows provides a conservative estimate. The 50-m width is the zone that can go through the propellers, but not all of this zone will go through the propellers. A subsequent section of this report defines the volume flow rate through the propellers.

Numerical Model Experiments

A three-dimensional numerical model simulation using the MAC3D (Bernard 1995) model was used to obtain tracer particle motion around a tow to ascertain roughly the size of the zone from which flow would be drawn through the propellers. MAC3D is a numerical model for incompressible flow using a finite volume discretization and a κ-ε turbulence model. The tow used in the numerical simulation was 297 m long, 32 m wide, with a 2.44-m draft plus a 42.7-m-long by 10.7-m-wide towboat centered at the stern of the tow. The towboat had two 2.44-m-diam propellers centered 2.3 m upstream of the stern of the towboat and 2.74 m to either side of the center line. Each propeller generated a thrust of 187,650 N, which was modeled by an equivalent body force uniformly distributed over a rectangular region 1.5 m long by 2.67 m wide and 2.44 m deep. The tow had a velocity of 2.1 m/s relative to the water, but the flow was computed from the standpoint of the observer on the boat. In other words, the flow was computed as though the boat were fixed with the water in motion.

The simulated channel was 681 m long and 142 m wide, with only one-half included in the computation, because the flow was assumed to be symmetric about the channel center line. The hull near the stern was simulated by a stepped grid representing the hull from 12.2 m upstream of the stern. The water surface was assumed to be flat and unchanged by the presence of the tow. By ignoring the occurrence of drawdown in the numerical model, the water depths in the numerical model alongside the vessel will be greater by the amount of the drawdown which is typically up to 0.23 m in the smallest channel sections such as found on the Intercoastal Waterway (IWW). For the minimum water depth of 3.7 m used in the numerical model, this amounts to a 6-percent change in water depth that would decrease velocity by about the same amount. There is no reason to expect that a small decrease in velocity and a comparable increase in depth will have a significant effect on the width of the inflow zone.

Bottom and sidewall friction were excluded from all computations because the numerical model used a fixed boat with water moving past the boat at the speed of the boat. The absence of bottom and side friction provides a vertical and lateral velocity distribution that better represents an actual tow. An eddy viscosity proportional to the local velocity and a user specified length scale (0.6 m) was included to crudely emulate the effects of turbulence. Steady-state flow calculations were executed using a uniform vertical grid spacing of 0.6 m and a variable horizontal spacing with greater resolution near the bow and stern. Tracer plots for 3.7- and 8.5-m water depths are shown in Figures 2 and 3, respectively, for tracers injected 0.6 m above the channel bottom. Other simulations (not shown) were conducted with tracers injected 0.6 m below the water surface. In analyzing the plots, any streamlines diverted laterally into the near wake of the towboat are indicative of flow being drawn into the propeller. Otherwise, the flow merely represents water displaced by the entire tow. Although the flow conditions and tow geometry were simplified for the computations discussed here, the results are satisfactory up to the stern of the

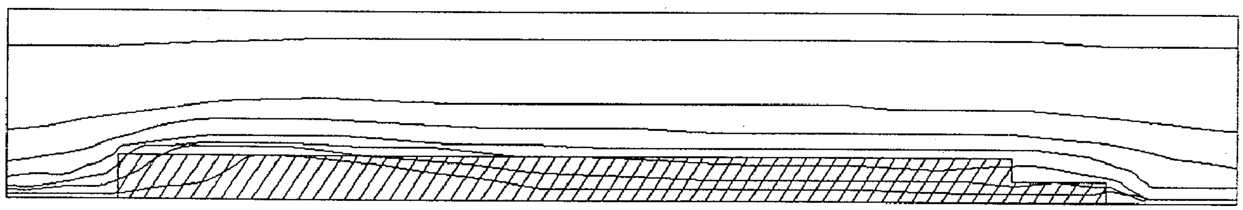

Figure 2. Bottom view of tracers injected 0.6 m above bottom. Numerical model MAC3D has water depth of 3.7 m

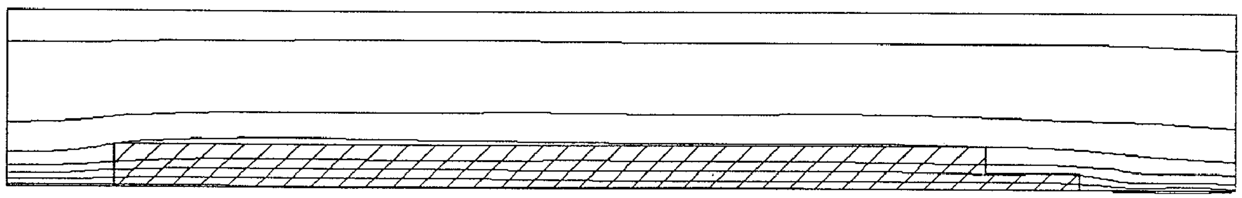

Figure 3. Bottom view of tracers injected 0.6 m above bottom. Numerical model MAC3D has water depth of 8.5 m

towboat, because numerical models are most successful when the flow is primarily converging, as is the case between the bow of the barge and the stern of the towboat. The flow is considerably more complicated (and much more difficult to compute) farther downstream in the wake of the tow, which is not shown on the plotted streamlines.

