Date: September 2015
Subject: Assessment of Pool 2 (River Mile 815.2 - 847.6) Sediment Sources and Dredging
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Objective

The objective of this assessment is to estimate future dredging throughout Pool 2 for consideration in the development of the Pool 2 Dredged Material Management Plan (DMMP). Changes in dredging practices in and above Pool 2 have recently occurred and further changes are expected to follow the closing of the Upper Saint Anthony Falls (USAF) Lock. Two proposed future scenarios were considered:

- No future dredging in the USAF Pool
- No future dredging in both the USAF Pool and Pool 1

If dredging operations ceased in one or both of these pools, the historic dredge cuts in these pools would continue to fill with sediment. As these areas fill in, their ability to trap additional sediment is reduced, resulting in increased sediment transport downstream. Bed material loads are therefore expected to increase throughout Pool 2, causing additional sedimentation and requiring higher dredge volumes in the future.

Analysis

Historic Dredging

A review of historic changes in dredging was performed to determine a representative average annual dredge volume at each site. Figures in Appendix A illustrate dredge cut and placement site locations from the USAF Pool through Pool 3 (St. Paul District Channel Maintenance Management Plan, Tab 8).

Figures in Appendix B illustrate the annual dredging of these sites from 1971 - 2014 plotted along with mean annual discharge on the Minnesota River at Jordan and the Mississippi River at St. Paul. Although there is variability from one year to another, there was a definite upwards shift in river discharge beginning in the early 1990s. On the Minnesota River, average annual discharge increased 68% for the two decade time period 1991 to 2010 compared to the previous two decade period, 1971 to 1990. On the Mississippi River, average annual discharge increased 24% for the two decade time period 1991 to 2010 compared to the previous two decade period, 1971 to 1990. This shift in average annual flows corresponds to the overall increase in dredging in Lower Pool 2.

The average annual dredge volumes between 1981 and 2014 were adopted as representative for most sites unless dredging practices had recently shifted (Table 1).

Table 1. Summary of USAF through Upper Pool 4 Dredge Sites: Average Annual Dredge Volumes.

Pool	River Mile	Name	Avg. Annual Dredge Vol. (yd^3)	Notes
USAF	856.8 – 857.6	Mpls. Turning Basin	12,500	1981 – 2014 average annual volumes adopted.
USAF	856.4 – 856.8	Abv & Below Lowry Ave. Br.	21,800	1981 – 2014 average annual volumes adopted.
USAF	855.3 – 856.1	Broadway Ave. Br.	4,500	1981 – 2014 average annual volumes adopted.
USAF	854.8 – 855.5	Abv. Plymouth Ave. Br.	2,340	1981 – 2014 average annual volumes adopted.
1	853.4	Lower Approach – LSAF	215	1981 – 2014 average annual volumes adopted.
1	852.5 – 853.0	Washington Ave. Br.	0	Reduced from 360 (1981 – 2014 average) to 0 yd^3 based on trend; no dredging has been done at this site in the last decade.
1	851.6 – 852.4	Abv. Franklin Ave. Br.	930	1981 – 2014 average annual volumes adopted.
1	850.7 – 851.4	Blw. Franklin Ave. Br.	3,900	1981 – 2014 average annual volumes adopted.
1	849.9 – 850.5	Abv. Lake St. Br.	9,150	1981 – 2014 average annual volumes adopted.
1	848.9 – 849.9	Blw. Lake St. Br.	4,360	1981 – 2014 average annual volumes adopted.
1	848.5 – 848.9	St. Paul Daymark	0	Reduced from 1,600 (1981 – 2014 average) to 0 yd^3 based on trend; no dredging has been done at this site in the last decade.
1	847.7 – 848.4	Upper Appch. L/D 1	1,750	1981 – 2014 average annual volumes adopted.
2	847.4 – 847.5	Lower Appch. L/D 1	210	1981 – 2014 average of Lower L/D 1 approach & L/D 1 Aux. Lock
2	840.0 – 841.3	Abv. & Blw. Smith Ave.	300	Reduced from 1,470 (1981 – 2014 average) to 300 yd^3 based on trend; only one dredging event has occurred between 2001 & 2014.
2	839.6	St. Paul Small Boat Harbor	4,750	1981 – 2014 average annual volumes adopted.
2	839.5 – 839.6	Abv. Wabasha Ave. Br.	0	Reduced from 40 (1981 – 2014 average) to 0 yd^3 based on trend; no dredging has been done at this site in the last decade.
2	838.0 – 839.0	Blw. Lafayette St. Br.	0	1981 – 2014 average annual volumes adopted.
2	836.4 – 837.8	St. Paul Barge Terminal	25,720	Adopted 2008 – 2014 average following discussions with Channels and Harbors personnel that future dredging will continue similarly.
2	827.5 – 828.3	Grey Cloud Slough	0	Reduced from 4,740 to 0 yd^3 due to construction of the Island 112 closure structure in 2005 that has eliminated dredging at this site (in recent years).
2	826.1	Robinson Rocks	0	Set to 0 yd^3; dredging has not been done here since 1954.
2	824.3 – 824.6	Pine Bend Landing	5,310	Annual average from 1993 to 2014 was used at this location to reflect recent dredging practices.

2	823.8	Access Pine Bend Site	880	Annual average from 1993 to 2014 was used at this location to reflect recent dredging practices.
2	822.7 – 823.7	Pine Bend	21,400	Annual average from 1993 to 2014 was used at this location to reflect recent dredging practices.
2	820.7 – 821.4	Boulanger Bend	26,640	Annual average from 1993 to 2014 was used at this location to reflect recent dredging practices.
2	819.0 – 819.8	Boulanger Bend Lwr. Lt.	7,725	Annual average from 1993 to 2014 was used at this location to reflect recent dredging practices.
2	818.0 – 818.9	Freeborn Light	20,390	Annual average from 1993 to 2014 was used at this location to reflect recent dredging practices.
2	815.2 - 816.5	Upper Appch. L/D 2	0	Set to 0 yd^3; dredging has not been done here in more than ten years.
3	814.9 -815.1	Lower Appch. L/D 2	3,110	1981 – 2014 average annual volumes adopted.
3	810.3 – 811.7	Prescott	0	1981 – 2014 average annual volumes adopted.
3	807.9 – 808.6	Truedale Slough	0	1981 – 2014 average annual volumes adopted.
3	807.0 – 807.9	Four Mile Island	0	1981 – 2014 average annual volumes adopted.
3	804.1 – 806.0	Big River	740	1981 – 2014 average annual volumes adopted.
3	802.2 – 802.9	Morgans Coulee	5,800	1981 – 2014 average annual volumes adopted.
3	800.8 – 801.9	Coulters Island	14,250	1981 – 2014 average annual volumes adopted.
3	798.8 – 800.4	Diamond Bluff	15,140	1981 – 2014 average annual volumes adopted.
4	794.0 – 794.6	Trenton	850	1981 – 2014 average annual volumes adopted.
4	792.1 – 793.5	Cannon River	9,050	1981 – 2014 average annual volumes adopted.
4	789.5 – 791.2	Red Wing Hwy Br. & Side Channel	412	1981 – 2014 average annual volumes adopted.
4	785.2 – 785.4	Head of Lake Pepin	1,340	1981 – 2014 average annual volumes adopted.

Bed Material Budget

A bed material budget developed for the St. Paul District (Hendrickson 2003) was adjusted and applied between the USAF Pool and the head of Lake Pepin (Upper Pool 4) to estimate the effects of both future scenarios. Future dredging was estimated for both scenarios with the following equation:

(1) $$D_p = D_e + (D_e/Q_{se} * \Delta Q_s)^{1.1}$$

where,

D_p = Proposed Dredging (tons)

D_e = Existing Dredging (should dredging continue as it is now, with Average Annual Quantities as outlined in Table 1, tons)

Q_{se} = Existing Bed Material Load (tons)

Q_{sp} = Proposed Bed Material Load (tons)

$\Delta Q_s = Q_{sp} – Q_{se}$ = Difference between Proposed and Existing Bed Material Loads (tons)

The assumption here is that sediment transport in navigation pools is supply limited, and that an increase in upstream sediment load will result in increased sediment deposition in downstream dredge cuts. This increase in deposition is estimated by multiplying the increase in bed material load (ΔQ_s) by the existing conditions trap efficiency at each dredge cut (D_e/Q_{se}). The exponent 1.1 was used to create a non-linear longitudinal response relationship (i.e. the effects of increased sediment load should be greatest at the first dredge cut downstream, and gradually decrease in the downstream direction). Existing conditions dredge material volumes are based on the average values reported in Table 1, converted to tons per year using Equation 2.

