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ACRES

Task 6 / Task 3

To: Wayne Coleman
Harza Engineering Company

Date: March 9, 1983

Acres Job No.: P5701.70

Attention:

Project: Susitna Hydroelectric Project

Subject: Transition/Hydraulic Design

The following are enclosed:

Description / Title	Drawing Number	Revision Number	Number of Each	Code*
Report				
Subtask 6.14 Scour Hole Development Downstream of High-Head Dams March 1982 (1)			1	
Internal Memos				
(2) R. Ruggles, "Ice Conditions Affecting Diversion Tunnels at Watana", Jan. 6, 1982			1	
? (3) D. Crawford, "Watana Reservoir Filling", October 14, 1982			1	
(4) A. Simon, "Aspects of Filling Watana Reservoir", December 29, 1980			1	
(5) D. Crawford, "Watana- Emergency Drawdown" October *, 1981.			1	

*A – For Approval or Comments
B – For Construction
C – See Explanatory Letter
D – For Information
E – For Purchasing
F – Drawings Approved
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Yours very truly,

David Crawford

ACRES AMERICAN INCORPORATED

David Crawford
Lead Hydraulic Engineer

ORIGINAL

ACRES

SUSITNA HYDROELECTRIC PROJECT

OFFICE MEMORANDUM

TO: J.W. Hayden Date: October 14, 1982

FROM: D. Crawford File: P5700.07.07.03

SUBJECT: Watana Reservoir Filling

As per your request, I have revised Watana filling analysis to include the following:

- Inflow based on statistical analysis of three year moving annual mean flow
- Case C downstream flow requirement
- Construction schedule as per Feasibility Report
- Flood protection as per Feasibility Report

3

Analysis of annual mean discharge at Gold Creek and Watana has been performed to determine the three year moving mean flow. From this three year series, an estimate of the 10, 50 and 90 percent probability level flows is made. These percents represent the percent of time the given flow will be exceeded. Figure 1 shows a plot of the three year flow against probability for Watana and Devil Canyon discharges.

The monthly distribution of the 10, 50 or 90 percentile flows is assumed to be equal to that of the long term average distribution of the flow at Gold Creek. The monthly flows for the three flows at Watana and Gold Creek are given in Table 1. Also, in Table 1 is the long term average flow at Gold Creek and the monthly (Case C) flow requirement at Gold Creek.

The construction schedule for the main dam at Watana is summarized in Table 2.

Flood protection during filling is assumed to ensure for at least protection from the 1:250 year flood volume, except during early construction stages with cofferdam control. During early construction stages, the protection is 1:50 years. In all estimates of flood volume requirements account has been made of outlet capacity and the changes to this capacity due to construction of expansion chamber, etc.

The reservoir filling for the 50 percent inflow case (median flow) is shown in Figure 2. Discharge requirements at Gold Creek are exceeded in all years except for 1992 where the requirement is matched.

October 14, 1982

Reservoir filling requires three spring runoff periods to achieve full pool elevation; however, unit commissioning could start in the fall of 1992. Normal power operations (as per energy simulations) could commence in May 1993.

The filling under the higher inflow of the 10 percent level is marginally faster than for the 50 percent inflow case due to spillage for flood protection. Unit commissioning could commence in September 1992 for this case with normal operation in April 1993.

Under the low inflow case (90 percent level) the reservoir fails to reach normal operating level and requires a further spring runoff to reach normal pool. However, levels are such to allow unit commissioning to commence in June 1993. Figure 3 shows the filling sequence.

Details of the filling sequences for the three inflow cases are given in Tables 3, 4 and 5.

In summary,

- Unit commissioning can begin about October 1992 for at least the median (50 percent) inflow.
- Normal operation could commence in May 1993 for inflow greater than the median inflow.
- Flows with less than a 90 percent chance of occurring (dry) would result in a delay of ten months in commissioning to June 1993.
- It requires about three years to fill the reservoir to levels at which normal power operation can commence.

Continuing studies:

- Determine critical percent inflow at which commissioning is delayed past January 1993.

DC/kt

David Crawford

David Crawford

Encl: as

cc: C. Debelius

Table 1. Discharge at Gold Creek and Watana

Month	Mean	Target Flow	Gold Creek Flows (cfs) Inflow			Watana Flows (cfs) Inflow		
			10	50	90	10	50	90
Oct	5757	2000	6453	5733	5073	5272	4713	4213
Nov	2568	1000	2878	2557	2263	2352	2102	1879
Dec	1793	1000	2010	1785	1580	1642	1468	1312
Jan	1463	1000	1640	1457	1289	1340	1198	1071
Feb	1243	1000	1393	1238	1095	1138	1018	910
Mar	1123	1000	1259	1118	990	1028	919	822
Apr	1377	1000	1543	1371	1213	1261	1127	1008
May	13277	6000 5678	14882	13221	11699	12158	10870	9715
Jun	27658	6000	31002	27541	24371	25326	22644	20238
Jul	24383	6480 6484	27331	24280	21486	22327	19963	17342
Aug	21996	12000	24655	21903	19382	20142	18008	16095
Sep	13175	9300 9100	14768	13119	11609	12064	10787	9641
Annual	9703	-	10876	9662	8550	8885	7944	7100

Table 2. Watana Dam Construction Schedule

Year	Quantity MCY	Accumulated Quantity MCY	Fill Elevation FT
1987	3	-	-
1988	6	9	-
1989	12	21	1660
1990	13	34	1810
1991	13	47	1950
1992	12	59	2130
1993	3	62	2210

TABLE 3

WATANA RES. FILLING: 10% INFLOW: CASE C

YEAR	MTH	INFLOW	REQ'D D/S FLOW	TOTAL OUTFLOW	FLOW @ D/S LOCATION	STORAGE ADDITION	WSEL FT	CREST EL FT
1	1	82415.4	61504.0	82415.4	1640.0	0.0	1460.0	1536.0
1	2	63218.2	55552.0	63218.2	1393.0	0.0	1460.0	1536.0
1	3	63226.1	61504.0	63226.1	1258.0	0.0	1460.0	1536.0
1	4	75054.7	59520.0	75054.7	1544.0	0.0	1460.0	1536.0
1	5	747765.6	201487.1	747765.6	14882.0	0.0	1460.0	1536.0
1	6	1507403.5	59520.0	1507403.5	31001.0	0.0	1460.0	1536.0
1	7	1373199.8	61504.0	1373199.8	27330.0	0.0	1460.0	1536.0
1	8	1238813.5	460480.4	1238813.5	24655.0	0.0	1460.0	1536.0
1	9	718049.3	392653.4	718049.3	14767.0	0.0	1460.0	1536.0
1	10	324249.1	61504.0	324249.1	6453.0	0.0	1460.0	1536.0
1	11	139991.0	59520.0	139991.0	2879.0	0.0	1460.0	1536.0
1	12	100989.6	61504.0	100989.6	2010.0	0.0	1460.0	1536.0
2	1	82415.4	61504.0	82415.4	1640.0	0.0	1460.0	1536.0
2	2	63218.2	55552.0	63218.2	1393.0	0.0	1460.0	1536.0
2	3	63226.1	61504.0	63226.1	1258.0	0.0	1460.0	1536.0
2	4	75054.7	59520.0	75054.7	1544.0	0.0	1460.0	1573.5
2	5	747765.6	201487.1	747765.6	14882.0	0.0	1460.0	1601.0
2	6	1507403.5	59520.0	1507403.5	31001.0	0.0	1460.0	1616.9
2	7	1373199.8	61504.0	1373199.8	27330.0	0.0	1460.0	1632.8
2	8	1238813.5	460480.4	1238813.5	24655.0	0.0	1460.0	1648.6
2	9	718049.3	392653.4	718049.3	14767.0	0.0	1460.0	1660.0
2	10	324249.1	61504.0	324249.1	6453.0	0.0	1460.0	1660.0
2	11	139991.0	59520.0	139991.0	2879.0	0.0	1460.0	1660.0
2	12	100989.6	61504.0	100989.6	2010.0	0.0	1460.0	1660.0
3	1	82415.4	61504.0	82415.4	1640.0	0.0	1460.0	1660.0
3	2	63218.2	55552.0	63218.2	1393.0	0.0	1460.0	1660.0
3	3	63226.1	61504.0	63226.1	1258.0	0.0	1460.0	1660.0
3	4	75054.7	59520.0	75054.7	1544.0	0.0	1460.0	1697.8
3	5	747765.6	201487.1	747765.6	14882.0	0.0	1460.0	1725.4
3	6	1507403.5	59520.0	1507403.5	31001.0	0.0	1460.0	1751.7
3	7	1373199.8	61504.0	1373199.8	27330.0	0.0	1460.0	1772.0
3	8	1238813.5	460480.4	1238813.5	24655.0	0.0	1460.0	1792.2
3	9	718049.3	392653.4	718049.3	14767.0	0.0	1460.0	1810.0
3	10	324249.1	61504.0	324249.1	6453.0	0.0	1460.0	1810.0
3	11	139991.0	59520.0	139991.0	2879.0	0.0	1460.0	1810.0
3	12	100989.6	61504.0	100989.6	2010.0	0.0	1460.0	1810.0
4	1	82415.4	61504.0	82415.4	1640.0	0.0	1460.0	1810.0
4	2	63218.2	55552.0	63218.2	1393.0	0.0	1460.0	1810.0
4	3	63226.1	61504.0	63226.1	1258.0	0.0	1460.0	1810.0
4	4	75054.7	59520.0	75054.7	1544.0	0.0	1460.0	1838.3
4	5	747765.6	201487.1	534485.6	11414.3	213280.0	1626.0	1862.9
4	6	1507403.5	59520.0	1190723.5	25680.4	316680.0	1699.4	1887.6
4	7	1373199.8	61504.0	326519.8	10311.9	1046680.0	1823.1	1909.6
4	8	1238813.5	460480.4	922133.5	19506.1	316680.0	1851.2	1929.8
4	9	718049.3	392653.4	401369.3	9446.4	316680.0	1874.9	1950.0
4	10	324249.1	61504.0	324249.1	6453.0	0.0	1874.9	1950.0
4	11	139991.0	59520.0	139991.0	2879.0	0.0	1874.9	1950.0
4	12	100989.6	61504.0	100989.6	2010.0	0.0	1874.9	1950.0

TABLE 3 CONTINUED

YEAR	MTH	INFLOW	REQ'D D/S FLOW	TOTAL OUTFLOW	FLOW @ D/S LOCATION	STORAGE ADDITION	USEL FT	CREST EL FT
5	1 JAN	82415.4	61504.0 1000	82415.4	1640.0	0.0	1874.9	1950.0
5	2	63218.2	55552.0	63218.2	1393.0	0.0	1874.9	1950.0
5	3	63226.1	61504.0	63226.1	1258.0	0.0	1874.9	1950.0
5	4	75054.7	59520.0	59520.0	1283.0	15534.7	1876.1	1988.5
5	5	747765.6	201487.1 3776	201487.1	6000.0	546278.	1914.4	2022.7
5	6 JUN	1507403.5	59520.0 4774 =6000	59520.0	6675.0	1447883.5	1998.5	2054.2
5	7	1373199.8	61504.0	555416.8	14033.6	817783.0	2036.1	2081.3
5	8	1238813.5	460480.4	531943.5	13161.9	706870.0	2065.5	2107.1
5	9	718049.3	392653.4	392653.4	9300.0	325395.9	2077.9	2130.0
5	10 OCT	324249.1	61504.0	61504.0 1000	2181.0	262745.1	2088.0	2130.0
5	11	139991.0	59520.0	59520.0 1000	1527.0	80471.0	2091.1	2130.0
5	12	100989.6	61504.0	62731.6	1388.0	38258.0	2092.6	2130.0
6	1	82415.4	61504.0	82415.4	1640.0	0.0	2092.6	2130.0 JAN 1993
6	2	63218.2	55552.0	63218.2	1393.0	0.0	2092.6	2130.0
6	3	63226.1	61504.0	63226.1 1028	1258.0	0.0	2092.6	2130.0
6	4	75054.7	59520.0	59520.0	1283.0	15534.7	2093.2	2145.6
6	5 MAY	747765.6	201487.1	201487.1	6000.0	546278.4	2111.9	2159.4
6	6	1507403.5	59520.0	626576.5	16202.2 12000	880827.0	2140.5	2172.6
6	7	1373199.8	61504.0	61504.0	6003.0	1311695.8	2177.8	2185.7
6	8	1238813.5	460480.4	975369.5	20371.6	263444.0	2185.0	2198.8
6	9	718049.3	392653.4	718049.3	14767.0	0.0	2185.0	2210.0
6	10	324249.1	61504.0	324249.1	6453.0	0.0	2185.0	2210.0
6	11	139991.0	59520.0	139991.0	2879.0	0.0	2185.0	2210.0
6	12	100989.6	61504.0	100989.6 1642 +366	2010.0 ✓	0.0	2185.0	2210.0
SUM		38606264.		29137270.	9469000.			

TABLE 4

WATANA RES. FILLING: 50% INFLOW: CASE C

YEAR	MTH	INFLOW	REQ'D D/S FLOW	TOTAL OUTFLOW	FLOW @ D/S LOCATION	STORAGE ADDITION	WSEL FT	CREST EL FT	
1	1	73681.8	61504.0	73681.8	1457.0	0.0	1460.0	1536.0	
1	2	56551.9	55552.0	56551.9	1238.0	0.0	1460.0	1536.0	
1	3	56522.2	56522.2	56522.2	1118.0	0.0	1460.0	1536.0	
1	4	67079.0	59520.0	67079.0	1371.0	0.0	1460.0	1536.0	
1	5	668548.5	224428.1	668548.5	13221.0	0.0	1460.0	1536.0	
1	6	1347770.9	65650.6	1347770.9	27541.0	0.0	1460.0	1536.0	
1	7	1227804.3	133033.2	1227804.3	24280.0	0.0	1460.0	1536.0	
1	8	1107564.0	498489.9	1107564.0	21903.0	0.0	1460.0	1536.0	
1	9	642042.3	414675.8	642042.3	13120.0	0.0	1460.0	1536.0	
1	10	289868.3	61504.0	289868.3	5732.0	0.0	1460.0	1536.0	
1	11	125111.0	59520.0	125111.0	2557.0	0.0	1460.0	1536.0	
1	12	90287.9	61504.0	90287.9	1785.0	0.0	1460.0	1536.0	
2	1	73681.8	61504.0	73681.8	1457.0	0.0	1460.0	1536.0	
2	2	56551.9	55552.0	56551.9	1238.0	0.0	1460.0	1536.0	
2	3	56522.2	56522.2	56522.2	1118.0	0.0	1460.0	1536.0	
2	4	67079.0	59520.0	67079.0	1371.0	0.0	1460.0	1573.5	
2	5	668548.5	224428.1	668548.5	13221.0	0.0	1460.0	1601.0	
2	6	1347770.9	65650.6	1347770.9	27541.0	0.0	1460.0	1616.9	
2	7	1227804.3	133033.2	1227804.3	24280.0	0.0	1460.0	1632.8	
2	8	1107564.0	498489.9	1107564.0	21903.0	0.0	1460.0	1648.6	
2	9	642042.3	414675.8	642042.3	13120.0	0.0	1460.0	1660.0	
2	10	289868.3	61504.0	289868.3	5732.0	0.0	1460.0	1660.0	
2	11	125111.0	59520.0	125111.0	2557.0	0.0	1460.0	1660.0	
2	12	90287.9	61504.0	90287.9	1785.0	0.0	1460.0	1660.0	
3	1	73681.8	61504.0	73681.8	1457.0	0.0	1460.0	1660.0	
3	2	56551.9	55552.0	56551.9	1238.0	0.0	1460.0	1660.0	
3	3	56522.2	56522.2	56522.2	1118.0	0.0	1460.0	1660.0	
3	4	67079.0	59520.0	67079.0	1371.0	0.0	1460.0	1697.8	
3	5	668548.5	224428.1	668548.5	13221.0	0.0	1460.0	1725.4	
3	6	1347770.9	65650.6	1347770.9	27541.0	0.0	1460.0	1751.7	1:200
3	7	1227804.3	133033.2	1227804.3	24280.0	0.0	1460.0	1772.0	1:100
3	8	1107564.0	498489.9	1107564.0	21903.0	0.0	1460.0	1792.2	
3	9	642042.3	414675.8	642042.3	13120.0	0.0	1460.0	1810.0	
3	10	289868.3	61504.0	289868.3	5732.0	0.0	1460.0	1810.0	
3	11	125111.0	59520.0	125111.0	2557.0	0.0	1460.0	1810.0	
3	12	90287.9	61504.0	90287.9	1785.0	0.0	1460.0	1810.0	
4	1	73681.8	61504.0	73681.8	1457.0	0.0	1460.0	1810.0	
4	2	56551.9	55552.0	56551.9	1238.0	0.0	1460.0	1810.0	
4	3	56522.2	56522.2	56522.2	1118.0	0.0	1460.0	1810.0	
4	4	67079.0	59520.0	67079.0	1371.0	0.0	1460.0	1810.0	1:200
4	5	668548.5	224428.1	455268.5	9753.3	213280.0	1626.0	1838.3	1:250
4	6	1347770.9	65650.6	1031090.9	22220.4	316680.0	1699.4	1863.9	
4	7	1227804.3	133033.2	181124.3	7261.9	1046680.0	1823.1	1887.6	
4	8	1107564.0	498489.9	790884.0	16754.1	316680.0	1851.2	1909.6	
4	9	642042.3	414675.8	414675.8	9300.0	227366.4	1868.2	1929.8	
4	10	289868.3	61504.0	200554.8	4279.8	89313.5	1874.9	1950.0	
4	11	125111.0	59520.0	125111.0	2557.0	0.0	1874.9	1950.0	
4	12	90287.9	61504.0	90287.9	1785.0	0.0	1874.9	1950.0	

TABLE 5

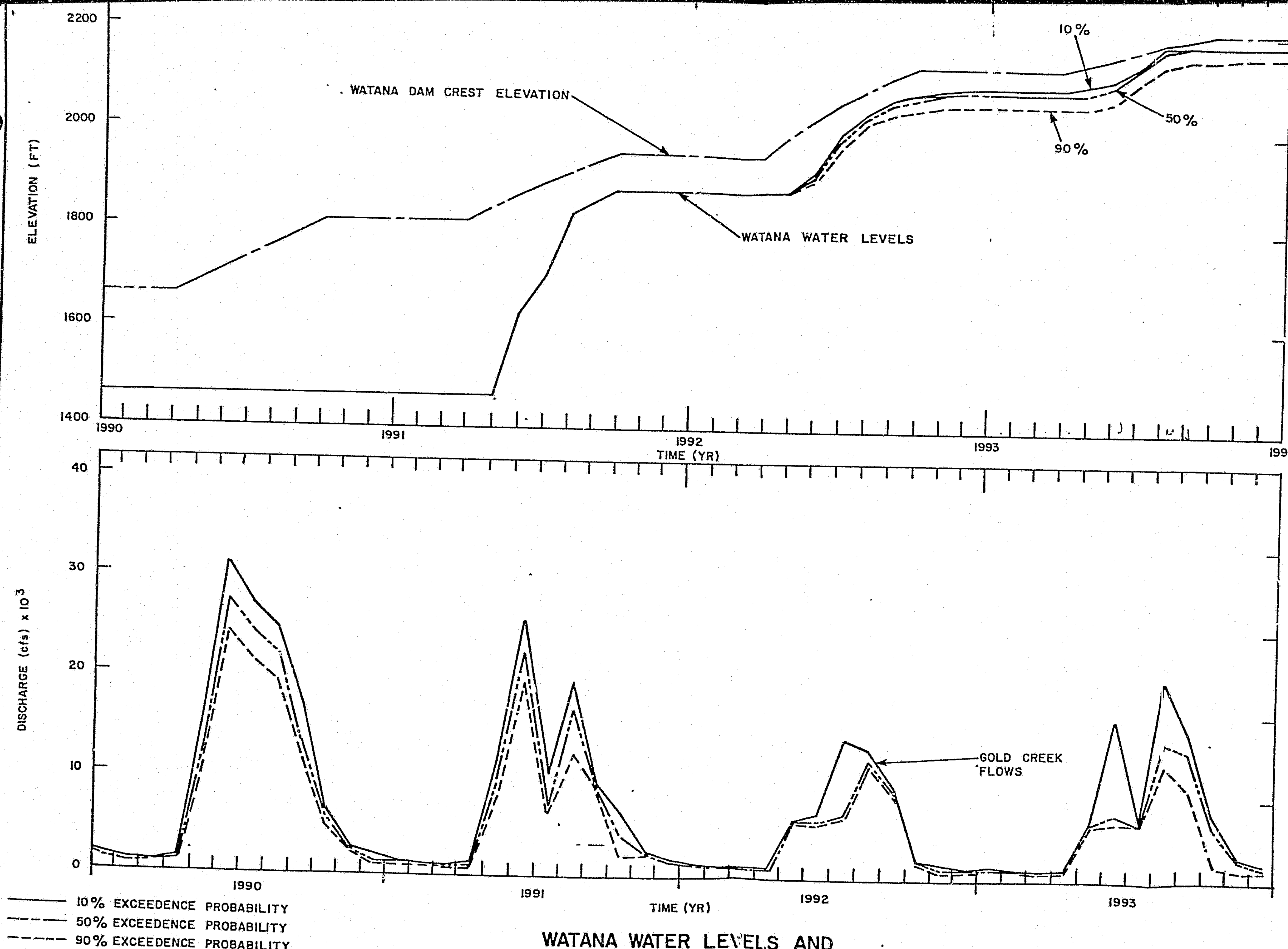
WATANA RES. FILLING: 9[illegible] INFLOW: CASE C

YEAR	MTH	INFLOW	REQ'D D/S FLOW	TOTAL OUTFLOW	FLOW @ D/S LOCATION	STORAGE ADDITION	WSEL FT	CREST EL FT
1	1	65870.8	61504.0	65870.8	1290.0	0.0	1460.0	1536.0
1	2	50552.3	50552.3	50552.3	1096.0	0.0	1460.0	1536.0
1	3	50556.3	50556.3	50556.3	990.0	0.0	1460.0	1536.0
1	4	59996.2	59520.0	59996.2	1214.0	0.0	1460.0	1536.0
1	5	597511.4	247000.0	597511.4	11699.0	0.0	1460.0	1536.0
1	6	1204565.8	111123.8	1204565.8	24371.0	0.0	1460.0	1536.0
1	7	1097354.4	174425.3	1097354.4	21486.0	0.0	1460.0	1536.0
1	8	989906.8	535884.4	989906.8	19382.0	0.0	1460.0	1536.0
1	9	573832.3	436341.1	573832.3	11610.0	0.0	1460.0	1536.0
1	10	259116.3	61504.0	259116.3	5073.0	0.0	1460.0	1536.0
1	11	111838.1	59520.0	111838.1	2263.0	0.0	1460.0	1536.0
1	12	80693.3	61504.0	80693.3	1580.0	0.0	1460.0	1536.0
2	1	65870.8	61504.0	65870.8	1290.0	0.0	1460.0	1536.0
2	2	50552.3	50552.3	50552.3	1096.0	0.0	1460.0	1536.0
2	3	50556.3	50556.3	50556.3	990.0	0.0	1460.0	1536.0
2	4	59996.2	59520.0	59996.2	1214.0	0.0	1460.0	1536.0
2	5	597511.4	247000.0	597511.4	11699.0	0.0	1460.0	1573.5
2	6	1204565.8	111123.8	1204565.8	24371.0	0.0	1460.0	1601.0
2	7	1097354.4	174425.3	1097354.4	21486.0	0.0	1460.0	1616.9
2	8	989906.8	535884.4	989906.8	19382.0	0.0	1460.0	1632.8
2	9	573832.3	436341.1	573832.3	11610.0	0.0	1460.0	1648.6
2	10	259116.3	61504.0	259116.3	5073.0	0.0	1460.0	1660.0
2	11	111838.1	59520.0	111838.1	2263.0	0.0	1460.0	1660.0
2	12	80693.3	61504.0	80693.3	1580.0	0.0	1460.0	1660.0
3	1	65870.8	61504.0	65870.8	1290.0	0.0	1460.0	1660.0
3	2	50552.3	50552.3	50552.3	1096.0	0.0	1460.0	1660.0
3	3	50556.3	50556.3	50556.3	990.0	0.0	1460.0	1660.0
3	4	59996.2	59520.0	59996.2	1214.0	0.0	1460.0	1660.0
3	5	597511.4	247000.0	597511.4	11699.0	0.0	1460.0	1697.8
3	6	1204565.8	111123.8	1204565.8	24371.0	0.0	1460.0	1725.4
3	7	1097354.4	174425.3	1097354.4	21486.0	0.0	1460.0	1751.7
3	8	989906.8	535884.4	989906.8	19382.0	0.0	1460.0	1772.0
3	9	573832.3	436341.1	573832.3	11610.0	0.0	1460.0	1792.2
3	10	259116.3	61504.0	259116.3	5073.0	0.0	1460.0	1810.0
3	11	111838.1	59520.0	111838.1	2263.0	0.0	1460.0	1810.0
3	12	80693.3	61504.0	80693.3	1580.0	0.0	1460.0	1810.0
4	1	65870.8	61504.0	65870.8	1290.0	0.0	1460.0	1810.0
4	2	50552.3	50552.3	50552.3	1096.0	0.0	1460.0	1810.0
4	3	50556.3	50556.3	50556.3	990.0	0.0	1460.0	1810.0
4	4	59996.2	59520.0	59996.2	1214.0	0.0	1460.0	1810.0
4	5	597511.4	247000.0	384231.4	8231.3	213280.0	1460.0	1838.3
4	6	1204565.8	111123.8	887885.8	19050.4	316680.0	1626.0	1863.9
4	7	1097354.4	174425.3	174425.3	6480.0	922929.1	1699.4	1887.6
4	8	989906.8	535884.4	549476.1	12221.0	440430.8	1812.1	1909.6
4	9	573832.3	436341.1	436341.1	9300.0	137491.2	1851.2	1929.8
4	10	259116.3	61504.0	79927.6	2159.6	179188.8	1861.5	1950.0
4	11	111838.1	59520.0	111838.1	2263.0	0.0	1874.9	1950.0
4	12	80693.3	61504.0	80693.3	1580.0	0.0	1874.9	1950.0

TABLE 5 CONTINUED

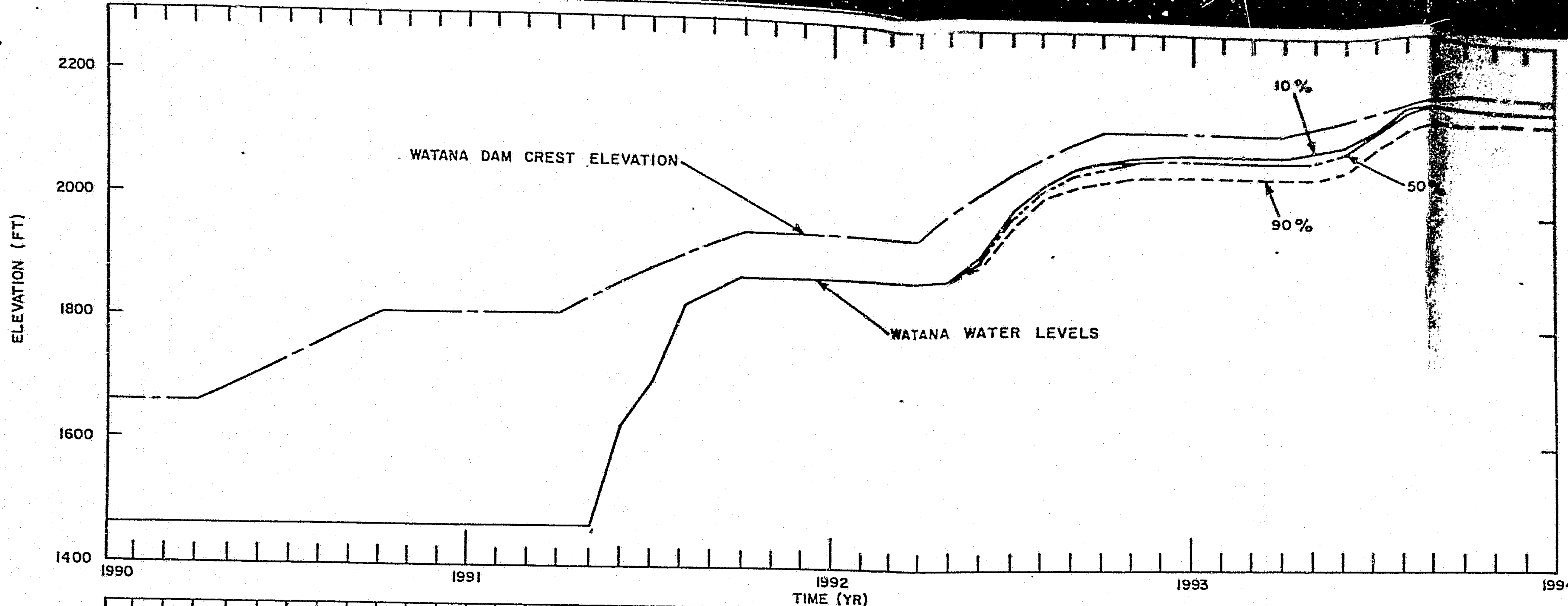
YEAR	MTH	INFLOW	REQ'D D/S FLOW	TOTAL OUTFLOW	FLOW @ D/S LOCATION	STORAGE ADDITION	WSEL FT	CREST EL FT
5	1	65870.8	61504.0	65870.8	1290.0	0.0	1874.9	1950.0
5	2	50552.3	50552.3	50552.3	1096.0	0.0	1874.9	1950.0
5	3	50556.3	50556.3	50556.3	990.0	0.0	1874.9	1950.0
5	4	59996.2	59520.0	59520.0	1206.0	476.3	1874.9	1988.5
5	5	597511.4	247000.0	247000.0	6000.0	350511.3	1901.0	2022.7
5	6	1204565.9	111123.8	111123.9	6000.0	1093441.[illegible]	1967.7	2054.2
5	7	1097354.4	174425.3	174425.3	6480.0	922929.1	2015.1	2081.3
5	8	989906.8	535884.4	535884.4	12000.0	454022.4	2035.8	2107.1
5	9	573832.3	436341.1	436341.1	9300.0	137491.2	2042.1	2130.0
5	10	259116.3	61504.0	61504.0	1860.0	197612.3	2051.0	2130.0
5	11	111838.1	59520.0	59520.0	1384.0	52318.1	2053.0	2130.0
5	12	80693.3	61504.0	61504.0	1268.0	19189.3	2053.7	2130.0
6	1	65870.8	61504.0	61504.0	1219.0	4366.8	2053.9	2130.0
6	2	50552.3	50552.3	50552.3	1096.0	0.0	2053.9	2130.0
6	3	50556.3	50556.3	50556.3	990.0	0.0	2053.9	2130.0
6	4	59996.2	59520.0	59520.0	1206.0	476.2	2053.9	2145.6
6	5	597511.4	247000.0	247000.0	6000.0	350511.3	2067.3	2159.4
6	6	1204565.8	111123.8	111123.9	6000.0	1093441.9	2107.8	2172.6
6	7	1097354.4	174425.3	174425.3	6480.0	922929.1	2137.7	2185.7
6	8	989906.8	535884.4	535884.4	12000.0	454022.4	2152.1	2198.8
6	9	573832.3	436341.1	436341.1	9300.0	137491.2	2155.8	2210.0
6	10	259116.3	61504.0	61504.0	1860.0	197612.3	2161.2	2210.0
6	11	111838.1	59520.0	59520.0	1384.0	52318.1	2162.6	2210.0
6	12	80693.3	61504.0	61504.0	1268.0	19189.3	2163.2	2210.0
SUM		30850756.		22180414.	8670350.			