All simulations showed that the zone of inflow to the propellers is confined to the region in front of the tow and having a width on the order of the width of the vessel.

2 Discharge through Propeller Jets

Methods for Propeller Jet Discharge

Two methods are presented herein for defining the discharge through the propeller jet. The first method uses thrust coefficient, vessel and propeller speed, and propeller diameter and type to define the discharge through the propeller. Because propeller speed and thrust coefficients may be difficult to obtain, the second method uses applied power, vessel speed, and propeller diameter and type.

Discharge based on thrust coefficient, vessel and propeller speed, diameter, and type

The method used herein follows Blaauw and Van de Kaa (1978) and uses the momentum theory to define the discharge through the propeller. The momentum approach has been widely used to determine the scour potential and protection requirements of the propeller jet on the bed of the river. Figure 4 shows the schematic of the flow through the jet. The Kort nozzle shown in Figure 4, also called a duct, is a streamlined cylinder around the propeller which increases thrust at low vessel speeds. The momentum theory defines the reaction force or thrust *T* as

$$T = \rho Q_p V_2 \tag{1}$$

where

ρ = water density
Q_p = discharge through a single propeller
V_2 = total velocity change imparted by the propeller jet

The thrust *T* can also be defined as

$$T = \left(P_2 - P_1\right) A_p = \Delta P \, \pi D^2 / 4 \tag{2}$$

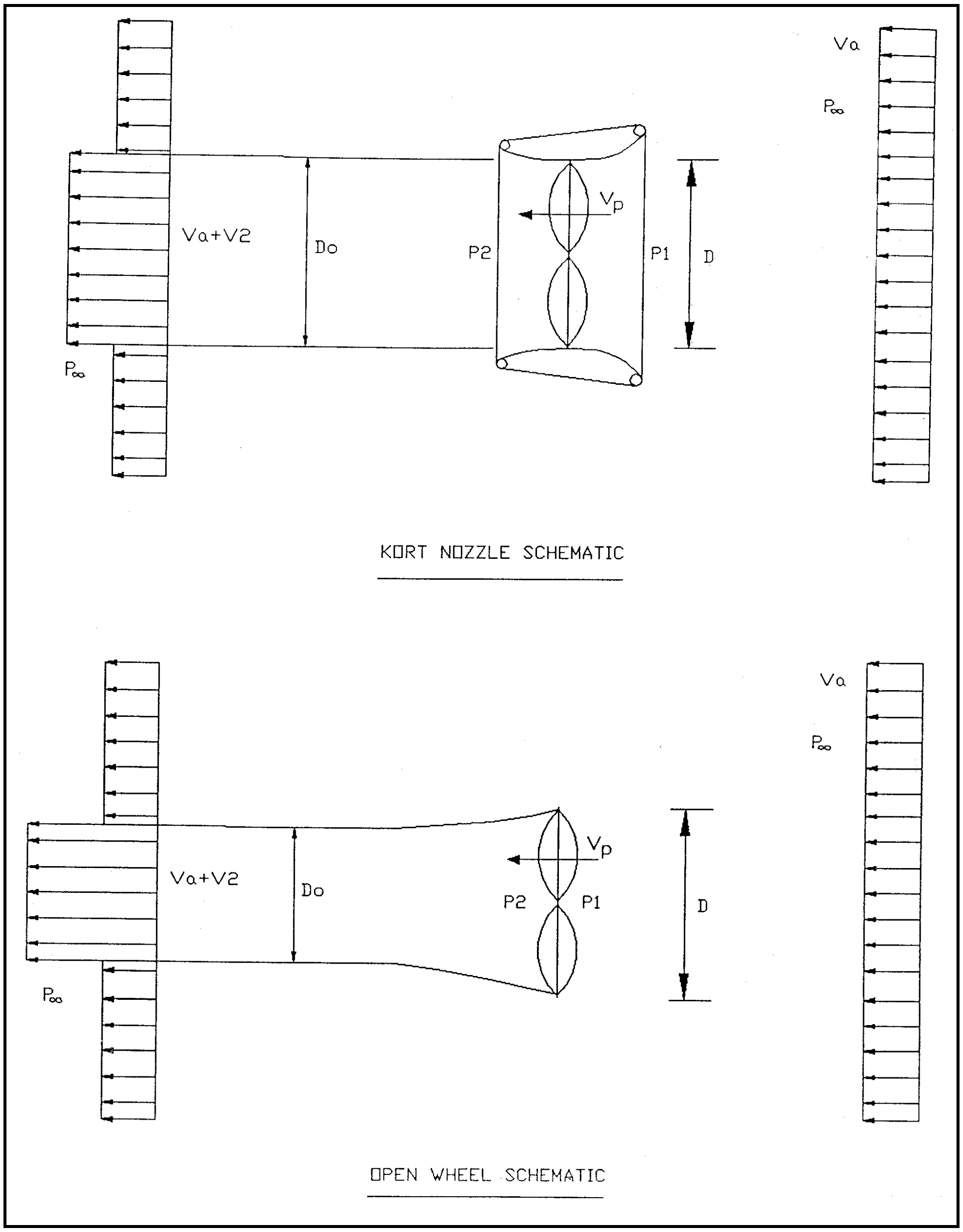

Figure 4. Schematic of flow through propeller

where

P_2 = pressure downstream of the propeller
P_1 = pressure upstream of the propeller
A_p = area of the propeller
$\Delta P = P_2 - P_1$
D = propeller diameter

The discharge through the propeller Q_p is

$$Q_p = V_p \, \pi D^2 / 4 \tag{3}$$

where V_p is velocity through the propeller.

Combining Equations 1, 2, and 3 results in

$$\Delta P = \rho V_p V_2 \tag{4}$$

The energy equation is written just downstream of the propeller as

$$1/2 \, \rho (V_a + V_2)^2 + P_\infty = 1/2 \, \rho V_p^2 + P_2 \tag{5}$$

where

V_a = speed of advance or inflow velocity to the propeller
P_∞ = pressure away from the propeller
P_2 = pressure just downstream of the propeller

The energy equation is written for the flow forward of the propeller as

$$1/2 \, \rho V_a^2 + P_\infty = 1/2 \, \rho V_p^2 + P_1 \tag{6}$$

where P_1 is the pressure just upstream of the propeller.

Combining Equations 5 and 6 results in

$$\Delta P = 1/2 \, \rho V_2 (2V_a + V_2) \tag{7}$$

Combining Equations 4 and 7 results in

$$V_p = V_a + V_2/2 \tag{8}$$

Equation 8, which applies to an open-wheel propeller, shows that one-half of the total velocity increase occurs at the face of the propeller and the remainder of the velocity increase is a result of the contraction of the jet downstream of the propeller. With a Kort nozzle, almost all of the velocity increase occurs at the end of the nozzle, and little contraction of the jet takes place downstream. A general form of Equation 8 applicable to open wheels or Kort nozzles is