(2) $$D_e = C * V_{avg} * (\%Sand)$$

Where,

C = dredge conversion factor from yd^3 to tons = 1.28

V_{avg} = Average annual dredge volume (yd^3)

%Sand = the percentage of the dredge cut composed of sand materials (from CMMP soil samples), expressed as a decimal

Proposed dredging (D_p) for both future scenarios was computed with Equation (1) for all reaches where the proposed bed material load (Q_{sp}) varied more than +/-1% from the existing bed material load (Q_{se}). If the proposed bed material load (Q_{sp}) was within +/-1% of the existing bed material load (Q_{se}), proposed dredging (D_p) was set equal to existing dredging (D_e).

It should be noted that the average annual dredge volumes are converted from cubic yards per year to tons per year immediately in the analysis. The bed material load is then computed by adding and removing sediment deposition and accumulation (in tons/year) as appropriate before converting the estimated future dredging (D_p) back to cubic yards per year. The quantitative figures referred to throughout this report refer to bed material loads in tons per year and dredge volumes in cubic yards per year. These parameters are not interchangeable and care should be taken to distinguish between the two.

Backwater Deposition

Sediment deposition is a problem in all Upper Mississippi River backwaters with deposition of sand-size sediment (D_{50} > 0.0625 mm) forming deltas where secondary channels enter backwaters, and fine sediment deposition occurring at rates that vary spatially and with vertical position in the river valley. Since eliminating dredging in USAF and/or Pool 1 would change the bed material (sand) load, but have no impact on the fine sediment load, only the increase in sand deposition needs to be estimated. With higher bed material loads expected, increased deposition is expected to occur throughout these backwater areas. This concept was considered in the bed material budget computations.

Backwater deposition was approximated utilizing a relationship developed based on an estimate of the rate of backwater delta expansion over time and Lateral Hydraulic Connectivity (K) between the main channel and backwaters via secondary channels:

(3) $$D_{BW} = 1.5 * K^{1.3} * Q_s$$

where,

D_{BW} = Backwater deposition (tons)

K = Lateral Hydraulic Conductivity (a percentage, entered in decimal form to the equation)

Q_s = bed material load (tons)

The rate of delta expansion was based on a comparison of existing and historic elevations in the delta. Lateral hydraulic connectivity is based on measurements obtained at secondary channels, and is equal to the ratio of the secondary channel flow to the total river flow at the downstream Lock and Dam. The 2-year flood is used as a reference flow for K.

Results

Bed Material Budget

Results estimate significant increases in bed material loads and therefore downstream dredge volumes with both future scenarios (Figures 1-2). If dredging was discontinued above Upper Saint Anthony Falls (USAF), dredge quantities are expected to increase about 22,600 yd^3/year (+113%) in Pool 1, 4,000 yd^3/year (+5%) in Pool 2, 1,500 yd^3/year (+4%) in Pool 3 and remain the same as existing in Upper Pool 4 (Table 2).

If dredging was discontinued in both the USAF Pool and Pool 1, dredge quantities are expected to increase about 35,500 yd^3/year (+39%) in Pool 2, 4,300 yd^3/year (+11%) in Pool 3, and remain the same as existing in Upper Pool 4 (Table 2). The total dredging in the reach from the Upper Saint Anthony Falls Pool to Upper Pool 4 actually decreases under the two future scenarios. This occurs because some of the sediment load deposits in backwaters in Pools 2, 3, and Upper 4.

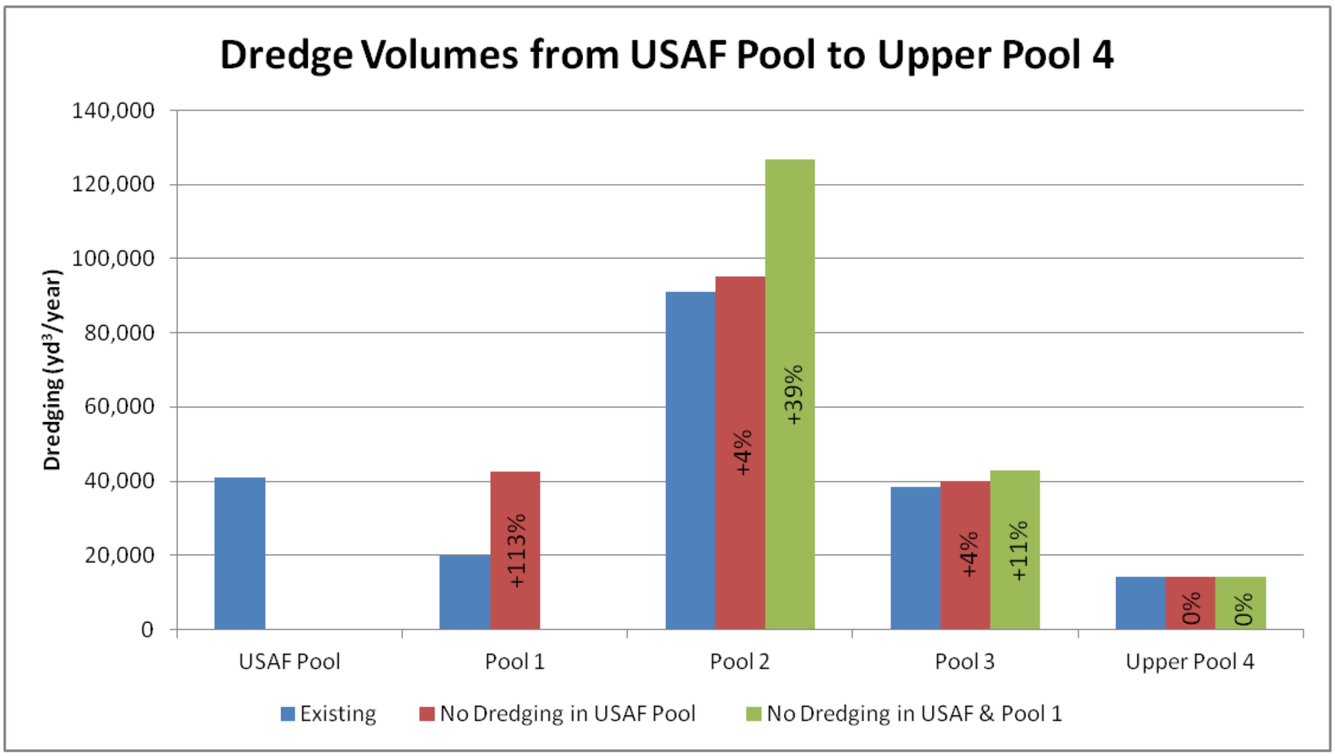


Figure 1. Estimated Dredge Volumes for Existing & Future Scenarios: USAF Pool to Upper Pool 4.

Table 2. Estimated Dredge Volumes for Existing & Future Scenarios: USAF Pool to Upper Pool 4.

