WATER INJECTION DREDGING IN U.S. WATERWAYS, HISTORY AND EXPECTATIONS

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ABSTRACT

Water Injection Dredging (WID), where large volumes of water are injected into sediments causing them to fluidize and resulting in a near bottom density current that causes the shoaled sediment to flow to deeper areas, has been used in the US since the early 1990s. WID presents a viable and economic form of navigation channel dredging in U.S. ports and waterways under suitable conditions. The US Army Corps of Engineers (USACE) contractors have successfully demonstrated capabilities and advantages of WID on multiple navigation dredging projects. WID has proved successful on smaller scale dredging projects, typically with fine sediments, by taking advantage of WID strengths, including rapid deployment, minimal mobilization / de-mobilization and completion time, and minimal interference to navigation. This paper describes the use and progress of WID in U.S. waterways, emphasizing both operational aspects and measurements of the density current. This paper further analyzes density current in terms of the Bulk Richardson Number, R_i, as a quantitative description of WID effectiveness and efficiency. This paper will compare and contrast US WID experience to that in the Eastern Hemisphere and conclude with summary and further recommendations for WID use in Corps dredging operations.

Keywords: Dredging Alternatives, Hydraulic Dredging, Non-Intrusive Dredging, Fluid Mud, Density Current.

INTRODUCTION

Water Injection Dredging (WID) defines the dredging process where a dredge vessel injects water at a relatively high flow rate at low pressure into the channel sediment bed thus diluting and fluidizing the sediment into suspended water/sediment mixture. Gravity then transports this high density mixture known as a density current. Channel and sediment dynamics control the production rate of this dredging process defined as how fast this sediment flows into the designated placement area. In some cases, WID operators must spend considerable time and effort forming the proper gradient for the density current to flow down the existing channel slope.

Factors such as sediment grain size, channel slope and channel geometry form a delicate balance between density current velocity and thickness ultimately governing the production rate. Suitable factors historically lead to effective production rates and costs. WID vessels perform dredging operations under these conditions in less time, causing less interference to navigation and resulting in lower overall cost. Unsuitable conditions can result in the opposite.

Fluid mud density current dynamics govern production rates in WID. van Kessel and Kranenburg conducted analytical and experimental analysis to quantify the governing principles of density currents in the form of the Richardson Number. Continuity principles can determine a bulk Richardson Number, R_i, from WID production rates. The Richardson Number determines if the WID project produces sub-critical or supercritical flow in the density current. On shallow slopes, high Richardson Numbers generally correspond to high production rates. Therefore, the Richardson Number associated with a WID project can quantify WID efficiency in transporting dredge material.

Aside from production rates, WID induces very little Total Suspended Solids (TSS) into the water column. Most of the fluidized material remains close to the density current. Low suspended solids in the water column means a much more environmentally sustainable approach to dredging.

Overall, WID presents a viable, efficient, economic and environmentally sustainable method of dredging under suitable conditions. These conditions vary from sediment grain size and channel shape and bed slope. Realizing these conditions, limitations, and balances will provide WID operators and sponsors the ability to effectively use WID.

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WATER INJECTION DREDGE CHARACTERISTICS

Weeks Marine, Inc. currently owns and operates the only water injection dredge and conducts the only WID in the United States of America. Weeks mounted the WID to a 30.5m (100ft) long by 9.8m (32ft) wide barge drawing 1.5m (5ft) (see Figure 1). A single 900 hp pump supplies the water down two 0.71m (28in) pipes 15.3m (50ft) long to a 11.6m (38ft) long pipe manifold 76.2cm (30in) in diameter. The manifold contains forty-two 7.62cm (3in) ports that inject the water into the channel bed. Operators maintain a pump discharge pressure of approximately 82.7kPa (12p.s.i) to supply an approximate injected flowrate, Q_i, of 1.85m³/s (29,000gpm). This flowrate corresponds to an injected velocity of 32ft/s (9.7m/s). Historically, a 2,000hp tug, *Evelyn James*, maneuvers the WID barge at speeds of 4-6 knots. The WID operator maintains the manifold in contact with the bed by "bumping" it along the bed surface. The manifold jets provide no forward or backward thrust. Therefore, direction of the WID barge with respect to the slope is irrelevant. However, WID operators must spend substantial time and effort controlling the slope of the channel, ensuring that the density current flows in the right direction in some cases.
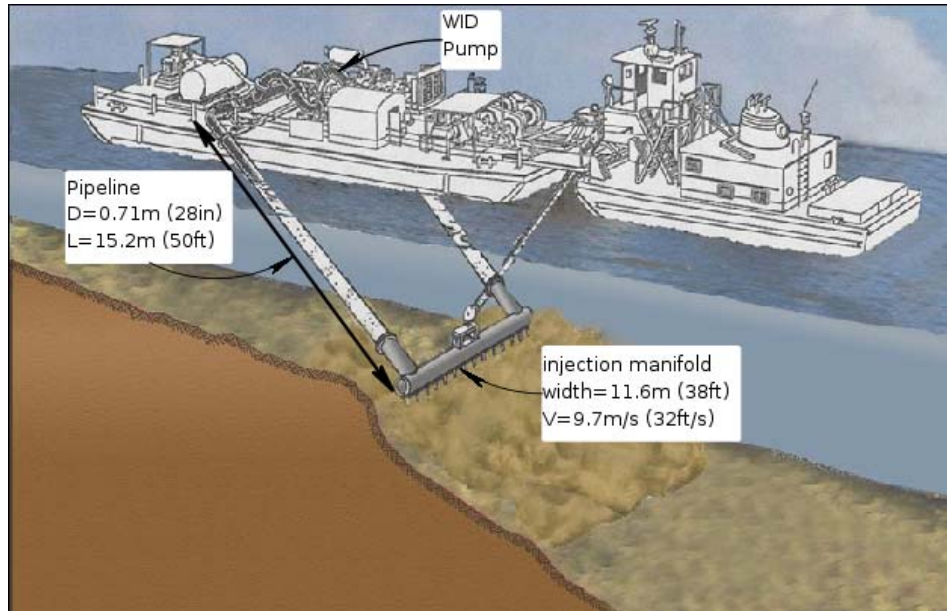

Figure 1. Water Injection Dredge Barge with pump, pipeline and manifold.