$$V_p = V_a + V_2/z \tag{9}$$

where z is 2 for open wheels and 1 for Kort nozzles.

The equation for thrust from propeller experimenting is given by

$$T = K_t \, \rho \, n^2 \, D^4 \qquad (10)$$

where
K_t = experimentally determined thrust coefficient
n = propeller speed in rev/sec

Combining Equations 1 and 10 results in

$$V_2 = \frac{K_t \, n^2 \, D^4}{Q_p} \qquad (11)$$

Combining Equations 3, 9, and 11 and solving for the discharge through a single propeller Q_p results in

$$Q_p = \frac{V_a \pi D^2}{8} + \sqrt{\frac{V_a^2 \pi^2 D^4}{64} + \frac{K_t n^2 D^6 \pi}{4z}} \qquad (12)$$

where K_t is the propeller thrust coefficient for open-wheel and the combined propeller/nozzle coefficient for Kort nozzle systems.

Equation 12 is valid for open-wheel vessels at any speed and for Kort nozzles for stationary vessels (vessel speed = 0). For a Kort nozzle vessel underway, published thrust coefficients contain losses caused by the nozzle, the actual thrust is less than given by Equation 1, and discharge will be underestimated using Equation 12. Discharge estimation for underway Kort nozzle tows will be addressed later in this paper.

For a maneuvering tow where $V_a = 0$, Equation 12 becomes

$$Q_p = 0.89 \sqrt{\frac{K_{t0}}{z}} \, n \, D^3 \qquad (13)$$

where K_{t0} is the thrust coefficient at zero speed of advance

The advance velocity V_a is the velocity approaching the propellers and is less than the vessel speed because of the blockage and wake effects of the towboat and barges in front of the propeller. The advance velocity V_a is determined from

$$V_a = V(1 - w) \qquad (14)$$

where

V = vessel speed

w = wake fraction which is determined experimentally by measuring a large number of velocities in the zone entering the propellers

For loaded push tows, Verhey(1983) reports $w = 0.3$ to 0.45. Fuehrer, Romisch, and Engelke (1981) found $w = 0.62$ to 0.85 for an inland vessel having a tunnel stern and depth/draft typical of UMRS tows. Fuehrer, Romisch, and Engelke's curve is replotted in Figure 5. The flat portion of the curve at a depth/draft of 1.32 represents the point at which almost all flow to the propellers is coming from the sides of the vessel rather than from beneath. A limited series of physical model measurements were conducted for a three-wide by five-long loaded tow, the design vessel on the UMRS. Velocity measurements were taken at the center line of the propeller shaft and just upstream of the face of the propeller which was in place but not turning. The experiment was conducted for a vessel speed of 2.0 m/s, and the measured velocity was 0.25 m/s for a depth/draft of 1.75. Solving Equation 14 results in a w = 0.87. This single measurement is far from a full-wake survey, but the relative closeness of the observed value to the Fuehrer, Romisch, and Engelke (1981) curve and the similarity of vessel types lead to the adoption of this curve for the UMRS vessels.