	USAF	Pool 1	Pool 2	Pool 3	Upper Pool 4	Total
Existing Conditions Dredging (yd^3/year)	40,844	20,012	91,163	38,555	14,087	190,574
No Future Dredging USAF (yd^3/year)	0	42,601	95,148	40,104	14,087	177,853
Difference in Dredging (yd^3/year)	*-40,844*	*22,590*	*3,985*	*1,548*	*0*	*-12,721*
No Future Dredging USAF + Pool 1 (yd^3/year)	0	0	126,663	42,804	14,087	169,466
Difference in Dredging (yd^3/year)	*-40,844*	*-20,012*	*35,499*	*4,248*	*0*	*-21,108*

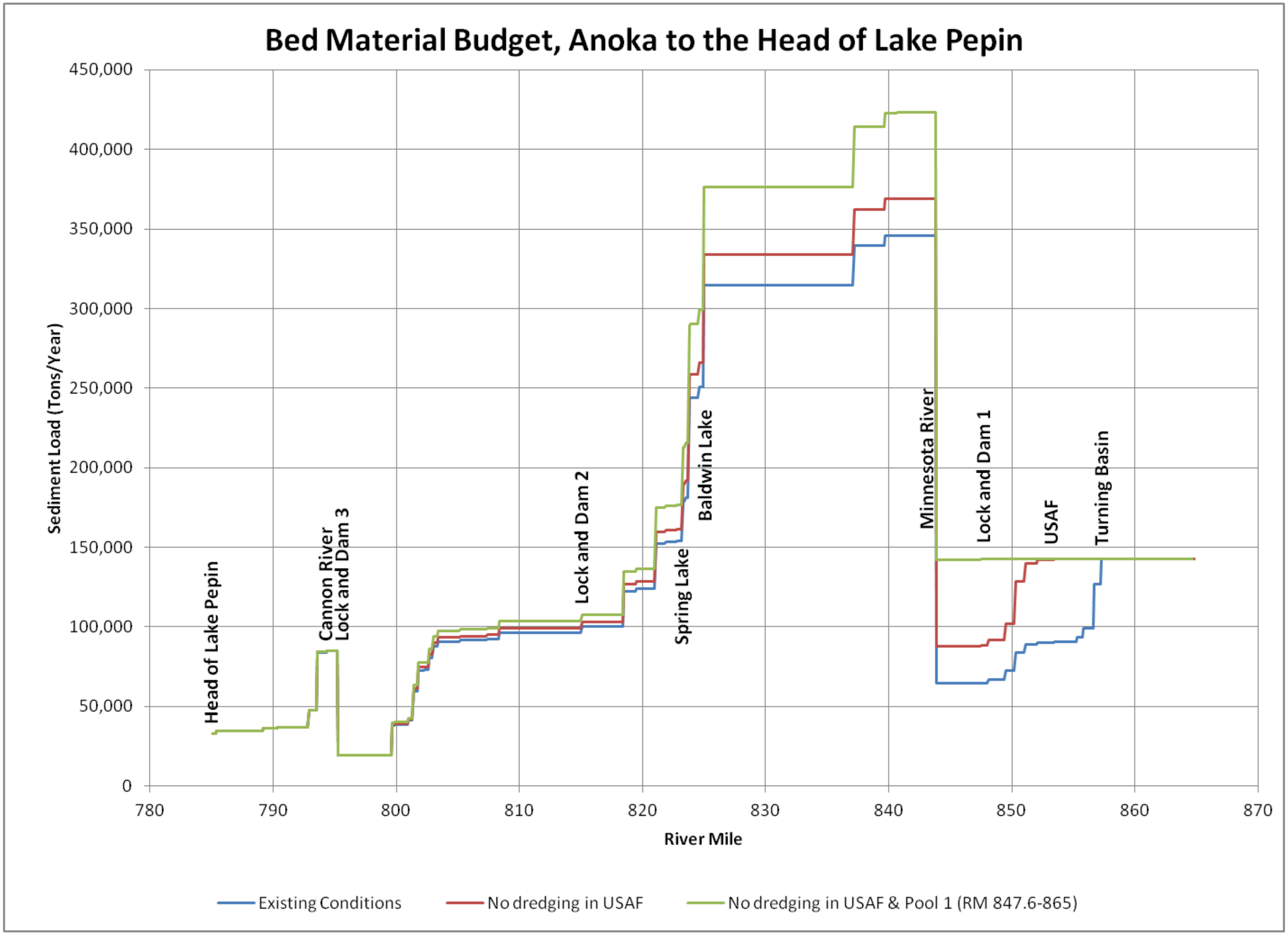


Figure 2. Estimated Bed Material Load (Sand) in Tons with Existing Conditions & Proposed Future Scenarios.

Backwater Deposition

Changes in backwater deposition throughout Pools 2, 3 and Upper Pool 4 are also expected with a change in dredging operations (Figure 3). If dredging was discontinued above USAF, backwater deposition is expected to increase by about 6% in Pool 2, 3% in Pool 3 and to remain the same in Upper Pool 4. If dredging was discontinued both above USAF and in Pool 1, backwater deposition is expected to increase by about 20% in Pool 2, 8% in Pool 3 and to remain the same in Upper Pool 4.

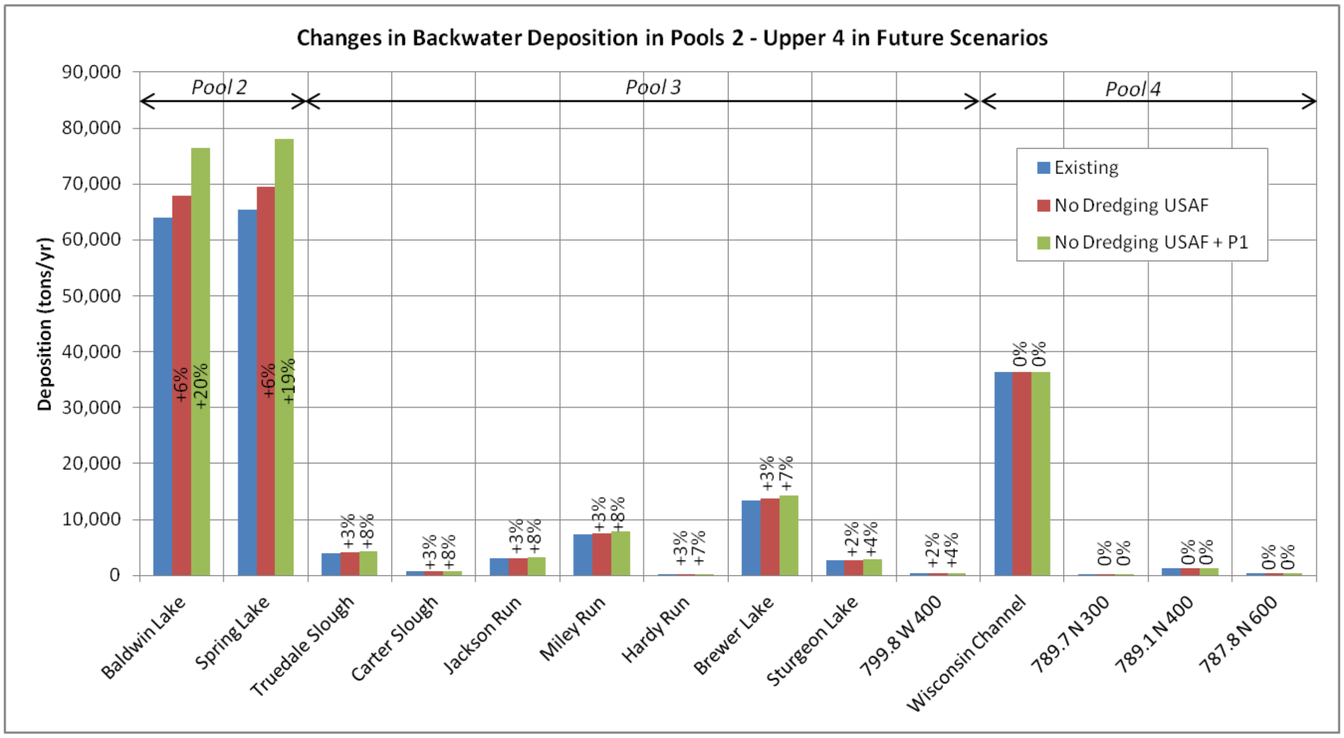


Figure 3. Changes in Downstream Backwater Deposition with Existing & Future Scenarios.