WID DENSITY CURRENT

Water Injection Dredging defines the dredging process of *fluidizing* channel sediment so that gravity can transport it down a slope to deeper water. van Kessel & Kranenburg define this transport process as a density or gravity current. van Kessel and Kranenburg studied movement of gravity currents on a sloping bed due to high concentration mud suspensions that closely resemble the WID process. Their analytical and experimental analysis lends valuable information and values for the WID density current profile. van Kessel & Kranenburg based the dynamics of the fluid mud flow on the Richardson Number (R_i). van Kessel & Kranenburg define the Richardson Number as:

$$R_i = \frac{\rho_m - \rho_f}{\rho_m} \frac{gH\cos\theta}{\overline{U}}$$
$$\frac{S_m - S_f}{S_m} \frac{gH\cos\theta}{\overline{U}}$$

(1)

where

ρ_m, S_m = density [kg/m³], Specific gravity of fluid mud layer

ρ_f, S_f = density [kg/m³], Specific gravity of carrier fluid

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<table>
<tr><td>g</td><td>=</td><td>gravitational acceleration 9.81m/s^2</td></tr>
<tr><td>H</td><td>=</td><td>density current thickness [m]</td></tr>
<tr><td>θ</td><td>=</td><td>bed slope angle</td></tr>
<tr><td>Ū</td><td>=</td><td>average density current velocity [m/s]</td></tr>
</table>

The Richardson Number quantifies stability of the fluid mud layer and provides a relationship between inertia and gravitational forces. Richardson numbers below 1 correspond to supercritical conditions where upstream boundary conditions control the fluid mud flow. Richardson numbers above 1 constitute sub-critical conditions where downstream boundary conditions prevail. Counter-intuitively, high Richardson Numbers correspond to sub-critical flow and vice versa, opposite of free surface Froude Numbers. Readers may also note that the Richardson Number becomes the reciprocal square Froude Number for free surface flow for $S_m >> S_f$ and θ=0.

van Kessel & Kranenburg experimented on fluid mud densities in a 12.2m (40ft) long laboratory flume. van Kessel & Kranenburg varied densities from 1050-1229kg/m^3 and bed slope from 1:43 to 1:19. van Kessel & Kranenburg noticed that low fluid mud density corresponded to low Richardson Numbers and vice versa. This implies that high density fluid mud adds gravitational stability and dependence on ambient conditions. Low concentrations mean upstream conditions prevail. This latter condition indicates that the fluid mud is traveling down slope only as fast as the source can provide it.

Density current analysis starts with the continuity and solid-water mixture principles of:

$$Q_{out} = wH\overline{U} \tag{2}$$

$$Q_{out} = Q_{in} + Q_{er} \tag{3}$$

$$C_{out} = \frac{C_{er}Q_{er}}{Q_{out}} \tag{4}$$

$$C_{out} = \rho_w c_{vd} S_s \tag{5}$$

$$c_{vd} = \frac{S_m - S_f}{S_s - S_f} \tag{6}$$

$$c_{vd} = \frac{S_m - S_f}{S_s - S_f} \tag{7}$$

where

<table>
<tr><td>Q_{out}</td><td>=</td><td>flow rate of sediment/water mixture out (i.e. the resulting density current) [m^3/s]</td></tr>
<tr><td>Q_{er}</td><td>=</td><td>flow rate of bed eroded material (taken as dredge production rate) [m^3/s]</td></tr>
<tr><td>Q_{in}</td><td>=</td><td>flow rate of clear water injected into the volume. [m^3/s]</td></tr>
<tr><td>C_{out}</td><td>=</td><td>solids concentration in density current [kg/m^3]</td></tr>
<tr><td>C_{er}</td><td>=</td><td>solids concentration of channel bed [kg/m^3]</td></tr>
<tr><td>ρ_w</td><td>=</td><td>density of water [1000 kg/m^3]</td></tr>
<tr><td>c_{vd}</td><td>=</td><td>volumetric solids concentration of mixture</td></tr>
<tr><td>S_s</td><td>=</td><td>specific gravity of solids</td></tr>
</table>

Figure 2 illustrates these principles. By equation manipulation, users can calculate the density current specific gravity and velocity as:

$$U = \frac{Q_{out}}{wH} \tag{8}$$

$$S_m = \frac{C_{er}}{\rho_w S_s} \frac{Q_{er}}{Qin + Q_{er}} \left(S_s - S_f \right) + S_f \tag{9}$$

Figure 2. Water Injection Dredge density current showing injection, erosion, entrainment and output flowrates and concentrations.

With these principles in place, users can estimate a density current Richardson Number by only knowing the dredge production rate, WID injected flow rate and *in-situ* material density.

U.S. WATERWAYS WATER INJECTION DREDGE PROJECTS

The U.S. Army Corps of Engineers (USACE) used water injection dredging for U.S. waterways navigation dredging contracts beginning in 1992. Gulf Coast Trailings Co. (GCT) and later Weeks Marine Dredging, Inc. conducted three of these projects for field demonstration of WID capabilities and for field data collection. The remaining WID projects lend valuable evidence towards WID economic and feasibility advantages for dredging projects. The following project discussions describe the WID projects on U.S. waterways in order to gain an appreciation and insight as to the WID operating characteristics, capabilities and limitations.

WID Demonstration 2002 (Michoud Channel, LA)

New Orleans Corps District (MVN) contracted Weeks Marine, Inc. to demonstrate Water Injection Dredging (WID) in the Michoud Channel in August of 2002 (see Figure 3). This demonstration aimed to clear a 77,000m³ (100,000yd³) shoal in the channel in a 72hr period. ERDC personnel gathered and analyzed data for this project, publishing a report on the findings.

The self-contained WID vessel operated along a 1,600m (5,248ft) reach of the Michoud Channel connecting the Gulf Intra-coastal Waterway (GIWW) and MRGO. The WID encountered a maximum shoal height of 1.52m (5ft) while the density current moved the material along a 1:1,000 slope towards the MRGO. Final surveys calculate that the WID successfully removed 178,642m³ (232,235yd³) of material in 96hrs of total operation time producing a sustained dredging rate of 1,861m³/hr (2,419yd³/hr).

The WID further maintained turbidity at a minimum. Acoustic Doppler Current Profiler (ADCP) back-scatter plots indicate sediments remained predominately ``in the bottom 0.91-1.52m (3-5ft) of the water column'' (Pollock *et al*,

2005). Figure 4 corroborates this estimate where TSS drops several orders of magnitude within the first 2m (6.56ft) from the channel bed. This information not only lends credible information about turbidity, but also the thickness of the density current.

Figure 3. Site of water injection dredging in Michoud Channel (August 2002). Photo taken from Google.com.