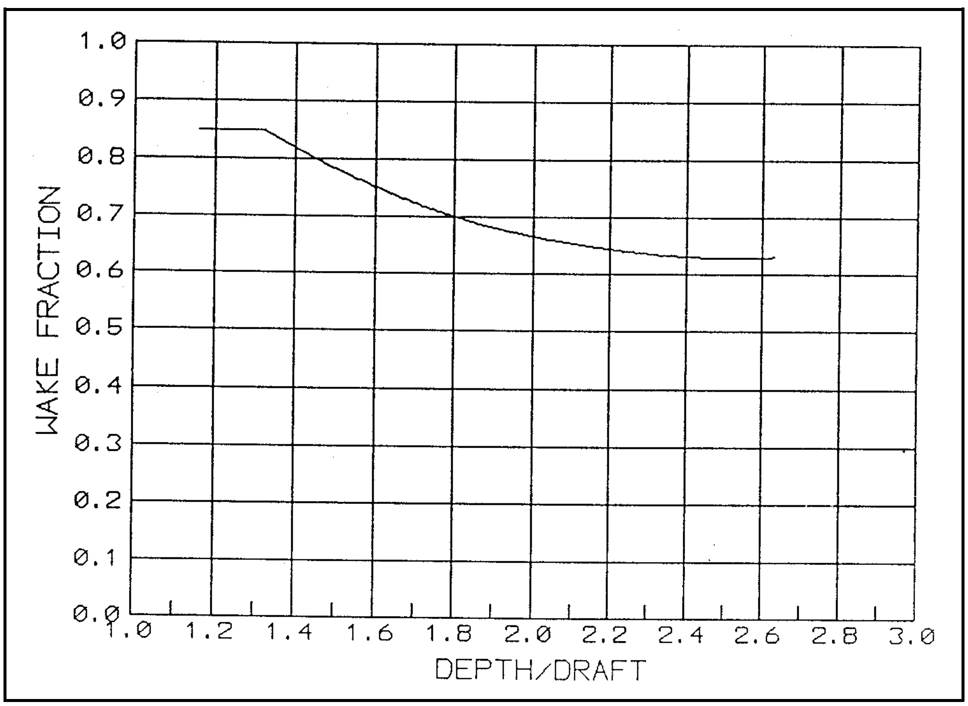

Figure 5. Wake fraction versus depth/draft. Replotted from Fuehrer, Romisch, and Engelke (1981)

Discharge based on applied power, vessel speed, propeller diameter and type

Equations 12 and 13 are the most accurate means of determining discharge through the propeller but require knowledge of the thrust coefficient and speed of rotation which may not be available for UMRS tows. This author has yet to find a towing company who would provide thrust coefficients for their propellers.

Two approaches are available which replace K_t and n with the applied horsepower. The first approach is the Toutant (1982) equations for effective push (EP) in pounds which are defined as

$$EP_k = 31.82\, Hp^{0.974} - 5.4(S)^2\,(Hp)^{0.5} \tag{15}$$

$$EP_o = 23.57\, Hp^{0.974} - 2.3(S)^2\,(Hp)^{0.5} \tag{16}$$

where

Ep_k = effective push from both propellers for Kort nozzles

Ep_o = effective push from both propellers for open wheels

Hp = applied towboat power from both propellers and must be expressed in horsepower

S = tow speed relative to the water and must be expressed in MPH

These empirical equations support the previous contention that push does not vary that much over the typical tow speeds found on the UMRS because the second term is relatively small. Combining Equations 1, 3, and 9 results in

$$Q_p = \frac{V_a \pi D^2}{8} + \sqrt{\frac{V_a^2 \pi^2 D^4}{64} + \frac{T \pi D^2}{4 z \rho}} \tag{17}$$

where T is assumed equal to one-half of EP computed from Equation 15 or 16 because Equations 15 and 16 provide the push from both propellers.

If metric units are used in Equation 17, T is in newtons where 1 lb = 4.448 N. The primary drawback of the Toutant equations are their empirical nature which limits them to shallow-draft towboats typical of those found on the Ohio and Upper Mississippi Rivers and operation behind loaded three-barge-wide by five-barge-long tows. The advantage of these relations is that they provide push estimates for UMRS towboats that may be valuable in fine tuning other, more generally applicable relationships. The Toutant equations also provide information on how the power relations vary with speed.

The second approach based on applied power rather than thrust coefficient and propeller speed is from Blaauw and Van de Kaa (1978) who define

$$V_2 = C_1 \left(\frac{P}{D^2} \right)^{1/3} \tag{18}$$

where P is the applied power per propeller.