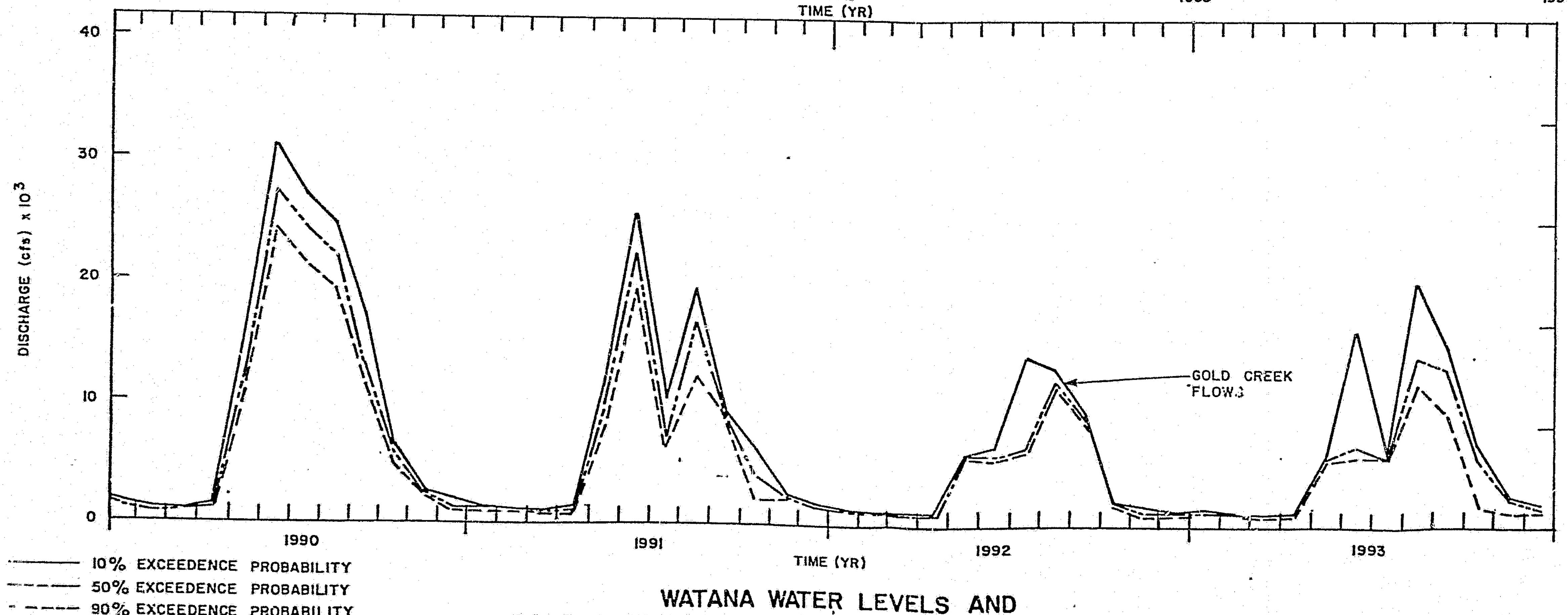
$



WATANA WATER LEVELS AND GOLD CREEK FLOWS DURING RESERVOIR FILLING

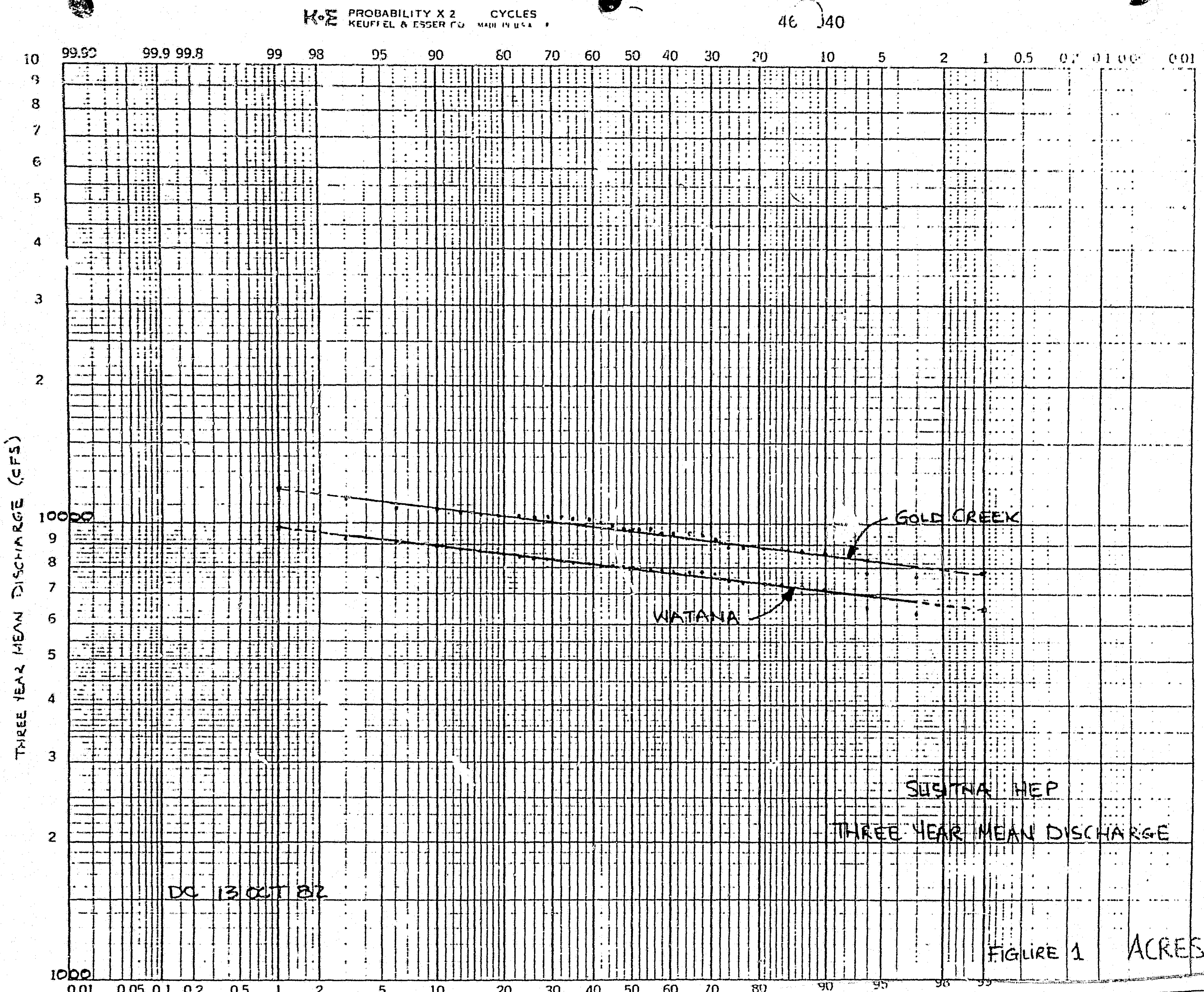
FIGURE E.2.76





WATANA WATER LEVELS AND
GOLD CREEK FLOWS DURING RESERVOIR FILLING

FIGURE E.2.76



K+E PROBABILITY X 2 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 040
THREE YEAR MEAN DISCHARGE (CFS)
GOLD CREEK
WATANA
SUSITNA HEP
THREE YEAR MEAN DISCHARGE
DC 13 OCT 82
FIGURE 1
ACRES

ACRES

OFFICE MEMORANDUM

TO: I. Hutchison/D. Crawford

Date: December 29, 1980

FROM: A. Simon

File: P5700.07.06

SUBJECT: Susitna Hydroelectric Project
Aspects of Filling Watana Reservoir

(4)

Attached are the notes concerning the probability of filling Watana Reservoir taking into account a dam construction schedule of six years.

A. Simon

A. Simon

AS:ccv
Attachments

Watana: Reservoir Filling

Watana reservoir filling probabilities were calculated based upon the dam construction schedule and making the following assumptions:

1. The downstream discharge is 2000 cfs.
2. There is no reserve for flood control.
3. The filling procedure starts at the end of the fourth year where the probability of overtopping the dam is only 2%.

Results:

The probability of filling the reservoir at the end of the 5th year is zero.

The probability of filling the reservoir at the end of the 6th year is 61%, but the probability of having 8000 af or more is 90%.

At the end of the 7th year the probability of having the reservoir full is 96%.

The normal operation of the reservoir can start at the end of the 6th year decreasing the probability of having the reservoir full at the end of the 7th year from 96% to about 80%.

ACRES

Calculations

SUBJECT: Watana
Dam construction schedule

JOB NUMBER
FILE NUMBER
SHEET 1 OF
BY A.J.S DATE
APP DATE

Schedule

Year	ELEVATIONS	VOLUMES (Acre-feet)
1	1400 – 1550	100,000
2	1550 – 1700	500,000
3	1700 – 1825	1,500,000
4	1825 – 1950	3,300,000
5	1950 – 2100	6,700,000
6	2100 – 2275	3,700,000 13,500

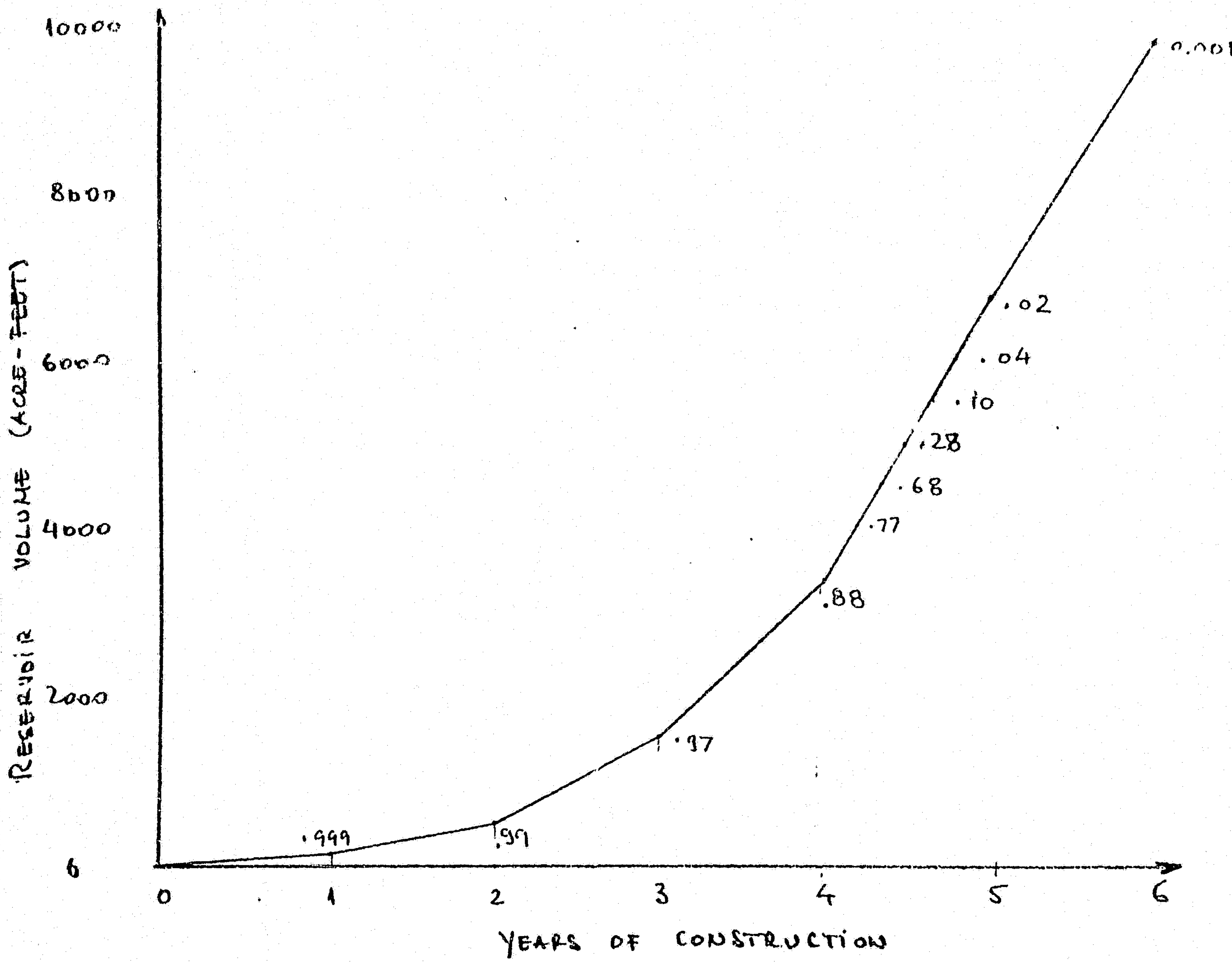
FORM NO. 152 REV. 1

ACRES

Calculations

SUBJECT: Watana - Dam construction schedule

JOB NUMBER
FILE NUMBER
SHEET ___ OF ___
BY AJS DATE
APP DATE



NOTE: THE NUMBERS WRITTEN ON THE CURVE ARE PROBABILITIES OF OVERTOPING THE DAM IF THE FILLING PERIOD STARTS AT THE END OF THE PREVIOUS YEAR.

ACRES	Calculations	
	SUBJECT: WATANA - THE CUMULATIVE PROBABILITY FUNCTION OF THE INFLOWS ASSUMING A DOWNSTREAM DISCHARGE OF 2000 cfs	JOB NUMBER FILE NUMBER SHEET OF BY AJS DATE APP DATE

	I (cfs)	J - 2000 (cfs)	Prob.
1	4916	2916	0.04
2	6190	4190	0.08
3	6493	4493	0.11
4	6678	4678	0.15
5	6799	4799	0.19
6	7526	5526	0.23
7	7598	5598	0.26
8	7846	5346	0.29
9	7962	5962	0.35
10	8060	6060	0.38
11	8072	6072	0.42
12	8320	6320	0.46
13	8389	6389	0.50
14	8461	6461	0.54
15	8497	6497	0.58
16	8540	6540	0.62
17	8684	6684	0.65
18	8769	6769	0.69
19	8959	6959	0.73
20	8966	6966	0.77
21	9123	7123	0.81
22	9149	7149	0.85
23	9309	7309	0.88
24	9356	7356	0.92
25	10264	8266	0.96

FORM NO. 152 REV. 1

JOB NUMBER
FILE NUMBER
SHEET OF
BY AJS DATE
APP DATE

Calculations

SUBJECT: WATANA THE CUMULATIVE PROBABILITY TRANSITION MATRIX

FINAL → / INITIAL ↓	< 2000	< 4000	< 6000	< 8000	≤ 9700
2000 (2760)	0	.03	.23	.96	1.0
4000 (5520)	0	0	.03	.23 .77	1.0
6000 (8280)	0	0	0	.03	1.0
8000 (11040)	0	0	0	0	1.0
9700 (13388)	0	0	0	0	1.0

Spill surplus.

NOTE: ALL THE STATES IN ACRE-FEET/YEAR

THE NUMBERS IN PARANTHESES ARE THE RESERVOIR STATES IN cfs

ACRES

Calculations

SUBJECT: WATANA THE TRANSITION PROBABILITY MATRIX DURING THE FILLING PERIOD

JOB NUMBER
FILE NUMBER
SHEET OF
BY KSS DATE
APP DATE

FINAL→ / INITIAL↓	2000	4000	6000	8000	9700	
2000	.03	.20	.73	.04	0.0	
4000	0	.03	.20	.73	.04	= 1.0
6000	0	0	.03	.20	.77	
8000	0	0	0	.03	.97	
9700	0	0	0	0	1	

ACRES

Calculations

SUBJECT: WATANA PROBABILITIES OF FILLING

JOB NUMBER
FILE NUMBER
SHEET OF
BY DATE
APP DATE

STATES

	≤2000	≤4000	≤6000	≤8000	≤9700
YEAR 5	0.0	0.03	0.23	0.96	1.0
6	0.0	0.0	0.012	0.096	1.0
7	0.0	0.0	0.004	0.005	1.0

STATES

	1.0	0.0	0.0	0.0	0.0
	2000	4000	6000	8000	9700
YEAR 5	0.03	.20	.73	.04	0.0
6	0.0	.012	.084	.294	.61
7	0.0	.004	.005	.025	.96

FORM NO. 152 REV. 1

ACRES

OFFICE MEMORANDUM

TO: R. Ibbotson

Date: October 8, 1981

File: P5700.06

FROM: D. Crawford

cc:

SUBJECT: Susitna Hydroelectric Project
Watana - Emergency Drawdown

As per your request, we have completed reservoir emergency drawdown analysis to determine elevation versus time relationships.

Discharge capacity was assumed to be that given by Figure 1 for the various facilities. Powerhouse capacity was omitted to give conservative estimates.

5

Plots of reservoir elevation versus time are given in Figure 2 for a wet year (wettest in period 1950-1975, year 1962) and for an average monthly flow year. Also differing starting times of drawdown were considered.

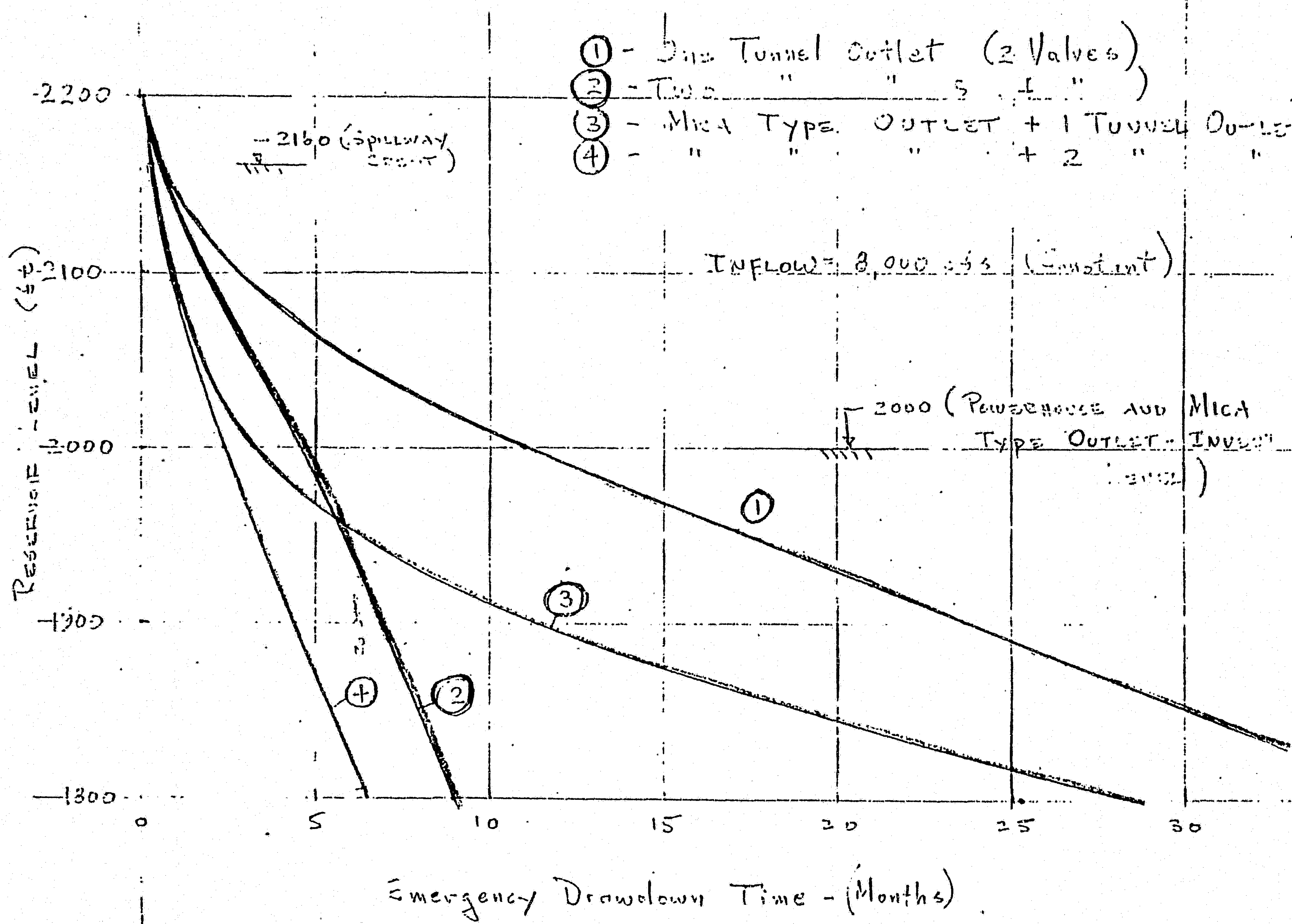
It appears that Watana Reservoir can be drawn down to acceptable levels in approximately 14 months with the given discharge facilities.

David Crawford

David Crawford

DC:md

DRAWDOWN TIME FOR VARIOUS LOW LEVEL OUTLET



ACRES

Calculations

SUBJECT:

JOB NUMBER P5700.05

FILE NUMBER

SHEET 14 OF

BY DATE

APP DATE

Calculations

ACRES

SUBJECT:

JOB NUMBER
FILE NUMBER
SHEET OF
BY DATE
APP DATE

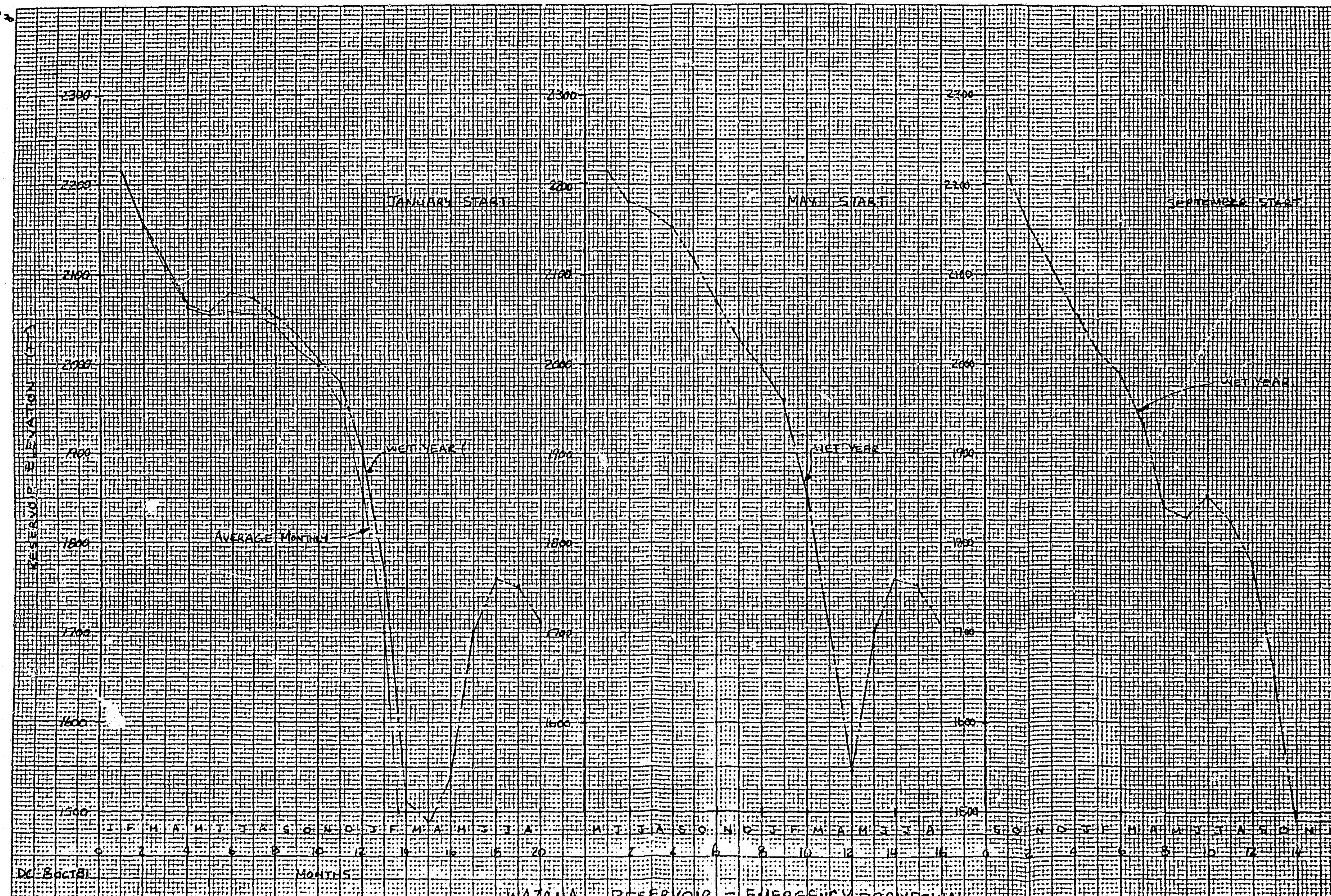
Average Watana Inflow.

	Ave	Wet	Dry
J	1147	- 1609	619
F	971	1257	608
M	889	1177	686
A	1103	1457	1262
M	10405	11334	9314
J	23093	36017	13962
J	20344	23443	14844
A	18012	19887	7772
S	10614	12746	4260
O	4394	4638	3135
N	1052	2263	1355
D	1385	1760	754

.DAT;3 - MAY. - WPEMWET.OUT;33.

DAT;2 - SEP - WEMWET.OUT;22

FORM NO. 152 REV. 1



WATANA RESERVOIR - EMERGENCY DRAWDOWN

Document Transmittal

ACRES

To: Wayne Coleman
Harza Engineering Company

Date: March 9, 1983

Acres Job No.: P5700.73

Task 6

Attention:

Project: Susitna Hydroelectric Project

Subject: Transition/Nitrogen Supersaturation

The following are enclosed:

Description / Title	Drawing Number	Revision Number	Number of Each	Code*
1. Technical Papers	—	—		
• Fickeisen, D.H., and J.C. Montgomery, "Tolerances of Fishes to Dissolved Gas Supersaturation in Deep Tank Bioassays", Battelle, Pacific Northwest Laboratories, Richland, WA. Trans. Am. Fish. Soc., Vol. 107, No. 2, 1978.			1	
• Wold, E. "Surface Agitators as a Means to Reduce Nitrogen Gas in a Hatchery Water Supply". The Progressive Fish Culturist, Vol. 35, No. 3, July 1973.			1	
• Nebeker, A.V. and J.R. Brett, "~~Effects of Air-Supersaturated Water on Survival of Pacific Salmon and Steelhead Smolts~~". ~~Trans. Am. Fish. Soc., No. 2, 1976.~~	Temperature and oxygen -nitrogen gas ratios affect fish survival in air-supersaturated water. Water Research, Vol 13, 1978		1	
• U.S. Army Corps of Engineers, "Nitrogen Supersaturation", ETL 1110-2-239, September, 1978.			1	

*A — For Approval or Comments
B — For Construction
C — See Explanatory Letter
X — For Information
E — For Purchasing
F — Drawings Approved
G — Drawings Approved Except as Noted
H —

Copies to: (First copy)

ACRES AMERICAN INCORPORATED
?00 LIBERTY BANK BUILDING
MAIN AT COURT
BUFFALO, NEW YORK 14202
Telephone: 716-853-7525
Telex: 91-6423

Please Sign and Return Acknowledgement Copy.

Rec'd by [illegible] on 3/9/83

Yours very truly,

David Crawford

ACRES AMERICAN INCORPORATED
David Crawford
Lead Hydraulic Engineer

ORIGINAL

FORM AAI-009 5/81

#6

Tolerances of Fishes to Dissolved Gas Supersaturation in Deep Tank Bioassays

D. H. FICKEISEN AND J. C. MONTGOMERY

Battelle, Pacific Northwest Laboratories
Richland, Washington 99352

ABSTRACT

Four species of fish were tested for tolerance to dissolved atmospheric gas supersaturation in 10-day bioassays. Based on median times to death at four levels of gas saturation, the fish displayed the following increasing order of tolerance: mountain whitefish (*Prosopium williamsoni*) < cutthroat trout (*Salmo clarki*) < largescale sucker (*Catostomus machrocheilus*) < torrent sculpin (*Cottus rhotheus*). Increasing hydrostatic pressure due to water depth reduced the levels of saturation of dissolved gases and increased survival. Torrent sculpins typically developed large bubbles of gas which caused them to float and would contribute indirectly to death.

The K... ...nai River is a clear mountain strear ... ...ary to the Columbia River. It supports an important sport fishery for mountain whitefish (*Prosopium williamsoni* (Girard)) and cutthroat trout (*Salmo clarki* (Richardson)) which are routinely planted by the Montana Department of Fish and Game. Impoundment of the river by Libby Dam located approximately 28 km upstream from Libby, Montana, has resulted in atmospheric gas supersaturation of the river water. Changes in abundance of important species have been noted (see Discussion) and gas bubble disease was hypothesized to be a primary cause of fish mortalities.

This paper reports the results of experiments to determine gas supersaturation tolerances of four fish species. They were selected based on abundance in the Kootenai River between Libby Dam and Kootenai Falls, economic or recreational value, behavior and habitat considerations, and importance in the food web. In addition to mountain whitefish and cutthroat trout, test species included *Catostomus machrocheilus* Girard (largescale sucker) which comprise the majority of fish biomass in the river, and *Cottus rhotheus* (Smith) (torrent sculpin).

Published tolerance data for these species are limited to studies of cutthroat trout and whitefish, and demonstrate hydrostatic pressure compensation for excess gas content. Blahm et al. (1976) reported whitefish to be more tolerant than cutthroat with median times to death of 21.0 and 119.5 h for [illegible] respectively. The comparable times for whitefish were 23.0 and 50.5 h, respectively. Both species were less tolerant than rainbow trout (*Salmo gairdneri*) or chinook salmon (*Oncorhynchus tshawytscha*) but more tolerant than steelhead trout. They also reported that permitting cutthroat trout to sound in a 2.5-m deep tank increased long-term survival relative to that in a 1.0-m deep tank.

METHODS

Tests were conducted in a single, Hyplon®-lined[1] deep tank, 2 m square and slightly over 3.2 m deep. The level of saturation to which a group of fish was exposed was controlled by suspending caged fish at predetermined depths along the saturation gradient in the deep tank. Henry's Law states that the solubility of a gas in water is linearly related to its gas-phase partial pressure. A water column of uniform gas concentration will therefore become less saturated as hydrostatic pressure increases due to depth. The degree of absolute saturation $S(\%)$ at a given depth, z, may be approximated by the formula $S_z = S_0/(1 + z/10)$, where S_0 is the surface % saturation and z is measured in meters. This principle of dissolved gas physics is the basis for the concept of hydrostatic pressure compensation and the "critical zone" of supersaturation (Dawley et al. 1976; Weitkamp 1975; Harvey 1975).

[1] Use of brand name does not imply Battelle endorse...

Exposure cages were constructed of Vexar® mesh on stainless steel rod frames. A muslin sleeve permitted removal of dead fish underwater. Cages were suspended from adjustable shelf brackets on the side of the deep tank. The supports were located so that each cage was centered at the depth for its nominal gas level (Table 1). Cages were about 1 m square and 20 cm high. Cage height resulted in some range about the nominal gas level. At the most severe case (the upper cage), this range was less than 3% of saturation. Smaller cages (15 cm × 15 cm × 12 cm) were placed inside the larger cages or directly suspended from the brackets for testing torrent sculpins.

Filtered Columbia River water was supplied at nearly 75 liter/min. Temperature was controlled at 10 ± 0.5 C. Supersaturation was generated in a pressure vessel that received pumped water and compressed air. The extent of saturation was controlled by backpressure, pressure and flow air, and height of the air-water interface in the pressure vessel, all of which were adjustable. After supersaturation, the water entered the bottom of the deep tank through a Y-diffuser, which resulted in uniform mixing and rapid diffusion of incoming water.

Gas levels were monitored at least daily by a Weiss saturometer (dissolved gas tensiometer) (Fickeisen et al. 1975). Saturation was calculated from the formula $S = 100(P_{atm} + P_{sat} - P_{H_2O})/P_{atm}$, where S = percentage dissolved gas saturation, P_{atm} = barometric pressure, P_{sat} = dissolved gas tension (saturometer), and P_{H_2O} = vapor pressure of water.

Little or no variation in gas tension occurred between the top and bottom of the deep tank, which was 132 ± 3% of equilibrium saturation at the surface. Temperature, recorded at least daily, showed less than 0.5 C difference between top and bottom.

Ten cutthroat trout, mountain whitefish, or torrent sculpins, or five largescale suckers were loaded in each cage at the surface. The cages were lowered to the desired depth. Two replicate tests were run for mountain whitefish and cutthroat trout, and four were run for torrent sculpins and

TABLE 1.—*Test gas levels in the deep tank (surface gas level = 132% saturation).*

Gas level % saturation	Tank depth, m
128	0.31
124	0.65
120	1.00
116	1.38
100	3.20

tested at each saturation level except sculpins which had 40 fish at each level. The exposure period was 10 days. Control fish were held at the bottom of the deep tank where gas saturation was 100%.

Test animals were monitored and dead fish removed daily. To avoid raising the cages, which could cause decompression and embolization, fish were checked by a scuba diver. Exhaled breathing air caused slight degasification of the water, but since diving time was usually less than 20 min test results were not considered to be significantly altered. The diver removed all dead fish and reported the number of live fish and those displaying loss of equilibrium or other manifestations of gas bubble disease.

All dead fish were examined for signs of gas bubble disease. Those displaying no externally visible signs were necropsied to determine cause of death. Fish were assumed to have died from gas bubble disease if they had external signs of it.

Test Organisms

Mountain whitefish and largescale sucker were collected by electroshocking in the lower Yakima River, Washington, and held in concrete ponds or fiberglass tanks continuously flushed with aerated Columbia River water. Torrent sculpins were collected by seining from the Fisher River, Montana. They were held at the Montana Department of Fish and Game (MDFG) Libby Hatchery in spring water prior to transportation to our laboratory. Westslope cutthroat trout were obtained from the MDFG hatchery at Lewistown. This stock of trout is reputed to be one of the few remaining pure strains of westslope cutthroat.