Initial analysis concluded successful WID-ing of Michoud Channel. Comparison of before and after dredge surveys show all of the dredge area below channel design depth of 11.3m (37ft) with the maximum depth of 14.2m (46ft) at the Westernmost dredged boundary (Pollock *et al*, 2005). Comparison reveals that the WID scoured out the channel initially sloped downward to the East. The WID cut 3.1m (10ft) into the channel at the western end and 1.8m (6ft) into the channel at the Eastern end, ultimately reversing the slope. TSS remained low in the water column according to Niskin Bottle Sample results. TSS reached as high as 219g/l near the bottom of the channel, yet only slightly higher than background TSS (36mg/l) near mid-depth. Figure 4 illustrates these measurements. Furthermore, acoustic backscatter data illustrates approximate density current thickness (see Figure 5).
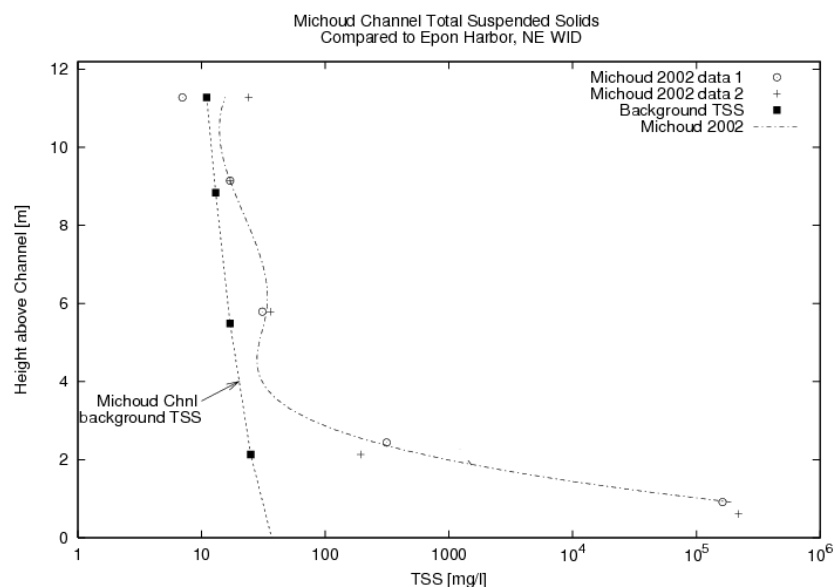

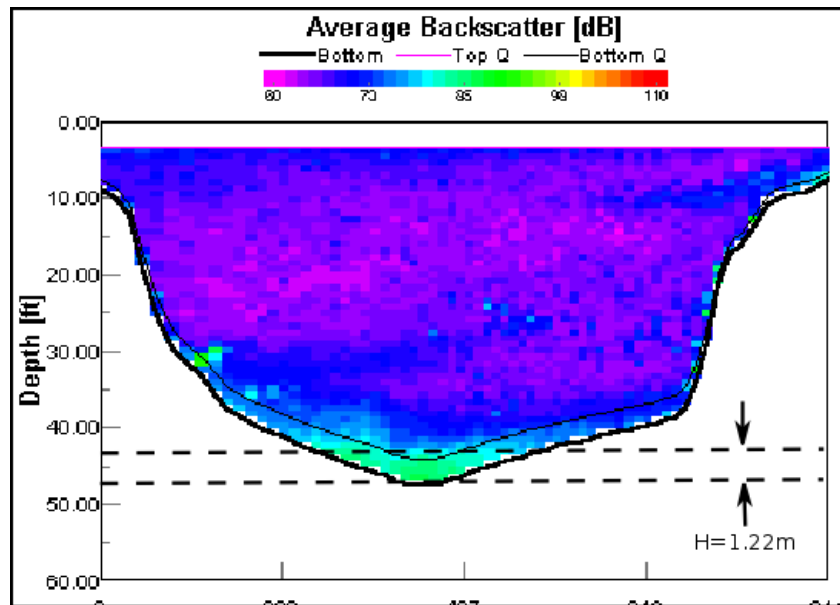
Figure 4. TSS data collected at Michoud Channel.

Figure 5. Acoustic Backscatter data collected at Michoud Channel.

MRGO 2003

Weeks Marine conducted a WID operation between Channel Mile 51.4 and 54.4 along a 3.2km (2mi) reach of the 91m (300ft) wide Mississippi River Gulf Outlet (MRGO) in August of 2003 (see Figure 6). Between June 17 and June 21, 2003, Weeks Marine worked in conjunction with New Orleans District (MVN) and ERDC personnel to collect TSS data from field data to verify WID environmental influence.
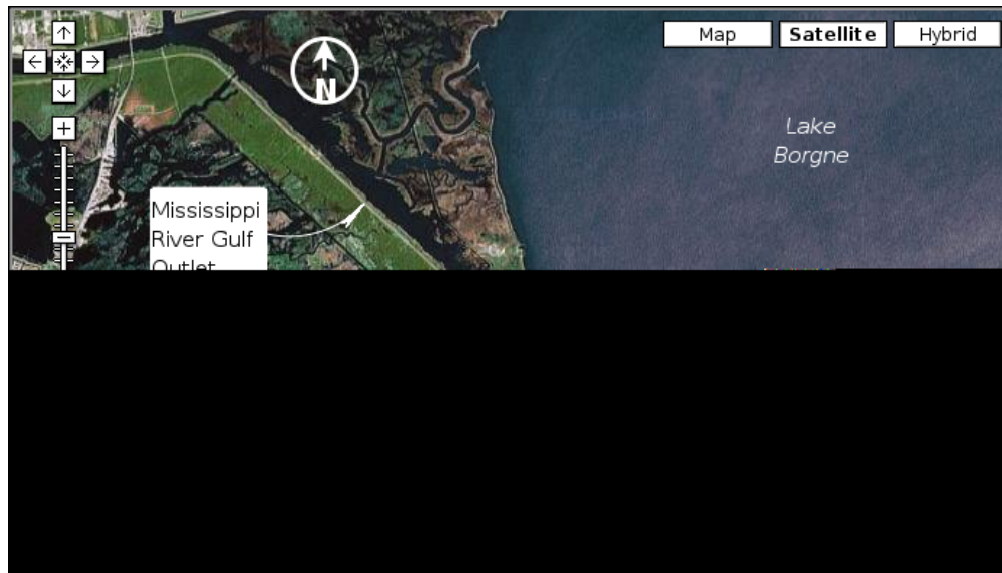

Figure 6. WID site on MRGO (June 2003). Photo taken from Google.com.

The Weeks Marine WID vessel conducted dredging operations along the 3.2km (2mi) reach for 96 hours ultimately removing 270,000m^3 (350,000yd^3) of material. To date, this project remains the most productive WID project in U.S. waterways averaging 2,803m^3/hr (3,645yd^3/hr) as well as the most economic at \$0.36/m^3 (\$0.28/yd^3). Table 1 summarizes these data. ERDC researchers collected Niskin Bottle samples to test for TSS. Samples showed that TSS reached as high as 384 and 324 mg/l near the bottom of the channel at two sampling points near mile 51.4, yet remained at 26 and 35mg/l at the mid-depth for the same locations (Welp, 2003). These low TSS values corroborate TSS levels obtained at Michoud Channel in 2002, where TSS remained low outside of the immediate density plume as shown in Figure 4.