<u>Time Scales for Geomorphic Adjustment</u>

A change in physical conditions at an upstream or downstream location in the river (whether it be hydrologic or geomorphic change), usually results in a long-term geomorphic response. The sediment budget used in this analysis estimates future conditions once equilibrium (or quasi-equilibrium) has been reached. The length of time to reach equilibrium varies depending on the magnitude of the change and the distance from the reach of concern to the reach where the change took place. Observed time scales due to side channel closures, as was done in Pool 5 in 1986, and island construction in Pool 8 in 1992, appeared to cause a downstream adjustment that took about a decade to result in observable changes in sediment deposition patterns and dredging in the navigation channel downstream of the change. Lock and Dam construction in the mid 1930s continues to cause geomorphic change in the navigation pools 80 years later. A big unknown from a Pool 2 planning perspective is the time scale when geomorphic equilibrium is reached in Pool 2. For a 40 year planning cycle for dredge material management it may be prudent to do a sensitivity analysis assuming that geomorphic equilibrium will be reached at different years in the future.

Interpretation

An increase in sedimentation and dredge quantities throughout Lower Pool 2 has already been observed in recent history. This is due to higher average annual flows on both the Minnesota and Mississippi Rivers throughout the last 20 years that increases the bed material load and sedimentation. A large uncertainty is whether the trend of increasing flows will continue into the future.

Two future scenarios were examined: no future dredging in the USAF Pool and no future dredging in both the USAF Pool & Pool 1. In each scenario, the historic dredge cuts will eventually fill and sediment that was previously trapped and dredged, will continue downstream, increasing bed material loads. These higher bed material loads are expected to increase sedimentation throughout Pool 2 and increase dredge volumes by as much as 5% with no future dredging above USAF and as much as 38% with no future dredging above Lock and Dam 1. Dredge volumes are also expected to increase by as much as 4-11% (respectively) in Pool 3 before returning to "existing" conditions in Upper Pool 4.

Elimination of dredging in the upper pools is also expected to impact annual sediment deposition throughout the backwaters of Pool 2. Increases of as much as 6% with no future dredging above USAF and as much as 20% with no future dredging above Lock and Dam 1 are expected.

Increases in annual flows, changes in dredging practices, and changes in lateral hydraulic connectivity affecting the rate of backwater deposition are all factors that affect the bed material load, sedimentation and dredge volumes throughout Pool 2. Significant increases are expected in certain reaches which could lead to higher dredging expenses and concern over placement site volumes.

Recommendations

The following additional analyses should be considered:

A sensitivity analysis regarding the time scale for geomorphic adjustment is recommended. A significant uncertainty associated with geomorphic change is the length of time until equilibrium is reached. For a 40 year planning cycle for dredge material management it may be prudent to do a sensitivity analysis assuming that geomorphic equilibrium will be reached at different years in the future.

A HEC-RAS hydraulic model with sediment transport is recommended for the reach from USAF to lower Pool 2. HEC-RAS is a widely used hydraulic and sediment transport model and is on the H&H Community of Practice list of accepted models. Results from this model would provide an additional sedimentation estimate for comparison with the bed material budget analysis.

Appendix A – Dredge Cuts & Placement Sites

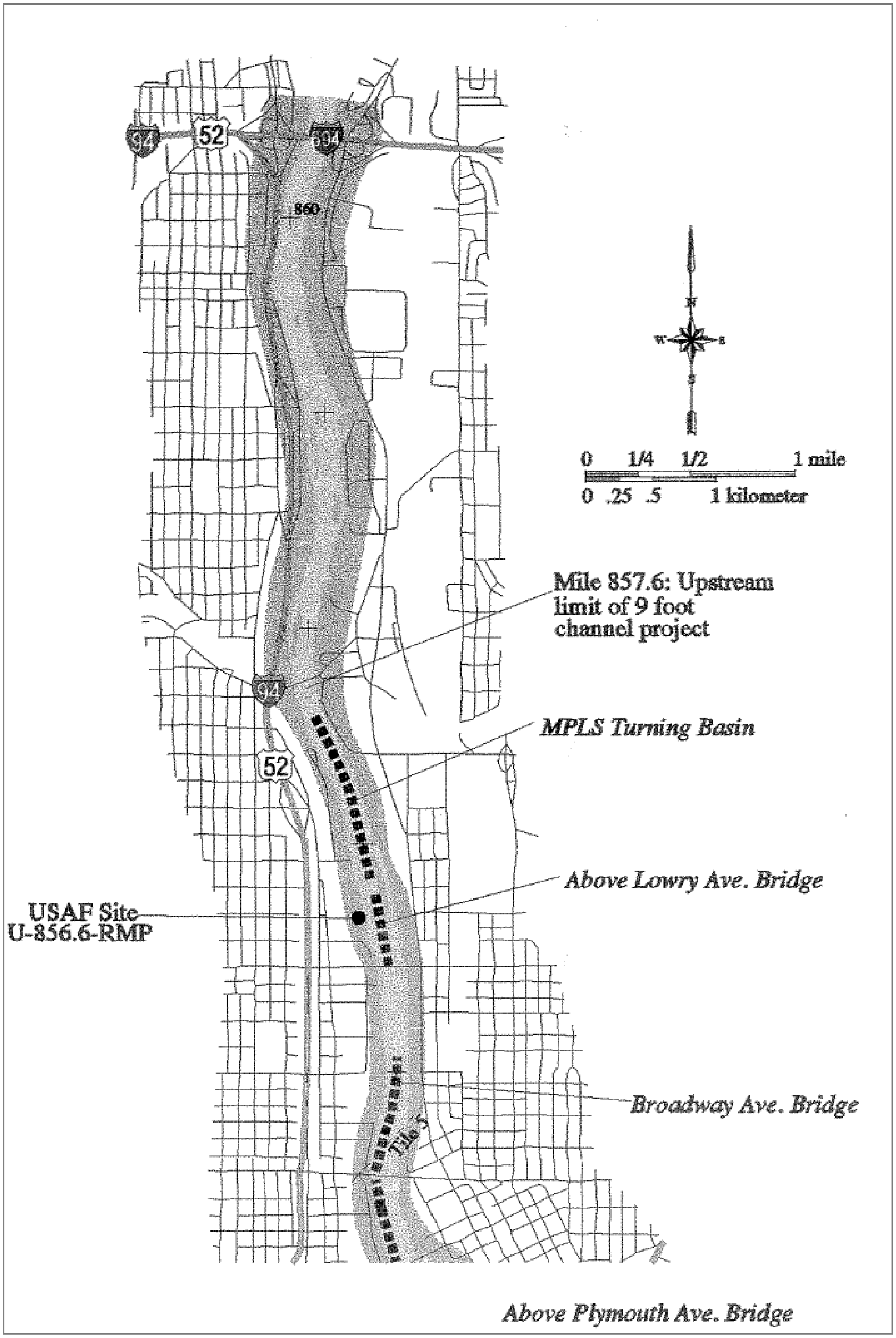


Plate A1. Dredge Cut (dashed lines) and Placement Site (black dots) locations in the Upper Saint Anthony Falls Pool.