Fish stocks were maintained at our laboratory in flowing aerated Columbia River

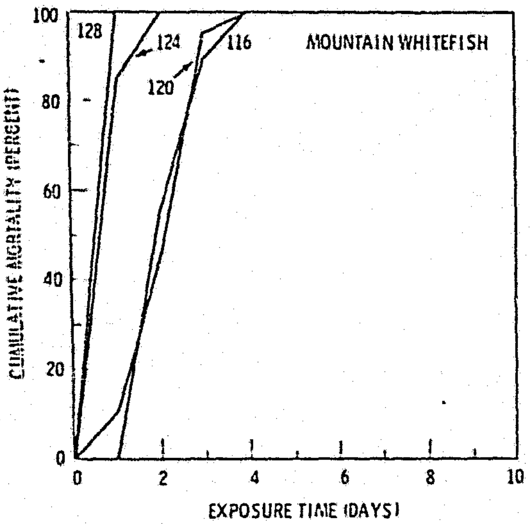


FIGURE 1.—*Mortality rates of mountain whitefish exposed to dissolved gas supersaturation. Numbers beside curves are percentage total gas saturation.*

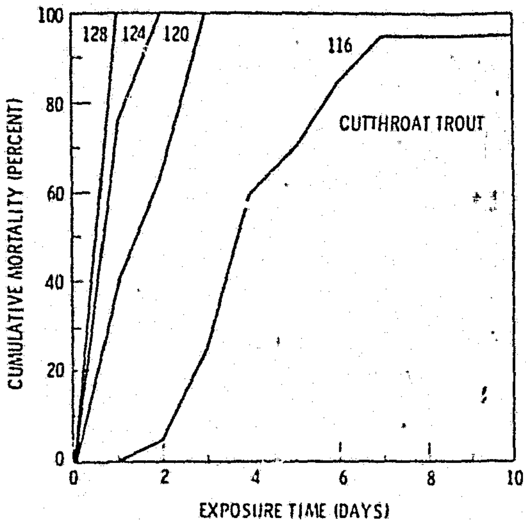


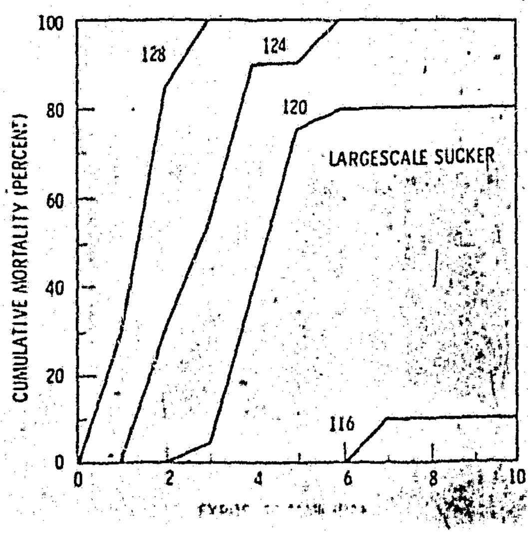
FIGURE 2.—*Mortality rates of cutthroat trout exposed to dissolved gas supersaturation. Numbers beside curves are percentage total gas saturation.*

water until tested. Initially water temperature was adjusted to match that of native streams at the time of collection. Fish were gradually acclimated up to 10 C and were held at the test temperature for at least 10 days. Cutthroat trout, whitefish, and suckers were fed hatchery trout pellets. In addition, suckers foraged for algal growth in their large tank. Sculpins were fed tubifex worms, sucker eggs, and salmonid fry.

Some of the mountain whitefish developed signs of piscine tuberculosis, a diagnosis confirmed by the Western Fish Disease Laboratory (U.S. Fish and Wildlife Service) in Seattle. A few fish died from this disease prior to beginning of testing, but mortalities were less than 10%. The disease can be readily distinguished from gas bubble disease by a trained observer. Piscine tuberculosis develops over a period of up to 2 or more years. Necropsies ensured that tuberculosis was not a prime factor in the mortality of test fish.

RESULTS

All fish that died or displayed loss of equilibrium during test exposures showed signs necropsies except as noted below. Torrent sculpin appeared to die of exhaustion as a result of struggling against positive buoyancy due to extremely large gas bubbles below their pectoral fins. Only two control fish died during the tests. Both were mountain whitefish with advanced piscine tuberculosis, including lesions in kidney and liver tis-



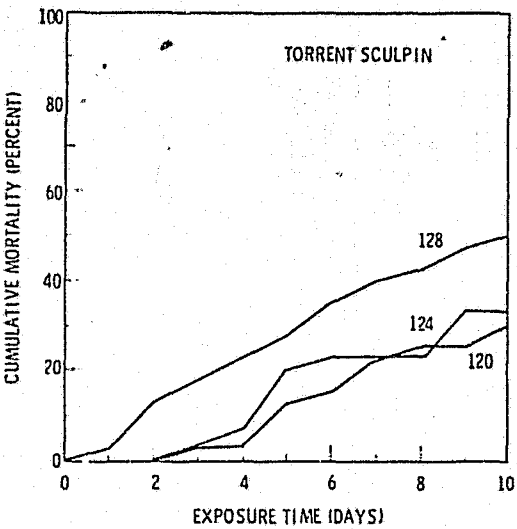


FIGURE 4.—*Mortality rates of torrent sculpin exposed to dissolved gas supersaturation. Numbers beside curves are percentage total gas saturation.*

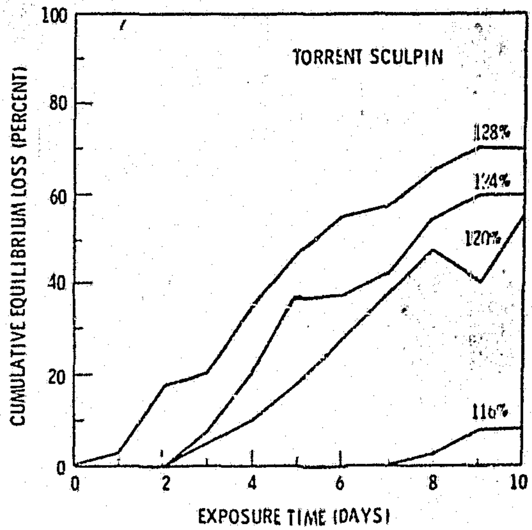


FIGURE 5.—*Rates of equilibrium loss for torrent sculpin exposed to dissolved gas supersaturation. Numbers beside curves are percentage total gas saturation.*

sue. None of the control fish had any signs of gas bubble disease. None of the other test fish had visible signs of tuberculosis. No statistical correlation was found between daily mortality rates and random variations about the mean dissolved gas saturation. The random variations were less than those that occur in the Kootenai River below Libby Dam.

Mountain Whitefish

Tolerances of mountain whitefish were lower than those of the other species tested. All whitefish tested at 128% total gas saturation died in less than 24 h. At 124% saturation they were all dead after 48 h. Even at 116% saturation all were dead after 96 h (Fig. 1). Median times to death (LT50) were 12 h at 128%, 14 h at 124%, 50 h at 120%, and 48 h at 116% total gas saturation.

Cutthroat Trout

Cutthroat trout were only slightly more tolerant than were whitefish (Fig. 2). All cutthroat were dead after 24 h at 128% gas saturation, by 48 h at 124%, and by 72 h at 120% saturation. One fish of the 20 tested survived the full 10 days at 116% saturation.

Largescale Sucker

Largescale suckers were more tolerant than salmonids: 90% survived the 10-day test at 116% saturation. At 128% saturation all suckers died in 72 h (Fig. 3). LT50's were 34 h, 67 h, and 103 h at 128%, 124%, and 120% saturation, respectively.

Torrent Sculpin

Torrent sculpin was the most tolerant species tested. Cause of death appeared to be exhaustion caused by struggles against positive buoyancy. Buoyancy resulted from gas bubbles as large as ¼ of body size that formed under or near the pectoral fins, causing loss of equilibrium and floating. Mortality curves were not as steep as those for the other species tested (Fig. 4) and only at 128% saturation was the LT50 reached (at 10 days). None of the sculpins died at 116% saturation and signs of gas bubble disease were rare at that gas level. Unlike other species, there was a significant time lag between loss of equilibrium and death for sculpins (Fig. 5). Median time to loss of equilibrium of sculpins was 127 h, 185 h, and 23

DISCUSSION

Cutthroat trout had a median time to death on exposure to 120% gas supersaturation of 34 h, while Blahm et al. (1976) reported a value of 119.5 h for cutthroat tested in a shallow tank. Our results with whitefish agree very closely with those of Blahm et al. (1976) with median times to death of 50 h and 50.5 h, respectively. The cutthroat trout tested were deemed in excellent condition and, with the exception of the few cases of tuberculosis among whitefish, the remaining fish stocks were healthy. As far as can be determined, test fish had not been previously exposed to significant levels of dissolved gas supersaturation. They were all temperature-acclimated and thus not thermally stressed during testing. Careful handling prevented decompression during testing, which otherwise might cause more rapid embolization.

Torrent sculpins lost buoyancy control after several days exposure and floated which would make them easy prey in nature. It is unlikely that a sculpin would recover from positive buoyancy as bubble size would grow due to reduction in hydrostatic pressure as it floated to the surface. Sculpins may be exposed to higher gas saturation levels than other species by inhabiti shallower areas. Their tendency to become buoyant ensures a high mortality rate and makes them readily detectable in gas-supersaturated streams.

Application of our bioassay results to predict effects of air supersaturation on river organisms requires detailed depth distribution data from which hydrostatic compensation may be calculated. Otherwise the assumption must be made that all organisms are affected at or near river-surface pressures and have no effective hydrostatic compensation. This assumption produces an estimate of maximum effect. Actual adverse effects will be somewhat less, but cannot be estimated on the basis of existing data. The Kootenai River in the area of interest is relatively shallow precluding com- ... partment of Fish and Game staff has conducted extensive electroshocking studies between Libby Dam and Kootenai Falls. They found changes in relative abundance immediately below the dam from approximately 50% mountain whitefish, 50% suckers, and 1% trout (mainly cutthroat and rainbow) prior to operation of the dam to about 10% whitefish, 90% suckers and less than 1% trout after the dam was closed and gas saturation levels exceeded 130%. Signs of gas bubble disease were found on about 80% of the whitefish and suckers. The number of fish with gas bubble disease decreased with distance downstream where supersaturation levels were reduced (Bruce May, personal communication). These field data are consistent with our relative tolerance data from which we would predict greater mortalities to whitefish and trout than to suckers. Apparently the shallow depth of the river or aspects of fish behavior have prevented significant compensation from the gas supersaturation generated by Libby Dam. The evidence indicates that dissolved gas supersaturation has been a prime factor in changes in Kootenai River fish populations below Libby Dam.

ACKNOWLEDGMENTS

The authors appreciate the ...fort of Bruce May, Montana Department of Fish and Game, for his assistance in obtaining torrent sculpins and cutthroat trout. E. W. Lusty, Battelle-Northwest, aided in design of the deep tank. M. J. Schneider, Battelle-Northwest, contributed to the experimental design. He and C. D. Becker, Battelle-Northwest, reviewed the manuscript.

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D. Crawford #7

SURFACE AGITATORS AS A MEANS TO REDUCE NITROGEN GAS IN A HATCHERY WATER SUPPLY

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NITROGEN SUPERSATURATION AND ITS EFFECT on fish (gas bubble disease) has been a problem in some fish hatchery operations for a number of years [*5, 7, 8, 9, 10, 11*]. Gas bubble disease in fish is characterized by small emboli in the vascular elements of the fins, gills, and skin. The bubble disease may not kill the fish outright, but may cause small ruptures in the skin making the fish more susceptible to secondary disease infections.

Wood [*10*] considered the following nitrogen saturation levels as detrimental or lethal for salmon (*Oncorhynchus* sp.): 103 to 104 percent for yolk-sac fry and young fingerlings; 105 to 113 percent for older fingerlings and yearlings; and 118 percent for adults. Wesigard [*9*] showed that adult chinook salmon (*O. tshawytscha*) held in water with nitrogen concentrations at 116 percent saturation developed definite symptoms of gas bubble disease. Harvey and Smith [*5*] reported that saturation levels of 108 percent produced gas bubble disease in trout fingerlings. Wyatt and Beiningen [*11*] reported that 152 percent nitrogen saturation in an Oregon hatchery killed all juvenile salmon and steelhead (*Salmo gairdneri*) in 5 hours.

At Dworshak National Fish Hatchery, steelhead yolk-sac fry held in water with 107 percent nitrogen saturation developed gas bubble disease causing them to float upside down in the water. When the nitrogen level was reduced to 105 percent the fry acclimated to the new environment and returned to normal swimming activities.

Since high nitrogen saturation levels are harmful to fish, some means to reduce the level to less than 105 percent in hatchery water supplies is necessary to maintain a healthy hatchery stock.

Several methods for aerating fish hatchery water supplies have been used successfully [*3, 4, 7, 8*]. Rucker and Tuttle [*8*] found that nitrogen saturation was reduced from 144 to 101 percent when water was dropped in a series of troughs to create thin sheets of water. Harvey and Cooper [*4*] used a structure with baffles set at right angles to reduce nitrogen saturation from 119.5 to 102 percent. Erdman [*3*] used a spray to aerate a heated water supply. Rucker and Hodgeboom [*7*] used a baffled flume to reduce nitrogen gas saturation from 120 to 115 percent.

At Dworshak National Fish Hatchery, located 1.6 miles below Dworshak Dam on the North Fork of the Clearwater River in Idaho, a water treatment facility was constructed to provide a settling basin and aeration facility for low oxygenated reservoir water. Since dams have different characteristic effects on nitrogen saturation [*2*], the effect of Dworshak Dam on the water quality of the hatchery supply was unknown. During the spring of 1972, 2,000 to 30,000 cubic feet per second water was released down the spillway from the low level outlet (elevation 1,230) at Dworshak Dam. This water plunged into the stilling basin (water surface elevation 973, bottom elevation 931) entrapping air and creating nitrogen levels ranging from 115 to 130 percent saturation. During this time surface mechanical agitators originally installed for use as aerators successfully reduced nitrogen to levels acceptable for fish culture purposes.

DESCRIPTION OF FACILITIES

The water treatment facility at Dworshak National Fish Hatchery is a large concrete structure with a total volume of 47,676 cubic

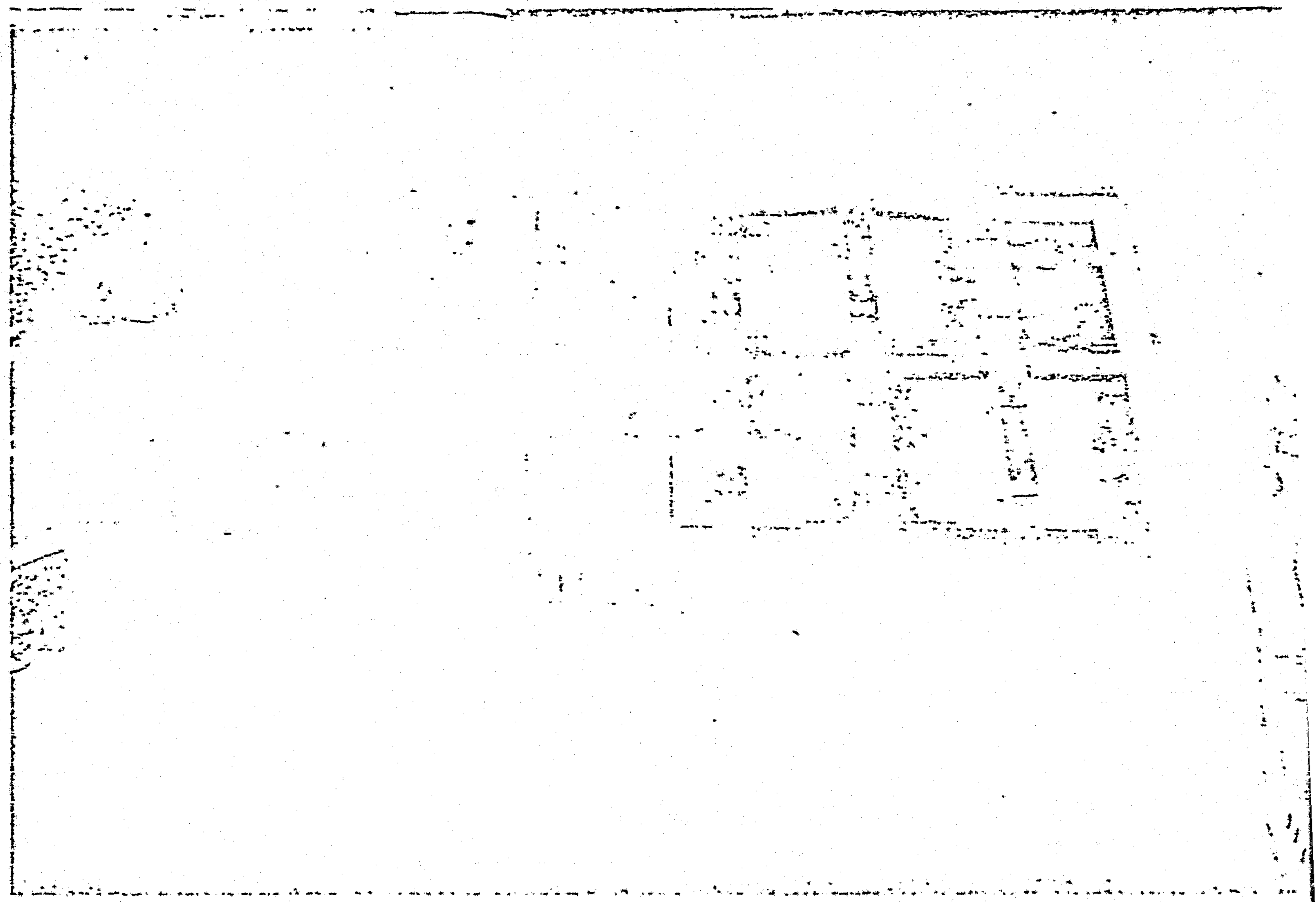

Figure 1.—Water treatment facility with aerators 2, 4, 5, 9, 10, and 12 in operation.

feet (356,641 gallons) (fig. 1). Twelve 30-horsepower surface aerators with a gear ratio of 25. 6:1 are platform mounted and supported on steel bridges (fig. 2). The impeller which rotates at 75 rpm is an inverted cone with blades radiating outward from a boss at the center. As the impeller turns, it draws the water upwardly towards the boss; it is propelled outwardly in a low trajectory as a fine spray.

The hatchery water supply is delivered to the water treatment facility from the river by any combination of three 15,500-gpm and two 8,000-gpm pumps. The aerators are installed in three rows with four aerators in each row (fig. 3). The water level is maintained by a weir to provide a continuous depth for best aerator efficiency.

CONSTRUCTION, OPERATION, AND MAINTENANCE COSTS

The water treatment facility described in this report costs $177,527 to construct in 1968 with each aerator costing $6,000. The pumping facility to deliver water from the river to the aerators cost an additional $581,000. With a rate of 3.6 mills/kilowatt-hour the cost of operating each aerator is $61.80 per month. The cost of labor and supplies is approximately $60 a year with six man hours of labor required for each aerator.

METHODS

Nitrogen and oxygen levels were measured from samples of water obtained from the North Fork of the Clearwater River and the effluent of the water treatment facility. Analysis for dissolved nitrogen was made using a Van Slyke manometric blood gas analyzer modified for water determinations [6]. Dissolved oxygen was analyzed using the Azide modification of the Winkler Method [7].

Analyses of water samples were made with combinations of 2 to 12 aerators in use with flows of 19,500 and 37,000 gpm.

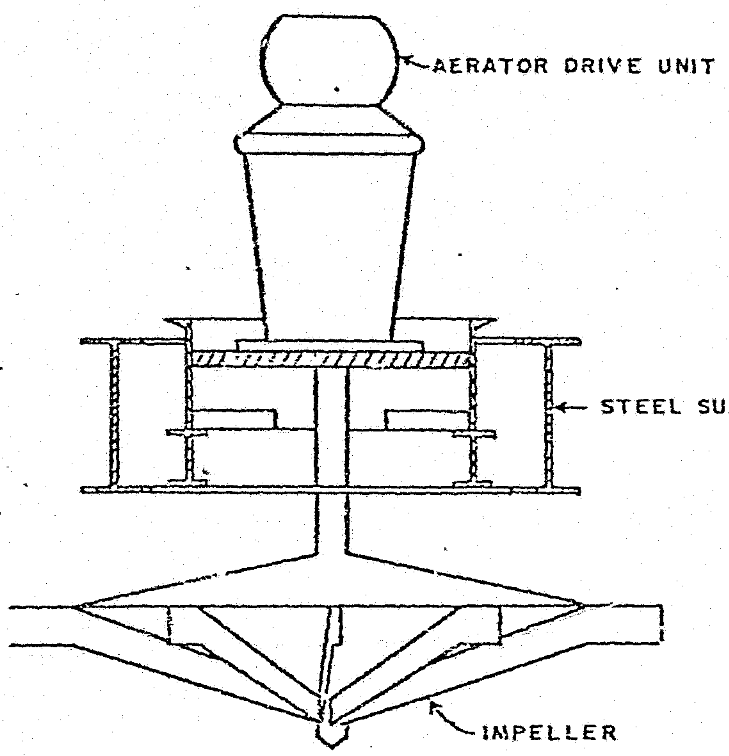

Figure 2.—Platform-mounted aerator used in water treatment facility.

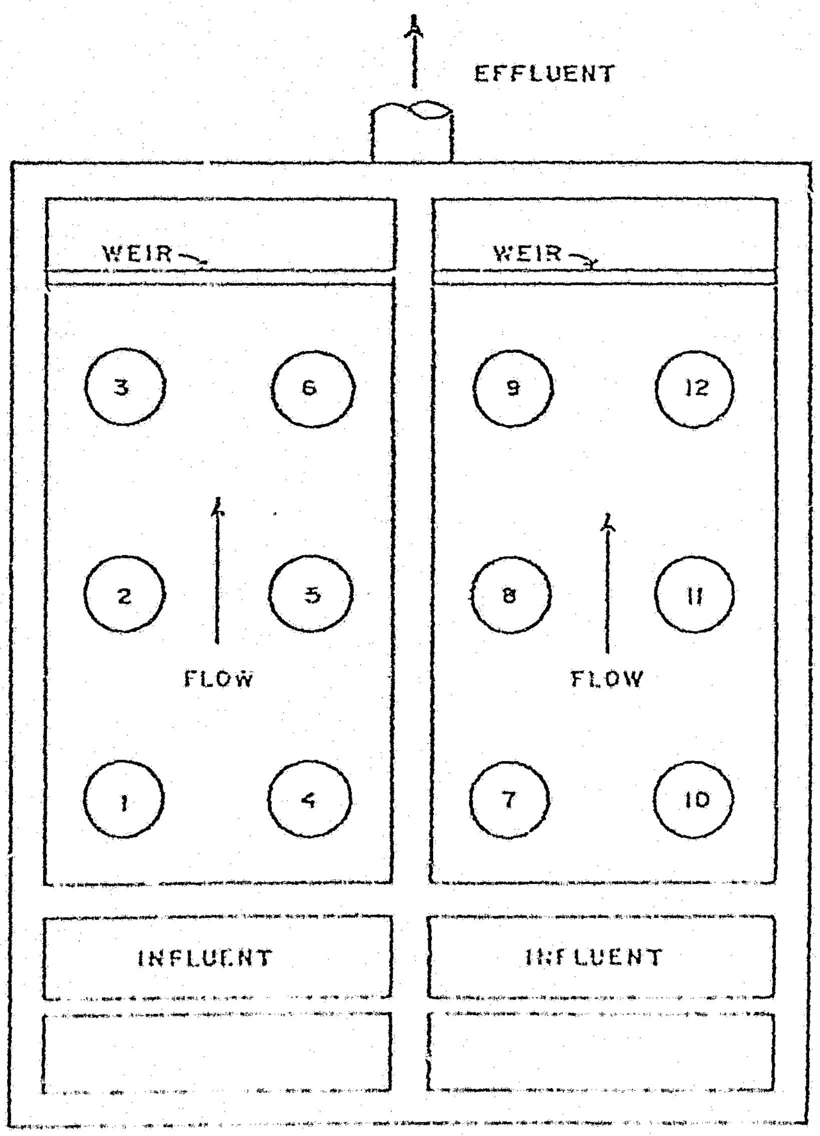

Figure 3.—Location of aerators in water treatment facility as indicated by numbered circles.

RESULTS

A minimum of four agitators was necessary to reduce the nitrogen levels from 115 to 130 percent saturation to an acceptable level. Some combinations using four agitators were not as efficient as others and only reduced the nitrogen levels to 108.8 percent. This decrease in efficiency was due to location and spacing of agitators.

Four corner agitators were less efficient than four agitators set in a line perpendicular to the flow. Efficiency of the aerators increased with increased flow rates. The results of nitrogen and oxygen determinations with regards to flow, temperature, and number of aerators operating are shown in the table.

Enough data have been obtained from tests run at Dworshak National Fish Hatchery to demonstrate that agitation provided by surface aerators provides an excellent method for reducing supersaturation of nitrogen to levels acceptable for fish propagation.

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Summary of nitrogen and oxygen analyses with several combinations of flows, temperatures, and numbers of aerators operating

Aerators operating	Flow (gpm)	Temperature (°C)	Percent saturation: Nitrogen (Van Slyke Method)		Oxygen (Winkler Method)	
			Influent	Effluent	Influent	Effluent
1 2 3 4 5 6 7 8 9 10 11 12	37,000	4.9	127.0	101.0	122.0	100.6
1 2 4 5 7 8 10 11	37,000	4.9	127.0	102.6	122.0	102.2
2 3 5 6 8 9 11 12	37,000	5.5	116.9	104.0	114.8	103.5
1 3 4 6 7 9 10 12	37,000	5.5	118.5	104.3	117.0	102.8
1 3 5 8 10 12	37,000	5.5	118.5	102.8	117.0	99.8
1 2 3 10 11 12	37,000	6.8	118.6	103.4	117.1	101.0
1 4 7 10	37,000	6.8	118.6	101.4	117.1	99.4
2 4 8 11	37,000	6.0	116.9	102.8	114.8	99.7
3 6 9 12	37,000	6.0	116.9	108.8	114.8	105.6
1 3 10 12	37,000	6.0	118.5	107.1	117.0	104.2
5 8	37,000	6.0	116.9	110.4	114.8	108.4
1 10	37,000	5.7	116.8	112.3	114.7	110.1
1 2 4 7 8 10	19,500	9.2	117.3	102.8	121.9	102.9
1 4 7 10	19,500	9.2	119.8	101.8	117.9	103.1

D. Crawford

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TEMPERATURE AND OXYGEN–NITROGEN GAS RATIOS AFFECT FISH SURVIVAL IN AIR-SUPERSATURATED WATER

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(*Received 16 August 1978*)

Abstract Juvenile steelhead trout and juvenile chinook, coho and sockeye salmon were tested at different temperatures (8°, 9°, 10°, 12°, 15°, 18° and 20°C) at the same concentration of air-supersaturated water. Supersaturated water concentrations in different tests were 115, 116, 117, 118 and 120% saturation. Increased temperatures caused a significant ($P < 0.005$) increase in steelhead mortality, a significant increase ($P < 0.025$) in chinook deaths, but no significant effect on coho or sockeye mortality. Regression model data for steelhead indicate that a 10°C increase in temperature will decrease the time to 50% death by a factor of 2.7, e.g. from 190 h at 8°C to 70 h at 18°C, when tested at the same total dissolved gas pressure.

Effects of different oxygen nitrogen gas ratios on fish mortality at the same total dissolved gas pressure in supersaturated water were demonstrated with juvenile steelhead trout. Mortality was rapid (time to 50% death in 1–6 h) at 140, 135 and 130% saturation, with fish dying more rapidly as the ratio of oxygen nitrogen decreased (decrease in O_2, increase in N_2). Mortality patterns were similar at 125%; time to 50% death occurred in 5–20 h, with more rapid deaths occurring as oxygen (O_2/N_2 ratio) was decreased.

INTRODUCTION

The varying solubility of gases in water at different temperatures is well known, and temperature tolerances and oxygen requirements of a variety of fishes and aquatic organisms are known for a wide range of conditions and with some toxic substances (Coutant & Talmadge, 1977). However, there is little information on the effects that temperature or varying oxygen nitrogen gas ratios may have on the lethality of air-supersaturated water to fish and other aquatic life. An increase in the temperature of saturated water will supersaturate the water with gases (Shelford & Allee, 1913; DeMont & Miller, 1971), but little is known of the effects when fish are subjected to the same concentration of air-supersaturated water at different temperatures. Three thermal studies have considered some aspects of the interaction of temperature and supersaturation (Coutant & Genoway, 1968; Ebel *et al.*, 1971; Bouck *et al.*, 1976). Fickeisen *et al.* (1976) determined effects of different temperatures on black bullhead (*Ictalurus melas*) survival at the same gas levels. They found little or no effect of supersaturation on the tolerance of the fish at temperatures of 8°, 12°, 16° and 20°C. Marcello *et al.* (1975) showed that there were no significant effects of temperature on the survival of menhaden (*Brevoortia tyrannus*) at different supersaturation concentrations.

The initial work on effects of varying oxygen and nitrogen gas ratios in supersaturated water by Rucker ([illegible]), using juvenile coho salmon, and the work by Nebeker *et al.* (1976*a*) with juvenile sockeye salmon, showed that varying gas composition of supersaturated water can affect fish survival. Nitrogen gas, which forms a significant portion of the total dissolved gas pressure, is a major factor causing mortality, though oxygen does cause severe external signs of gas bubble disease. Rucker used 119% total gas saturation and varied the O_2/N_2 ratios. Nebeker *et al.* used 120, 125 and 130% total saturation with several O_2/N_2 ratios. The two papers summarize other relevant literature that need not be cited again here.

The purpose of the present study was to determine if different temperatures might have an effect on the survival of juvenile salmon and steelhead at a constant supersaturation concentration and to present data for juvenile steelhead trout (*Salmo gairdneri*) tested at several total dissolved gas pressure levels and O_2/N_2 ratios.

METHODS AND MATERIALS

Fish

Steelhead trout smolts (*Salmo gairdneri*), and juvenile chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*), and sockeye salmon (*O. nerka*) were reared from eggs at the Western Fish Toxicology Station. Fish were fed daily with Oregon Moist Fish Diet and were acclimated to test temperature for at least one week before testing, with rates of temperature change not exceeding 1.5°C/day. Steelhead used for temperature tests were tested at ~15 months of age during the time they were smolts and would nor-

Table 1. Times to 50 and 20% death for juvenile steelhead trout and juvenile sockeye, chinook and coho salmon at different gas saturation levels and water temperatures. Each value represents time to 50% death, using 20 fish for each test tank

Test number	Mean measured % total gas saturation*	Nominal water temp (°C)	Time to 50% death (h) steelhead	sockeye	chinook	coho	Time to 20% death (h) steelhead	sockeye	chinook	coho
1	119.6	8	102	45	82	235	70	29	47	152
	119.8	12	84	51	84	‖	61	30	55	195
	119.7	16	35	63	198	‖	27	37	54	160
	119.3	20	40	57	53	270	28	34	40	51
2	114.3	10	510, ‖†	‖,‖	—	—	320, 380	‖	—	—
	114.5	12	505, 408	‖,‖	—	—	285, 215	‖	—	—
	114.8	15	268, 305	‖,‖	—	—	150, 156	‖	—	—
	114.7	18	202, 258	‖,‖	—	—	107, 135	‖, 480	—	—
3	116.1	9	462, 223	515, 418	—	—	175, 108	165, 177	—	—
	116.2	12	242, 252	395, 525	—	—	141, 158	214, 205	—	—
	116.2	15	193, 118	490, 470	—	—	92, 57	154, 173	—	—
	116.4	18	72, 52	313, 453	—	—	39, 37	162, 212	—	—
4‡	116.5	9	160, 193	287, 456	—	—	101, 127	116, 158	—	—
	116.8	12	211, 183	397, 603	—	—	88, 122	122, 195	—	—
	117.0	15	178, 143	‖,‖	—	—	93, 87	272, 320	—	—
	116.8	18	102, 113	‖,‖	—	—	55, 54	‖,‖	—	—
5	120.4	9	45, ‖	‖,‖	—	—	29, 35	‖, 30	—	—
	120.8	12	44, 40	‖,‖	—	—	28, 27	43, 39	—	—
	120.6	15	43, 40	49, 36	—	—	30, 28	34, 21	—	—
	121.8§	18	—	—	—	—	—	—	—	—
6	120.2	10	56	49	90	43	31	20	46	30
	120.9	12	33	46	55	41	20	23	31	26
	120.3	15	42	‖	50	55	27	41	29	31
	119.6	18	32	37	31	46	24	22	22	0
7	117.2	9	121	226	440	230	56	128	200	100
	117.8	12	123	250	311	276	73	131	220	156
	117.5	15	96	216	235	319	76	104	145	172
	117.6	18	62	332	205	136	45	105	94	58

* Control tanks remained near 18°C and 100% saturation at all times.
† Two tests were completed at each temperature.
‡ The formula $\frac{BP + \Delta P}{BP} \times 100 = \%$ sat. was used for this test only. Other tests used $\frac{BP + \Delta P - VP}{BP} \times 100 = \%$ sat.
§ Saturation level significantly higher than other tanks, data not used.
‖ Insufficient deaths to achieve 50 or 20% mortality.

mally be migrating down to the ocean. Average fork length was 15 cm; mean blotted wet wt was 32 g. Mean steelhead size when tested in mixed gases ranged from 5.8 g (7.9 cm) to 40.5 g (16.2 cm), depending upon age and time of year tested. Chinook ranged from 23.8 g (12.6 cm) to 95.8 g (20.6 cm), sockeye from 6.6 g (8.4 cm) to 111.5 g (20.9 cm), and coho from 20.5 g (11.9 cm) to 51.6 g (16.7 cm), again depending on age and time of year tested.

Water and test facility

Unchlorinated, aerated well water was used for all testing and had the following average characteristics: hardness (as $CaCO_3$) 31 mg l^{-1}; alkalinity (as $CaCO_3$) 23 mg l^{-1}; pH 7.1. Water chemical analyses were conducted according to the American Public Health Assoc *et al.* (1971). Water temperature, velocity and flow rate were controlled, and natural photoperiod was utilized during testing.

Test facilities consisted of five 6000-l fiberglass tanks, each with a water depth of 60 cm and containing a four-chambered nylon net cage for testing 4 groups of fish at the same concentration or temperature. Each tank had a separate supersaturation generator (Nebeker *et al.*, 1976*b*) where water was supersaturated by injecting compressed air, or air and O_2 or N_2 gas, into water under pressure and then releasing the water into the test tanks. The per cent saturation was controlled by the amount of air (and gases) metered into the test water. Because supersaturation of gas in water increases with elevated temperature, a different amount of gas had to be added at each temperature to maintain the same total per cent saturation. A Van Slyke gas analyser, the Winkler method for dissolved oxygen, and a Weiss saturometer were used to determine saturation concentrations. The formula $BP + \Delta P - VP/B_i \times 100 = \%$ saturation, where BP = atmospheric pressure, ΔP = saturometer reading, and VP = water vapor pressure, was used to calculate total dissolved gas pressure with the Weiss saturometer. Per cent oxygen and nitrogen (+argon) saturation values were determined using the methods and calculations outlined by Nebeker *et al.* (1976*a*).