Upper Mississippi River

USACE first employed WID capabilities on U.S. waterways in July and August 1992 in the Upper Mississippi River for two dredging locations. The GCT WID vessel worked from July 27-29 on the sand bar at Lower Zumbro at River Mile (RM) 744.2 and August 5-7 at Savannah, IL at RM539.2. The cross-sectional areas correspond to 229mx46m (750ftx150ft) and 213mx61m (700ftx200ft), respectively (Knox *et al*, 1994). The WID operation produced a 0.61m (2ft) thick density current (Knox *et al*, 1994). These sites exhibited a median grain size of 0.3mm and 0.4mm (0.011-0.016in), respectively. Knox *et al* (1994) concluded that dredging sites with grains sizes over 0.2mm requires certain criteria met, such as, substantial downward slope. Coarser material settles significantly faster.   WID would encounter some difficulties keeping the coarse sediment in suspension long enough for the density current to carry it away. Therefore, grain size distribution can play an important role in the effectiveness of WID.

Calumet Floodgates 1992

The New Orleans Corps District (MVN) first contracted the water injection dredge for the Calumet Floodgates on Bayou Teche near Morgan City, LA in 1992 (Scuria-Fontana, 1994). The WID barge dredged 77,872m^3 (23,234yd^3) of material ranging from 0.004-0.05mm (0.0016-0.0020in) in just 16.25 hrs of actual dredge time (Scuria-Fontana, 1994). GCT completed the project at \$49,098 (Scuria-Fontana, 1994). Typical bucket dredging operations cost \$85000 (Scuria-Fontana, 1994) and require 2 to 3 weeks for completion (Knox *et al*, 1994). The conditions at Calumet prove very conducive to the WID process given its steep side slopes to adjacent deep water and fine grain size (Knox *et al*, 1994). The high production rate and low cost reflect these statements.

Corps Dredge Contract Comparison

Table 1 summarizes all Corps sponsored WID projects between 1992 and 2005. Each project contains Richardson Number analysis for each project based on Equations 1-9 and estimates for. Figures 7-10 illustrate WID projects compared to conventional dredging contracts in the same channels from 1990-2005. The Navigation Data Center provides these dredge contract data for all Corps districts and contracts. These navigation data are available at http://www.iwr.usace.army.mil/ndc/data/. SQL database queries and filters out each navigation channel of interest such as MRGO, New Orleans Harbor, Calumet Channel, and Houston Ship Channel. These queries then determine production rate, project duration, volume and cost of all conventional dredge projects in these respective channels producing the plots in Figures 7-10. For instance, Figure 7 shows that WID projects in the MRGO compare favorably well to conventional dredge techniques (usually pipeline) in MRGO. Both WID projects on or near MRGO were completed dredging in four days with a relatively high production rate. Furthermore, these WID projects completed the projects with the lowest unit cost of all MRGO projects although overall volume was far less. New Orleans harbor WID projects compared to conventional dredging as having far less advantage. Not only did WID projects fall below some conventional dredge projects in New Orleans Harbor in terms of productivity, but also, in one case, the most expensive over conventional dredging projects. However, WID can still hold the advantage over conventional dredging in terms of non-invasive operation. Calumet harbor WID projects in New Orleans District and Houston Ship Channel WID projects in Galveston District compared favorably to conventional dredging techniques. These projects sustained high production in very little time. Furthermore, their cost compared, more or less equal to conventional dredging costs in their respective areas. Overall, WID proves to hold an advantage over conventional dredging under the right criteria and site-specific conditions.

Table 1. USACE WID Projects Summary.