Appendix A – Dredge Cuts & Placement Sites

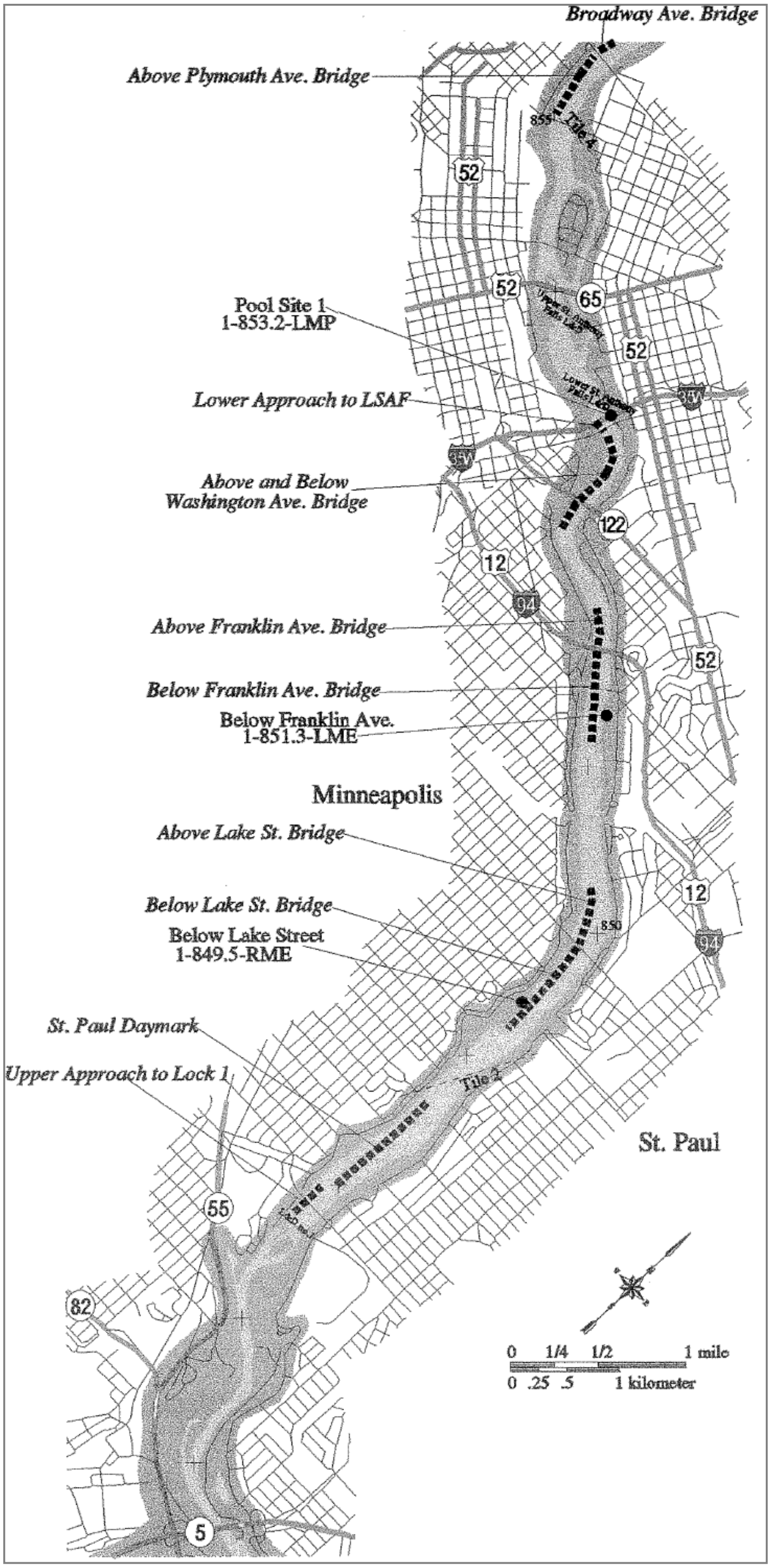


Plate A2. Dredge Cut (dashed lines) and Placement Site (black dots) locations in the Upper Saint Anthony Falls Pool and Pool 1.

Appendix A – Dredge Cuts & Placement Sites

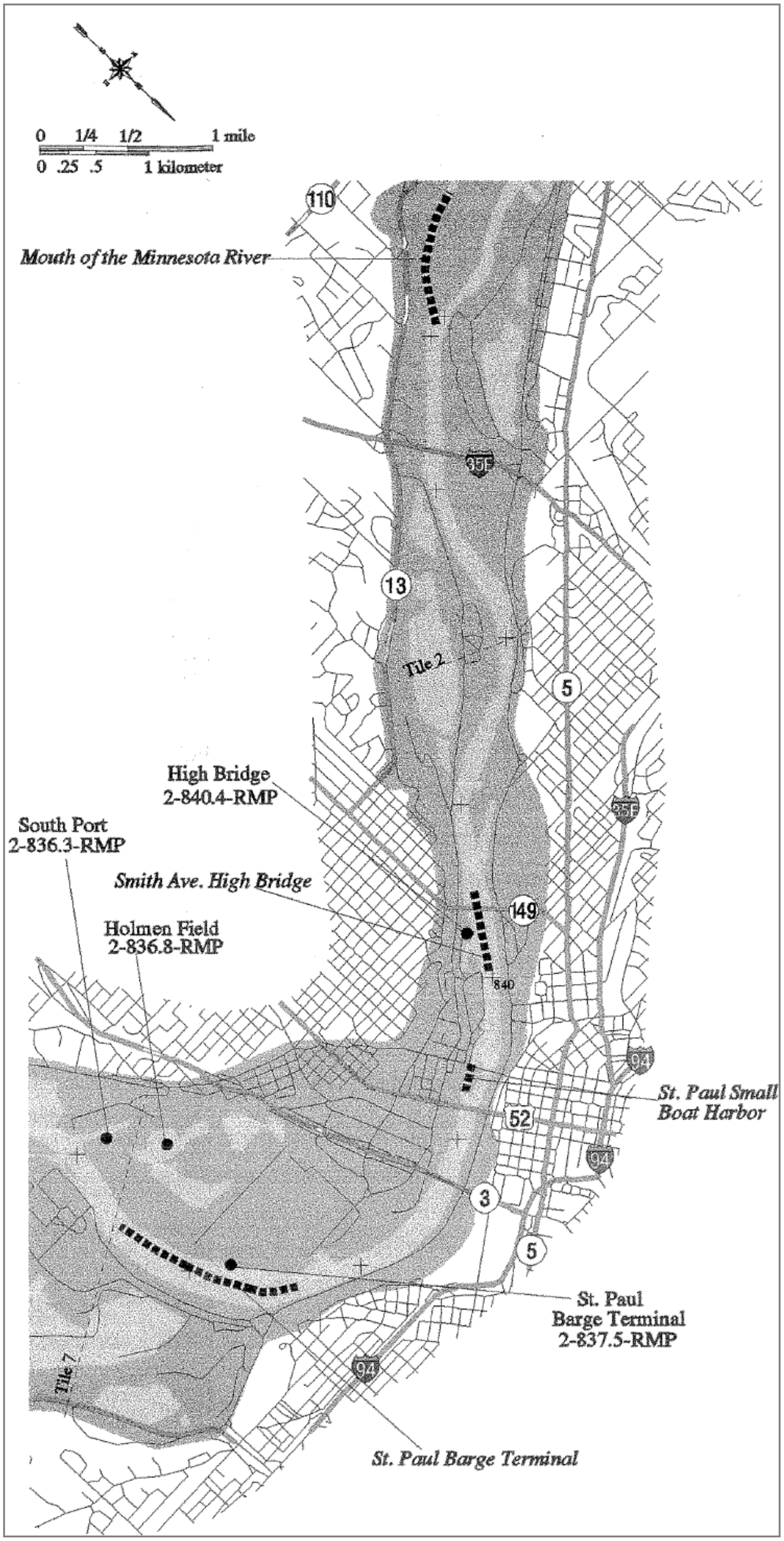


Plate A3. Dredge Cut (dashed lines) and Placement Site (black dots) locations in Pool 2.