Temperature testing

Fish were tested at 8°, 9°, 10°, 12°, 15°, 18° and 20°C at total gas supersaturation concentrations of 115, 116, 117, 118 and 120% (Table 1). In each tank of supersaturated water one or two tests were conducted at each temperature with one test cage per species, 20 fish per cage. After acclimation to test facilities and temperatures, the water was supersaturated, requiring about 8 h to reach test levels. The fish were in the test water while supersaturated conditions

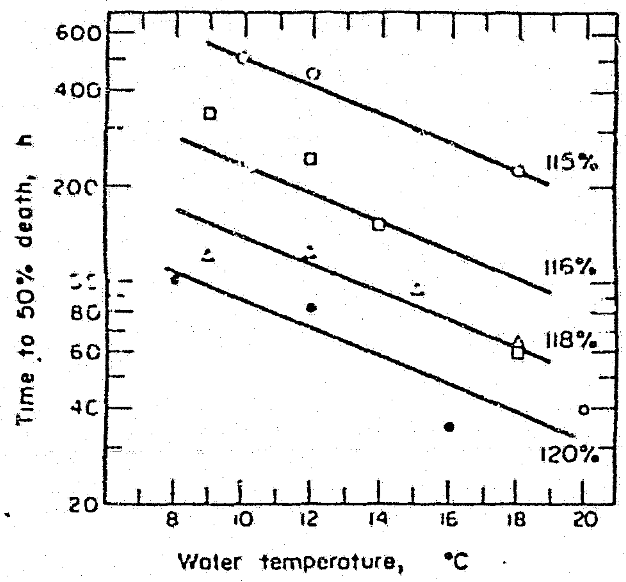

Fig. 1. Effect of different exposure temperatures on the survival of juvenile steelhead trout at four different concentrations of supersaturated water.

were being produced. Fish were observed for mortality frequently during the day and evening, especially during tests involving higher concentrations. Time to 50% death (LT50) was determined by plotting cumulative mortality against time on log-probit paper. A straight line was fitted through the points and where it crossed the 50% mortality mark was considered the time to 50% mortality (LT50) for that group of 20 fish. The slopes of the lines (Fig. 1) were not significantly different so they were set equal to each other (regression of log (LT50)).

Mixed gas testing

Fish were tested at total gas supersaturation concentrations of 125, 130, 135 and 140% total dissolved gas with 37 different oxygen-nitrogen (O_2/N_2) ratios, ranging from 40% (4.4 mg l) to 307% (33.1 mg l) O_2 saturation: and 96-162% nitrogen saturation (Table 2). In each tank of supersaturated water, two or more tests were completed at each O_2/N_2 gas ratio and supersaturation concentration, with 10 or 20 fish used during each test. Fish were under continuous observation until greater than 50% had died. Fish were transferred directly to the supersaturated water from holding tanks at the same temperature (12°C), rather than being placed in the tanks prior to supersaturating the water. Time to 50% death (LT50) was determined in the same manner as in temperature testing.

RESULTS AND DISCUSSION

Temperature tests

The effect of different temperatures and constant supersaturation concentration on survival of the juvenile steelhead and salmon varied with species (Table 1). Increased temperatures caused a very significant ($P < 0.005$) increase in steelhead mortality, a significant ($P < 0.025$) increase in chinook deaths, but no significant effect on coho or sockeye mortality. Using regression models, highly significant ($P < 0.001$) and significant ($P < 0.005$) temperature effects were shown on steelhead and chinook, respectively. For sockeye and coho, such regressions did not show a significant effect of temperature for either the LT50 or the LT20.

Table 2. Summary of mean time to 50% death for juvenile steelhead trout at 125, 130, 135 and 140% total dissolved gas pressure and varying O_2/N_2 ratios

125% total gas			130% total gas		
Gas concentration O_2%	N_2%	Mean time to 50% death (h)	Gas concentration O_2%	N_2%	Mean time to 50% death (h)
*44.2	146.6	4.7	*45.9	151.8	3.7
93.0	133.4	5.9	99.2	138.1	4.2
95.7	133.5	8.2	100.4	138.3	4.5
99.5	132.2	5.0	128.4	131.1	5.0
117.4	128.1	16.5	129.2	130.8	4.2
120.2	125.9	16.7	139.0	128.0	5.5
123.8	125.3	12.0	140.0	128.2	6.0
123.8	125.8	20.0	140.0	127.8	5.0
129.4	125.6	15.5	166.4	121.1	5.5
135% total gas			**140% total gas**		
Gas concentration O_2%	N_2%	Mean time to 50% death (h)	Gas concentration O_2%	N_2%	Mean time to 50% death (h)
*40.5	159.6	2.5	56.6	162.4	1.7
107.8	142.3	1.6	99.0	151.9	1.9
110.1	143.0	2.3	104.1	150.3	1.7
131.7	137.3	3.0	138.2	141.4	2.2
135.3	136.1	2.7	140.9	140.7	2.0
135.6	135.3	1.8	187.1	129.1	1.7
[illegible]	125.9	1.5	210.0	122.1	1.9
[illegible]72.5	99.4	5.7	237.9	118.0	4.5
			307.9	96.1	5.0

* Possible additional stress due to low oxygen.

These data indicate the likelihood of increased mortality of steelhead trout and chinook salmon juveniles in supersaturated water at higher temperatures. Apparently coho and sockeye are not significantly affected, as long as the temperatures are below those which do not directly cause temperature-related mortality. The supersaturation concentrations used during this study are near the 96-h LC50 values (50% mortality after 96 h) determined from previous studies (Bouck *et al.*, 1976) and have been shown to occur in the Columbia and Snake Rivers (Ebel & Raymond, 1976). Regression data for steelhead trout in this study indicated that a 10 C decrease in temperature will increase the LT50 by a factor of 2.72; if the LT50 for 118% saturation at 18°C was 70 h it would be near 190 h at 8 C (Fig. 1). There was no significant difference in LT50 at different temperatures for sockeye juveniles.

As mentioned in the Methods section, the formula used to calculate supersaturated water concentrations subtracted water vapor from the saturometer reading. In test No. 4 water vapor was not subtracted during calculations to see if this would result in survival data different from the other 6 tests. It can be seen (Table 1) that similar mortality would occur with either method of calculating supersaturated water concentrations.

It is apparent from this study that the temperature of supersaturated water may have an effect on fish survival, depending on species and total dissolved gas pressure. Therefore, water temperature should be considered when determining if levels of supersaturation are safe for a fish species in a given water system. This apparent biological difference due to temperature increase is different from the physico-chemical increase in supersaturation when water is heated and becomes supersaturated. In general, air supersaturation in water will increase 2.5% for every 1 C rise in water temperature, i.e. water will be supersaturated to 125% if temperature is raised from 5 to 15°C.

When the temperature of a water system increases, either naturally from solar insolation or from thermal springs, artificially due to man's activities, or due to a combination of both, the resultant temperature may have a deleterious effect on fish populations. If the water is supersaturated by spillage over dams and subsequently heated, fish and invertebrate populations would be seriously threatened, if not completely eliminated from affected areas.

Mixed gas tests

As in the two earlier studies by Rucker (1976) with coho salmon and Nebeker *et al.* (1976) with sockeye salmon, the present study with steelhead showed that there was a significant difference ($P < 0.05$) in time to death at different O_2/N_2 ratios when fish were tested at the same total dissolved gas pressure. Fish died rapidly at 140 and 135% saturation, with fish dying more quickly at the lower oxygen nitrogen ratios where nitrogen made up a much greater portion of the total gas. Mortality also occurred more rapidly at the lower O_2/N_2 ratios at 130%. Mortality patterns at 125% were similar to the other three total gas concentrations but the LT50 increased as the oxygen concentrations increased (Fig. 2). The lower oxygen concentrations in the four tests: 4.8 mg l^{-1} at 125%, 4.9 mg l^{-1} at 130%, 4.4 mg l^{-1} at 135%, and 6.1 mg l^{-1} at 140%, may have contributed to the mortality caused by supersaturation, but this was not determined due to the rapid mortality at the high nitrogen levels needed to maintain the desired total gas pressures.

In plotting the effects of different O_2/N_2 ratios on the survival of steelhead (time to 50% death) at the same total dissolved gas pressure, it was found that the same results could be obtained using dissolved oxygen rather than O_2/N_2 ratios, making the graphs simpler to prepare and understand. The curves in Fig. 2 show, based on the data available, what the time to death might be at different O_2 levels and total dissolved gas pressures. We were unable to construct a reasonably simple mathematical model which fits the patterns found in Fig. 2.

The curve (X) showing time to 50% mortality for juvenile coho salmon from Rucker (1976) is superimposed on Fig. 2 to see how it compares with the data in this paper. Although the mortality pattern was similar, the time to death cannot be compared because more tolerant coho salmon were used in the Rucker study, and steelhead trout were used in the present study.

At 125% total gas saturation steelhead died most rapidly at the lowest O_2 concentration of 4.8 mg l^{-1} (O_2/N_2 ratio of 44.2/146.6), indicating that the low oxygen–high nitrogen combination was rapidly lethal, with 50% mortality occurring at 4.7 h exposure. At the highest O_2 concentration of 14.3 mg l^{-1} (O_2/N_2 ratio of 129.4/125.6), the LT50 was 16.5 h, 4 times as long as the lower O_2/N_2 ratio. The low O_2 concentration of 4.9 mg l^{-1} (O_2/N_2 ratio of 45.9/151.8) at 130% had 50% mortality at 3.7 h, while the high O_2 concentration of 18 mg l^{-1} (O_2/N_2 ratio of

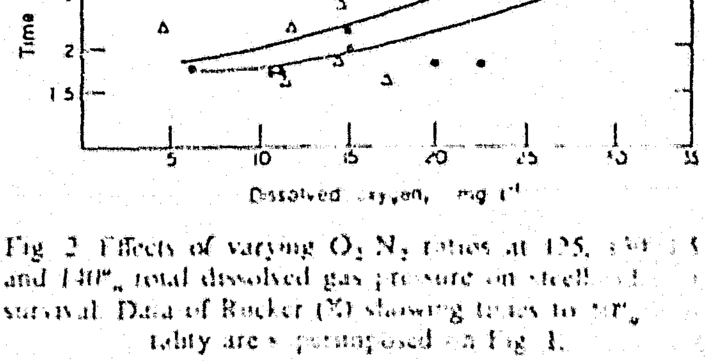

Fig. 2. Effects of varying O_2/N_2 ratios at 125, 130, 135 and 140% total dissolved gas pressure on steelhead survival. Data of Rucker (X) showing time to 50% mortality are superimposed on Fig. 1.

166.5/121.1) had an LT50 of 5.5 h. The difference is not as great as that of 125%, because the total gas concentration of 130% kills fish more rapidly. Table 2 gives a summary of the times to 50% death (LT50) for steelhead trout for each total gas concentration and each O_2/N_2 ratio.

A significant change in the ratio of oxygen to nitrogen in air-supersaturated water will result in a change in the lethality of that water to fish. If photosynthetic activity occurs, dissolved oxygen in the water will increase, the total dissolved gas pressure will increase, and the oxygen/nitrogen ratio will change, unless the water is vigorously agitated. The actual nitrogen concentration may decrease due to the physical stripping of nitrogen from the water column as oxygen bubbles rise to the water surface. In most instances water temperature increases during active photosynthetic activity because of increased insolation. This increased water temperature results in an increase in the total dissolved gas pressure, or supersaturation. If the temperature of the water increases without increased photosynthesis (from algae or higher aquatic plants) the oxygen nitrogen ratio (O_2/N_2) may not change significantly though the total per cent supersaturation will increase. If the temperature stays the same during increased photosynthetic activity (e.g. an algal bloom), the O_2/N_2 ratio will increase due to greater amounts of oxygen being produced. If the temperature increases during an algal bloom, supersaturation levels and the O_2/N_2 ratio will increase, depending upon the rate of temperature and O_2 changes.

The other main cause of change in the O_2/N_2 ratio is biological respiration, or use of oxygen by algae, higher plants, bacteria, fishes, etc. This decreases oxygen in the water, lowering the O_2/N_2 ratio and the total dissolved gas pressure, or supersaturation in the water. Man may radically alter aquatic systems by introducing nutrients which stimulate algal growth or increase bacterial respiration, causing even greater fluctuation in the O_2/N_2 ratio.

The results of this study are consistent with those of Rucker (1976) and Nebeker *et al.* (1976). Increased total air supersaturation causes greater mortality and a reduction in the LT50. An increase in the amount of oxygen (decrease in nitrogen), keeping the total gas saturation level the same, will reduce the mortality and increase the LT50. Conversely, an increase in the nitrogen concentration (decrease in oxygen) keeping the gas saturation concentration the same, will increase the mortality and decrease the LT50. The work of Knittel *et al.* (1978) showed clearly that if fish are removed from supersaturated water prior to death they can recover. Fish and other aquatic life may be able to tolerate brief higher levels of supersaturation because increased water temperature and photosynthetic activity during the day are offset by cooling and high respiration rates at night. Further studies with intermittent exposures simulating the daily changes in total per cent saturation and O_2/N_2 ratios in supersaturated water would be useful in predicting extent of fish mortality in those situations.

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DAEN-CWE-HD

DEPARTMENT OF THE ARMY
Office of the Chief of Engineers
Washington, DC 20314

ETL 1110-2-239

Engineer Technical
Letter No. 1110-2-239

15 September 1978

Engineering and Design
NITROGEN SUPERSATURATION

1. Purpose. The purpose of this letter is to provide guidance for the evaluation and identification of those projects with hydraulic structures having the potential to produce nitrogen supersaturation.

2. Applicability. This letter applies to all field operating agencies having responsibilities for the design of Civil Works projects.

3. References.

a. ER 1130-2-334

b. ER 15-2-11

4. Bibliography.

a. ER 1110-2-1402

b. EM 1110-2-1602

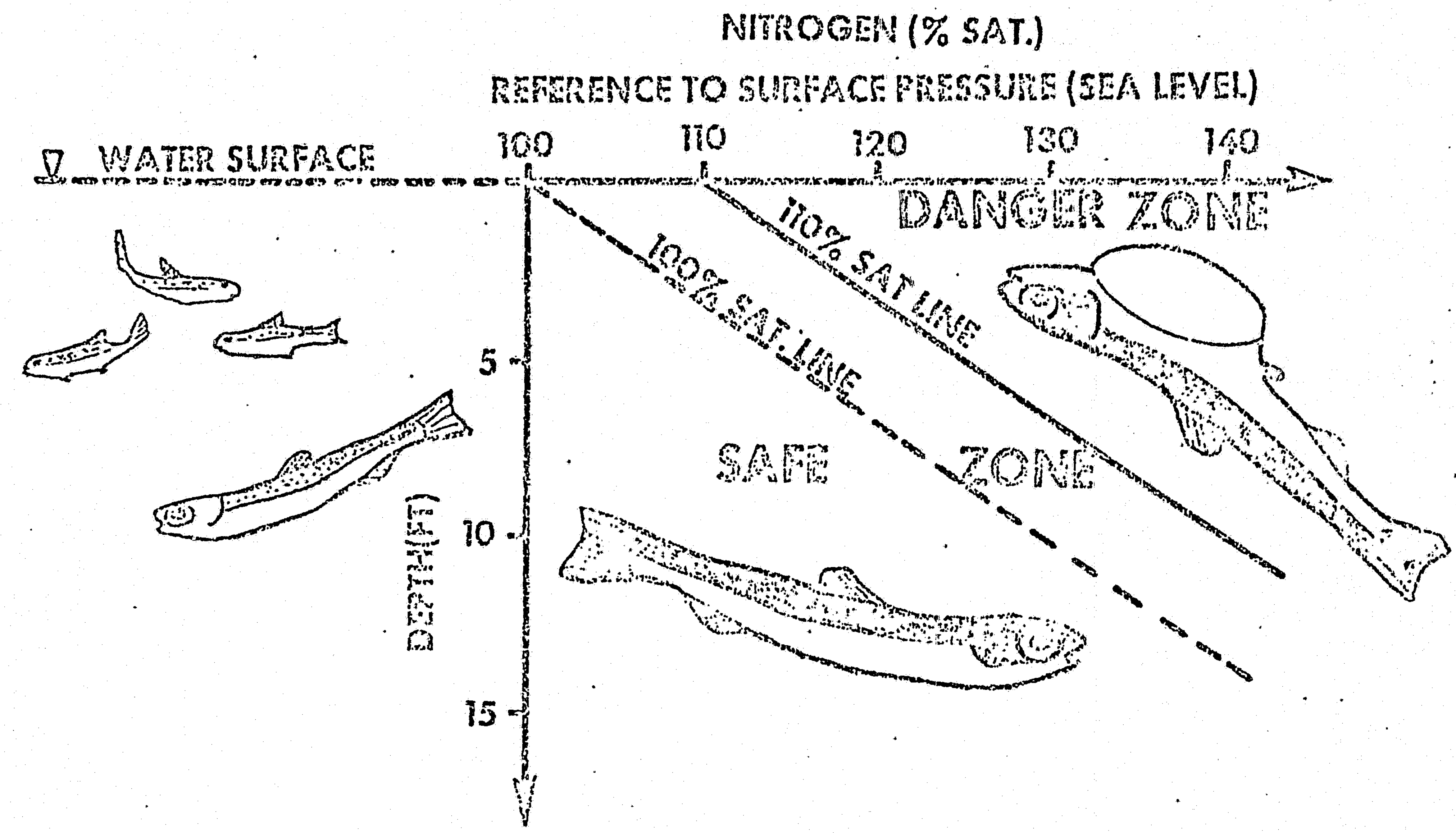
c. EM 1110-2-1603

5. Discussion.

a. Nitrogen supersaturation and associated fish mortality due to gas bubble disease has occurred at Corps of Engineers projects on the Columbia River in the North Pacific Division (NPD) and more recently at the Harry S. Truman project in the Missouri River Division. Nitrogen supersaturation can result at any hydraulic structure from entrained air introduced by the spillway-stilling basin action. As the flow is subjected to hydrostatic pressure in the stilling basin, a portion of the entrained air is driven into solution before it has the opportunity to rise to the surface and escape into the atmosphere. A potential problem situation will exist if the characteristics of the flow within or downstream of the stilling basin are such that the flow does not have the necessary turbulence to degas or purge itself of the excess dissolved nitrogen. Flow conditions below projects conducive to rapid equilibration with the atmosphere are shallow, turbulent streams. The reaeration and gas transfer characteristics of deep, slow moving rivers or downstream reservoirs are relatively small. Generally, fish will not suffer from gas bubble disease so long as they swim in depths below 15 feet. At those depths the external and internal gas pressures on fish are approximately equal. If the fish swim to the surface, however, the internal gas pressure exceeds the external gas pressure on the fish resulting in gas embolism or gas bubble disease. The tolerance of fish to levels of nitrogen supersaturation depends upon the time of exposure and the age and species of the fish; however, dissolved nitrogen levels referenced to surface pressure above 110 percent are generally considered to be harmful. (Figure 1.)

b. The phenomenon of nitrogen supersaturation below hydraulic structures is complex and depends upon a number of factors. Normally the problem of nitrogen supersaturation has been associated with aerated flows plunging into deep stilling basins with slow moving downstream flow conditions. If the hydraulic jump in the stilling basin is a free jump, sufficient turbulence should be present to degas the flow so that dissolved nitrogen levels referenced to surface pressure will not exceed 110 percent. If the hydraulic jump is submerged, the flow may plunge to the bottom of the basin. With submerged hydraulic jump flow conditions, the change in momentum of spillway or outlet works releases due to a typical 50 foot radius toe curve subjects the flow to a pressure about 1.16 times the hydrostatic pressure on the apron due to the downstream tailwater. The jump will become fully submerged when the tailwater depth is greater than approximately 125 percent of the theoretical d_2 value. It should be noted that roller bucket stilling basins are designed for tailwaters greater than 125 percent of d_2. In general, if for a given discharge the tailwater exceeds a depth of 25 feet and if the tailwater depth is greater than 110 percent of theoretical d_2 (partially submerged jump) and if flow conditions downstream of the project are not conducive for degassing the flow, the potential for nitrogen supersaturation exists and should be investigated.

c. Nitrogen levels can be determined by measuring total gas content with a gas saturometer and subtracting dissolved



THEORETICAL SAFE AND DANGER ZONES FOR FISH

FIGURE 1

oxygen content measured or by using a calibrated gas chromatograph. Techniques to estimate the percentage of nitrogen supersaturation below a hydraulic structure have been developed by NPD and by the U.S. Bureau of Reclamation (USBR). Inclosure 1 gives a summary of the development and evaluation procedure for the NPD method. Inclosure 2 gives a summary of the USBR method. The technique developed by NPD was based on projects in the Columbia River Basin. The spillways are all gate-controlled ogee crests and with the exception of The Dalles, they have similar stilling basin characteristics. The NPD method should be used to evaluate the effects of structures similar to those in the Columbia River Basin. The coefficients for this technique are based on these types of structures. The technique developed by the USBR is more general than the NPD technique and utilized data from a wider variety of hydraulic structures. The USBR technique should be used to evaluate the effects of structures other than the type found in NPD. Both techniques compute downstream nitrogen concentration values by considering such variables as upstream concentration, headwater and tailwater elevations, head loss, angle of the jet, residence time of the bubbles, and pressure conditions in the basin.

site specific?

d. If measurements or estimates indicate that a potential for nitrogen supersaturation problems exists, then detailed model studies of the project may be necessary to develop alleviation measures. Assistance in the studies can be obtained from the Waterways Experiment Station. Also, technical assistance can be obtained from both the Federal Interagency Steering Committee on Reaeration Research and the Committee on Water Quality (reference 3b). Requests for the services of either of these committees should be coordinated through HQDA (DAEN-CWE-H) WASH DC 20314.

6. Action Required. Review all reservoir projects, following the procedures outlined in Inclosures 1 and 2, to determine potential for nitrogen supersaturation problems under all operating conditions including interim conditions during construction.

a. Existing Projects. Report results and proposed corrective measures in Annual Division Water Quality Reports (reference 3a).

b. Projects under Planning, Design or Construction. Report results and proposed alleviation measures if required in appropriate portions of Survey-Feasibility Reports, Design Memoranda, Detailed Project Reports, etc.

FOR THE CHIEF OF ENGINEERS:

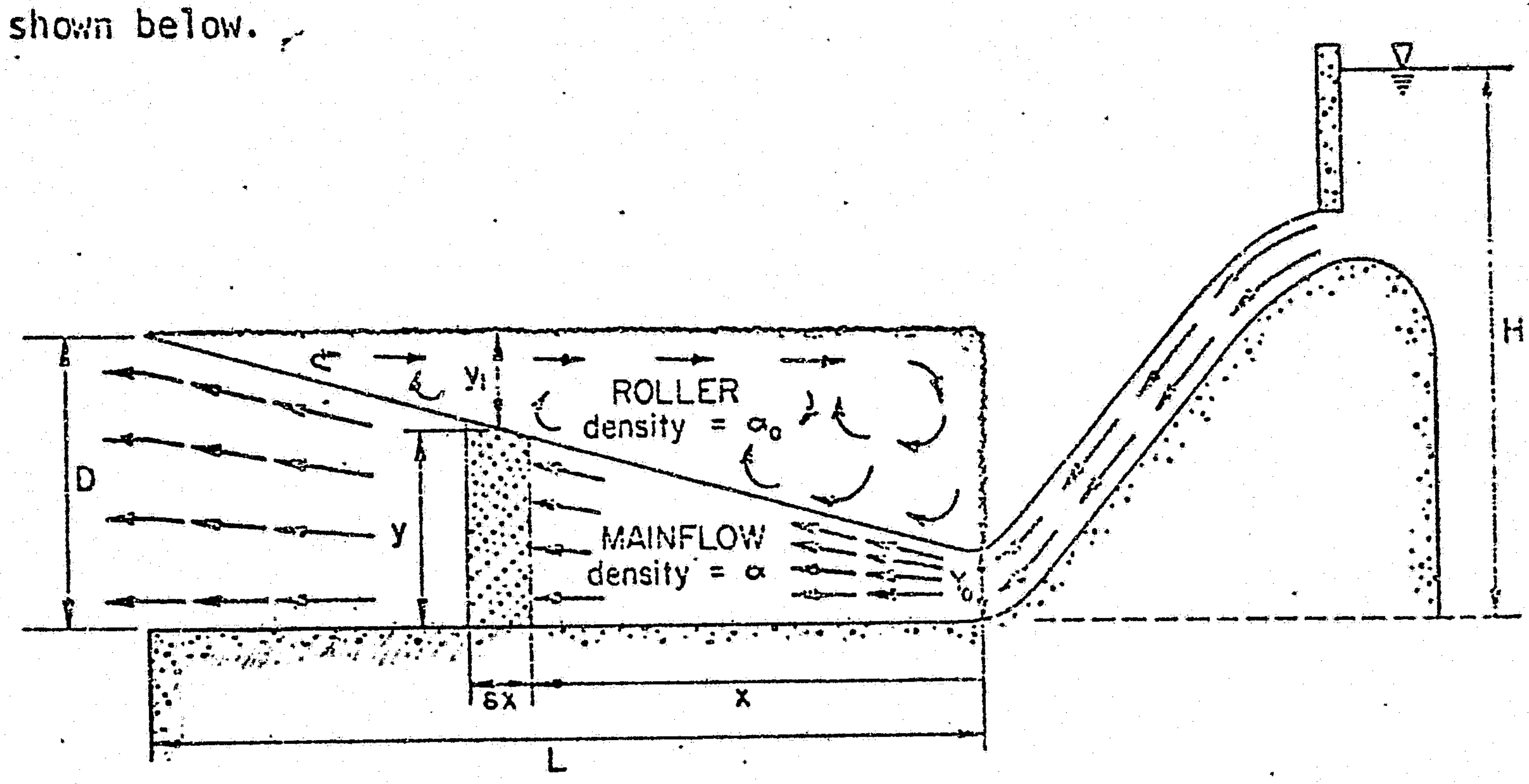
Homer B. Willis

2 Incl
as

HOMER B. WILLIS
Chief, Engineering Division
Directorate of Civil Works

DERIVATION OF THE SPILLWAY-STILLING BASIN MODEL*

Consider the conceptual representation of the stilling basin shown below.



CONCEPTUAL REPRESENTATION OF SPILLWAY-STILLING BASIN COMBINATION

The water parcel indicated in cross-section by the shaded area moves through the stilling basin, decelerating and increasing in height. It extends laterally the full effective width, w of the stilling basin as illustrated in Figure 3 of the main report.

We now make the following assumptions for the water parcel and stilling basin:

1. For that length of spillway that is in operation at a given time, the discharge is uniform along the

*Taken from: "A Nitrogen [illegible] (N_2) Model for the Lower Columbia River," Final Report, Water [illegible] Engineers, Inc., [illegible] contract to US Army Corps of Engineers, North Pacific Division, January 1971 crest (this is equivalent to assuming that the properties of the water parcel are constant along any line parallel to the spillway crest).

2. The value Y_o is the initial depth of the spill before the jump. It is computed as:

$$Y_o = \frac{q}{V_o} = \frac{q}{\sqrt{2gH}} \qquad \text{(A-1)}$$

where

q = discharge per foot along the crest

H = total reservoir head above the stilling basin floor.

3. The only effect of the roller which overlies the main flow is to increase the static pressure within the water parcel by an amount $\alpha_o y_1$.

4. A given mass of air M_A is entrained as discrete bubbles into the water parcel at the point $x = 0$ and remains uniformly distributed within the water parcel as it passes through the stilling basin.

5. The distribution of the mass of air among the various bubble sizes remains unchanged during the water parcel's journey through the stilling basin.

6. The dissolved nitrogen within the water parcel is uniformly distributed.

7. Rate of nitrogen dissolution $\frac{dM}{dt}$ in the water parcel is governed by Fickian diffusion as:

$$\frac{dM}{dt} = K_L A (C_E - C) \qquad \text{(A-2)}$$

where

M = the mass of dissolved nitrogen in the water parcel,

K_L = rate coefficient,

A = total surface area of the air bubbles contained in the water parcel,

C_E = effective saturation concentration of dissolved nitrogen in the water parcel, and

C = actual concentration of dissolved nitrogen in the water parcel.

With these assumptions, we can now define the parameters M, A, and C_E in equation A-2 as functions of the location of the water parcel in the stilling basin.

Assumption 6 allows us to write the mass M as the product of the concentration C and the volume of the water parcel,

$$M = (wy\delta x)C \qquad \text{(A-3)}$$

where w is the effective width of the stilling basin, i.e., w = (number of gates open) x (width per gate).

The saturation concentration of a gas such as N_2 or O_2 that is only slightly soluble in water is governed by Henry's Law which states that the equilibrium or saturation concentration of the gas in solution is directly proportional to the pressure existing at the gas-liquid interface. In the water parcel the pressure P at an elevation z above the stilling basin floor is

$$P = P_o + \alpha_o y_1 + \alpha(y-z) \qquad \text{(A-4)}$$

where P_o is the atmospheric (or barometric) pressure, and the α parameters are the densities of the roller and main flow as shown in Figure A-1. Hence, the saturation concentration at any elevation z in the parcel is given as:

$$C_{sat} = [P_o + \alpha_o y_1 + \alpha(y-z)]C^* \qquad \text{(A-5)}$$

where C^* is the saturation concentration under one atmosphere of pressure. In equation A-5, the pressure term has units of atmospheres of pressure. From equation A-5, it is seen that C_E varies linearly with z. It follows that the average or *effective* saturation concentration, C_E in the water parcel is the value of C_{sat} at mid-depth, or at $z = y/2$: Thus,

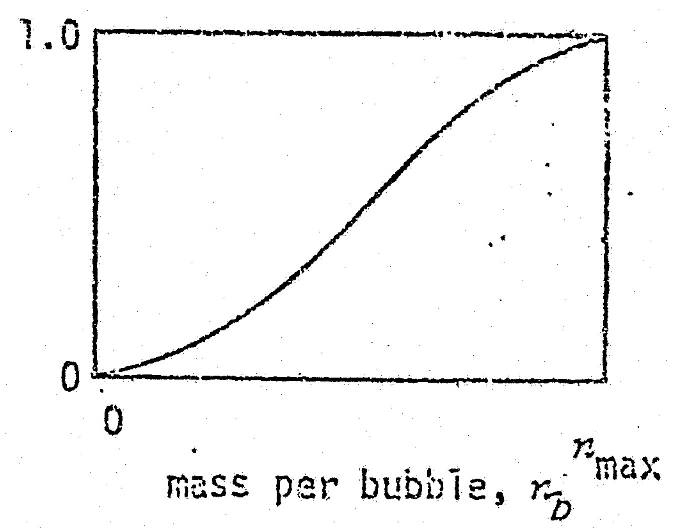
$$C_E = [P_o + \alpha_o y_1 + \alpha(y/2)]C^* \qquad \text{(A-6)}$$

Noting that $y_1 = D-y$ gives the final form of C_E as

$$C_E = [P_o + \alpha_o D - (\alpha_o - \frac{\alpha}{2})y]C^* \qquad \text{(A-7)}$$

The total surface area A of the air bubbles in the water parcel depends upon the total mass of air entrained and, upon the bubble size distribution. It is not unreasonable to expect that the entrained mass of air will be distributed among the various bubble sizes in a manner similar to that shown below.

B = fraction of total air mass in the water parcel with bubbles having a mass less than or equal to m_b



The volume V_b of an air bubble with mass m_b can be found from the ideal gas law:

$$V_b = \frac{mRT}{P} \qquad \text{(A-8)}$$

where

m = number of moles of air in the bubble,

R = universal gas constant,

T = absolute temperature, and

P = the total pressure in the bubble.