Equation 18 becomes dimensionally correct with the addition of water density

$$V_2 = C_2 \left(\frac{P}{\rho D^2} \right)^{1/3} \tag{19}$$

In metric units, P is in watts (1 hp = 0.746 KW) and ρ is in kg/m^3 (usually about 1,000). In English units, P is in foot-pound/second (1 hp = 550 ft-lb/s) and ρ is in slugs/ft^3 (usually about 1.94). For open-wheel propellers at bollard push (V=0) conditions, one equation used by Blaauw and Van de Kaa (1978) to derive Equation 19 is

$$V_2 = 1.6\, nD\sqrt{K_t} \tag{20}$$

However, Hamill and Johnston (1993) found that the coefficient in Equation 20 is equal to 1.33 as opposed to 1.6. Thus, for open-wheel propellers, the coefficient C_2 in Equation 19 has been found equal to 1.48 by Blaauw and Van de Kaa (1978) and 1.23 if results by Hamill and Johnston (1993) are used to derive C_2.

Combining Equations 3, 9, and 19 for zero speed of advance results in

$$Q_p = \frac{C_2 \left(\frac{P}{\rho D^2} \right)^{1/3} \pi D^2}{4z} \tag{21}$$

Using Toutant's Equations 15 and 16 for UMRS towboats along with Equation 17 will allow determination of the proper value for C_2. Table 1 provides C_2 for a range of horsepower for a vessel speed equal to 0 using a typical propeller size of 2.74 m.

The coefficients in Table 1 for open-wheel propellers are between the two values found by Blaauw and Van de Kaa (1978) and Hamill and Johnston (1993) and are relatively constant. A C_2 of 1.32 is adopted herein for open-wheel propellers on the UMRS. Blaauw and Van de Kaa (1978) found C_2 equal to 1.17 for Kort nozzle or ducted propellers. A C_2 equal to 1.08 is adopted herein for Kort nozzles based on Toutant's equations for shallow draft tows. Figure 6 shows discharge per propeller versus paver for open-wheel and Kort nozzle propellers.

Table 1 **C_2 for Equation 21 Determined from Toutant Equations for Vessel Speed = 0**[1]				
Applied Power kW (Hp)	**Open-Wheel Propellers**		**Kort Nozzle Propellers**	
	Q_p from Eq 16 and 17 M^3/sec (cfs)	**C_2**	**Q_p from Eq 15 and 17 M^3/sec (cfs)**	**C_2**
2,835 (3,800)	21.8 (769)	1.29	37.7 (1,329)	1.06
3,730 (5,000)	24.9 (880)	1.34	41.0 (1,446)	1.10
[1] C_2 based on Q_p and Equation 21.				

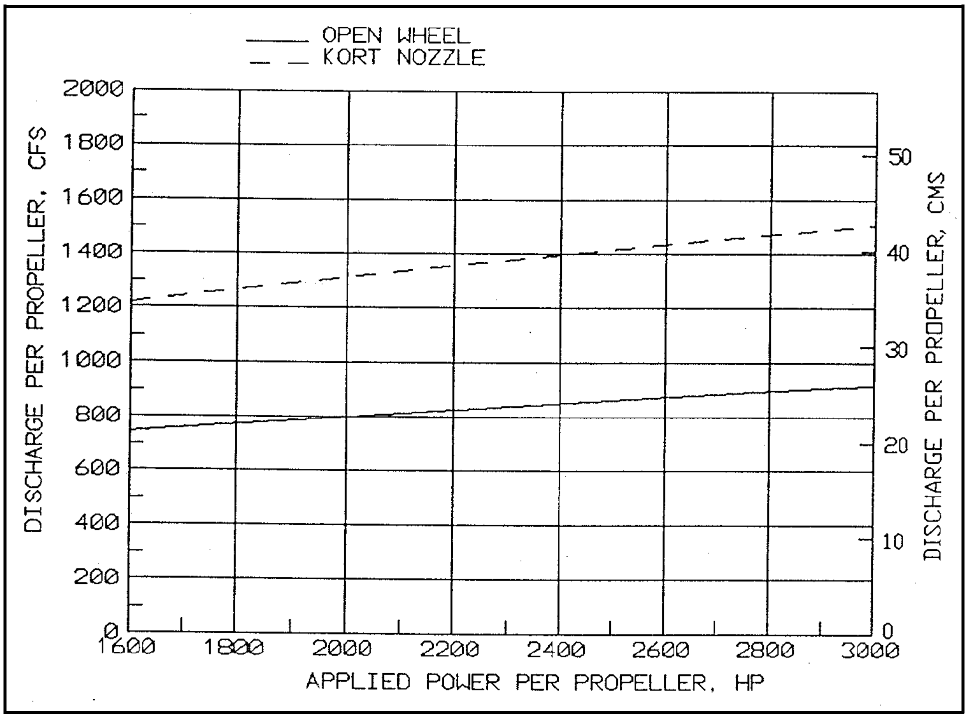

Figure 6. Discharge per propeller versus applied power per propeller based on Equation 21 and zero vessel speed. D = 2.74 m