| Project Name	Project Site	Soil / d_{50}	Cost ($)	Volume m^3 (yd^3)	Duration (days)	Production Rate m^3/hr (yd^3/hr)	Unit Cost $/m^3$ ($/yd^3$)	Richardson Number (Ri)
Upper Mississippi River 1992	Lower Zumbro, MN and Savannah, IL (*Jul 27-29 & Aug 5-7, 1992*)	fine sand 0.3-0.4mm (0.012-0.016in)	-N/A-	6,154 (8,000)	4	140 (182)	-N/A-	1.16
Calumet 1994	Calumet, LA (*Dec 20-21, 1996*)	silt 0.004-0.05mm (0.00016-0.0020in)	41,438	12,034 (15,644)	1	502 (652)	3.44 (2.65)	7.43
N.O. Harbor 1998	Miss River (*Jan 28-Mar 26, 1998*)	-N/A-	731,975	500,371 (650,482)	57	366 (476)	1.46 (1.13)	5.76
N.O. Harbor 2001	Miss River (*Feb 01-Mar 19, 2001*)	-N/A-	794,260	257,331 (334,530)	46	303 (394)	3.09 (2.37)	3.9
Houston Ship Channel 2001	Emergency (Galveston Dist) (*July 6-10, 2001*)	-N/A-	335,810	87,077 (113,200)	4	907 (1,179)	3.86 (2.97)	11.3
Houston Ship Channel 2001	Bayport Flare (Galveston Dist) (*Aug 20-22, 2001*)	-N/A-	-N/A-	89,747 (116,671)	2	1,870 (2,431)	-N/A-	15.98
Houston Ship Channel 2001	Carpenters to Green Bayou (Galveston Dist) (*Aug 23-27, 2001*)	-N/A-	-N/A-	20,199 (26,259)	4	211 (274)	-N/A-	3.56
Houston Ship Channel 2001	Bayport Flare (Galveston Dist) (*Sep 21-24, 2001*)	-N/A-	-N/A-	75,308 (97,900)	3	1,046 (1,360)	-N/A-	12.30
N.O. Harbor 2002	Miss River (*Jun 17-Jul 27, 2002*)	-N/A-	1,619,968	683,389 (888,406)	40	712 (925)	2.37 (1.82)	9.63
Michoud 2002	Michoud Channel (*Aug 06-09, 2002*)	silt 0.06mm (0.0024in)	79,264	178,642 (232,235)	4	1,861 (2,419)	0.44 (0.34)	15.96
MRGO 2003	MRGO (*Jun 17-21, 2003*)	silt	98,900	269,230 (350,000)	4	2,804 (3,645)	0.37 (0.28)	17.32
Houston Ship Channel 2004	Mid Bay Project Galveston Dist (*Jun 29-Aug 07, Sep 30-Nov 19, 2004*)	-N/A-	1,183,014	435,775 (566,507)	89	204 (265)	2.71 (2.09)	3.46
N.O. Harbor 2005	Miss River (*Mar 01-28, 2005*)	-N/A-	2,339,686	408,497 (531,046)	28	608 (790)	5.73 (4.41)	8.60
Horn Island 2005	Mobile Dist Rental (*Jun 07-16, 2005*)	-N/A-	180,313	-N/A-	5.5	-N/A-	$1366/hr	-N/A-
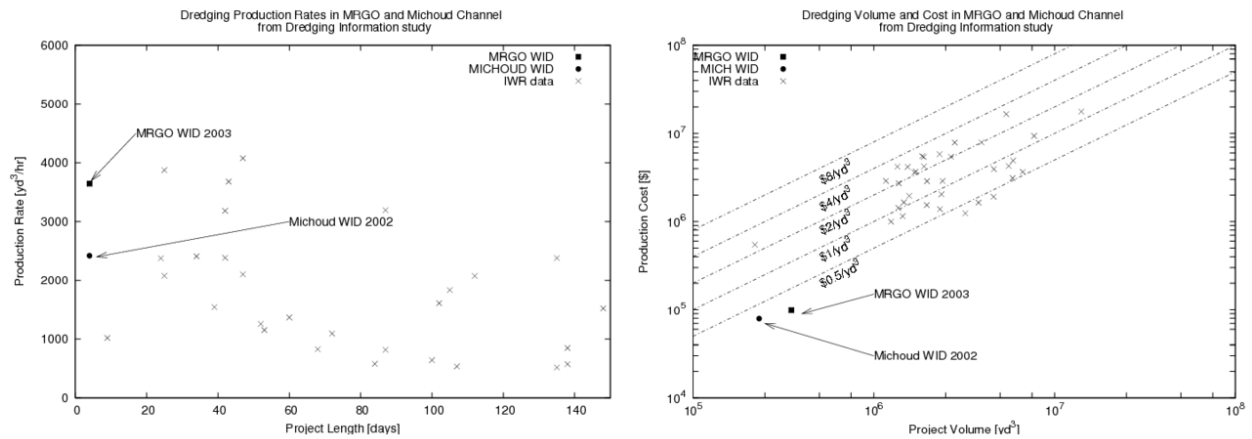
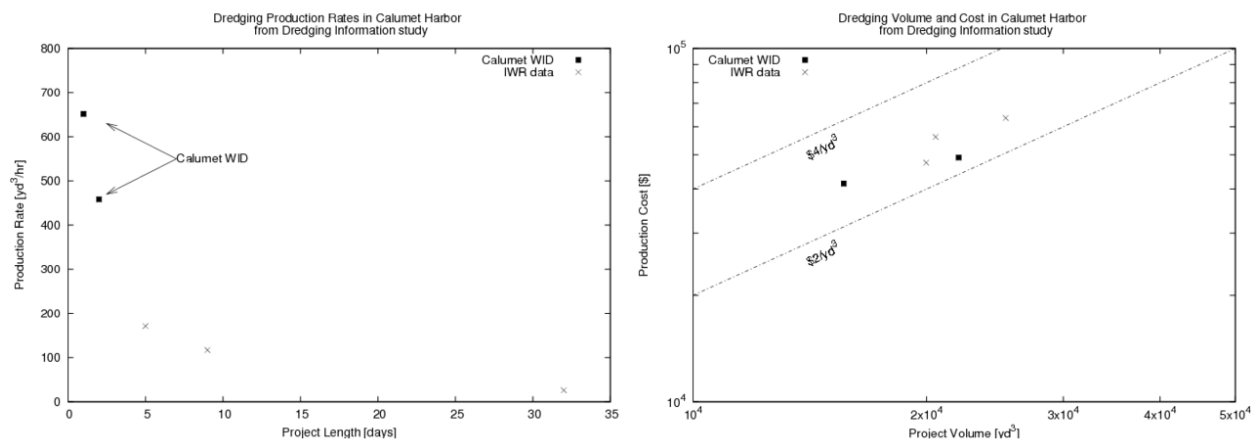**Figure 7. MRGO WID production and cost.**

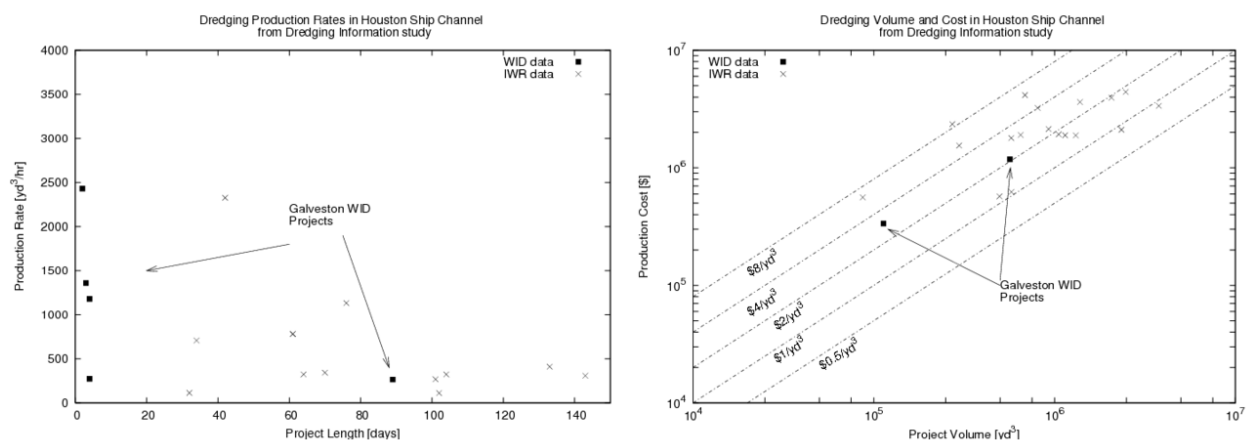**Figure 8. Calumet floodgates production and cost.**