In equation A-8, m can be replaced by $n_b/28.9$ where 28.9 is the molecular weight of air. The diameter d_b and the area A_b of a sphere are given by:

$$d_b = \left(\frac{6}{\pi} V_b\right)^{1/3} \qquad \text{(A-9a)}$$

$$A_b = \pi d_b^{\,2} \qquad \text{(A-9b)}$$

Now, combining equations A-8 and A-9, the following expression results for the surface area A_b of an air bubble with mass n_b:

$$A_b = \left(\frac{6\sqrt{\pi}RT}{28.9}\right)^{2/3} \left(\frac{n_b}{P}\right)^{2/3} \qquad \text{(A-10)}$$

Thus, if the total air mass entrained per unit volume of water at Y_o is M_A, the total air bubble surface areas A', per unit volume of water is found from the bubble size distribution and equation A-10 as

$$A' = \int_o^{n_{max}} A_b \frac{M_A \frac{dB}{dn_b} dn_b}{n_b} \qquad \text{(A-11)}$$

or

$$A' = \left(\frac{6\sqrt{\pi}RT}{28.9P}\right)^{2/3} M_A \int_0^1 n_b^{-1/3} dB \qquad \text{(A-12)}$$

Finally, to get the total bubble surface area in the water parcel it is necessary to integrate equation A-12 over the volume of the parcel $wy\delta x$, i.e.,

$$A = \int_{\delta x}\int_{w}\int_{z} A'\,dx\,dw\,dz \qquad \text{(A-13)}$$

Applying assumptions 4 and 5 and substituting for A' from equation A-12 gives

$$A = w\delta x\left(\frac{6\sqrt{\pi}RT}{28.9}\right)^{2/3} M_A\int_0^1 n_b^{-1/3}dB \int_{z=0}^{y} \frac{dz}{P^{2/3}} \qquad \text{(A-14)}$$

Replacing P with equation A-4 and integrating,

$$A = 3\left(\frac{6\sqrt{\pi}RT}{28.9}\right)^{2/3} M_A\int_0^1 n_b^{-1/3}dB\;(w\delta x)\;\frac{(P_o + \alpha_o y_1 + \alpha y)^{1/3} - (P_o + \alpha_o y_1)^{1/3}}{\alpha} \qquad \text{(A-15)}$$

Substituting $(D-y)$ for y_1 gives the final form as

$$A = K_A\,(w\delta x)\left\{[P_o + \alpha_o D + (\alpha-\alpha_o)y]^{1/3} - [P_o + \alpha_o D - \alpha_o y]^{1/3}\right\} \qquad \text{(A-16)}$$

where

$$K_A = \frac{3}{\alpha}\left(\frac{6\sqrt{\pi}RT}{28.9}\right)^{2/3} M_A\int_0^1 n_b^{-1/3}dB$$

If the expressions for M, C_E, and A from equation A-3, A-7 and A-15 respectively are substituted into the rate expressions given in equation A-2, there results

$$(yw\delta x)\frac{dC}{dt} = (w\delta x)\ K_L K_A \left\{[P_o + \alpha_o D + (\alpha - \alpha_o)y]^{1/3} - [P_o + \alpha_o D - \alpha_o y]^{1/3}\right\} \cdot$$
$$\left\{[P_o + \alpha_o D - (\alpha_o - \frac{\alpha}{2})y]C^* - C\right\} \qquad \text{(A-17)}$$

We can now write rate expression $\frac{dC}{dt}$ in terms of the location in the stilling basin by using the relationship

$$\frac{dC}{dt} = \frac{dx}{dt}\ \frac{dC}{dx} = v\ \frac{dC}{dx} = \frac{q}{y}\ \frac{dC}{dx} \qquad \text{(A-18)}$$

where v is the velocity of the parcel and q is the discharge per unit width of the stilling basin. In addition, we define a system parameter K, which we will call the *entrainment coefficient*, as

$$K = K_L K_A = \frac{3}{\alpha}\left(\frac{6\sqrt{\pi}R}{28.9}\right)^{2/3} \left[T^{2/3} K_L\ a_A \int_0^1 n_b^{-1/3} dB\right] \qquad \text{(A-19)}$$

Substituting equation A-18 and A-19 into A-17 gives the expression for the concentration change in the water parcel as

$$\frac{dC}{dx} = \frac{K}{q}\left\{[P_o + \alpha_o D + (\alpha - \alpha_o)y]^{1/3} - [P_o + \alpha_o D - \alpha_o y]^{1/3}\right\}$$
$$\left\{[P_o + \alpha_o D - (\alpha_o - \frac{\alpha}{2}y)]C^* - C\right\} \qquad \text{(A-20)}$$

The solution is obtained as follows. Evaluate the pressure terms at the midpoint of the stilling basin $y = \frac{D+Y_o}{2}$ to obtain

$$\frac{dC}{dx} = \frac{K}{q}\left\{[\overline{P} + \frac{\alpha}{4}(D + Y_o)]^{1/3} - [\overline{P} - \frac{\alpha}{4}(D + Y_o)]^{1/3}\right\}\left\{\overline{P}C^* - C\right\}. \qquad \text{(A-21)}$$

where $\overline{P} = P_o + \frac{\alpha_o}{2}(D - Y_o) + \frac{\alpha}{4}(D + Y_o)$

Now let

$$\overline{\Delta P^{1/3}} = [\overline{P} + \frac{\alpha}{4}(D + Y_o)]^{1/3} - [\overline{P} - \frac{\alpha}{4}(D + Y_o)]^{1/3} \qquad \text{(A-22)}$$

Rewriting equation A-21, with these substitutions gives

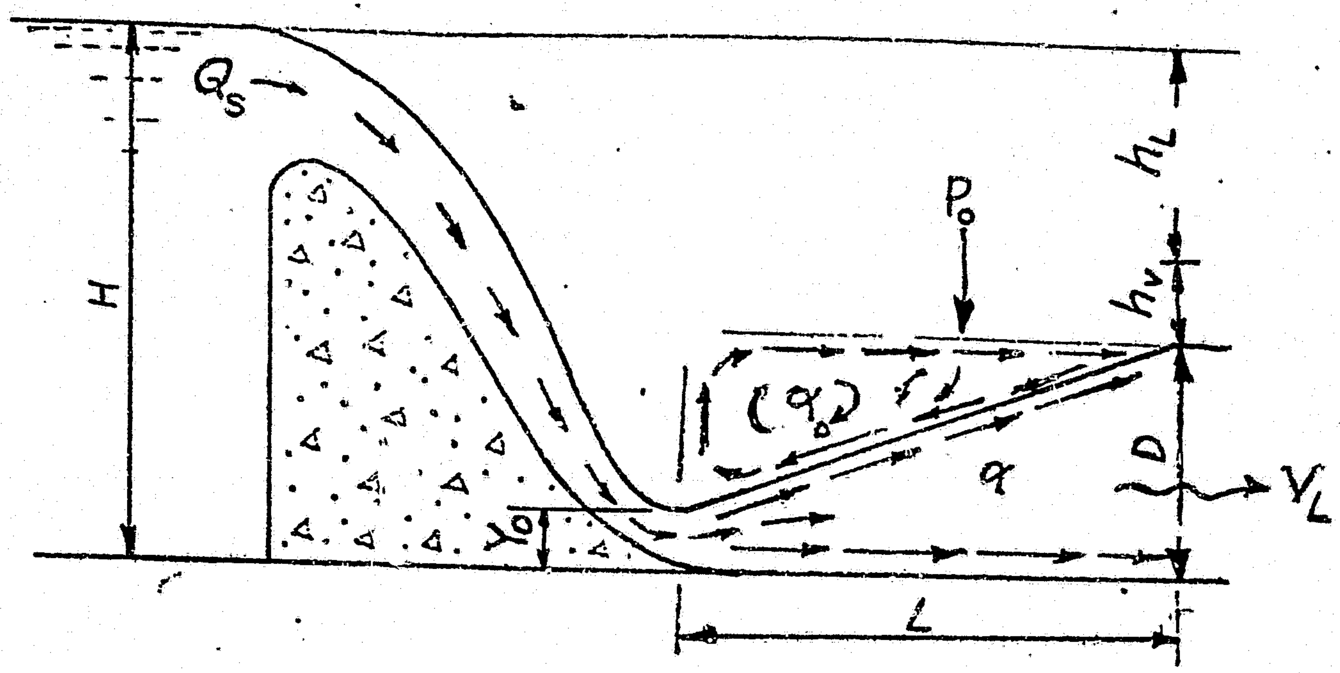
$$dC + C\frac{K}{q}\ \overline{\Delta P^{1/3}}\ dx = \frac{K}{q}\ \overline{\Delta P^{1/3}}\ \overline{P}C^*\ dx \qquad \text{(A-23)}$$

which has the solution

$$C = \overline{P}C^* + ke^{-\frac{K}{q}\ \overline{\Delta P^{1/3}}\ x} \qquad \text{(A-24)}$$

Evaluating equation A-24 at $x = 0$, where C equals the forebay concentration C_F, and at $x = L$ where C equals the stilling basin concentration C_S, yields the spillway-stilling basin model as

$$C_S = \overline{P}C^* - (\overline{P}C^* - C_F)\ e^{-\frac{K}{q}L\ \overline{\Delta P^{1/3}}} \qquad \text{(A-25)}$$



DEFINITION SKETCH

RESIDENCE TIME = t_R = $WDL/Q_s = DL/q \approx L/V_L$

TOTAL HEAD LOSS = $h_L = H-D-h_v = H-(D+v_L^2/2g)$

ENERGY LOSS RATE = $E = h_L/t_R$

AVE. PRESSURE = $\overline{P} = P_o + \frac{\alpha_o}{2}(D-Y_o) + \frac{\alpha}{4}(D+Y_o)$. α = 0.0295 atm./ft.
$\alpha_o = \alpha c$

N_2 CONCENTRATION (K) AT END OF STILLING BASIN, L

$$C_s = \overline{P}C^* - (\overline{P}C^* - C_F)\exp\left(-\frac{K}{q} L\, \overline{\Delta P}^{1/3}\right)$$

$$\overline{\Delta P}^{1/3} = \left[\overline{P} + \frac{\alpha}{4}(D+Y_o)\right]^{1/3} - \left[\overline{P} - \frac{\alpha}{4}(D+Y_o)\right]^{1/3}$$

$$K = \frac{q}{L\,\overline{\Delta P}^{1/3}} \ln\left(\frac{\overline{P}C^*-C_f}{\overline{P}C^*-C_s}\right) = K_{20}(1.028)^{(T-20)}$$ T = Water Temperature.

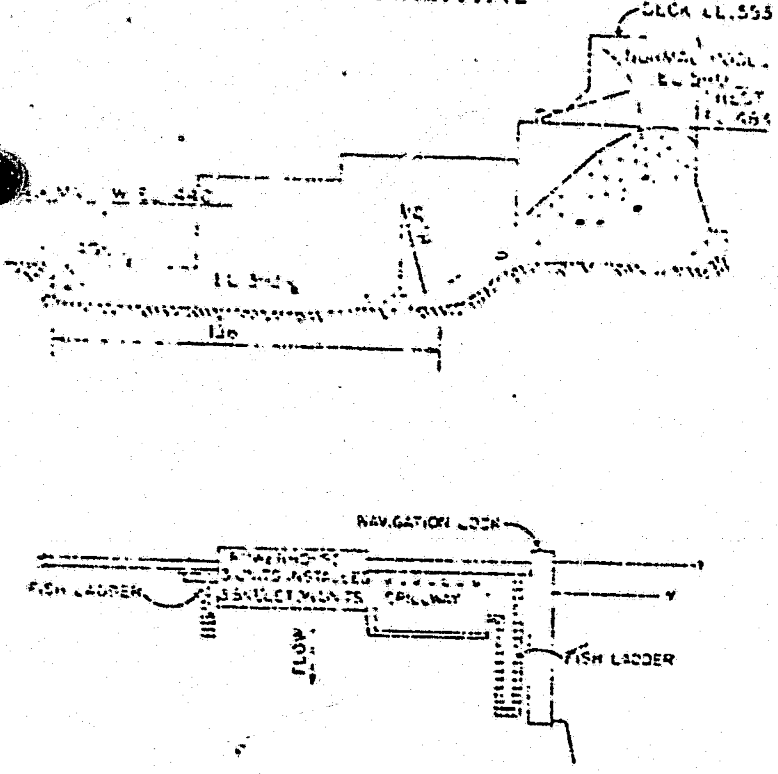
$K_{20} = aE^b$. a & b are empirically determined from observed data. They are shown below:

MODEL COEFFICIENTS

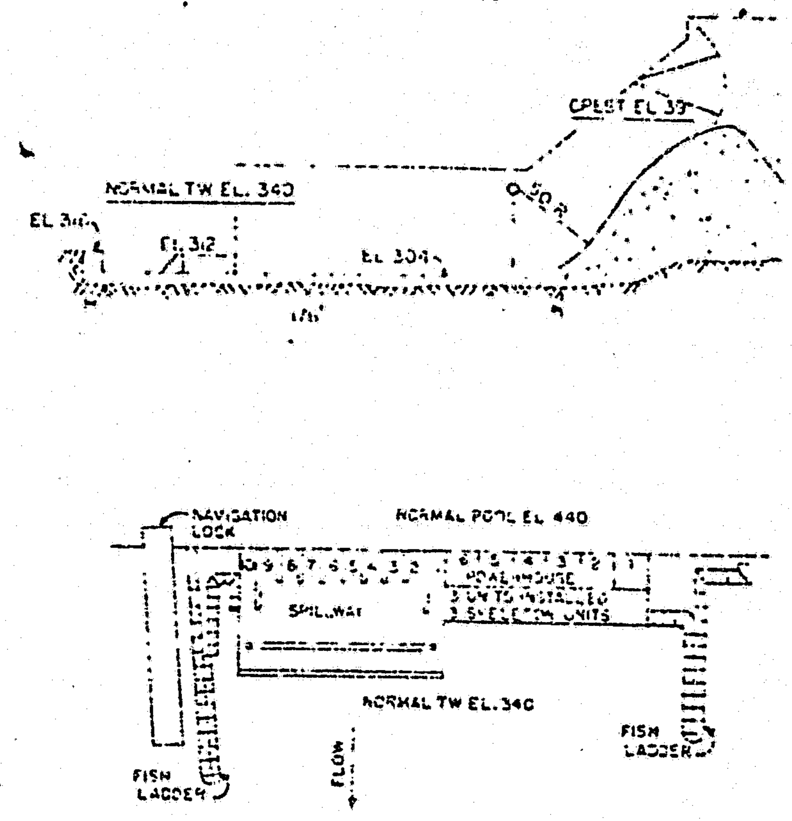
PROJECT	c	a	b
Little Goose	1.00	0.09	2.45
Lower Monumental	1.00	0.09	2.45
Ice Harbor	1.00	[illegible]	[illegible]
McNary	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]		[illegible]
The Dalles	0.50	0.80	2.50
Bonneville	1.00	1.90	1.00

1/ Developed by Water Resources Engineers, Inc. for the Corps in 1971.

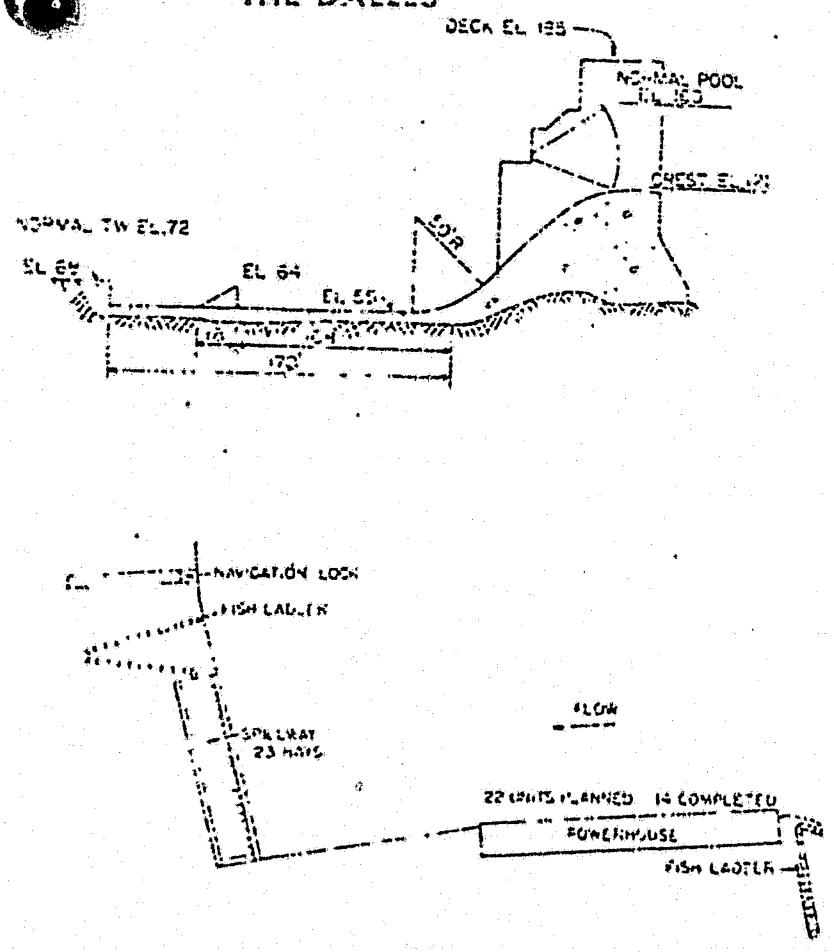
LOWER MONUMENTAL



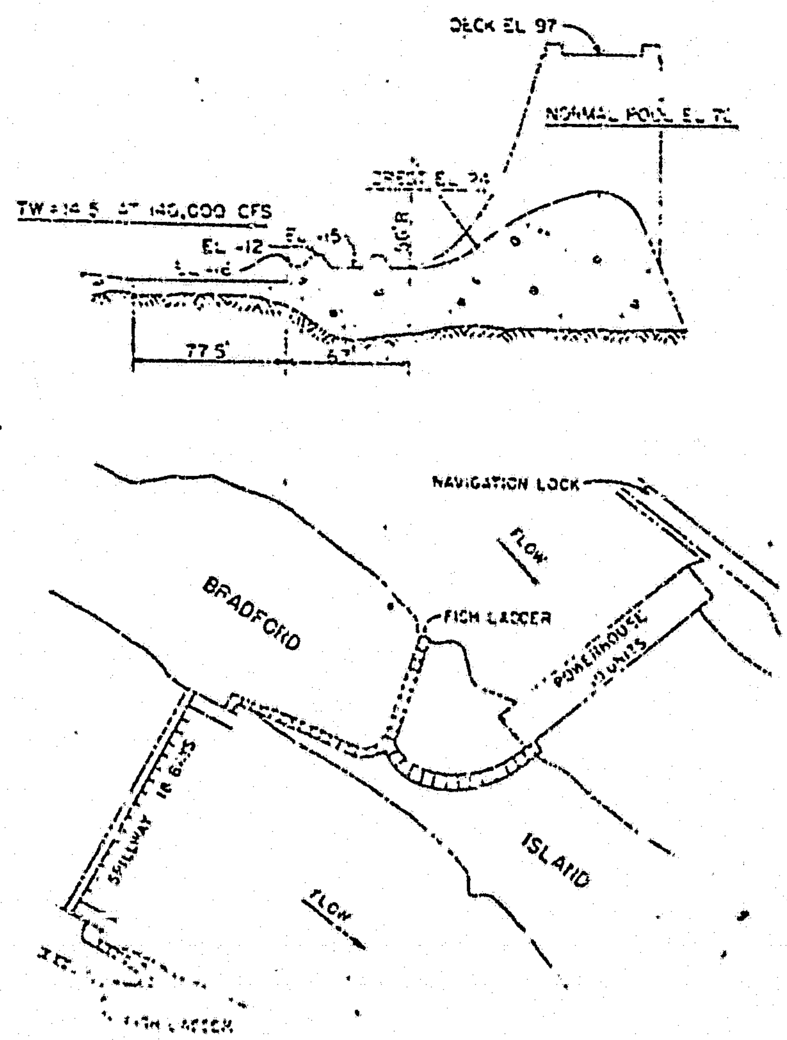
ICE HARBOR



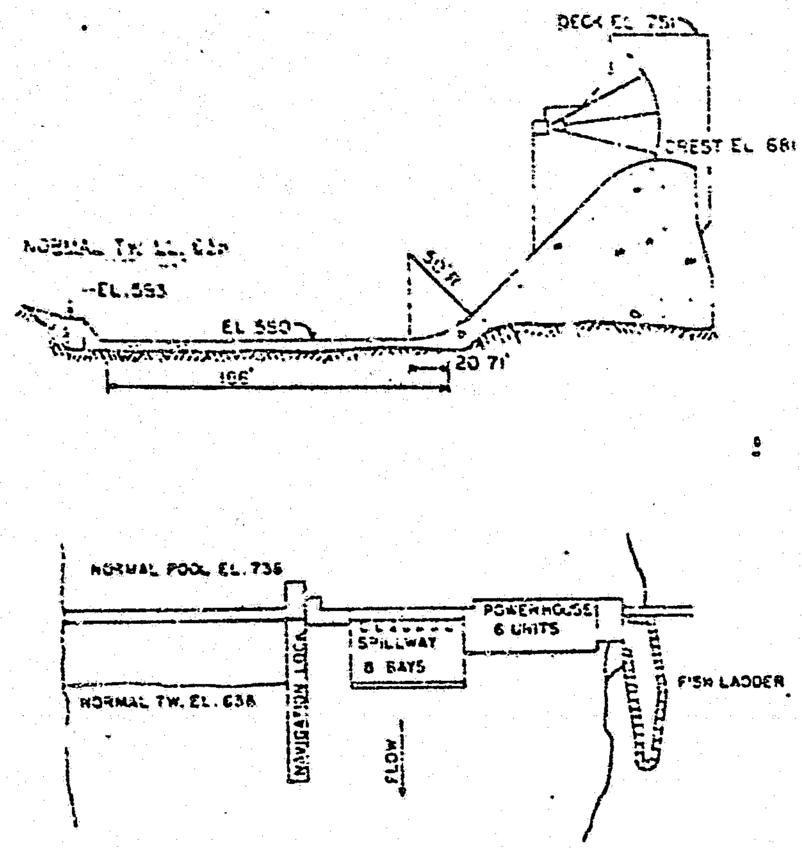
THE DALLES



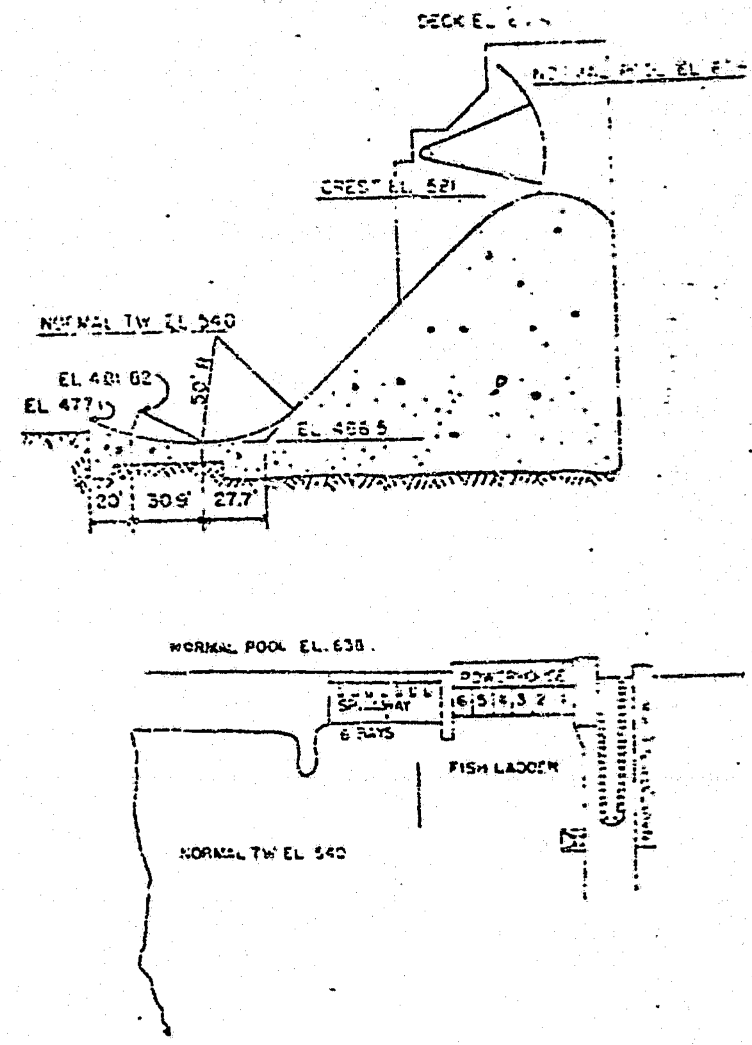
BONNEVILLE



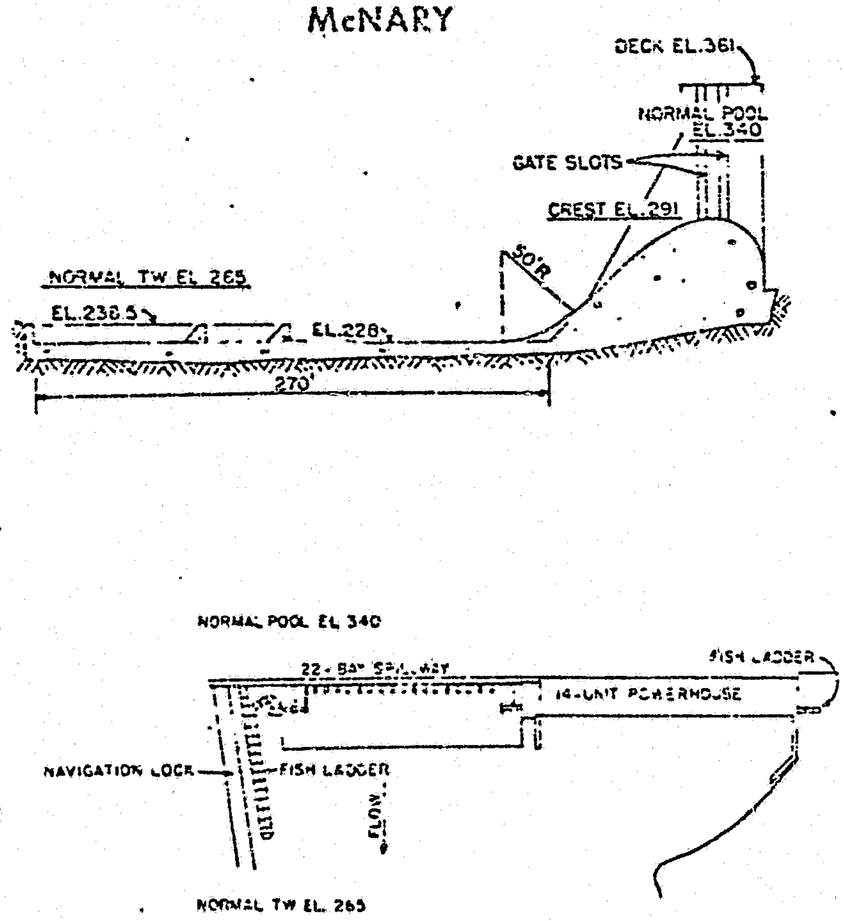
LOWER GRANITE



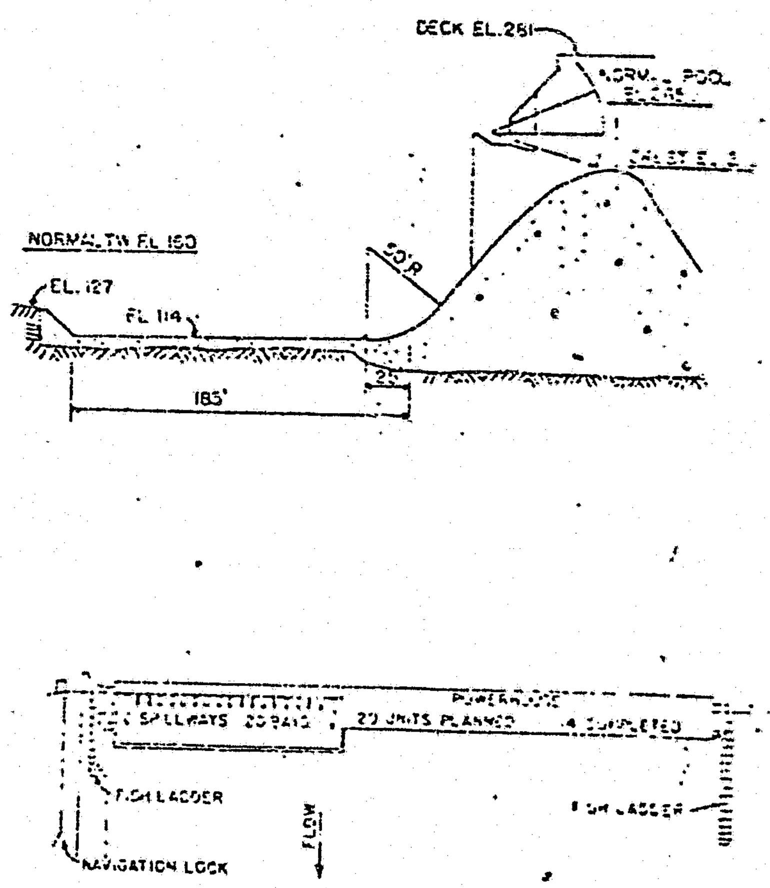
LITTLE GOOSE



McNARY



JOHN DAY



PREDICTION OF DISSOLVED GAS AT HYDRAULIC STRUCTURES[1/]

by Perry L. Johnson[2/] and
Danny L. King[3/]

Introduction

With the increased interest in the effects of hydraulic structures on the dissolved gas concentration of the flow, it becomes desirable to be able to predict how particular structures operating under specific conditions will change the dissolved gas concentration.

At existing structures a predictive ability would enable the facility operator to select the method of release that would have the most desirable effect on the dissolved gas concentration of the flow. Prototype data indicate that the change in the dissolved gas concentration is dependent on the type of structure through which the flow passes, the magnitude of the discharge, the barometric pressure, and the water temperature. To establish an operating criteria for each structure based on actual measurement of resulting dissolved gas concentrations would be a difficult task. A predictive ability could yield an understanding of a structure's potential and allow preparation for the possible consequences, even if the structure had never operated.

Also, with a predictive ability designers would have an additional factor which could be considered in structure selection. Depending on the situation, it is conceivable that the dissolved gas potential might even control the design. Planners could also use a predictive ability to evaluate the potential effects of a single hydraulic structure, or a series of hydraulic structures, on a river.

Initially, the dissolved gas concentration above the structure (both oxygen and nitrogen) is equal to the concentration established by the inflowing stream. The nitrogen, being relatively inert, will maintain this concentration for quite some time. The oxygen, however, especially in the lower depths of a resevoir, may be depleted from the decaying of organic material. Thus, if water is released it may be low in dissolved oxygen and yet may conceivably be high in dissolved nitrogen. Furthermore, the water may be high in biochemical oxygen demand (BOD) which would reduce the dissolved oxygen concentration in the stream below the dam. Therefore, the analysis should be able to evaluate how effectively structures increase depleted gas concentrations as well as evaluate whether supersaturated conditions might be created.

Such predictive methods have been developed for the spillways of the U.S. Army Corps of Engineers dams on the Columbia River (1). Most of these structures are geometrically similar. They are low head, run-of-the-river structures, with gate-controlled ogee spillways. The stilling basins are also of similar design. This similarity enabled the development of a predictive analysis that is quite satisfactory for the structures considered. The Bureau of Reclamation has few structures that correspond to these Columbia River dams. In general, Bureau structures vary widely in type and size. Thus, a much more generalized predictive analysis is required for significant application.

1/ [illegible]

2/ Hydraulic Engineer, Bureau of Reclamation, Denver, Colorado
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As a basis for development of the analysis, the following data were collected:

1. Reservoir water temperature, dissolved oxygen concentration, and dissolved nitrogen concentration at the elevation from which the water is withdrawn
2. Discharge and a record of which gates or valves are operating if releases are being controlled
3. Tailwater elevation, temperature, and dissolved oxygen and nitrogen concentrations in the tailrace
4. Local barometric pressure
5. Photographs of the structure operating and dimensioned drawings of the structure's configuration

By fall of 1973 the monitoring program of the Bureau's Engineering and Research Center had reached 16 sites and had observed 24 structures in operation. Forty-nine different operating conditions had been studied. In addition the Pacific Northwest Region of the Bureau of Reclamation has closely studied Grand Coulee Dam and made observations at 36 other sites. The Upper Missouri Region of the Bureau has performed monitoring at Yellowtail Afterbay Dam. Combined, these data provided an adequate base from which the predictive analysis could be developed.

Analysis

The process of gas transfer is described by the equation:

$$C(t) = C_S - (C_S - C_I)\, e^{-Kt} \qquad (1)$$

where $C(t)$ = final dissolved gas concentration
C_S = saturation concentration
C_I = initial concentration
K = a constant of proportionality
t = time

$C(t)$, C_S, and C_I are concentrations in mg/L of water.

Equation 1 shows that the final dissolved gas concentration, $C(t)$, below a hydraulic structure is dependent on the initial concentration, C_I, in the reservoir, the saturation concentration, C_S, in the stilling basin, the length of time, t, that gas is being dissolved into the flow, and a constant, K, that would be expected to vary with the specific hydraulic structure and operating condition. C_I will be either set at a known level or assumed. The other three parameters (C_S, t, and K) are dependent on the type of stucture, operating condition, temperature, and barometric pressure. Efforts were directed at evaluating C_S, t, and K computationally.

The saturation concentration level, C_S, in the stilling basin, is dependent on the pressure that can be developed in the basin and the water temperature. The pressure obtained in a stilling basin is dependent on the depth of water over the flow in which the bubbles are entrained and the barometric pressure. Thus, surface water at sea level will hold 33 percent more gas than surface water at an elevation of 8000 ft (2438 m). Also, water at the surface of a pool will hold 50 percent less gas than water at a depth of 34 ft (10.4 m). [illegible] pressure is basically [illegible] structure is located, with daily fluctuations that result from atmospheric conditions. The effects caused by daily fluctuations in atmospheric pressure are not large but they may be significant and should be considered in the evaluation of C_s. In this analysis measured barometric pressures were used when available. If measured values were not available a standard atmosphere was assumed and barometric pressures were computed according to elevation.

The depth of water over the flow in which gas is being dissolved is generally dependent on the depth of water in the stilling basin. Thus, variations in the tailwater elevation will have some effect. Throughout this analysis a water depth equal to two-thirds of the basin depth was used to compute saturation concentrations. It was thought that initially the fairly compact jet from a spillway or outlet would penetrate to the floor of the stilling basin. The flow would then be deflected downstream and out of the basin. As the flow moved through the basin it would be diffused and its velocity reduced. This diffusion would be linear and result in a triangular pattern with the average depth through the diffusion being two-thirds of the total basin depth. Bubbles rising from the flow and incomplete flow penetration would tend to reduce this average depth, but the two-thirds depth was considered representative and therefore used in the analysis. A major point of support for the two-thirds depth assumption is the fact that later applications proved the assumption reasonable. If the flow being studied does not penetrate to the bottom of the pool the maximum depth of flow penetration may be used in this calculation in place of the basin depth.