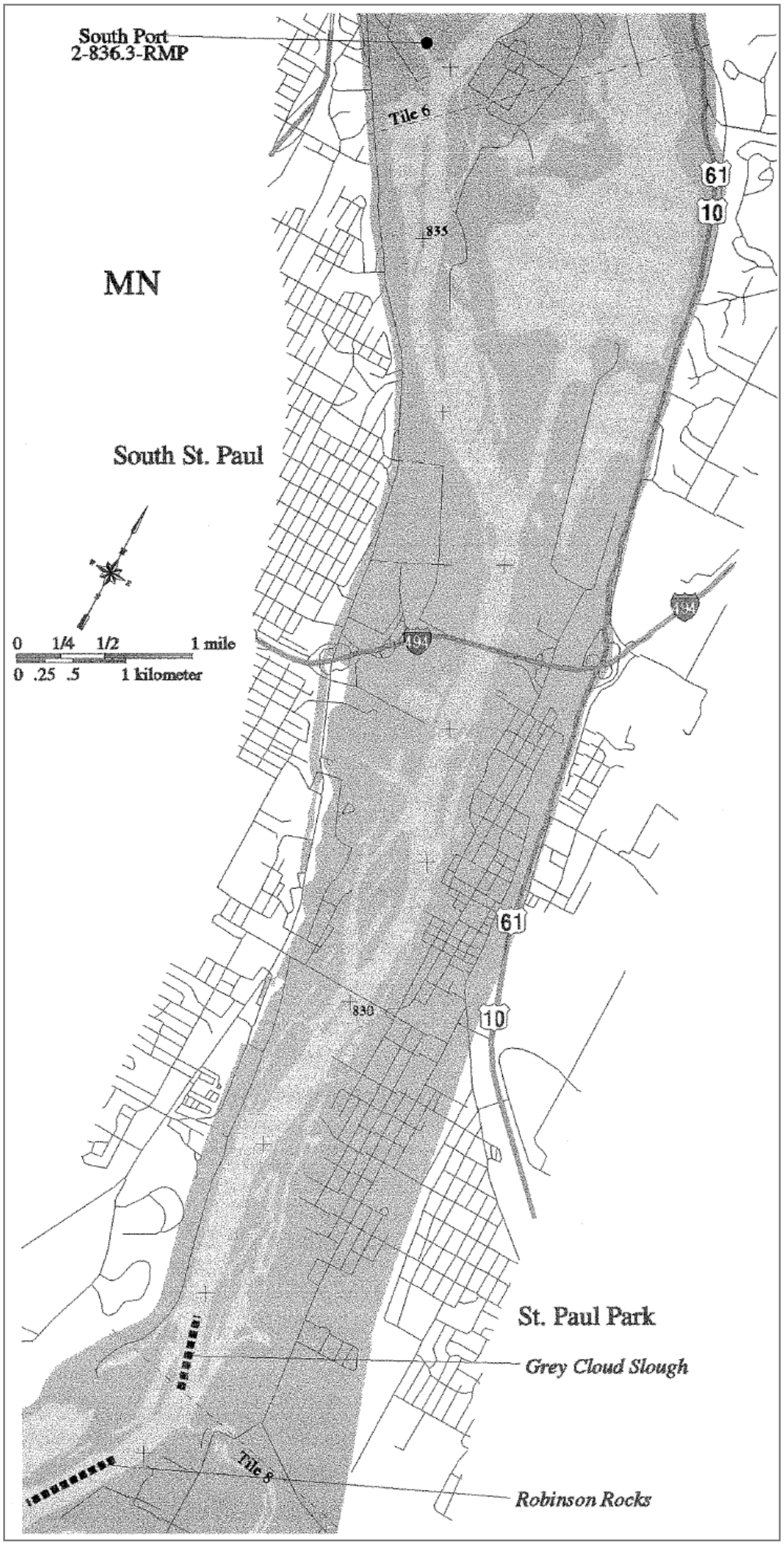


Plate A4. Dredge Cut (dashed lines) and Placement Site (black dots) locations in Pool 2.

Appendix A – Dredge Cuts & Placement Sites

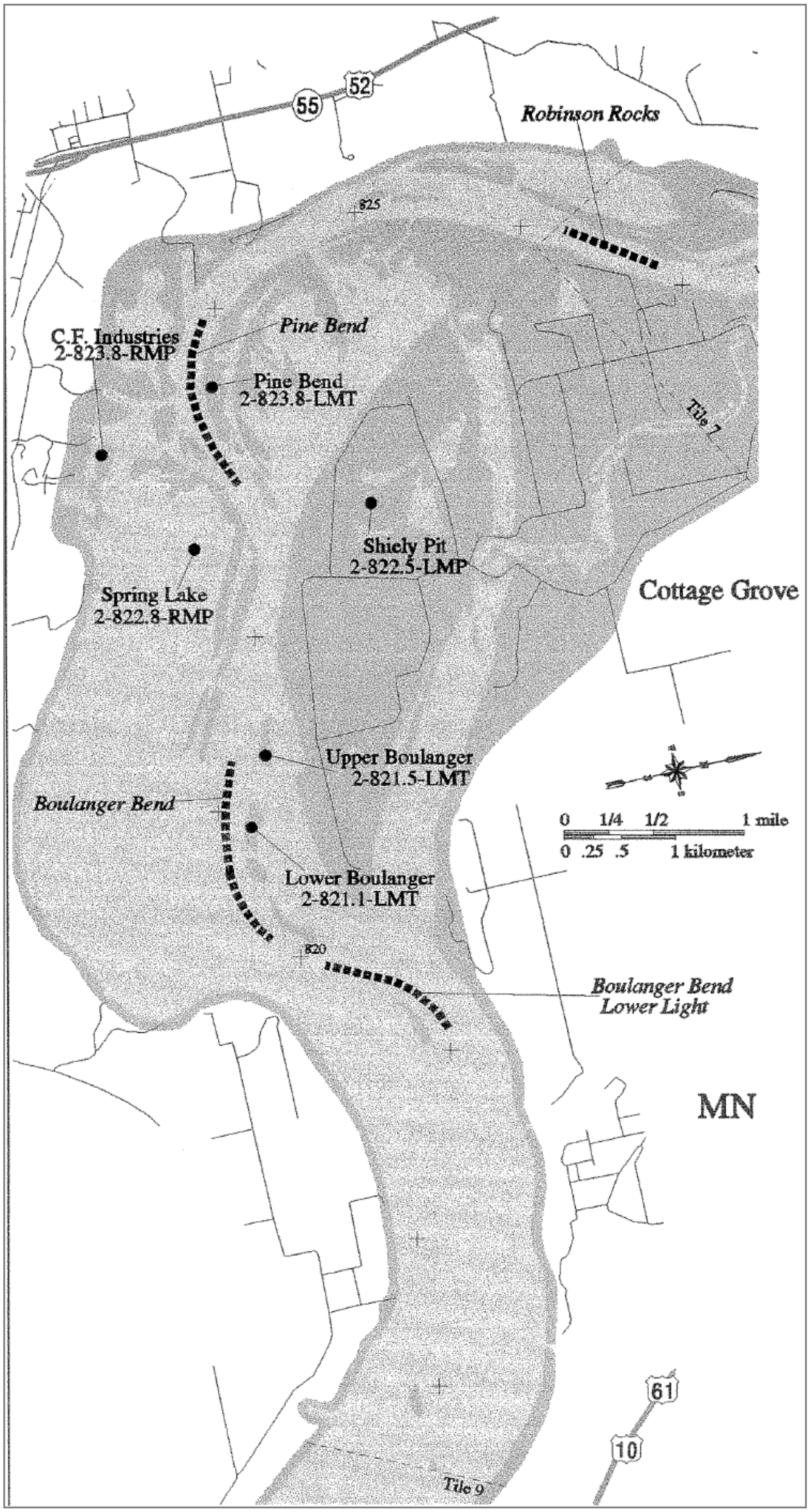


Plate A5. Dredge Cut (dashed lines) and Placement Site (black dots) locations in Pool 2.