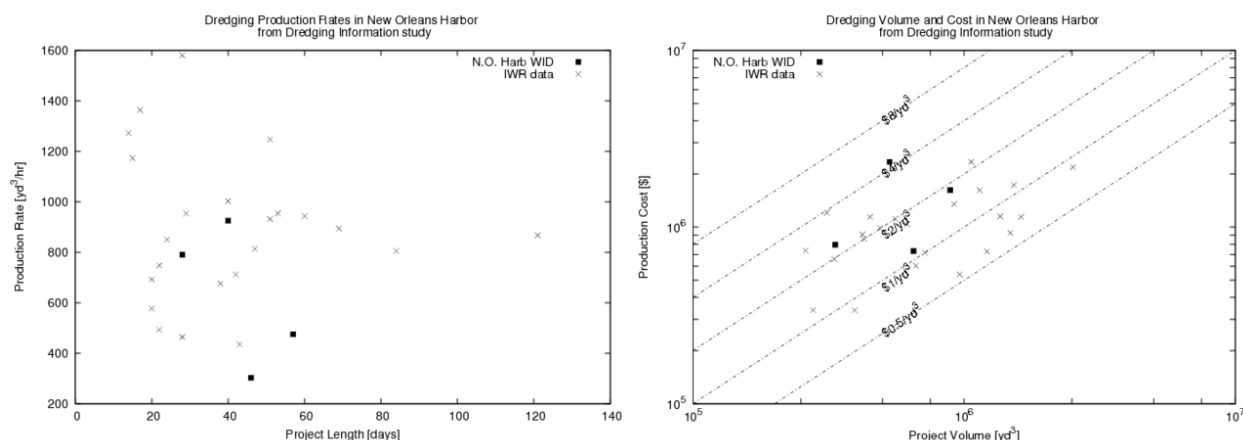**Figure 9. Houston ship channel WID production and cost.**

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Figure 10. New Orleans Harbor WID production and cost.

U.S. WID PROJECTS RESULTS AND DISCUSSION

U.S. WID projects produced a variety of results. Production rates ranged from 140m^3/hr (182yd^3/hr) to 2804m^3/hr (3645yd^3/hr) with corresponding Richardson Numbers of 1.16 and 17.32, respectively. Richardson Numbers generally increase with production rate, Q_{er}. Richardson Numbers came suspiciously close to unity for Upper Mississippi River WID projects. New Orleans Harbor 1998 and 2001 WID projects were close behind. This information suggests that Upper Mississippi River WID and New Orleans Harbor WID with some exceptions came close to supercritical conditions. Furthermore, analysis did use a conservatively high estimate for density current thickness. Actual conditions may very well have been supercritical for lower density current thickness values. This implies that the production rates were essentially as high as the vessel could produce. Richardson Numbers in MRGO and in some Houston Ship Channel WID projects showed exceptionally sub-critical conditions. This implies the WID vessel produced the density current fast enough to where the channel slope now controls the WID production rate.

The graphs in Figures 7-10 corroborate Richardson Numbers to WID effectiveness. New Orleans Harbor WID did not compare as well to conventional dredge methods in terms of cost and production under confined conditions. MRGO WID projects did compare well with conventional dredge methods in terms of cost and production on the long, clear channel reaches. This information suggests that WID production highly depends on the dredge operator's ability to maintain the density current in terms of thickness and bed slope. Neglecting to keep steady flow into the density current causes it to flatten out and diminish as in the case for the Upper Mississippi River low production rate. Therefore, WID productivity greatly depends on ambient conditions in terms of slope and confinement of the dredge location.

Furthermore, grain size played as important a role in WID projects. Upper Mississippi River WID encountered grain size of 0.3mm (0.012in) with a fall velocity of 4.1cm/s (1.6in/s) opposed to those for MRGO and Michoud Channel of 0.06mm (0.024in) with a fall velocity of 3.2mm/s (0.12in./s). Upper Mississippi River WID represents the lowest WID production rates on U.S. Waterways while MRGO and Michoud Channel WID produced the highest. Therefore, as Knox *et al (1994)* suggest, sites with over 0.2mm grain sizes require site-specific reasons to use the WID.

Figure 4 illustrates that during the Michoud WID project, TSS fell sharply from 193mg/l at 2.1m (7ft) above the channel bed to 36mg/l at 5.8m (19ft) above the channel bed. Essentially, TSS went back to normal values within 6m (20ft) of the channel bed during WID production. Collected TSS samples during the MRGO WID project show that mid-depth and surface TSS stayed low even when bottom TSS reached as high as 384mg/l. Therefore, TSS during WID projects remained low. This suggests WID remains environmentally sustainable as a dredge solution.

Table 2. European WID Projects.

Project Name	Soil Description d_{50}	Volume m^3 (yd^3)	Duration (days)	Production Rate m^3/hr (yd^3/hr)	Richardson Number (Ri)
Epon Harbour, Delfzigl, Netherlands	Silt & fine sand 0.3mm	160,000 (209,600)	8	800 (1,048)	10.42
Shipping Lane Boontjes, Waddenzee, Netherlands	-N/A-	20,000 (26,200)	19	800 (1,048)	10.42
Ferry Harbor and Entrance Channel, Den Burg, Texel, Netherlands	-N/A-	20,000 (26,200)	13	1,500 (1,965)	14.73
Wesbuitenhaven, Terneuzen, Netherlands	-N/A-	500,000 (655,000)	9	2,250 (2,948)	16.78
Haringvliet Harbor, Netherlands	silt/clay	121,000 (157,300)	-N/A-	480 (624)	Actual = 7.41
Crouch River, Great Britain	clayey silt	6,200 (8,060)	1	540 (702)	7.86
Elbe Estuary, Germany	fine sand 0.06mm	-N/A-	-N/A-	-N/A-	-N/A-

EUROPEAN WATER INJECTION DREDGING

European dredge companies Volker Stevin and Ham-Vow practiced WID since 1987. Volker Stevin published 4 WID projects each with interesting consequence. Other WID projects in Elbe Estuary Germany, Haringvliet Harbor Netherlands and Crouch River in Great Britain provide valuable field data and analysis lending much insight as to the dynamics and productivity of WID. Table illustrates and summarizes some key WID projects in the Netherlands, Europe.