Evaluation of C_s is achieved by summing the barometric pressure and two-thirds of the basin depth (expressed in mm of Hg) and dividing this total pressure by standard atmospheric pressure (760 mm of Hg) to obtain the average absolute pressure on the dissolving bubbles in terms of atmospheres. This average absolute pressure is then multiplied by the dissolved gas saturation concentration at sea level, for the desired water temperature, to obtain C_s.

The next parameter from equation 1 to be considered is the time, t. It is representative of the length of time that the inflowing jet with entrained air is under pressure in the stilling basin and, thus, the length of time that gas is being dissolved in the flow. Consideration of time revealed two possible limitations that could control its value. First, it would seem that given sufficient time the entrained air bubbles would rise out of the flow and end the dissolving of gas. In some cases it would seem that an evaluation of this bubble rise time could be used to represent time. On the other hand, situations might occur where the flow with entrained air would pass through the basin and be deflected to a shallow depth in a fairly short time. Therefore, the actual length of time required for the flow to pass through the basin could represent t. During this analysis the assumption was made that either of these time periods might be critical in specific situations. For each flow condition and structure studied, t was evaluated for both limitations. The smaller of the two computed values was considered applicable to the particular situation and was used in the remainder of the analysis.

Bubble rise time. - Evaluation of t based on the bubble rise time, t_1, would be, if strictly pursued, a very complex computation which would probably produce questionable results. The vertical distance [illegible] the jet (thickness of jet that the bubble would rise [illegible]) [illegible] on bubble rise time, t_1, was evaluated by dividing the calculated vertical thickness of the jet at the tailwater surface by the terminal rise velocity of the bubble. By trial and error, it was determined that an assumed 0.028-inch (0.7-mm) diameter bubble with a theoretical terminal velocity of 0.656 ft/s (0.2 m/s) yielded the most consistent results with respect to observed prototype conditions. Also, when an analysis was developed that predicted K (equation 1) from two dimensionless parameters, it was found that the 0.028-inch-diameter bubble yielded predicted values of K that were consistent with the predicted values of K based on the basin retention time.

Basin retention time. - Computation of the flow retention time, t_2, in the basin is accomplished by dividing the path length of the flow by the average flow velocity along the path. The path length is generally controlled by the basin shape. The path length is the distance from the point at which the jet enters the tailwater pool to the point at which the majority of the flow is directed toward the surface and, therefore, into a lower pressure zone. If a large portion of the flow is deflected upward at a point by baffle piers, for example, this point would be considered the end of the path.

To compute the average flow velocity over the path length, the first step is to obtain the jet velocity at the tailwater surface (or at the start of the flow path) from the previous analysis of bubble rise time. To determine the average flow velocity, the velocity at the end of the path must be found. This is done through the use of figure 1 which is a summary of information from studies of jet diffusion by Yevdjevich (2) and Henry (3). Observation of velocity distributions in jet diffusions indicates that half of the maximum velocity would be an approximation of the jet's average velocity at the end of the flow path. This average velocity might also be evaluated by dividing the discharge, Q, by the channel cross sectional area, A, which would assume complete diffusion of the jet. The larger of the computed velocities should be used, since the average jet velocity at the end of the path could be higher, but not lower than the average velocity through the full cross section. The velocities at the beginning and end of the flow path are then averaged, then this average is divided into the flow path length to obtain the basin flow retention time (t_2). As previously stated, the value of t to be used in equation 1 is the smaller of the two computed values (t_1 or t_2).

The final term in equation 1 to be evaluated is K. K is unlike the other terms evaluated in that it is not directly representative of any specific physical parameter. K is a measure of the ability of a particular structure, operating under a particular condition, to dissolve gas. It is representative of the degree of air entrainment and the rate at which the water at the gas-liquid interface is replenished.

It appears that K is dependent only on the hydraulic performance of the basin. Attempts to find a predictive procedure that could be used to evaluate K resulted in the curves shown in figure 2. To obtain these curves the prototype data were manipulated into various parameters until useable results were found. Only dissolved nitrogen data were used in the development due to the stability of nitrogen. At a few of the reservoirs data were collected at several depths. These data indicated that dissolved oxygen concentrations may vary widely through the depth of a reservoir but that dissolved nitrogen concentrations are fairly constant. At some other reservoirs dissolved gas data were collected only near the surface and not at the withdrawal location. Therefore, if dissolved nitrogen and oxygen concentrations are measured at the reservoir surface and the withdrawals are made from deep in the reservoir, the measured values of the initial dissolved gas concentrations, C_i, are probably more accurate for nitrogen than oxygen. Even though dissolved nitrogen data were used as a base for the analysis, application of the analysis for observed prototype conditions indicates that resulting dissolved oxygen levels may also be predicted.

Figure 2 shows that the value of K is dependent on two parameters. The first is H_v/X, the velocity head, H_v, at the tailwater surface divided by the flow path length X. H_v/X is an energy gradient parameter for the flow; it relates the amount of energy in the flow to the path length in the basin over which the energy is dissipated. The greater the value of H_v/X the more turbulent the basin flow and the larger the resulting K value. The path length used corresponds to the value of t selected. If t_2 is applicable, then the value used for X would be the path length used to evaluate t_2. But if t_1 is applicable, the path length is adjusted to determine the effective path length for the time interval, that is, the length of time the bubbles remain in the jet. Flow deceleration is assumed linear and the ratio of t_1/t_2 is multiplied by the total velocity drop to determine the velocity drop along the adjusted path length. The average velocity along the adjusted path is then computed (initial velocity minus one-half the velocity drop) and multiplied by t_1 to determine the adjusted path length.

The other parameter on which the value of K is based is a ratio of the shear perimeter of the jet to the jet's cross-sectional area at the tailwater surface. This term is a measure of the jet compactness and shape. The shear perimeter for a jet is defined as the length of the jet's perimeter over which a shearing action is occurring between the jet and the water of the stilling basin pool. For a free jet plunging into a pool the shear perimeter would equal the total perimeter of the jet, while for a flow passing down a chute spillway and into a basin the shear perimeter would be the chute width at the tailwater surface. Situations exist where the walls of the stilling basin are offset from the jet entering the basin. If this offset is small, questions may arise as to whether the sides of the jet should be included in the shear perimeter. This is a judgment factor and is probably best handled by individual consideration. Another common structure that might raise a similar question would be a hollow jet valve discharging into a pool. Although the flow would have a ring-shaped cross-section, only the outside perimeter should be included in the evaluation. In general, if it appears that significant shear will occur along the section of perimeter in question then those lengths should be included in the analysis.

With the evaluation of K from figure 2, equation 1 may be applied and the final dissolved gas concentration, C(t), determined. The prototype data were used extensively to evaluate the coefficients that are applied throughout the analysis. This empirical approach is mandatory because of the complexity of the flows being considered. Very few of the situations studied have clearly defined flow conditions that are well suited for direct analysis. Not only are the jets that leave the spillway chutes, the valves, and the gates often quite complex, but the stilling basin pools are equally complex. Any analysis of these flow conditions would be quite involved and the accuracy would be questionable. However, the coefficients resulting from this analysis [illegible] a rational [illegible] physical phenomena. The coefficients can be interpreted to yield additional insight into the significance of the various factors.

Although some entrainment of air is needed for the dissolved gas uptake to occur, the amount of entrained air required seems to be quite small. At some of the prototype structures releases were exposed only briefly to the air. In some of these cases the water surfaces of the releases were also relatively smooth. Thus, it is assumed that little air was entrained. This assumption was verified by the small quantities of air that were observed returning to the tailwater surface. However, in some instances, the structures with little apparent air entrainment were among the worst in creating supersaturated conditions.

Example Application

Included with the example is a drawing of the structure (figure 3) and photographs (figure 4) of operation. The computations are described step by step. All critical points and all judgments or approximations are discussed and the results of the analysis are compared to actual field findings. Results are also included for examples for which the calculations are not shown. Variations between the observed and calculated dissolved gas concentrations may be attributed to several factors. First, and probably one of the most important, is that the entire analysis was based on average prototype data. Therefore, some structures will fit the analysis better than others and some structures will yield more accurate predicted results. A second significant source of variation would be errors in measuring the prototype dissolved gas concentrations. The chemical analyses used are not completely accurate, but even more important, samples may be collected from regions that are not representative of the total flow. Extreme errors of this sort may or may not be obvious. In several cases, two or more readings were available which gave some additional assurance. Variations due to errors in data collection may be small or they may be quite large. Application of the analysis and use of the graphs may also result in some error, but this error should be small. All factors considered, the results are very encouraging.

Example. - Sluiceway. - The following information is known:

Reservoir water surface elevation = 3196 ft (974 m)
Tailwater surface elevation = 3168 ft (966 m)
Barometric pressure = 677 mm Hg
Water temperature = 4.4 °C
Discharge = 3550 ft^3/s (100 m^3/s)
Reservoir dissolved nitrogen concentration = 104 percent of saturation
Reservoir dissolved oxygen concentration = 85 percent

The structural dimensions in figure 3 and the photograph in figure 4 are also available. From these sources the following terms are deduced:

H_v = 3196 - 3168 = 28 ft (8.5 m)
Angle of jet penetration ≃ 25°
Basin depth = 3168 - 3146 = 22 ft (6.7 m)
Basin flow path length, X ≃ 95 ft (29 m)

It should be observed that no head loss was included in the evaluation of the jet velocity head, H_v. For this particular structure, this assumption should be reasonably valid in that the flow path between the control gate and the stilling basin pool is short and unobstructed. Because of the changing slope of the flow surface as it enters the stilling basin, the angle of penetration was approximated to be 25° below horizontal. The basin depth of 22 ft (6.7 m) was computed for the deepest portion of the pool. Finally, the flow path length, X, of 95 ft (29 m) is approximately the distance from the point where the jet would attain significant penetration to the end sill of the basin. It was reasoned that at the end sill a large portion of the flow will be deflected upward, the flow will no longer be under the higher pressure, and dissolving of gases in the basin will be complete. These approximations are quite rough, but attempts to refine the evaluations would yield only slight improvements and would call for and indicate unwarranted accuracy.

The absolute dissolved nitrogen concentration in the reservoir is evaluated as the first step in the analysis. This is accomplished by referring to appropriate standard tables and obtaining the nitrogen saturation concentration for the specific water temperature (4.4 °C) and multiplying it by the relative reservoir dissolved nitrogen concentration (104 percent).

$$C_I = (1.04)\ (20.7) = 21.5 \text{ mg/L}$$

Next the potential absolute dissolved nitrogen concentration for the stilling basin is computed. As stated before, it is dependent on the barometric pressure, water temperature, and basin depth. Two-thirds of the basin depth is assumed as the average depth over the flow while the gas is being dissolved. Using this approximation an average pressure on the flow (in atmospheres) is computed and multiplied by the absolute dissolved nitrogen concentration obtained earlier.

$$C_S = \frac{677 + 2/3(22)(304.8/13.55)}{760}\ (20.7) = 27.4 \text{ mg/L}$$

This term has been adjusted to reflect the barometric pressure and, thus, the structure's elevation. If the barometric pressure is unknown, a standard atmosphere may be used.

Two of the terms (C_S and C_I) of equation 1:

$$C(t) = C_S - (C_S - C_I)\ e^{-Kt}$$

have now been evaluated. The time, t, that gas is being dissolved, is the next term of interest. The bubble rise time, t_1, is evaluated first. To do this, the vertical dimension of the jet at the tailwater surface is found. The 28-foot velocity head yields a velocity of 42.5 ft/s (13.0 m/s). The discharge is then divided by the velocity to obtain a total flow cross sectional area for three gates.

$$3550/42.5 = 83.5 \text{ ft}^2\ (7.8 \text{ m}^2)$$

Assuming equal flow through each results in a flow cross sectional area of 27.8 ft^2 (2.6 m^2) for a single gate. When equal flow conditions are assumed for the gates, the analysis of each individual gate is identical and, thus, the analysis of the flow for only one gate will predict the performance of the entire structure. If the flow cross sectional area is then divided by the gate width [illegible] is determined.

$$27.8/8 = 3.5 \text{ ft } (1.1 \text{ m})$$

Since the flow is not horizontal the flow depth must be divided by the cosine of the angle of penetration to obtain the vertical dimension of the jet.

$$3.5/\cos 25° = 3.5/0.9063 = 3.9 \text{ ft } (1.2 \text{ m})$$

If this distance is then divided by the terminal bubble velocity, a bubble rise time, t, is obtained.

$$t_1 = 3.9/0.696 = 5.6 \text{ seconds}$$

The length of time, t, is also evaluated by considering the length of time that the flow is at an effective depth in the basin. To do this the curves in figure 1 are used. First, the flow path length, X, is divided by the flow depth, B_o.

$$X/B_o = 95/3.5 = 27.1$$

The flow width (L_o) is then divided by the flow depth.

$$L_o/B_o = 8/3.5 = 2.3$$

Figure 1 is then referred to and the ratio of the maximum velocity, V_m, within the velocity distribution at the end of the flow path to the initial flow velocity, V_o, is obtained.

$$V_m/V_o = 0.36$$

or

$$V_m = (0.36)(42.5) = 15.3 \text{ ft/s } (4.7 \text{ m/s})$$

If the average flow velocity at the end of the path is then assumed to be one-half of V_m, an average velocity through the basin can be determined.

$$V = ((15.3)/2 + 42.5)/2 = 25.1 \text{ ft/s } (7.7 \text{ m/s})$$

An average velocity at the end of the path based on cross sectional area and discharge would be:

$$3550/((22)(28)) = 5.8 \text{ ft/s } (1.8 \text{ m/s})$$

This is less than (15.3/2) or 7.7 ft/s (2.3 m/s), so 7.7 ft/s should be used.

The path length divided by this average velocity gives the basin retention time;

$$t_2 = 95/25.1 = 3.8 \text{ seconds}$$

The smaller of the two computed times is the one that is applicable to the problem. For this particular case, the shorter time is 3.8 seconds, the time interval based on the flow velocity.

The first term to be evaluated is K, which is found through the use of figure 2. To apply figure 2, two parameters must be computed. [illegible] interval used is based on basin retention time, the basin flow path length (evaluated from the basin geometry) is used. If the smaller time results from the consideration of the bubble rise time then the flow path length to be used is less then the basin flow path length. For the sample problem the time based on the basin retention time is the smaller so the initially determined path length of 95 ft (29 m) is used. Therefore,

$$H_v/X = 28/95 = 0.295$$

For application of figure 2, the second parameter that must be evaluated is the ratio of the shear perimeter length of the jet to the cross sectional area of the jet. For this problem the shear perimeter is the jet width plus the jet height for each side or

$$8 + 3.5 + 3.5 = 15.0 \text{ ft } (4.6 \text{ m})$$

The cross sectional area has already been found to be 27.8 ft^2 (2.6 m^2). Thus the ratio is

$$15.0/27.8 = 0.54$$

The value of K is 0.1 from figure 2. The user will note the possibility of interpolation error. All the terms may now be substituted into equation 1 and a dissolved nitrogen concentration that is not corrected for barometric pressure is obtained.

$$C(t) = 27.4 - (27.4 - 21.5)\, e^{-(0.1)(3.8)} = 23.4 \text{ mg/L}$$

If this is then divided by the saturation concentration, the percent nitrogen saturation is obtained.

$$23.4/20.7 \times 100 = 113 \text{ percent}$$

The observed value for nitrogen, N_2 was also 113 percent. To obtain a predicted absolute concentration, multiply the predicted percentage by the absolute concentration adjusted for barometric pressure.

$$(1.13)(677/760)(20.7) = 20.8 \text{ mg/L of } N_2$$

Considering dissolved oxygen, we compute:

$$C_I = (0.85)(12.9) = 11.0 \text{ mg/L}$$

where 12.9 mg/L is the saturation concentration of oxygen at 4.4 °C.

Also:

$$C_S = \frac{677 + 2/3(22)(304.8/13.55)}{760}(12.9) = 17.1 \text{ mg/L}$$

$t = 3.8$ seconds

$K = 0.1$

all of which follow from the nitrogen calculations above. Applying equation I:

$$C(t) = 17.1 - (17.1 - 11.0)\, e^{-(0.1)(3.8)} = 12.9 \text{ mg/L}$$

The percent oxygen saturation calculated is:

$$12.9/12.9 \times 100 = 100 \text{ percent}$$

The actual observed value for oxygen, O_2 was also 100 percent.

An approximation of the percent total dissolved gas would be:

$$(100)\ (23.4 + 12.0)/(20.7 + 12.9) = 105 \text{ percent}$$

This considers nitrogen and oxygen, which together comprise over 99 percent of the total dissolved gas.

Several other examples were calculated with the following results:

Structure	Calculated N_2	Calculated O_2	Observed N_2	Observed O_2
Spillway with roller bucket, three gates operating	201%	197%	199% 1/	2/
Chute spillway into hydraulic jump basin	116	112	116	108
Auxiliary outlet works (four discharges) through spillway face into hydraulic jump basin	148	145	147	130 4/
	153	152	155	132 4/
	153	153	153	134 4/
	154	153	125 3/	130 4/
Chute spillway with flip bucket and shallow plunge pool	109	2/	103	2/

1/ Considerably less after dilution by powerplant discharge.
2/ Data not available.
3/ Believe that gas escaped from sample.
4/ Possibly lower because of heavy organic loading.

Conclusions

1. Given the velocity head of the inflow jet at the tailwater surface, the angle of penetration of the jet into the tailwater, the shape of the jet, the basin length and depth, the water temperature, the barometric pressure, and the initial dissolved gas levels in the reservoir, the dissolved gas levels that will result from the passage of flow through a hydraulic structure can be predicted with reasonable accuracy. Model studies can be used to great advantage in refining the hydraulic characteristics to be used in the analysis.

2. The basic equation developed to predict the resulting dissolved gas concentrations is:

$$C(t) = C_S - (C_S - C_I)\, e^{-Kt}$$

where $C(t)$ is the dissolved gas concentration created by the hydraulic structure, C_I is the dissolved gas concentration in the reservoir, C_S is the saturated dissolved gas concentration at a depth which is two-thirds of the maximum basin depth, t is representative of the length of time during which gas is being dissolved, and K is a constant that varies with structure and operating condition. A method is developed for prediction of the K value.

APPENDIX - REFERENCES

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3. Henry, H. R., Discussion of "Diffusion of Submerged Jets," Paper No. 2409, pp. 687-694, Transactions of the American Society of Civil Engineers, Vol. 115, 1950

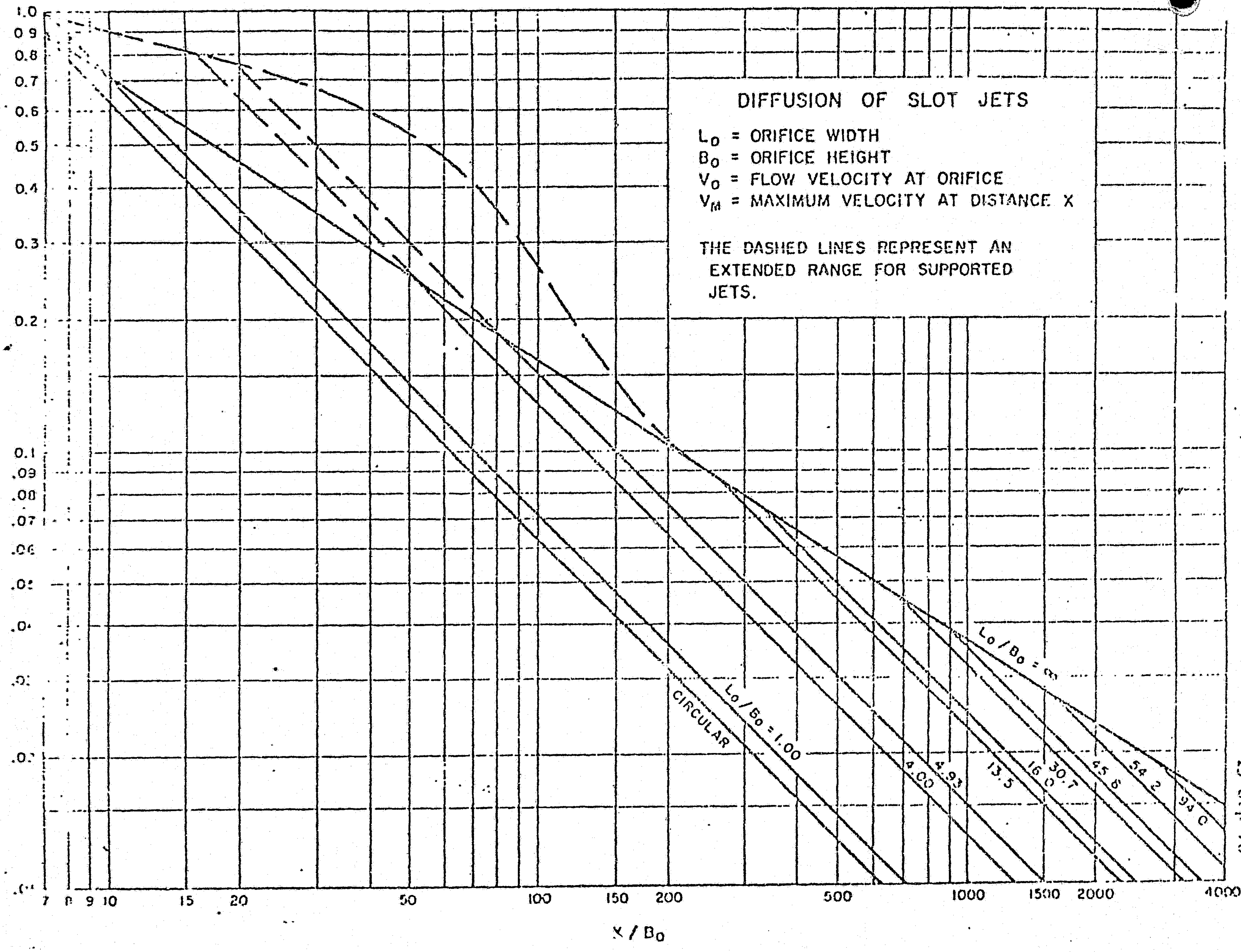

FIGURE 1 - DIFFUSION OF SLOT JETS

15 Sep 78

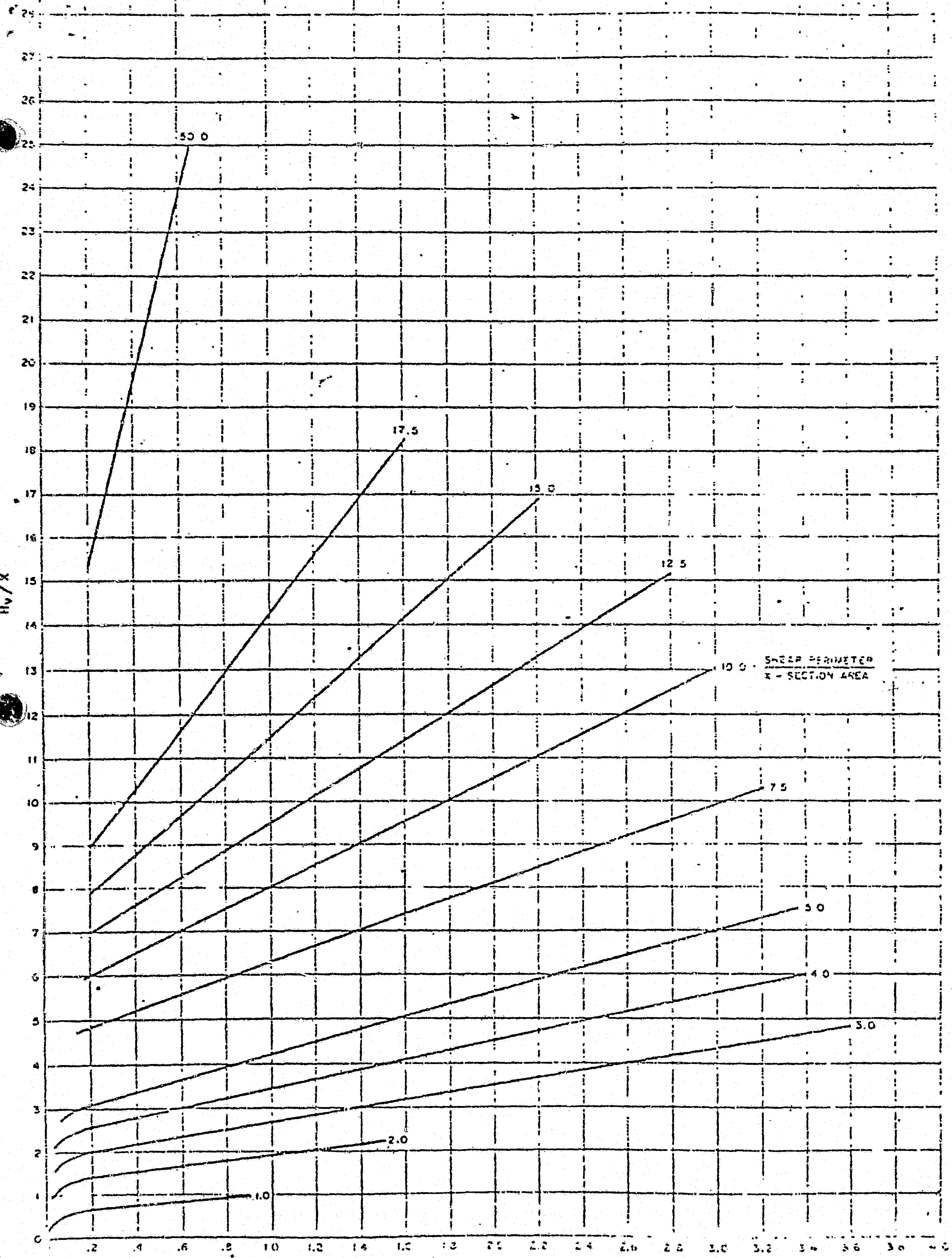

FIGURE 2 - EVALUATION OF K

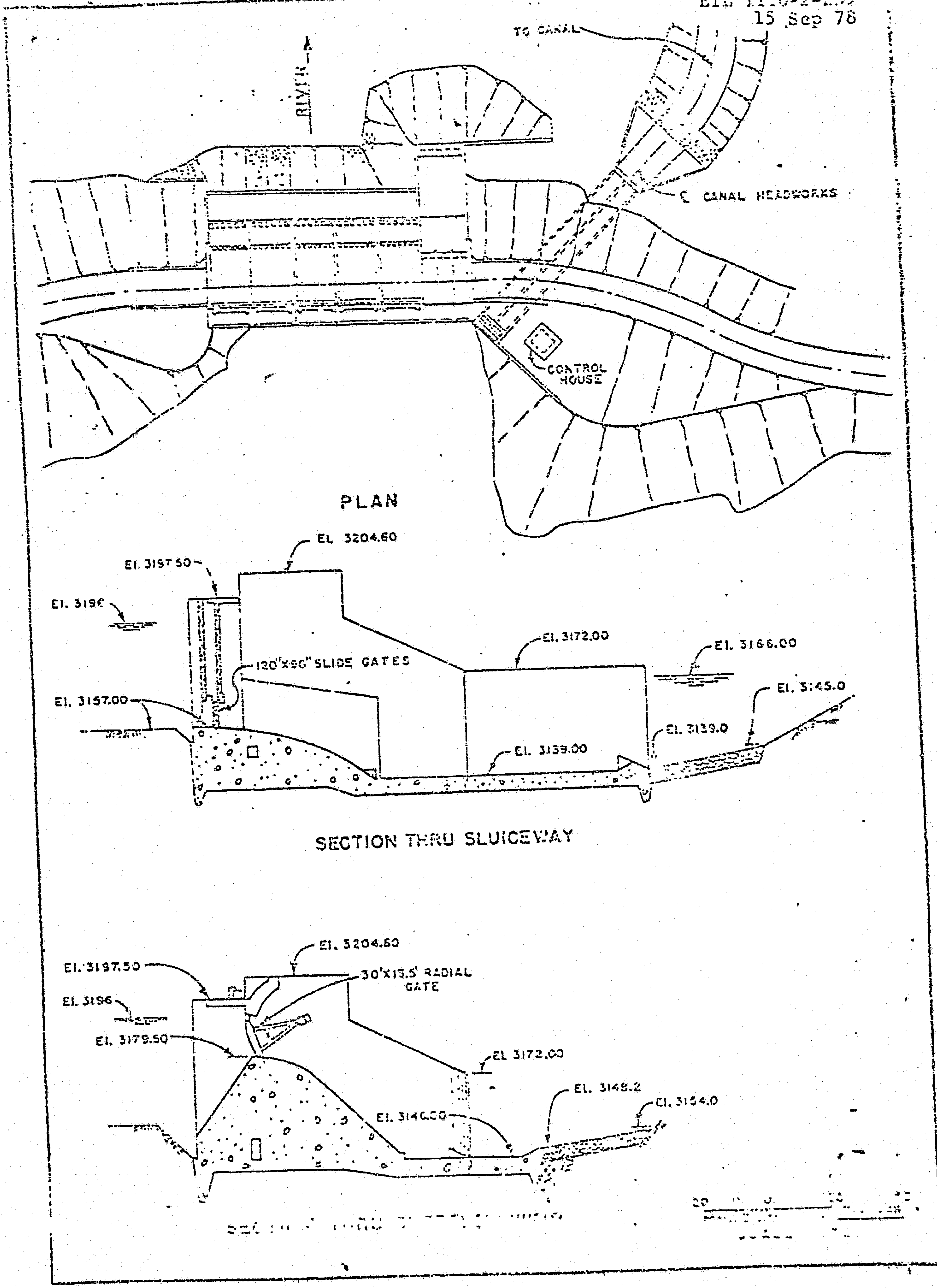

FIGURE 3 - SLUICEWAY IN EXAMPLE PROBLEM

ACRES Document Transmittal

TASK 6

To: Wayne Coleman
Harza Engineering Company

Date: March 9, 1983

Acres Job No.: P5700.73

Attention:

Project: Susitna Hydroelectric Project

Subject: Transition/Nitrogen Supersaturation

The following are enclosed:

Description / Title	Drawing Number	Revision Number	Number of Each	Code*
Reports				
• Peratrovich, Nottingham & Drage, Inc., "Nitrogen Supersaturation Study", January, 1983			1	
Acres American Internal Memos				
• D. Crawford, "Nitrogen Supersaturation Downstream of Susitna Developments Discussion Paper", Aug. 4, 1981.			1	
• G. Krishnan, "Nitrogen Supersaturation Studies", September 13, 1982.			1	

*A — For Approval or Comments
B — For Construction
C — See Explanatory Letter
D — For Information
E — For Purchasing
F — Drawings Approved
G — Drawings Approved Except as Noted
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Yours very truly,

ACRES AMERICAN INCORPORATED
David Crawford
Lead Hydraulic Engineer

ORIGINAL

SUSITNA HYDROELECTRIC PROJECT
NITROGEN SUPERSATURATION STUDY

Prepared for:
Acres American, Inc.

Prepared by:
Peratrovich, Nottingham & Drage, Inc.

January, 1983

SUSITNA HYDROELECTRIC PROJECT

NITROGEN SUPERSATURATION STUDY

The following letter/report presents results from recent studies undertaken to assess the potential problem of gas supersaturation of spill waters from the proposed Watana and Devil Canyon dams. In particular, this study investigated the potential levels of gas supersaturation due to eliminating fixed-cone valves at the Watana damsite. The preliminary draft submitted in December 1982 has been reviewed by personnel at Acres American, Inc., and the Alaska Department of Fish and Game. Recommended changes and review components have been incorporated where appropriate.

1. Study Approach

In the time available to carry out this study, the following elements have been covered:

- Review of studies to-date as described in Acres Office Memorandum from G. Krishman dated September 13, 1982.
- Review and summary of limited relevant literature available on dissolved gas supersaturation.
- Analysis of available data on natural river conditions received from Alaska Department of Fish and Game.
- Prediction of the range of supersaturation values for spills from Watana reservoir only and for both Devil Canyon and Watana dams.