The remaining question is how does discharge vary with speed when using the power relation given by Equation 21. Toutant's equations suggest that push varies only with vessel speed, but it should be reiterated that these equations are for 3-wide by 5-long loaded barges which fixes the wake fraction. Propeller manufacturers have reported to the author that river wheels generally have a design tip speed of about 60 mph (88 ft/s or 26.8 m/s). A constant tip speed fixes the product *nD* which is the denominator in the advance ratio *J* defined as

$$J = V_a / nD \tag{22}$$

A plot of thrust coefficient versus advance ratio J is shown in Figure 7 for a Wageningen propeller B5-60, propeller pitch/D = 1.0. For fixed values of wake fraction, nD, and a given propeller, J is only a function of V. Using Figure 7, the thrust coefficient in Equation 12 is only a function of V, and Equation 12 can be used to define the variation of discharge with V if one assumes that n = 2.7 rps and D = 2.74 m which are common on the UMRS. The resulting variation of Q_p with vessel speed from Equation 12 is shown in Figure 8 using w = 0.7. This is based on Figure 5 for depth/draft equal to 1.8. Results from Toutant's equations are also shown in Figure 8. The agreement is good up to 6 mph, but the two methods depart above that point. The recommended curve is based on Equation 12. Use of Equation 12 and thrust coefficients versus advance coefficient curves to determine discharge increase for Kort nozzle systems is difficult because a significant decrease in thrust with speed occurs because of resistance of the nozzle. Lacking better information, the increase in discharge ratio for open wheels is recommended for Kort nozzles. The increase in discharge for typical vessel speeds on the UMRS is only about 10 percent.

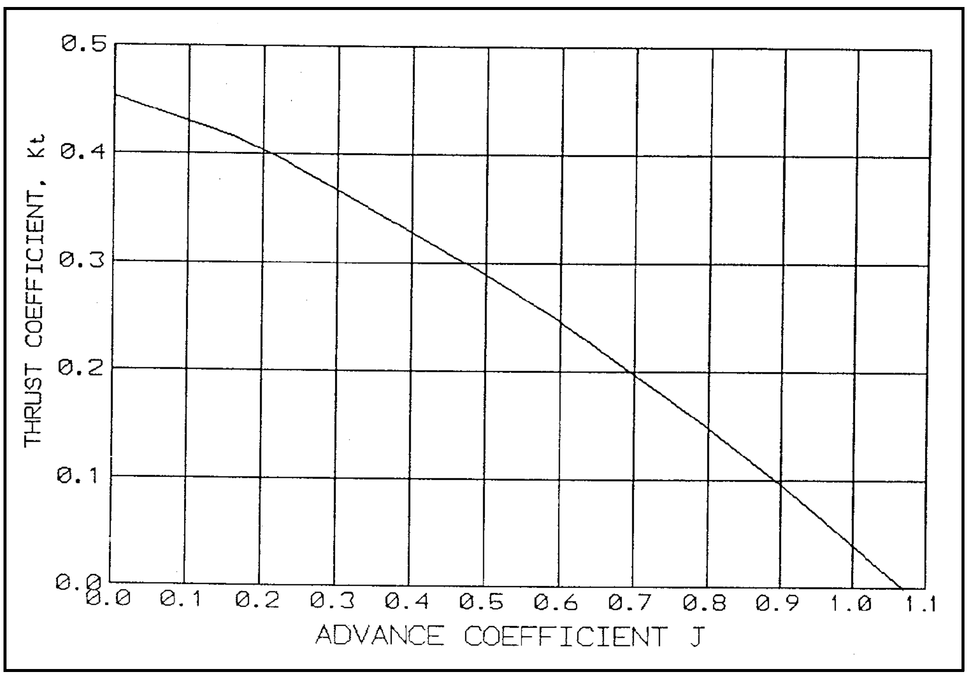

Figure 7. Thrust coefficient versus advance coefficient for Wageningen series B5-60 open-wheel propeller having a blade area ratio = 0.6 and pitch/diameter = 1.0