Elbe Estuary, Germany

The Federal Waterways Engineering and Research Institute (BAK-AK) studied a 10 day WID project in Elbe Estuary, Germany in October 1999. This project served to evaluate the WID field performance and analyze sediment mobilization and transport (Maushake and Collins, 2002). Maushake and Collins (2002) noticed considerable changes in grain size distribution before and after dredging. Maushake and Collins (2002) conducted acoustic pre- and post surveys showing considerably less silt after dredging. Maushake and Collins (2002) further collected field samples of sediment. Grain size distributions(GSD) taken before and after dredging shows that the median grain size increased from 0.06mm (0.0024in) to 1.2mm (0.047in) as a result of water injection dredging as illustrated in Figure 11. Furthermore, the two GSD lines start to deviate at 0.2mm (0.0079in) signaling the largest grain size WID transported for this particular project. Maushake and Collins' (2002) analysis clearly shows that WID particularly transports finer grained particles leaving behind coarser grains.
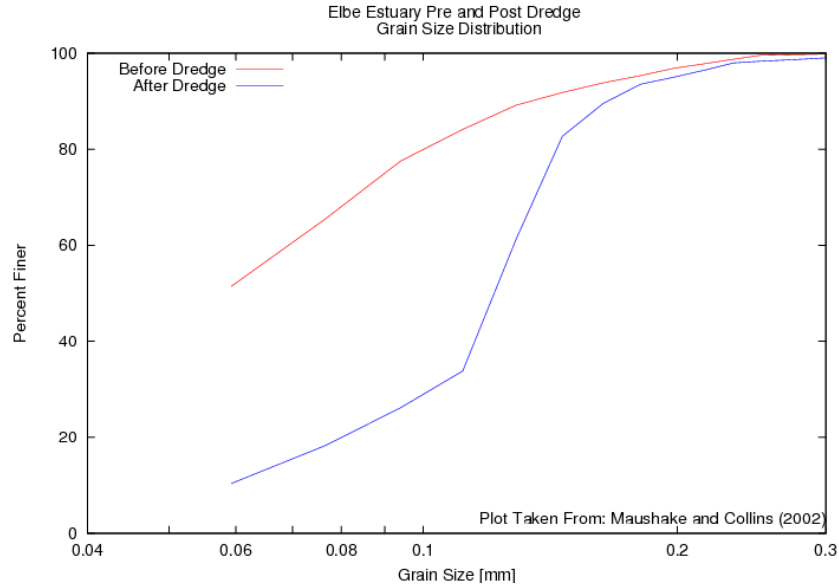
Figure 11. Grain size distribution before and after WID on Elbe Estuary, Germany.

Haringvliet, Netherlands

HAM-VOW Dredging used the WID vessel, *Jetsed*, to transport 121,000m^3 (157,300yd^3) of material from the estuary to a deposition area about 1,000m (3280ft) downstream. Delft Hydraulics and Delft Dredging Consultants used a vast array of vessels and equipment to monitor and analyze the WID process. The WID project in Haringvliet remains the most extensively documented WID field analysis in Europe. As a result, the Haringvliet WID project analysis and data provide some of the most insight into WID dynamic properties.

Borst *et al* (1994) of Delft Hydraulics and Delft Dredging Consultants conducted field analysis on the to determined a Silt/Clay sediment bed mixture in the 10m (32.8ft) deep channel with a 1:1000 average slope. Borst *et al* (1994) used 7 vessels to track and survey the WID process. Borst *et al* (1994) employed nuclear density probes to measure density current density, electro-magnetic flowmeters to measure current profiles, echosounders and multibeam sonar to measure bathymetry response, and turbidity probes and Niskin Bottles to measure water quality and TSS.

Borst *et al* (1994) noted that HAM-Vow dredge operators spent considerable time and effort "cutting'" the slope to ensure the material flowed to the designated area. Analysis further identified a density current averaging 70cm thick and an average velocity of 20cm/s (see Figure 12). Delivered sediment densities ranged from 1,020kg/m^3 to 1,100kg/m^3 averaging 1,065kg/m^3. The *Jetsed*, like the Weeks WID Barge delivers a maximum flow rate of 12,000m^3/h (15,600yd^3/h) through 42 jets across a 13.8m (45.3ft) manifold (Borst *et al*, 1994). Substitution of these direct field measurements into Equation 1 yields a corresponding Richardson Number of 7.41 without having to estimate Q_{out} or C_{out}. This measurement indicates that the density current stayed sub-critical similar to USACE projects. Further field echo-soundings concluded that the density plume maintained suspension well past 4 hours from time of suspension (Borst *et al*, 1994). During the entire process, contractors measured TSS at or below 100mg/l at intermediate water depths, further concluding low turbidity induced by the WID process (Borst *et al*, 1994).
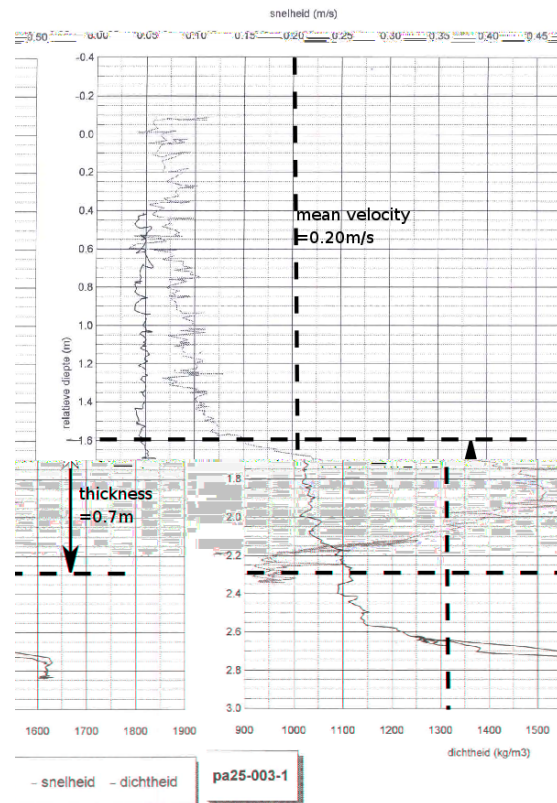
Figure 12. Density and velocity profile of density current during WID in Haringvliet, NE (source: Borst et al, 1994).

Crouch River

HAM Dredging used its WID vessel, *Baldur*, to dredge the Crouch River Estuary in January of 1996 (Winterwerp *et al*, 2003). Similar to the Haringvliet study, Delft Hydraulics conducted field analysis for the density current and surrounding turbidity. The WID project dredged 6,200m³ (8,060yd³) of clayey silt sediment from the channel at a sustained rate of 500.4m³/hr. (651yd³/hr) (Winterwerp *et al*, 2003). The study team reported field sample densities in the density current layer and the consolidated bed of 1066kg/m³ and 1,266kg/m³, respectively (Winterwerp *et al*, 2003). These densities correspond to mass concentrations of 74.79 and 400.00g/l, respectively by Equations 5-7. Density current analysis uses substitutions of the parameters into Equations 2-9 to yield a *Ri* of 10.06.

Winterwerp *et al* (2003) also conducted numerical model studies using 2L FLUID MUD Model to determine "far field" settling of the WID material. Model results predicted only centimeters at most of re-accumulation in confined areas (Winterwerp *et al*, 2003). However, Winterwerp *et al* (2003) noted that these results are too fine to measure with numerical models alone and require corroborating field measurements. Numerical results predicted TSS concentration up to 200mg/l in only very shallow areas of dredging and only 50mg/l at most for the rest of the channel (Winterwerp *et al, 2003*). Winterwerp *et al (2003)* note density currents only exceed critical (i.e. $R_i<1$) for the steepest slopes in the estuary. *Table 2* contains estimates for the Richardson Number based on production data and other available data.