2. Baseline Conditions

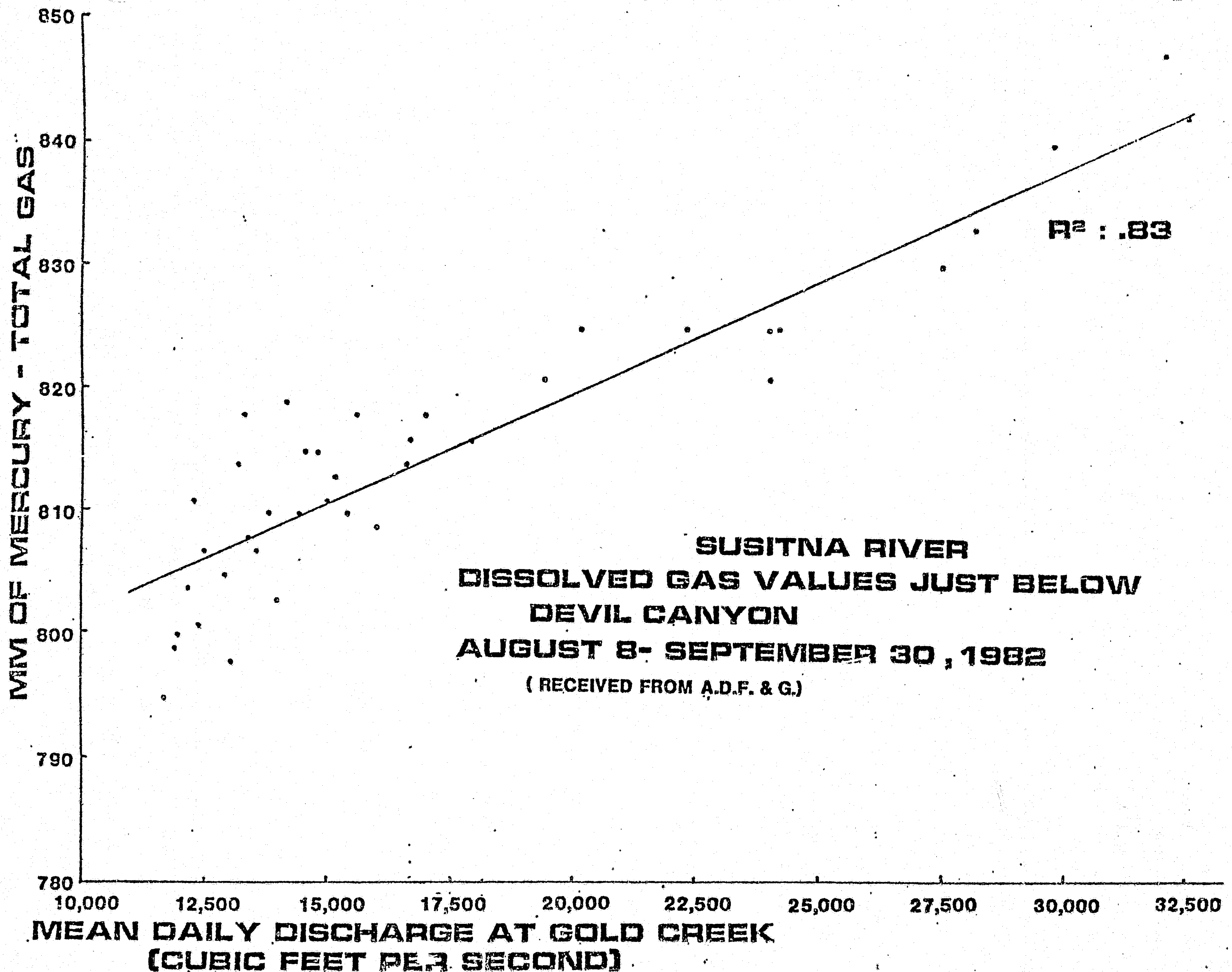
Dissolved gas concentration studies conducted by the Alaska Department of Fish and Game on the Susitna River in the vicinity of Devil Canyon attempted to answer two questions. The first involved variation of gas supersaturation with discharge; the other involved determination of the decay rate of the supersaturated condition downstream from Devil Canyon.

Figure 1 shows a plot of results from a continuous recording tensionmeter located just below Devil Canyon. A relatively good relationship is shown between total gas pressure and mean daily discharge at Gold Creek. This linear regression analysis was improved by averaging the range of gas pressures for the lower flows. At each mean daily flow level between 11,000 and 17,000 cfs, the range of recorded gas pressure values are averaged and this average value with the corresponding flow level has been used in developing the regression line. The relationship could be further improved by using the continuous chart from the Gold Creek gauge to provide instantaneous streamflow corresponding to the hourly measurements of dissolved gas. Peaks in dissolved gas concentration corresponding to storm events could be plotted more exactly and result in a tighter fit of data points to the line. Further refinement would require adjustment of the data to account for the high concentration of data points at lower streamflow levels. These adjustments would not significantly change the slope of the regression line for total gas pressure versus discharge, but would improve the strength of the relationship.

The second part of the ADF&G field program involved development of a supersaturation decay rate at varying flow levels. Using data points from field studies in 1981 and 1982, a set of decay curves have been developed for dissolved gas below Devil Canyon. Data from the 1981 field season suggested that the rate of decay of supersaturated dissolved gas was dependent on mainstem discharge. A similar relationship was shown in data collected from the Kootenai River below Libby dam in Montana (Alaska Department of Fish & Game, personal communication). However, recent data collected during the summer of 1982 on the Susitna River did not improve the relationship shown in the 1981 data.

The main conclusion from analysis carried out by Alaska Department of Fish and Game is that dissolved gas concentrations for the 11.8 mile river reach below Devil Canyon can be predicted using discharge and distance downstream as two significant variables in multiple regression analysis.

Channel morphology also appears to play a significant role in influencing decay rates. If the upper line on Figure 2 is divided into two segments with decay rates determined for both parts, the slope of the upper section would be



850
840
830
820
810
800
790
780
MM OF MERCURY - TOTAL GAS
10,000
12,500
15,000
17,500
20,000
22,500
25,000
27,500
30,000
32,500
MEAN DAILY DISCHARGE AT GOLD CREEK
(CUBIC FEET PER SECOND)
R² : .83
SUSITNA RIVER
DISSOLVED GAS VALUES JUST BELOW
DEVIL CANYON
AUGUST 8- SEPTEMBER 30, 1982
(RECEIVED FROM A.D.F. & G.)

FIGURE 1

approximately -0.030 while the lower part representing the river reach below Indian River would have a steeper slope due to changes in river slope and morphology (Alaska Department of Fish and Game). Additional data points are needed to confirm this hypothesis.

Finally, studies have shown that decay rates are proportional to the particulate content in the water which provide additional gas nuclei for bubble formation.[5] To more accurately predict saturation levels, information must be gathered on the relationship between particulate content and rates of supersaturation decay.

With the decay coefficients, an exponential function has been used to model the decay of gas saturation in the Susitna River downstream from Devil Canyon:

$$y = ae^{-bx}$$

where: y = concentration of dissolved gas at a given distance downstream + 100

a = percent saturation at initial point - 100

$-b$ = decay coefficient

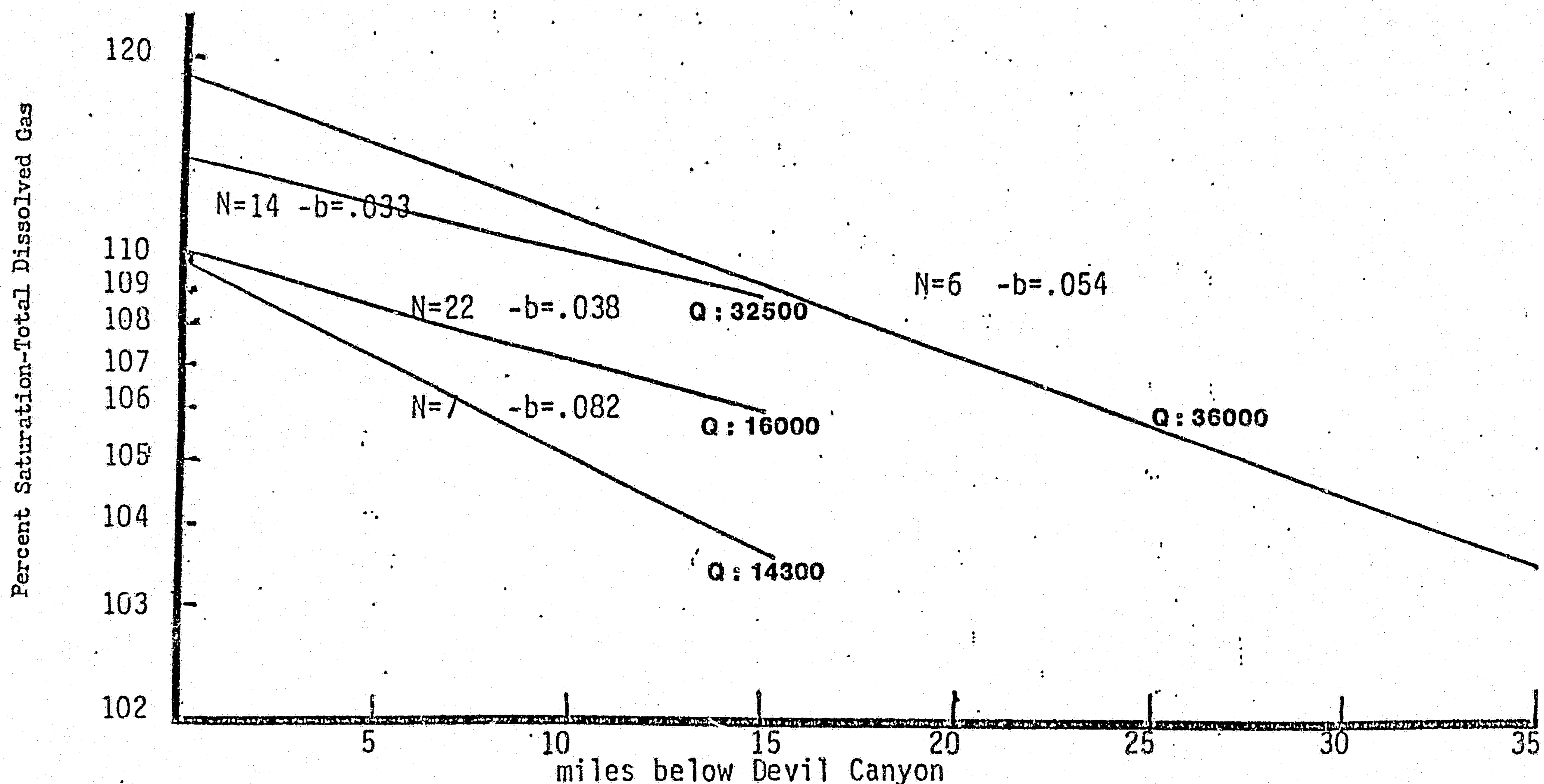
x = distance downstream from initial point (miles)

This basic function has been used in all of the following calculations to determine decay of supersaturated dissolved gas in the downstream direction.

3. Watana Reservoir Only

For this part of the study, the decay curve at Q = 16,000 cfs has been used to determine decay coefficients downstream of the proposed Watana dam. Using the curves presented on Figure 2, the coefficient is -0.038.

The river slope and morphology in the reach between the damsite and Devil Creek are similar to that of the measured reach downstream of Devil Canyon.



SUSITNA RIVER

DISSOLVED GAS DECAY CURVES

(RECEIVED FROM ADF&G)

FIGURE 2

Therefore, a decay coefficient of -0.038 has been used to determine changes in supersaturation level below the Watana damsite to near Devil Creek.

In the reach from Devil Creek through the lower end of Devil Canyon, the pattern of increase and decay of dissolved gas concentration observed may also vary with discharge, but insufficient data base exists to define the relationship between dissolved gas and discharge through the length of the canyon. However, data collected on the Kootenai River near the Kooten Falls suggest that waters with elevated dissolved gas concentrations entering an area of entrainment, such as the rapids of Devil Canyon, may only partially dissipate (Alaska Department of Fish and Game, personal communication). Therefore, significant reductions in dissolved gas levels through Devil Canyon would not be expected if higher than natural concentrations enter the rapids. In determination of decay rates in the Susitna River during early years of development with only the Watana dam on-line, no change in dissolved gas concentrations has been applied to water travelling through Devil Canyon.

The remaining stretch of river from the lower end of Devil Canyon to Gold Creek is expected to show a similar exponential decay rate as the river above Devil Canyon.

Table 1 summarizes the percent saturation predicted at key locations downstream of the proposed Watana dam using the exponential decay function and a decay coefficient of $b = -0.038$. Determination of the initial saturation level below Watana has not been finalized due to uncertainties in the effect on dissolved gas saturation levels of powerhouse operations, outflow water temperatures, and distance of fall and depth of water plunge below the dam. An expected range of supersaturation values has been tested and the results shown on Table 1. Review of limited available literature indicate that levels could exceed 155 percent[12]; for the Watana dam 110 to 155 percent represents the expected range assuming no fixed-cone valves are used. High volume spills falling over the spillway could cause significant scour in the plunge pool below the dam. Supersaturation levels resulting from entrained air bubbles going into solution as water plunges through the depth of this scour hole could yield the values on the upper end of this range.

TABLE 1

WATANA DAM ONLY

• no fixed-cone valves

% SATURATION @ KEY LOCATIONS

DISCHARGE AT WATANA DAM	% SATURATION BELOW WATANA	AT DEVIL CREEK	DEVIL CANYON	LOWER END OF DEVIL CANYON	AT PORTAGE CREEK	AT GOLD CREEK
16,000 cfs	155	115		115	114	109
	150	113	Assume	113	113	108
	145	112	no	112	111	107
	140	110	change	110	110	106
	135	109	in	109	109	105
	130	108	elevated	108	108	105
	125	107	dissolved	107	107	104
	120	105	gas	105	105	103
	110	103	concentrations	103	103	102
miles (x) downstream		35		54	1	14

Assumptions:

- o Supersaturation level below Watana dam will not exceed 155%.
- o Slope from Watana damsite to near Devil Creek is similar to slope from below Devil Canyon to Gold Creek same exponential [illegible]ay rate used.
- o No change in saturation level through Devil Canyon when water enters at elevated level.
- o Exponential decay: $y = ae^{-bx}$ where $b = -0.038$

  a = initial % saturation −100

  y = resulting saturation +100

  x = distance travelled

The levels of dissolved gas at Portage Creek and Gold Creek in some cases exceed equilibrium saturation of 100 percent; however, fish exposed to these predicted levels should be able to avoid the supersaturated conditions by moving to greater depths in the mainstem Susitna River, or by moving to side channels and sloughs fed primarily by groundwater and downstream of inflowing tributaries where dilution of mainstem river water may reduce levels of supersaturation. Studies on the Snake and Columbia River system have shown that generally fish either avoided areas of supersaturation or assumed a deeper vertical distribution during periods of high supersaturation[12].

4. Devil Canyon and Watana Dams On-Line

The next step in this study is to consider the effect on downstream water quality of eliminating fixed-cone valves at the proposed Watana dam after the Devil Canyon dam has been commissioned in the year 2002. Review of the Acres American, Inc., weekly energy simulation computer printout has shown that, in fact, the year 2002 represents a worst case situation in terms of volume of spill at Watana. During the early years of operation of both dams, the generating capacity greatly exceeds the energy demand. As a result a lesser proportion of outflow from Watana will be run through the powerhouse and volume of spills will be higher than in later years. This assumes that the Devil Canyon development would be used for base load power generation and Watana for peak load.

A summary of the maximum and average weekly spills at Watana and Devil Canyon dams during the summer months for year 2002 demand is presented in Table 2. These maximum values represent the maximum spill for a given week over the full 32 years of simulation. The number in parentheses gives the year in which that maximum is predicted. The average values represent the average spill for a given week using the 32 years of simulation. From these an average spill for each month has been computed.

In review of Table 2, it appears that spills at Watana during the month of September in year 32 of the energy simulation output represent a worst-case situation. The average September spill for that year is 32,680 cfs. This is a result of high inflow to the reservoir already at full capacity and zero

TABLE 2
WEEKKLY SPILL RATE AT WATANA AND DEVIL CANYON DAMS
BASED ON YEAR 2002 DEMAND

	WATANA			DEVIL CANYON		
	MAXIMUM	(YR.)	AVERAGE	MAXIMUM	(YR.)	AVERAGE
JULY	-		0	-		0
	18,523	(13)	579	6,379	(13)	199
	24,573	(7)	2,344	12,925	(7)	855
	30,993	(14)	5,395	22,636	(14)	2,801
		AVG.	2,080			
AUGUST	26,909	(14)	9,529	17,904	(14)	3,837
	26,044	(9)	11,470	16,783	(9)	4,465
	24,589	(32)	12,327	13,399	(31)	4,304
	36,483	(18)	14,033	28,083	(18)	5,946
		AVG.	11,840			
SEPTEMBER	40,964	(10)	14,540	32,851	(10)	6,191
	39,811	(32)	12,476	31,299	(32)	3,855
	33,888	(32)	10,252	24,397	(32)	2,510
	24,733	(32)	8,279	14,317	(32)	1,740
		AVG.	11,387			
OCTOBER	15,862	(9)	5,444	4,845	(9)	373
	18,031	(17)	3,545	7,755	(17)	455
	15,083	(32)	3,482	4,926	(32)	342
	9,646	(27)	1,207	-		0
		AVG.	3,420			

Notes:

- Year in parentheses corresponds to year of maximum weekly spill taken from Acres American, Inc., energy simulation computer printout.
- All values reported in cubic feet per second.

powerhouse flow. For all further determinations of dissolved gas levels, this spill rate has been used. It represents a worst-case situation and also corresponds to discharge at Gold Creek during one of the 1982 field sampling trips carried out by the Alaska Department of Fish and Game. Table 3 lists the percent saturation at key locations computed using the decay coefficient and exponential decay function determined for this flow level under natural conditions.

Several assumptions have been made in developing this table which should be kept in mind when reviewing it. It has been assumed that:

1) Watana releases will not mix completely in the Devil Canyon reservoir but travel through in the upper 100 feet of the reservoir.

Forces of wind mixing and thermal regime in the Devil Canyon reservoir have not been determined at this time, therefore their effect on the behavior of inflowing water from the Watana reservoir cannot be considered. Results from on-going computer thermal modeling of the Devil Canyon reservoir could negate this first assumption, but for simplicity all water entering the reservoir is assumed to remain in the upper layers.

2) Water drawn for the powerhouse at Devil Canyon will come from the upper 100 feet of the reservoir.

Design drawings in Volume 3 of the Feasibility Report show the power intake at Devil Canyon in the upper 100 feet of the reservoir.

3) There will be little or no decay of dissolved gas supersaturation during travel time through the reservoir generally due to insufficient mixing.

Studies on the Columbia River system have shown no significant change in dissolved gas levels during travel time through each reservoir.[10] The reason given is lack of mixing in the water bodies resulting in limited interaction at the air-water interface.

TABLE 3

WATANA AND DEVIL CANYON DAMS

• no fixed-cone valves at Watana

% Saturation @ Key Locations

DISCHARGE AT WATANA DAM	% SATURATION BELOW WATANA	AT TSUSENA CREEK	DEVIL CANYON RESERVOIR	DEVIL CANYON TAILRACE PORTAL	AT PORTAGE CREEK	AT GOLD CREEK
32,000 cfs	155	148		148	147	130
	150	144		144	143	128
	145	140		140	139	125
	140	135		135	134	122
	135	131	No	131	130	120
	130	126		126	125	116
	125	122	Decay	122	121	113
	120	118		118	117	111
	115	113		113	113	108
	110	109		109	109	106
	105	104		104	104	103
miles (x) downstream	0	4	30	0	1	14

Assumptions:

- Supersaturation level below Watana dam will not exceed 135%.
- No decay between Tsusena Creek confluence and Devil Canyon outfall.
- Flow through Devil Canyon powerhouse will not be further supersaturated.
- Constant exponential decay downstream from Devil Canyon tailrace portal:

$y = ae^{-bx}$ where $b = -0.033$

a = initial % saturation −100

y = resulting saturation +100

x = distance travelled

4) Power generation at Devil Canyon will not significantly change the supersaturation level of water drawn from the reservoir.

Passage of water through the penstock and turbines at Devil Canyon by nature of the operation is unlikely to result in release of dissolved gas from solution. If anything the power generation process would tend to increase supersaturation levels by 2 to 5 percent in water that may already be supersaturated. This is the case on the Columbia River system.[5] However, for this study dissolved gas levels are assumed to be unchanged going through the powerhouse.

If these assumptions hold, Table 3 shows potentially harmful levels of dissolved gas at Portage Creek and Gold Creek. Looking back at Table 2, it appears that these elevated levels of dissolved gas could be sustained for several consecutive weeks. Studies in fish hatcheries and natural river systems have shown that fish can tolerate intermittent periods of supersaturated conditions depending on species and life stage; however, continuous exposure results in high mortality rates.[12]

Holding to the same assumptions presented above, travel times through the Devil Canyon reservoir under worst-case and average conditions have been computed as a check on Table 3. The average weekly spills at Watana under year 2002 energy demand are averaged to yield monthly values of inflow to the Devil Canyon reservoir. Tributary inflow is assumed to be insignificant. These have been used to compute travel time and determine the likelihood of filling the live storage of Devil Canyon reservoir with supersaturated water. Sheet 1 of 3 shows that for worst-case spills at Watana the travel time is 5.5 days. This sheet also shows the water travel time using the total reservoir storage is 16.8 days. This would indicate that in certain years of sustained high spills at Watana, i.e. year 32 of the year 2002 demand simulation, the live or total storage water at Devil Canyon would be supersaturated. Water drawn through the power intake and eventually released would be at a level of supersaturation potentially harmful to fisheries resources downstream.

Sheets 2 and 3 show that under average conditions, using average weekly spills at Watana, this possibility still exists, though it would be somewhat reduced due to the longer travel time and greater possibility of mixing.

During periods of high spills at Watana, spill rates at Devil Canyon are also relatively high. The position of the fixed-cone valves near the bottom of the reservoir at Devil Canyon will draw water from the hypolimnion which should not be supersaturated. This assumes that thermal stratification will develop in the reservoir in spite of relatively short water retention time. Movement of the water through the valves, the fall to the existing tailwater elevation, and travel through the lower end of Devil Canyon will result in dissolved gas levels aproaching the levels observed under natural conditions. Though still supersaturated, it may serve to dilute powerhouse flow entering the river at higher dissolved gas levels. However, it is believed that resulting values downstream will be higher than under pre-project conditions.

In summary, it appears that elimination of fixed-cone valves at the proposed Watana dam would result in an increase in the levels of dissolved gas downstream of the proposed Devil Canyon development. However, additional field data on existing levels of saturation through Devil Canyon and the downstream decay rate of supersaturation at various discharges is needed to confirm the relationships used in this analysis. Also, the degree of wind-induced mixing and the thermal regime of Devil Canyon reservoir will allow more detailed analysis of the behavior of the inflowing water from Watana and posible dilution effects due to mixing.

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JOB 82066 - Susitna
SHEET NO. 1 of 3 OF
CALCULATED BY L. Griffith DATE 1-4-83
CHECKED BY DATE
SCALE

TRAVEL TIME THROUGH D.C. RESERVOIR UNDER WORST CASE

DEVIL CANYON

MAXIMUM LIVE STORAGE = 702900 cfs = 355000 ac.ft

AVERAGE DAILY SPILL @ WATANA = 32,680 cfs
(YEAR 32 SIMULATION, YEAR 2002 DEMAND)

Travel Time:

$$\frac{43560 \text{ cuft/ac.ft}}{32680 \text{ cfs}} \times 355{,}000 \text{ ac.ft} \times \frac{1}{86400 \text{ sec/day}}$$

= 5.5 days

DEVIL CANYON TOTAL STORAGE = 1,092,000 ac.ft

Travel Time:

$$\frac{43560 \text{ cuft/ac.ft}}{32680 \text{ cfs}} \times 1{,}092{,}000 \text{ ac.ft} \times \frac{1}{86400 \text{ sec/day}}$$

= 16.8 days

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JOB 82066 - Susitna Nitrogen Study
SHEET NO. 2 of 3 OF
CALCULATED BY L. Griffiths DATE 1.4.83
CHECKED BY DATE
SCALE

TRAVEL TIME THROUGH D.C. RESERVOIR UNDER AVERAGE CONDITIONS

AVERAGE WEEKLY SPILL @ WATANA
BASED ON YEAR 2002 DEMAND

JULY	2080 cfs
AUGUST	11840
SEPTEMBER	11387
OCTOBER	3720

TRAVEL TIME

JULY: $\frac{43560 \text{ cu.ft/ac.ft}}{2080 \text{ cfs}} \times 355000 \text{ ac.ft} \times \frac{1}{86400 \text{ sec/day}}$

= 86 days

AUGUST $\frac{43560}{11840} \times 355000 \times \frac{1}{86400}$

= 15 days

SEPTEMBER $\frac{43560}{11387} \times 355000 \times \frac{1}{86400}$

= 16 days

OCTOBER $\frac{43560}{3720} \times 355000 \times \frac{1}{86400}$

= 52 days

Note: · all flow data from Acres American, Inc. energy simulation computer printout
· computations include volume of spill only, powerhouse flow not included.
· LIVE STORAGE = 355000 ac.ft TOTAL STORAGE = 1092,000 a.ft.

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JOB 82066 - Susitna
SHEET NO. 3 of 3 OF
CALCULATED BY J. Griffiths DATE 1.4.83
CHECKED BY DATE
SCALE

TRAVEL TIME UNDER AVERAGE CONDITIONS - continued

- assume high August & September flows mix with whole reservoir volume

TOTAL STORAGE = 1,092,000 ac.ft

AUGUST: $\frac{43560 \text{ cu.ft/ac.ft}}{11840 \text{ cfs}} \times 1092000 \text{ ac.ft} \times \frac{1}{86400 \text{ sec/day}}$

= 46 days

SEPTEMBER: $\frac{43560}{11387} \times 1,092,000 \times \frac{1}{86400}$

= 48 days

If total mixing occurs there will be decrease in supersaturation due to dilution effects & slower travel time allowing greater influence of wind mixing.

TO: Distribution

FILE: P5700.07.06

FROM: D. Crawford

4 Aug, 1981

SUBJECT: Susitna Hydroelectric Project
Nitrogen Supersaturation Downstream
of Susitna Developments Discussion Paper

Introduction

Nitrogen supersaturation has been identified as a potential lethal problem to fish populations downstream of Watana and Devil Canyon dams. The extent of the problem can be gaged by considering the extent of spills and the method of spilling. Generally, the lower the spills the less of a problem nitrogen supersaturation will be. The method of spilling (valves, flip bucket, stilling basin, or cascade) will determine the level of saturation.

The question of nitrogen supersaturation has apparently been raised due to experience from the Columbia River. The analogy that the Susitna Development will be similar to the Columbia River is in many aspects erraneous. The Columbia River, in the United States, is an almost fully developed river and forms a classical cascade with one dam spilling into the reservoir of the next. The amount of storage available on the Columbia is limited so that spillage along the system is a common occurrence. This, consequently, causes a buildup of saturation levels progressively downstream. The problem was severe causing serious damage to fish populations and required extensive remedial action.

The high nitrogen supersaturation levels and the consequential high incidence of gas bubble disease in fish have been lowered by alterations to spillway flips and with increases in powerhouse capacities. The later change plus the developments of Mica and Revelstoke have substantially reduced the frequency and magnitude of spills. Lower spills and the structural alterations have reduced the saturation problem to a tolerable level.

In comparison to the Columbia River, the Susitna River development has considerable storage and regulation at Watana resulting in a low frequency of spills. The powerhouse capacities at Watana and Devil Canyon are considerable and further reduce the need to spill. Consequently, the analogy between the Columbia and Susitna Rivers is not correct from several aspects. Other aspects which differ between the river are operation, fish passage, tributary inflows, and length of reach downstream.

Nitrogen Supersaturation

Nitrogen supersaturation will result when aerated discharges are subjected to pressures greater than atmospheric. Generally, the plunging of a jet, such as from a flip bucket, into a pool greater than 30 ft will result in saturation levels up to 150%.

The critical level at which fish become seriously affected is generally accepted at 116% although regulatory authorities use 110% as a water quality standard. Levels in excess of 116% saturation would eliminate, given enough time, most fish occupying the top five feet of a river. This level and greater can be tolerated by fish which swim to greater depths. The greater tolerance is due to hydrostatic compensation which increases the tolerable saturation level by about 3% per foot of depth.

Exposure time to lethal levels of saturation required to seriously damage fish populations is dependent upon several factors. Generally, fish will show significant recovery from elevated saturation levels (up to 125%) if exposure time is limited.

Analysis of Watana Spills

To illustrate the levels of nitrogen supersaturation downstream of Watana due to spills, an analysis of floods has been performed. This analysis assumes that the spill facilities at Watana consist of the following arrangement:

	Capacity (cfs)	Operation
Powerhouse:	12,000	WSEL ≥ 2,200
Service (H-B valves, Expansion Chamber):	18,000	QINF > 12,000 WSEL ≥ 2,200
Auxiliary (Flip or Stilling Basin):	15,000	QINF > 30,000 2,200 < WSEL ≤ 2,205
	>15,000	WSEL > 2,205

The analysis considered the thirty year period used in energy simulation analysis and floods with given return periods up to 1:100 years. The latter assumed peaks and hydrograph shapes derived by R&M Consultants for the August-October period.

Historical Spills

The energy simulation model showed that four years in the thirty year period had spillage. Obviously, use of the monthly flow model will not indicate the true day to day operation of powerhouse and spillway. Daily discharges were determined from streamflow records at Gold Creek prorated to Watana to give an indication of the daily flows. Table 1 shows the discharges for days in which all three discharge facilities operated.

The historical period indicates that a total of 15 days in the 30 year period had spills from the auxiliary spillway. This represents an average~~s~~ ~~on~~ frequency of operation of one day every two years. Assuming auxiliary spillway, service spillway, and powerhouse discharges have saturation level of 140%, 100%, and 100%, respectively. The maximum saturation obtained was 118%. Fourteen of the fifteen days had saturation levels below 116%. The mean saturation level for the fifteen days was 110%.

The above historical analysis has assumed no initial storage of discharges exceeding 30,000 cfs or limited auxiliary spillway discharge to 15,000 during the first five feet of surcharge. If some initial storage was assumed, saturation levels would be reduced and would have not have exceeded

114%. However, an increase in the number of days that the auxiliary spillway operated would occur.

Flood Spills

Floods with given return periods have been analyzed as above and show similar results. For these flows a discharge limit for the auxiliary spillway of 15,000 cfs has been assumed for water surface elevations less than 2,205 ft.

The 1:100 year flood would result in nitrogen supersaturation for 14 days. Smaller floods show a reduction in the number of days of supersaturated conditions. However, the maximum remains at 113%. The 2 year flood results in no elevated saturation levels. The results of this analysis are given in Table 2.

Devil Canyon

The nitrogen supersaturation problem downstream of Devil Canyon is potentially more severe than at Watana. By proper design of spillway facilities that do not cause plunging conditions, the supersaturation of flows can be maintained within acceptable limits. Analysis of spill occurrences and nitrogen levels have not been carried out, but a qualitive assessment of the discharge facilities concludes that with the inclusion of Howell-Bunger valves into a service spillway facility, the nitrogen saturation levels downstream should be acceptable.

Other Considerations

A further consideration is the dissipation of supersaturated conditions under turbulent flow in the river reach downstream of Devil Canyon. This reach would provide some reduction of saturated conditions, however, no quantifiable rates of dissipation could be estimated due to inadequate data on the reach and on typical dissipation rates. Obviously, further analysis would be beneficial, but qualitively, the conclusion would be that saturation levels would be significantly reduced by the time the flow reaches Talkeetna.

Nitrogen saturation levels are also reduced due to the ~~diluation~~ dilution of Devil Canyon releases by tributary flows. This is also significant and would further reduce the problem.

Summary

This paper is intended for discussion and to aid in determining the extent of the nitrogen supersaturation levels that can be expected from the proposed spillway facilities. Obviously, changes in spillway design will effect any conclusions drawn here so a reassessment of this feature is required for final design.

The main conclusions from this assessment are:

1. The saturation level downstream of Watana due to spills resulting from a 1:100 year flood are acceptable given the proposed operation.

2. The saturation level downstream of Devil Canyon are also acceptable for the 1:100 year flood occurrence and the proposed spillway facility.

3. Saturation levels will significantly dissipate downstream due to turbulence and diluation effects.

Discussion and comments are requested on the above analysis.

David Crawford
D. Crawford

DC:ccv

Distribution:

T. Lavender
J.W. Hayden
J.D. Lawrence
K.R. Young
G. Krishnan
R.K. Ibbotson

TABLE 1

Residual Nitrogen Supersaturation Levels
and Duration: Historical Analysis

Year of Occurrence	Powerhouse	Discharge (cfs) Service	Auxiliary	Saturation Percent
1955	12,000	18,000	18,000*	1.15
	12,000	18,000	15,600*	1.14
	12,000	18,000	12,600	1.12
	12,000	18,000	5,300	1.06
1959	12,000	18,000	8,700	1.09
	12,000	18,000	1,100	1.01
	12,000	18,000	2,800	1.03
1960	12,000	18,000	3,700	1.04
1967	12,000	18,000	3,800	1.04
	12,000	18,000	18,400*	1.15
	12,000	18,000	23,900*	1.18
	12,000	18,000	12,500	1.12
	12,000	18,000	8,400	1.09
	12,000	18,000	7,800	1.08
	12,000	18,000	1,300	1.02

NOTES:

* Probable use of storage. Discharge would be limited to 15,000 cfs.

TABLE 2

Residual Nitrogen Supersaturation Levels and Duration - Flood Frequency Analysis

Auxiliary Discharge cfs[1/]
Return Period

1:100		1:50		1:10		1:5	
Flow	N_2 %	Flow	N_2 %	Flow	N_2 %	Flow	N_2 %
1,100	1.01	670	1.01	4,200	1.05	5,000	1.06
4,500	1.05	3,800	1.04	12,200	1.12	4,700	1.05
8,000	1.08	15,000	1.13	11,900	1.11		
15,000[2/]	1.13	"	"	5,800	1.06		
"	"	"		3,100	1.04		
"	"	"					
"	"	"					
"	"	"					
"	"	"					
"	"	15,000	1.13				
"	"	2,400	1.03				
"	"						
"	"						
15,000	1.13						
3,100	1.04						

NOTES:

1/ Powerhouse and service flows assumed 12,000 and 18,000 cfs, respectively.