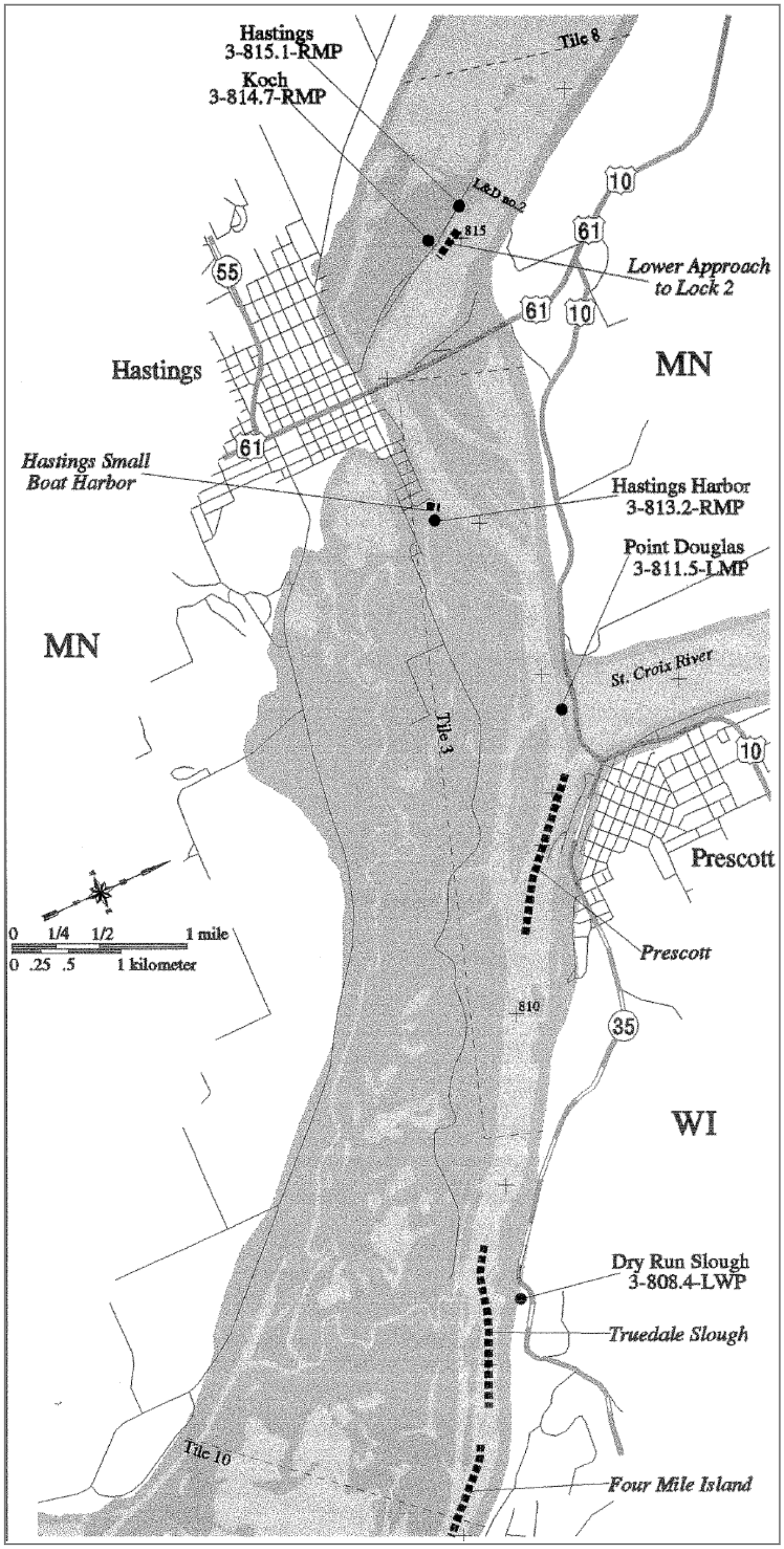
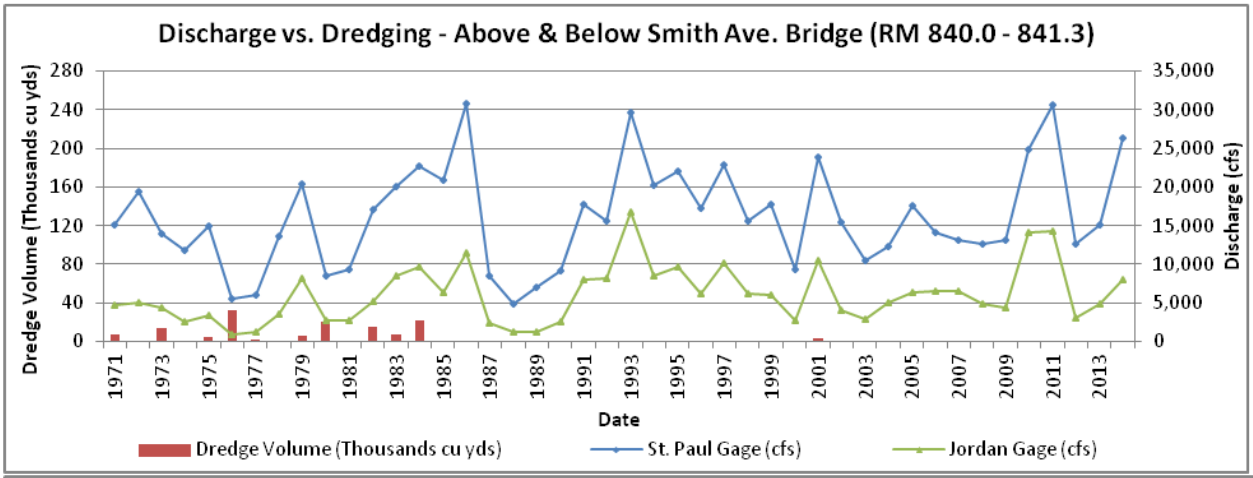
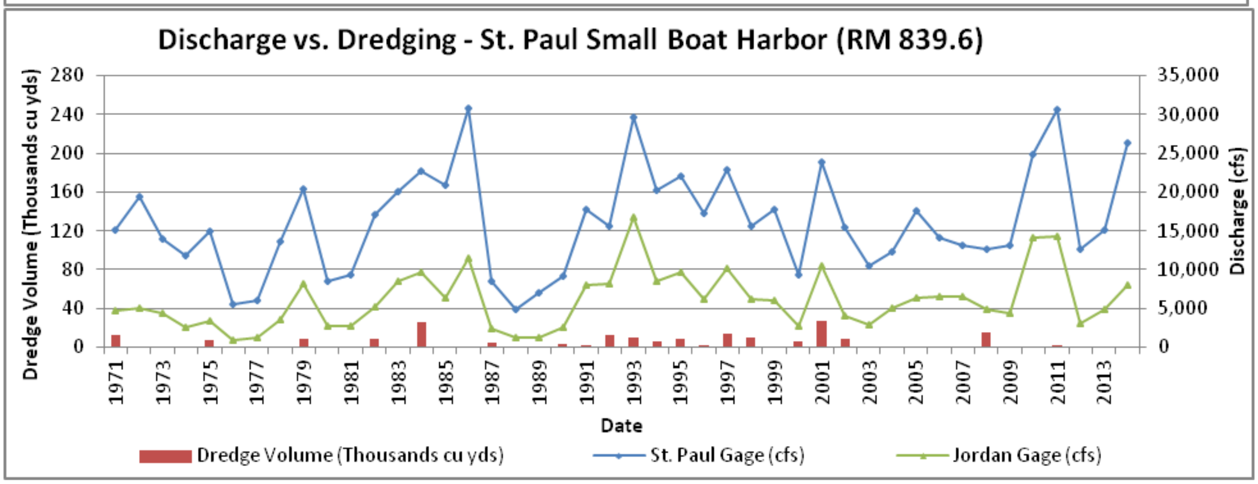


Plate A6. Dredge Cut (dashed lines) and Placement Site (black dots) locations in Pools 2-3.

Appendix B – Annual Dredging & Average Annual Discharge Plots

Plate B1. Annual dredging at Pool 2 dredge cuts between 1971 and 2014 plotted with mean annual discharge on the Minnesota River at Jordan and the Mississippi River at St. Paul.