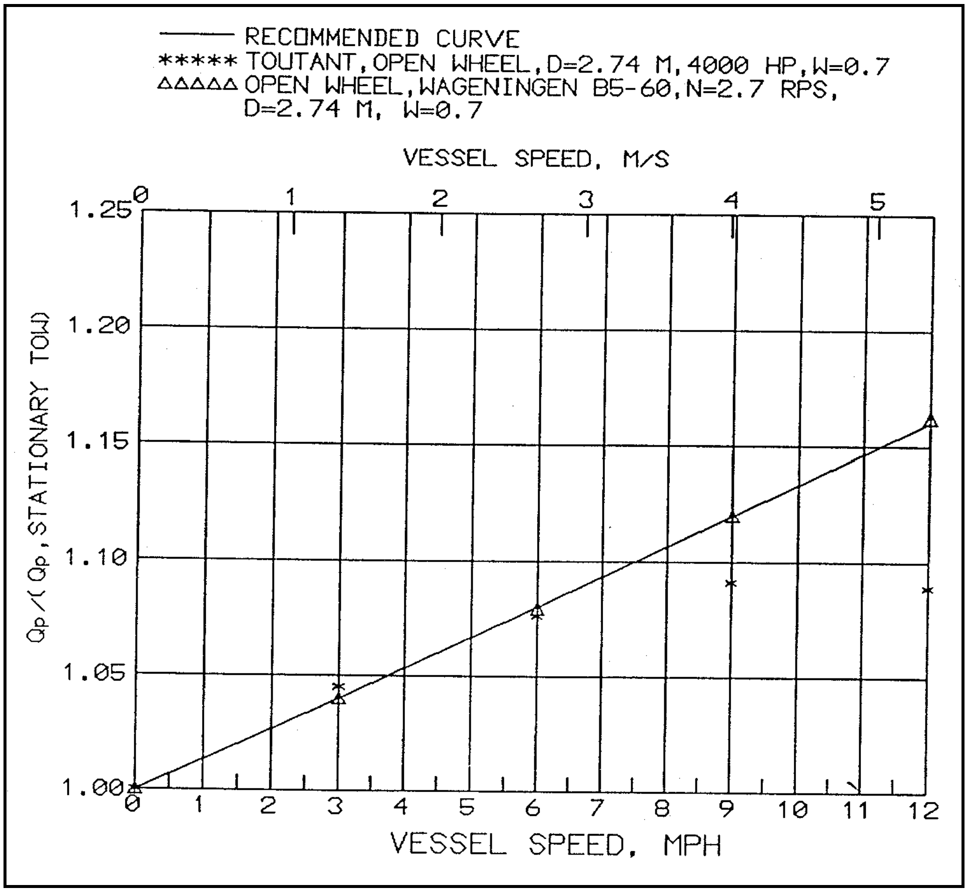

Figure 8. Correction for vessel speed based on Equation 12 and Toutant equations. Use with Equation 21. Use for open-wheel and Kort nozzle

Typical UMRS Tows

UMRS towboats represent a wide range of horsepower and propulsion systems. The Illinois State Water Survey (ISWS) conducted field experiments at five different sites on the Illinois and Mississippi Rivers (Bhowmik et al. in preparation) to measure tow-induced return velocity and drawdown. Experiment results provide a database with which to determine distribution of power and type of propulsion. From 178 tows from the ISWS experiments, the following tabulation presents fleet information derived:

% of Total Tows	Towboat Power, Hp	Propulsion
36	≤3,200	92% open wheel, 8% Kort nozzle
47	3,201 - 5,599	56% open, 44% Kort
17	≥5,600	87% Kort nozzle, 13% open wheel

To determine the average horsepower and speed through the water, local traffic in the ISWS data set was removed by assuming that long distance traffic consisted of tows having 12 barges or greater. Results show that the average speed through the water (speed over ground plus ambient for upbound, minus ambient for downbound) during the ISWS field experiments was 5.0 mph (Illinois River) and 6.2 mph (Mississippi River) and the average installed towboat power was 4,050 hp (Illinois River) and 4,450 hp (Mississippi River).

Consider a typical UMRS tow with twin 2.74-m-diam open-wheel propellers and an installed total power of 4,178 kW. Assume the vessel is using 90 percent of its installed power or 3,760 kW. For zero speed of advance, the discharge through each propeller is 24.6 m^3/s based on Equation 21.

For the above tow traveling at 3.0 m/s, Equation 21 and Figure 8 give a discharge per propeller of 1.085 (24.6) = 26.7 cms. This open-wheel vessel can be compared to an equivalent Kort nozzle vessel by equating the push in Toutant's Equations 15 and 16. Both open wheel and Kort nozzle are assumed to have 2.74-m-diam propellers. For 3.0 m/s (6.7 mph) and an applied open-wheel power of 3,760 kW, the Kort nozzle vessel producing the same effective push will have an applied horsepower of 3,003 kW. The discharge through the Kort nozzle based on Equation 21 and Figure 8 will be 1.085(37.3) = 40.5 cms. For vessels having equal effective push according to Toutant, the Kort nozzle will propel a larger flow rate. Since thrust is defined by the product of density times flow rate times velocity change, the open wheel must have a higher velocity change to produce the same thrust. This higher velocity change takes place because of the contraction downstream of the propeller that is significant for open-wheel propellers and not so for Kort nozzles.