Epon Harbor, Delfzigl, NE

Volker Stevin dredged 160,000m³ (208,000yd³) of silt and fine sand from Epon Harbor using *Jetsed*. WID operations lasted 8 days averaging 800m³/hr (1,040yd³/hr) production rate in the 5.7m deep channel. Volker Stevin monitored TSS and current. Volker Stevin reported that the WID proved highly versatile and effective in the fine

sand subject to desiccation and difficult to dredge by conventional methods due to the suction produced by disturbing the sediment.

Shipping Lane Boonjtes, Waddenzee, NE

Volker Stevin dredged 15,000m^3 (19,500yd^3) of consolidated silt and clay from the shipping lanes. Despite the high shearing strength of the sediment at 25kPa (3.65psi) instead of 5kPa (0.73psi) for silt, Volker Stevin dredged the material at a rate of 800m^3/hr (1,040yd^3/hr) working only 18hrs with water injection dredging (Volker Stevin).

Ferry Harbor and Entrance Channel, Den Burg, NE

Volker Stevin dredged 20,000m^3 (26,000yd^3) of material from the 7.5m (24.6ft) deep channel in Den Burg. Despite having to "lift" the material over a 2.5m (8.2ft) sand bar, Volker Stevin maintained 1,500m^3/hr (1,950yd^3/hr) production rate consuming only 13hrs of operation. Although Volker Stevin does not mention how the WID vessel propelled the material uphill, Jetsed crews probably used its side jets at the end of its manifold to propel the density current horizontally up slope. Knox *et al* (1994) refer to this practice as side jetting.

Wesbuitenhaven, Terneuzen, NE

Volker Stevin dredged 500,000m^3 (545,000yd^3) of material along a 1.6km (0.99mi) long, 14m deep channel. Volker Stevin completed the operation after just 9 days of operation, sustaining production rates between 1500-3000m^3/hr (1,950yd^3/hr-3,900yd^3/hr) with a maximum of 4,000m^3/hr (5,200yd^3/hr). Long channel reaches may lend considerable evidence towards high production rates. The WID vessel spends more time traveling forward rather than maneuvering laterally thereby increasing productivity. Therefore, longer reaches may prove more conducive to WID effectiveness.

EUROPEAN WID DISCUSSION

The studies conducted at Haringvliet harbor and Crouch River Estuary by Delft Hydraulics and HAM-Vow lend considerable insight and suggest that WID in Europe and on USACE projects coincide greatly. Field measurements in all European studies parallel those ERDC collected at Michoud Channel and MRGO in 2002 and 2003, respectively. Corresponding Richardson Numbers also exceed unity in all cases suggesting that ambient conditions govern the production rates rather than the dredge capacity. Production rates mostly resemble each other for these WID vessels of similar size and scale. Both estuary studies reported less than 100mg/l of TSS near the WID. Epon Harbor TSS exceeded 1000mg/l but only within 4m (13.1ft) of the channel bed. Epon Harbor also presented the thickest density current at 3.3m (10.8ft). Therefore, turbidity remained low an appreciable distance outside the density current itself.

Maushake and Collins' (2002) analysis lends considerable evidence that WID encounters limitations for coarser grained materials. Although, Volker Stevin documented that WID can overcome limitations through increased effort as in the case of the sand bar in DenBurg, NE and the fine sand with d_{50}=0.3mm (0.012in) in Epon Harbor, NE. The remaining Volker Stevin cases, however, encounter finer grain sizes where WID shows the maximum advantage. WID further achieves an advantage dealing with long channel reaches as in the case of Terneuzen WID. Dredge environments that allow a WID vessel to stay a fore and aft course tend to yield more production than those requiring considerable lateral maneuvering. However, given a WID vessel's maneuverability and non-intrusive operation, water injection dredging can serve in almost any environment despite encountering production limitations.

CONCLUSIONS

Water Injection Dredging (WID) proves a viable and productive dredge method in both hemispheres. Both U.S. and European WID projects exhibited high production rates under the right conditions. WID dredge locations having long channel reaches facilitated primarily back-and-forth WID movement yielded the highest production rates at 2,782m^3/hr (3,645yd^3/hr) in MRGO, U.S. and 2,250m^3/hr (2,948yd^3/hr) in Wesbuitenhaven, Netherlands. Confined areas yielded some of the lowest production.

Richardson Numbers provide a good indicator of WID efficiency based on production rate. Even though these projects lacked field data, estimates for density current thickness and velocity, injected flowrate and *in-situ* density provide for reasonable Richardson Number calculations. All U.S. WID projects, however, required estimates for

density current thickness. Direct measurements for density current using density meter probes such as those used during European WID projects make very sound conclusions on the productivity of water injection dredging.

Finally, grain sizes govern and dominate a WID projects entirely. Upper Mississippi River WID projects exhibited the lowest production rate with median grain sizes of 0.3-0.4mm (0.011-0.016in). Elbe Estuary WID project showed that WID left all grain sizes greater than 0.2mm (0.079in) completely behind.

Aside from the pros and cons of WID production, readers must remind themselves that although WID works to varying degrees of success, it never actually removes sediment from a channel. Rather WID only redeposits this sediment somewhere else down the channel allowing natural currents to carry them to their final destination. Therefore, WID users must carefully define dredge production in the channel and ultimately accept the possibility of leaving the material in the channel outright. Finally, this research concludes with some soundness and validity that WID serves as a viable dredging method under the following conditions:

1. Long, straight channel reaches provide the best WID environment allowing WID operators to maintain a downward slope and density current. Typically, 1.62km (1mi) sections present the most conducive opportunity for WID capability.

2. Small sediment grain sizes much less than 0.2mm (0.079in) mean much more effective use of WID. Median grain sizes of 0.05-0.06mm (0.0020-0.0024in) produced the highest production rates known.

3. Smaller volumes than usual for a given dredge area produced the most cost effective WID operations with cases in point being MRGO and Michoud Channel WID projects. WID, therefore, serves as a viable emergency dredging option.

4. Extensive Field data collection always helps analyze the WID process. Density profile data, for example, always provide invaluable data on how effective WID works in a given environment such as the field data collected for Haringvliet, NE.

Conclusively, WID provides a reasonably effective dredging method with some limitations. Under the right conditions as illustrated in Conclusions 1-4, WID can work just as well if not better than conventional dredging techniques. WID can provide a powerful and versatile dredge tool to maintaining U.S. waterway infrastructure on the principle that it uses gravity rather than defies it.

ACKNOWLEDGMENTS

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