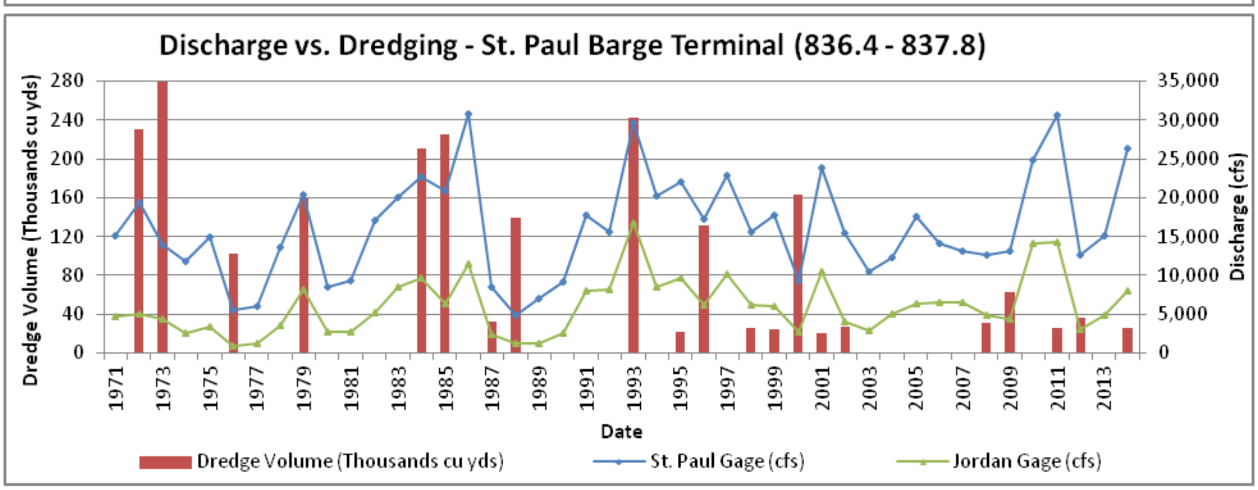
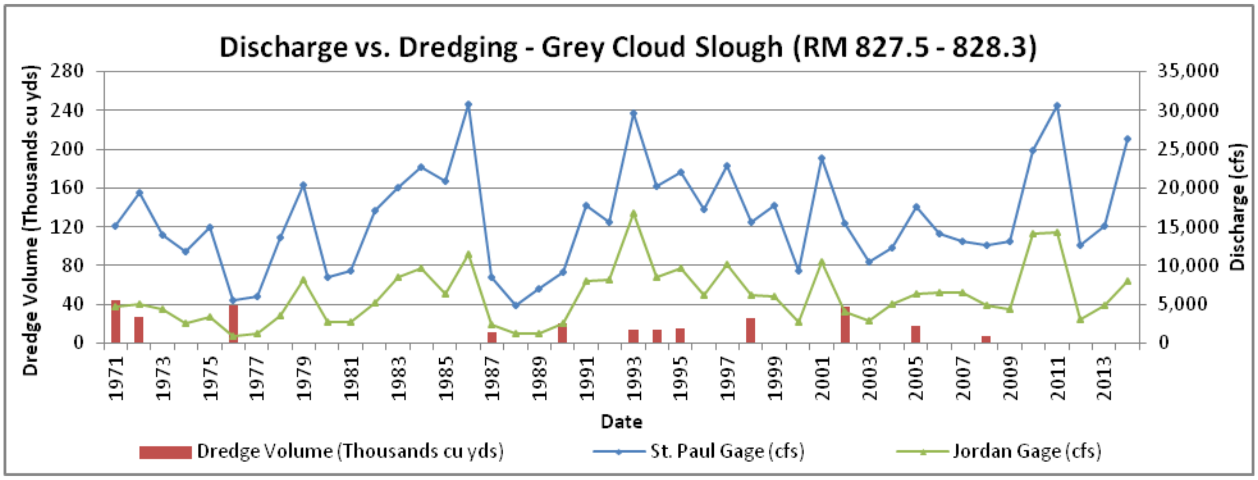
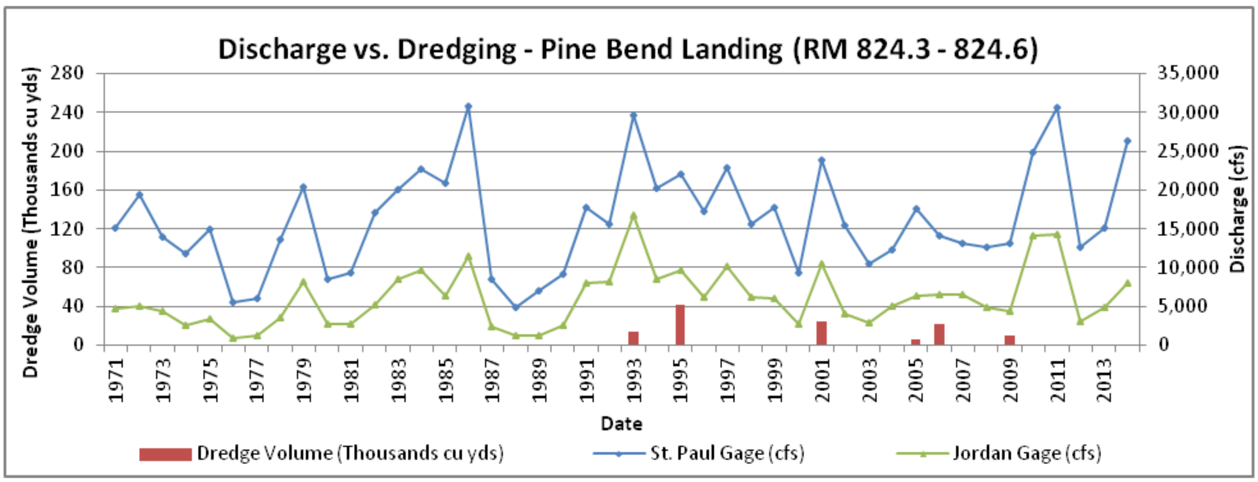
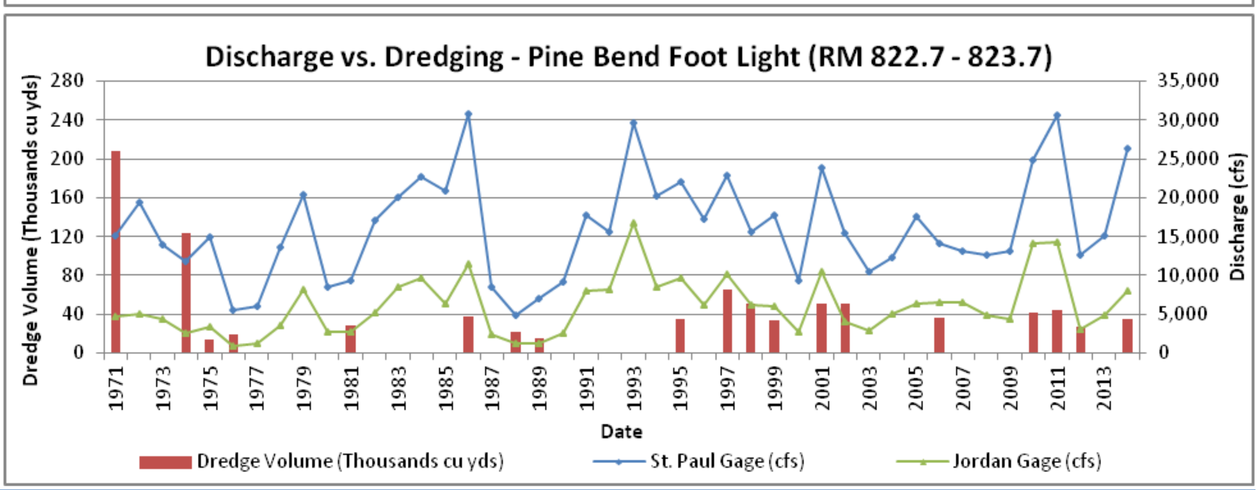


Plate B1 (cont'd). Annual dredging at Pool 2 dredge cuts between 1971 and 2014 plotted with mean annual discharge on the Minnesota River at Jordan and the Mississippi River at St. Paul.







Appendix B – Annual Dredging & Average Annual Discharge Plots

Plate B1 (cont'd). Annual dredging at Pool 2 dredge cuts between 1971 and 2014 plotted with mean annual discharge on the Minnesota River at Jordan and the Mississippi River at St. Paul.