Comparison of Momentum Theory Discharge with Measurements

"Does the computed discharge based on the momentum theory and empirical thrust coefficients agree with discharge based on measured velocity times representative area?" is the question that must be answered. This question was addressed using three sets of velocity data measured downstream of propeller jets. The first was presented by Hamill and Johnston (1993) in which detailed point velocities were measured ½ D (D = propeller diameter) downstream of the face of a 15.4-cm-diam open-wheel propeller spinning at 600 rpm and having a thrust coefficient of 0.3885. Hamill and Johnston presented isovels based on the point velocities in Figure 2 of their report. As part of this investigation, the area between isovels was measured and multiplied by a representative velocity equal to the average of the two isovels to provide a discharge between isovels. The discharges were summed and yielded a total discharge of 14,574 cm^3/s. The computed discharge based on the momentum approach presented herein (Eq 13) using thrust coefficient of 0.3885, propeller speed of 10 rev/s, $V_a = 0$, and D = 15.4 cm was 14,326 cm^3/s.

The second comparison was an open-wheel propeller in a water tunnel having an approach velocity of 3.14 m/s (Blaurock and Lammers 1987). The propeller diameter was 0.26 m, thrust coefficient = 0.185, and n = 20 rps. Mean values of flow velocity were presented 1D downstream of the propeller. The plane of the propeller was broken down into concentric rings and a representative velocity for each ring was multiplied by the area of each ring to provide discharge. The computed discharge based on the velocity measurements of Blaurock and Lammers (1987) was 0.22 m^3/s. The computed discharge based on Equation 12 was 0.21 m^3/sec.

The third comparison was the Kort nozzle data presented in Blaauw and Van de Kaa (1978). Velocity measurements were mean axial flow velocitity, and discharge was computed as described above for Blaurock and Lammers. Propeller diameter was 1.6 m, n = 5 rps, $V_a = 0$, and the measured thrust coefficient was 0.4 for the ducted propeller system. Discharge based on measured velocity was 12.1 m^3/s. Computed discharge based on Equation 12 was 11.5 m^3/s.

3 Discussion of Results and Conclusions

Results from the physical model and numerical simulations show that the inflow zone is limited to the portion of the cross section near the vessel. The inflow zone for typical three-barge-wide by five-barge-long vessels operating in depths from 4.3 to 12.2 m extends about 25 m on either side of the center line of the tow. The 25-m-wide inflow zone on either side of the tow center line is the region that can go through the propellers, but not all flow in this zone will go through the propellers. Dye injected on the channel bottom was not pulled into the propeller jet for depths greater than or equal to 9.8 m when viewing the model at the dye injection point. When viewing the model about one vessel length downstream of the dye injection point, the tow and ambient currents had caused enough mixing for a portion of the dye to be entrained into the propeller jet for the maximum depth experimented, 12.2 m. The clearance between hull and channel bottom is analogous to the flow depth in an open channel. Almost complete vertical mixing will occur in an open channel having a length of about 50 channel depths. For the typical UMRS three-barge-wide by five-barge-long vessel with total barge length of 297 m, near complete vertical mixing will have occurred at or before the stern for all underkeel clearances of 6 m or less, which represents the majority of UMRS tows.

Two methods with basis in the momentum theory of propeller design are presented for computing the discharge through propeller jets for UMRS towboats. The first method (Eq 12) uses thrust coefficients, propeller and vessel speed, propeller diameter and type to determine Q_p. Since thrust coefficients and propeller speed can be difficult to obtain, the second method defines Q_p in terms of applied power, vessel speed, propeller diameter and type. Two approaches are given for the method based on applied power and are presented in Equations 17 and 21. The recommended C_2 values in Equation 21 are 1.32 for open wheels and 1.08 for Kort nozzles. The adjustment for vessel speed in Figure 8 is only applicable to vessels similar to UMRS tows.

Kort nozzle propellers have a higher discharge but lower velocity change for equal thrust when compared to open wheels having the same diameter.

Discharge from the momentum approach used herein agreed well with discharge based on measured velocities from two open-wheel propellers and one Kort nozzle propeller.

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13. ABSTRACT *(Maximum 200 words)*

The inflow zone and discharge through propeller jets are used in evaluating the environmental effects of navigation on the Upper Mississippi River and Illinois Waterway (UMR-IWW). Both physical and numerical models were used to define the zone of inflow to typical tows used on the UMR-IWW. Results showed that the inflow zone for underway vessels is about 25 m on either side of the centerline of the vessel for the typical three-barge-wide by five-barge-long push tow used on the UMR-IWW. Water in this zone can go through the propellers but not all water in this zone will go through the propellers.

Discharge through propeller jets is defined using the momentum theory of propellers design. Equations for discharge are presented based on thrust coefficients and propeller speed and are the most accurate means of defining discharge. However, thrust coefficients are rarely provided by vessel operators and approximate methods for discharge are developed based on applied power. Equations are presented for discharge as a function of applied power, propeller diameter, propeller type, and vessel speed. Equations for discharge based on thrust coefficients are compared to measured velocities for two open-wheel systems and one ducted propeller system. The measured and calculated valves were in agreement.

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