2/ Eleven days at 15,000 cfs

UNIVERSITY OF WASHINGTON
SEATTLE, WASHINGTON 98195

TO: WEYERHAEUSER COMPANY

TYPE OF SUPPORT REQUESTED: Research Contract

TITLE OF PROJECT: Ore-Aqua Coho Scale Analysis

PRINCIPAL INVESTIGATOR:

Robert L. Burgner
Professor and Director
Fisheries Research Institute
College of Fisheries, WH-10
University of Washington
Seattle, Washington 98195
(206) 543-4650

AMOUNTED REQUESTED: $ 6,662

DESIRED PERIOD: 15 January 1981 - 1 April 1981

UNIVERSITY OFFICE TO BE CONTACTED REGARDING GRANT OR CONTRACT NEGOTIATION:

Grant and Contract Services
Rm 22, Administration Bldg., AD-24
University of Washington
Seattle, Washington 98195
(206) 543-4043

DATE: 12 January 1981

Robert L Burgner
Principal Investigator

OFFICIAL AUTHORIZED TO GIVE UNIVERSITY APPROVAL:

Donald R. Baldwin, Director
Grant and Contract Services

ACRES

OFFICE MEMORANDUM

TO: J.W. Hayden

Date: September 13, 1982

FROM: G. Krishnan

File: P5700.14.53

SUBJECT: Susitna Hydroelectric Project
Nitrogen Supersaturation Studies

Enclosed is a copy of the final draft of the report on Gas Concentration and Temperature of Spill Discharges Below Watana and Devil Canyon Dams.

Please note that no graphics efforts have been spent on getting the figures in the Acres standard format. This has been postponed until after your review of the material and advice on the inclusion of any field measurements of natural supersaturation in the river. Messers M. Bell and J. Douma had expressed an interest to receive copies of this report. Please advise if this can be done at this time.

G. Krishnan

GK:ccv
Enclosure

cc: J.D. Lawrence
A.F. Coniglio
K.R. Young
W. Dyok/D. Crawford

GAS CONCENTRATION AND TEMPERATURE OF
SPILL DISCHARGES BELOW
WATANA AND DEVIL CANYON DAMS

1 - INTRODUCTION

Supersaturation of atmospheric gases (especially nitrogen) in hatchery and aquarium facilities was first noted in the 1900's (1) and was ascribed as causing the condition in fish known as gas bubble disease. Supersaturation caused by entrainment of air in waters spilled over dams on the Columbia River was recognized as a problem for anadromous fisheries in the river in 1965. A comprehensive study (2) of dissolved gas levels in the Columbia River showed that waters plunging below spillways was the main cause of supersaturation in the river waters. Several later studies have confirmed the harmful effects of nitrogen supersaturation to fisheries. The tolerence of fish to levels of nitrogen supersaturation depends on the time of exposure, age, and species of the fish; dissolved nitrogen levels referenced to surface pressure above 110 percent are generally considered harmful (3). The state of Alaska water quality criterion is set of 110% for total gas saturation in its waters.

With this background, the potential problem of supersaturation of spill waters from the proposed Watana and Devil Canyon developments on the Susitna River was recognized early during the feasibility studies. Alternative spillway facilities were studied to minimize such a potential problem, and a scheme comprising fixed cone valves and overflow spillway was selected for each development based on detailed discussions with environmental study groups.

This report describes the selected spillway schemes briefly and presents the analyses and field investigations carried out to assess the performance of the proposed schemes with respect to gas supersaturation in spill waters. A related concern on temperature of spill waters is also discussed.

A summary of the studies undertaken and the important conclusions are presented in Section 2. A short description of the proposed schemes is given in Section 3. Section 4 details the engineering analyses carried out. Results of these analyses, field investigations, and their interpretation are presented in Section 5. The next section presents the major conclusions drawn from these studies. Appendix A comprises the field study report and Appendix B deals with the temperature of spill waters, its impacts downstream, and possible reservoir operation scenarios to minimize such impacts.

2 - SUMMARY

Relatively little information is available in the literature on the performance of fixed-cone valves to reduce gas supersaturation in their discharges. Published studies (4) on the aeration efficiency of Howell Bunger valves (the more commonly known type of fixed-cone valves) were reviewed, and a theoretical assessment of the performance of the proposed valve layouts was made based on the physical and geometric characteristics of diffused jets discharging freely into the atmosphere. Results of a companion study on assessment of scour hole development below high-head spillways (5) were used to estimate the potential plunging of the valve discharges into tailwater pools at the proposed developments, and the resulting supersaturation in the releases was calculated. Specific field tests were conducted at the Lake Comanche Dam on the Mokelumne River in California (6) to study jet characteristics and the efficiency of the existing Howell Bunger valves in reducing supersaturation level in the reservoir releases.

The analyses indicate that no serious supersaturation of nitrogen is likely to occur in the releases from the proposed Watana and Devil Canyon developments for spills up to 1:50 year recurrence interval. Field test results tend to confirm some of the assumptions made in the theoretical analysis with respect to jet shape, diffusion, and gas concentration in the valve discharges. Several assumptions and approximations, albeit conservative, have been made in the analyses which should be confirmed in later study phases, perhaps in a physical model. For the purpose of feasibility studies, however, it is felt that the analyses adequately support the proposed schemes for their intended purpose.

A related question of the temperature of spill waters and its effects on the downstream water temperature has been analyzed and detailed in Appendix B. Simulation studies of the two-reservoir operations indicate that continuous (24 hour) spills would occur in the month of August in 30 out of 32 years of simulation and in 18 out of 32 years in September for the Case "C" operation which maintains a minimum instantaneous flow of 12,000 cfs in August at Gold Creek. This spill frequency is simulated for a system energy demand in the year 2010 (Bettelle forecast) and assumes that the entire demand is met by

Watana and Devil Canyon developments where possible. The spills will be greater and more frequent in the years between 2002 (Devil Canyon commissioning) and 2010. When Watana alone is operational (between 1993 and 2002), less frequent spills are simulated to occur. Reservoir operation studies are currently being refined to finalize acceptable downstream flows.

Temperature of spill waters at Watana is expected to be close to that of power flow, and hence, it is not expected to create temperature problems downstream when Watana is operating alone (1993-2002) or when it spills into Devil Canyon. At Devil Canyon, however, spill temperature is expected to be close to 39°F compared to a power flow temperature of 48-49°F in August and 45°F in September. This is based on the conservative assumption that the temperature of spill water does not increase significantly while in contact with the atmosphere despite the highly diffused valve discharge. It is, therefore, considered necessary to keep the spill from Devil Canyon to a minimum to avoid unacceptably low downstream temperatures. The analyses indicate that by operating Devil Canyon to meet most or all of the base load demand and with Watana generating essentially to meet peak demands and spilling continuously when necessary, it would be possible to maintain downstream flow temperatures below Devil Canyon close to that of power flow while reducing spill frequency considerably.

During major floods (1:10 year or rarer), there will be significant spills from Devil Canyon in addition to the power flow resulting in cold slugs of water downstream for a few days. It will be necessary to establish criteria for acceptability of lower temperatures for short durations in August and September in consultation with fisheries study groups and concerned agencies. Currently, downstream water temperature analyses are being refined, and when the results are available, the above spill temperatures and duration should be reviewed to confirm downstream temperatures during normal power operation as well as flood events. If the projected temperature regime downstream is unacceptable, alternative means to remedy the situation should be considered. These may include provision of higher level intakes to several or all fixed-cone valve discharges at Devil Canyon, multilevel power intake at Devil Canyon, limited operation of main overflow spillway (for floods 1:50 year or more frequent) to improve temperature without serious increase in nitrogen supersaturation, etc.

3 - SCOPE OF ANALYSES

The objective of the analyses presented in the following sections is to provide an assessment of the performance of the fixed-cone valves in their proposed configuration with respect to their potential in reducing gas concentration in spill waters from the Watana and Devil Canyon developments. The analysis is a theoretical study supplemented by available field information on performance of these valves for aeration. Field measurements were conducted on the Howell Bunger valves at the Lake Comanche dam on the Mokelumne River in California. Results of the tests are interpreted to confirm some of the study assumptions.

A related question of temperature of spill waters is analyzed in Appendix B. The data for the analyses has been drawn from the Feasibility Report (7).

4 - SCHEME DESCRIPTION

This section presents a short description of the selected spillway and outlet facilities for the proposed Watana and Devil Canyon developments.

4.1 - Scheme Description

Selection of the discharge capacity and the type of spillway and outlet facilities has been based on project safety, environmental, and economic considerations. At each development, a set of fixed-cone valves is provided in the outlet works to discharge spills up to 1:50 year recurrence interval. The main spillway comprises a gated control structure and a chute with a flip bucket at its end. This facility has a capacity to discharge, in combination with the outlet works, the routed design flood which has a return period of 1:10,000 years. A fuse plug with an associated rock-cut channel is provided to discharge flows above the design flood and up to the estimated probable maximum flood at the dam. Detailed descriptions of the facilities are presented in the Feasibility Report (7).

The primary purpose of the outlet facility is to discharge the spill waters up to 1:50 year recurrence in such a manner as to reduce potential supersaturation of the spill with atmospheric gases, particularly nitrogen. This frequency was adopted after discussions with environmental study groups as an acceptable level of protection of the downstream fisheries against the gas bubble disease. A set of fixed-cone valves were selected to discharge the spills in highly diffused jets to achieve significant energy dissipation without provision of a stilling basin or a plunge pool where potentially large supersaturation develops. The valves have been selected to be within current world experience with respect to their size and operating heads. At Watana, six 78 inch diameter valves are provided and are located about 125 ft above average tailwater level in the river. The design capacity of each valve is 6,000 cfs. At Devil Canyon, seven fixed cone valves with a total design capacity of 38,500 cfs are provided at two levels within the arch dam, four 102 inch valves at the high level some 170 ft above average tailwater level, and three 90 inch valves about 50 ft above average tailwater level. The lower valves have a capacity of 5,100 cfs each and the higher ones 5,800 cfs each. In sizing these valves, it has been assumed that the valve gate opening will be restricted to 80% of full stroke to reduce vibration.

5 - ENGINEERING ANALYSES

This section details the analyses carried out to estimate potential supersaturation in the releases from the Watana and Devil Canyon developments when the reservoirs spill.

5.1 - Available Data

Fixed cone valves have been used in several water resource projects for water control, energy dissipation, and aeration of discharge waters, and data on their performance for such operations is readily available. However, no precedence has been reported on the use of such valves for reducing or eliminating gas supersaturation in spill waters. Manufacturer's catalog information on Howell Bunger valves and Boving Sleeve type discharge regulators (both particular types of fixed cone valves) and the Tennessee Valley Authority Study (4) on aeration efficiency of Howell Bunger valves form the specific data available. Theoretical analyses are carried out based on the geometric and physical characteristics of diffused jets discharging freely into the atmosphere.

5.2 - Field Data Collection

A review of existing facilities where a potential for spilling during the spring of 1982 existed was made, and the Lake Comanche dam, on the Mokelumne River in California, was selected as a feasible site for specific testing.

The Comanche Lake dam is of the rockfill type with outlet facilities fitted with four Howell Bunger valves. These valves are located at the toe of the dam and spray the discharge into confined concrete conduits before releasing the water to the stream.

Outflow through the valves was around 4,000 cfs during the test on May 28, 1982. Water samples were collected at several depths in the reservoir near the valves and at downstream locations and analyzed for nitrogen and oxygen concentrations. Details of the test procedure and results are presented in Appendix 1.

5.3 - Method of Analysis

(a) Flow from the fixed cone valves leaves the structure as a free-discharging jet diffusing radially at the cone angle. The path of the jet depends on the energy of flow available at the valve and the angle at which the jet leaves the valve (assumed as 45°). Referring to Figure 5.1, the path of the trajectory is given by the following equation (8):

$$y = x \tan \theta - \frac{x^2}{k(4 H_n \cos^2 \theta)} \qquad (1)$$

where:

θ = angle of the jet to the horizontal;

k = a factor to take account of loss of energy and velocity reduction due to the effect of air resistance, internal turbulences, and disintegration of the jet (assumed at 0.9);

H_n = net energy of the jet, ft.

The proposed valve operation restricts the opening of the valve gate to 80% of full stroke. This may be interpreted as equivalent to producing an additional head loss in the system, thereby reducing the discharge to 80% of the theoretical capacity. The general discharge equation for the valve:

$$Q_T = CA \sqrt{2g\ h_n} \qquad (2)$$

may then be written as:

$$Q_D = 0.8\ Q_T = CA \sqrt{2g\ (\cdot 8)^2\ h_n} \qquad (2a)$$

$$= CA \sqrt{2g \times \cdot 64 \times h_n} \qquad (3)$$

where:

Q_T = theoretical capacity of valve, cfs;
A = area of valve, ft;
C = coefficient of discharge ($\sim$ .85 for fixed-cone valves);
h_n = net head upstream of valve, cfs;
Q_D = design capacity of valve, cfs.

Equation (1) may be rewritten now as:

$$y = x \tan \theta - \frac{x^2}{k \quad 4 \times (0.64 \times h_n) \times \cos^2 \theta} \qquad (4)$$

Referring to Figure 5.1, the longitudinal throw of the jet is calculated with θ=45° and -45° while its laterial throw calculated when θ=0°.

Vertical rise of the jet above the valve is calculated as a simple projectile subject to gravity and neglecting air friction to yield a conservative value.

(b) Potential Plunging Depth of Jet(s) Into Tailwater Pool

As part of the feasibility studies of the Watana and Devil Canyon developments, a study was made by Acres on the scour hole development below high head spillways, and the results therefrom have been used to estimate the potential plunging of the jets from the fixed cone valves into tailwater. Figure 5.2 presents a definition sketch for the study carried out for a typical flip bucket spillway configuration. It may be readily observed that significant differences exist between a "solid" jet leaving a flip bucket and the diffused discharge jet from the fixed-cone valves in the available energy and its concentration in the jet for scouring downstream or plunging into the tailwater pool. Equation (5) was developed in the above mentioned studies to estimate scour depth for a solid jet:

$$y = 0.24 \, q^{0.65} \, H^{0.32} \qquad (5)$$

where:

y = estimated scour depth, ft;
q = unit discharge, cfs/ft;
H = net fall of the jet, ft.

This equation was modified to take account of the maximum discharge intensity, q^1 in cfs/ft^2 of the fixed cone valves assuming the longitudinal spread of the solid jet as equal to its flow depth at the toe of the flip bucket (Figure 5.2). This assumpation is expected to yield a conservative estimate of the scour depth for diffused jets. The fall height H was taken as the drop of the diffused jet from the highest point of its rise to the tailwater pool (Figure 5.1). With these modifications, equations (6) and (7) were developed to estimate the scour depth due to the valve discharges at Watana and Devil Canyon, respectively.

$$y_W = .24\ (q^1{}_W)^{0.92}\ H_W{}^{0.32} \qquad (6)$$

$$y_{DC} = .24\ (q^1{}_{DC})^{0.98}\ H_{DC}{}^{0.32} \qquad (7)$$

W and DC represent Watana and Devil Canyon, respectively.

Scour depths, as calculated by equations (6) and (7), give an estimate of the depth to which water may plunge should the jet fall into a tailwater pool instead of on solid ground. The values y_W and y_{DC} are calculated for the highest intensity $q^1{}_W$ or $q^1{}_{DC}$ when all the jets are operating at each of the developments and taken as the plunge depth of the jets.

5.4 - Supersaturation of Spills

(a) Gas Concentration in Valve Discharges

Results of the Lake Comanche dam tests indicate that the Howell Bunger valves have been successful in preventing supersaturation of the spills and, to some extent, have reduced the gas concentration in the spill waters.

The Tennessee Valley Authority studies which were conducted to assess aeration efficiency of the Howell Bunger valves, suggest that the discharge from the valves are well aerated. The test results indicated that small supersaturation (101-102%) of oxygen may be found in the spills but suggested that this may be due to calculation procedure used. The report concluded that since saturation concentrations were not measured in the field, it is not certain whether supersaturation acually occurred in the runoff downstream.

Based on the above test results, it has been conservatively assumed that a 100% saturation level of atmospheric gas is likely to exist in the valve discharges at Watana and Devil Canyon.

(b) Supersaturation Due to Plunging

Each component of gas in the atmosphere will dissolve in water independently of all other gases and, when at equilibrium (i.e. saturation condition) with the air, the pressure of a specific dissolved gas is equivalent to its partial pressure in the air. Approximating one atmospheric pressure to 34 ft head of water, the above relationship translates roughly to 3% saturation per foot of hydrostatic head. Thus, it may be extended that fully saturated water mass when plunging into a pool would develop a supersaturation of gas at the rate of 3% per foot of plunge provided that adequate supply of air is entrained.

(c) Gas Concentration in Downstream Discharges

Average power flows at the two developments during spills have been estimated in the reservoir simulation studies. For the current analyses, it is conservatively assumed that these powerhouse discharges will be fully saturated. Estimates of final gas concentrations in the total downstream discharges is calculated assuming the laws of dilution to hold for mixing discharges at different gas concentrations.

It is assumed that spills from Watana will get completely mixed in the Devil Canyon storage during their passage through 26 miles of reservoir and that no supersaturation would build up in the reservoir due to Watana spills.

ACRES

Calculations

SUBJECT:

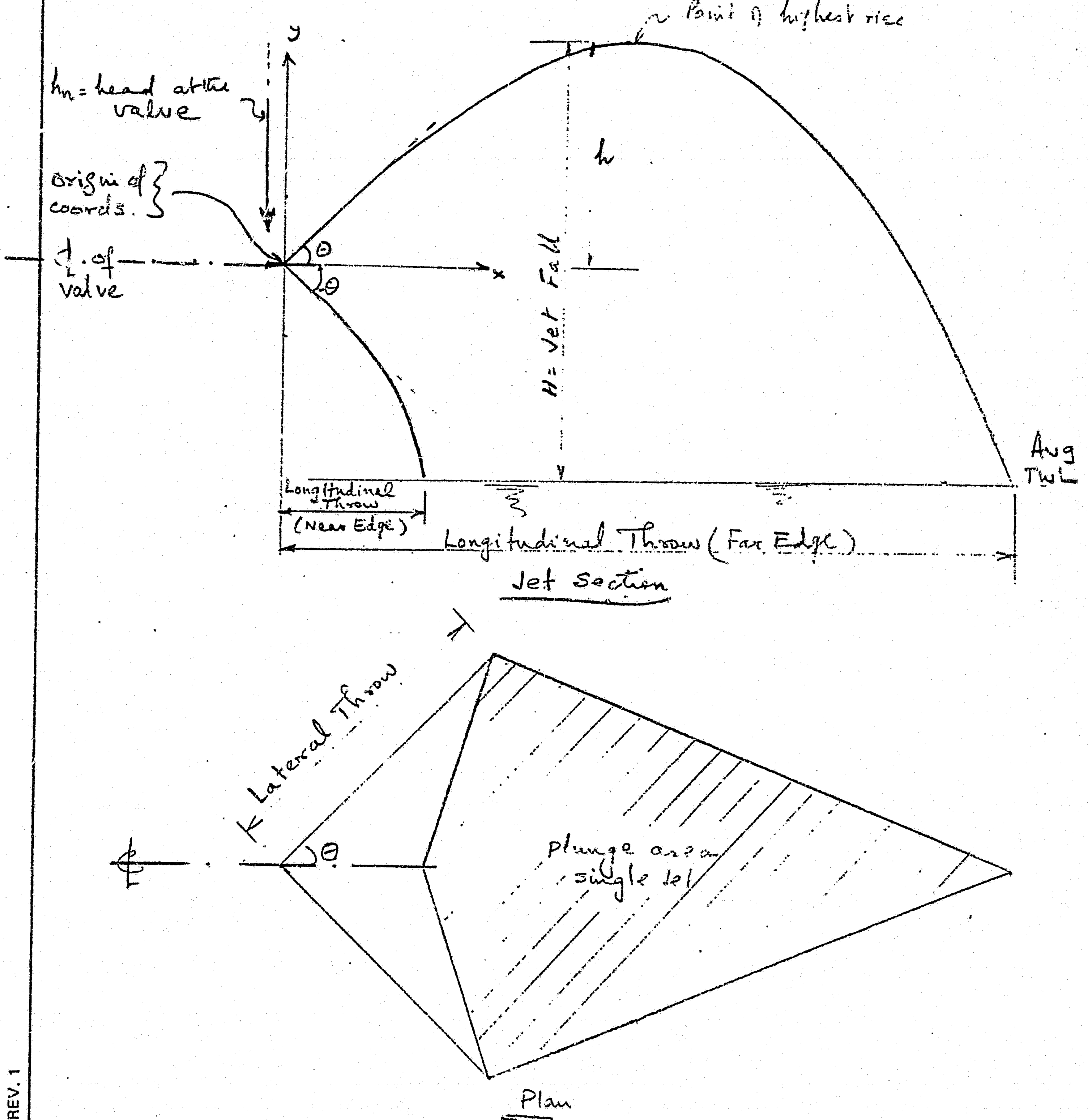
JOB NUMBER ______

FILE NUMBER ______

SHEET ______ OF ______

BY ______ DATE ______

APP ______ DATE ______



DEFINITION SKETCH FOR DIFFUSED JET

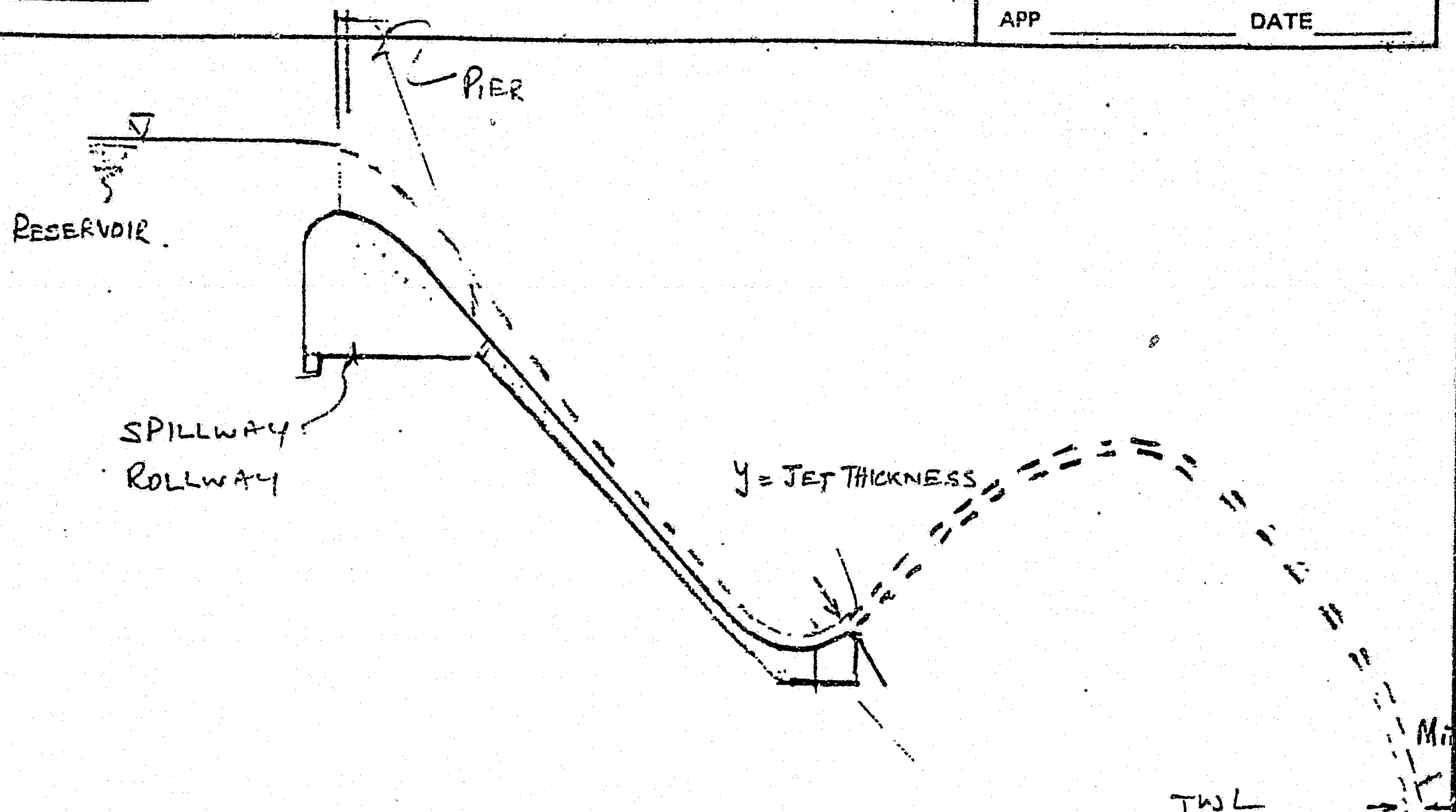
FIGURE 5.1

FORM NO. 152 REV. 1

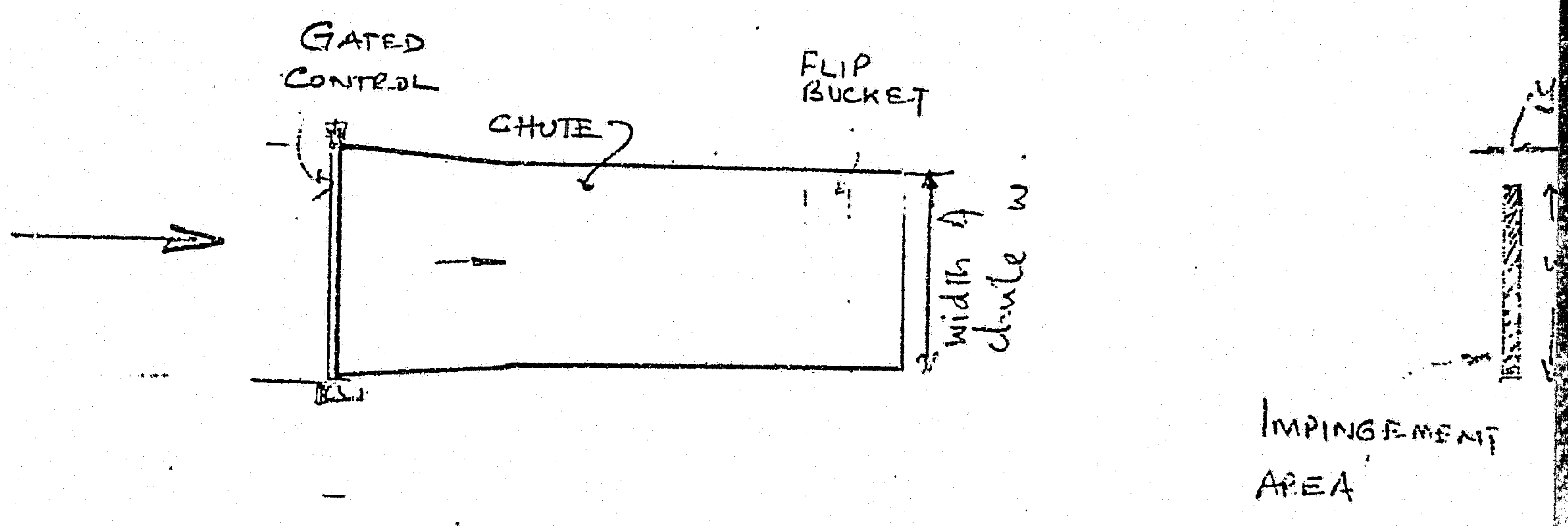
Calculations

SUBJECT:

JOB NUMBER
FILE NUMBER
SHEET OF
BY DATE
APP DATE



SPILLWAY SECTION



PLAN

DEFINITION SKETCH FOR 'SOLID JET' FROM CHUTE - FLIP BUCKET SPILLWAY

FIGURE S.2

FORM NO. 152 REV. 1

6 - RESULTS

Table 6.1 presents the results of the analyses carried out to assess the performance of the fixed cone valves at the proposed Watana and Devil Canyon developments in relation to the potential gas supersaturation of spill waters. Figures 6.1 and 6.2 present the jet interference pattern and the areas of impingement.

Estimated supersaturation in the spill discharges with a recurrence interval of 1 in 50 years is 101% at Watana and 102% at Devil Canyon. For more frequent spills, these concentrations are expected to be somewhat lower due to lower intensity of spill discharge and consequent lower plunge in the tailwater pool. For spills of rarer frequency, the main chute spillway will operate leading to potentially greater supersaturation in the downstream discharges.

Results of spill temperature analysis is presented in Appendix B.

TABLE 6.1 - RESULTS OF ANALYSES

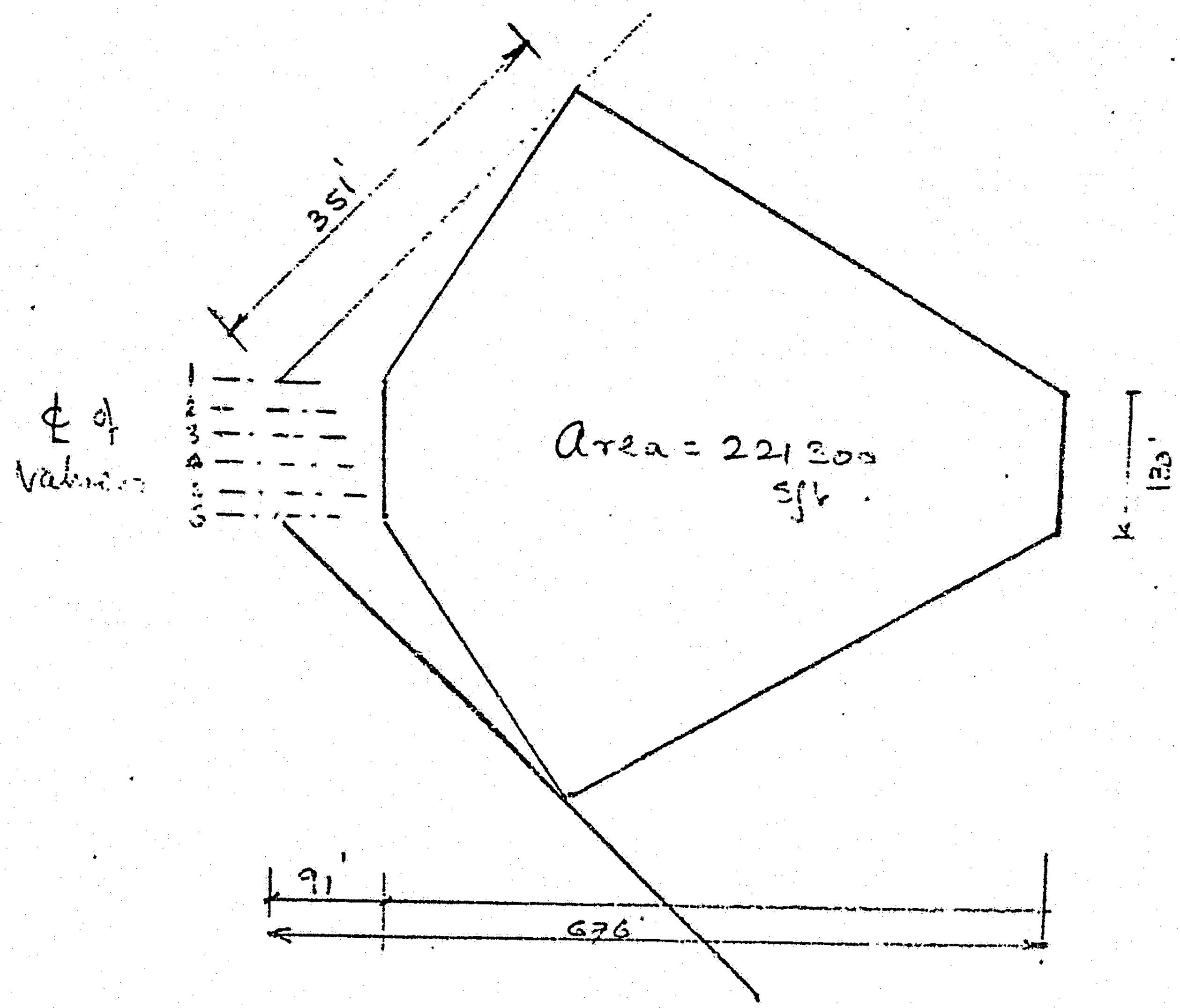
Description	Watana Valves	Devil Canyon Valves: Upper Level	Devil Canyon Valves: Lower Level
1. Valve Parameters			
Diameter of fixed cone valves-inches	78	102	90
Number of valves	6	4	3
Design capacity-cfs	4,000	5,800	5,100
Elevation of valve centerline-ft	1,560	1,050	930
Elevation above average tailwater-ft	105	170	50
Net head (h_n) at the valve-ft	508	365	450
Angle of valve discharge with horizontal-degrees (assumed)	45	45	45
2. Jet Geometry			
Longitudinal throw-near edge-ft	91	130	46
Longitudinal throw-far edge-ft	676	750	564
Lateral throw-ft	351	378	228
Impingement area of single jet-ft^2	145,200	112,250	83,400
Impingement area of all jets-ft^2	221,300	173,250	
Maximum fall of jet (H)-ft	359	353	275
3. Jet Characteristics			
Average intensity of discharge of single jet cfs/ft^2	0.028	0.052	0.061
Maximum intensity (q^1) when all jets are operating cfs/ft^2	6 x 0.028 ≈ 0.168	4 x ·052 + 3 x ·061 = 0.391	
Estimated plunge depth-ft	0.3	0.62 (H=353[1])	
4. Supersaturation Estimates (1:50 year flood)			
Design valve discharge-cfs	24,000	38,500	
Assumed simultaneous power flow-cfs	7,000	3,500	
Total downstream discharge-cfs	31,000	42,000	
Assumed gas concentration in power flow-percent and valve discharge at valve-%	100.0	100.0	
Maximum gas concentration in valve discharge below dam-%	100.9	101.9	
Maximum gas concentration in total downstream discharge-%	100.7	101.7	

ACRES

Calculations

SUBJECT:

JOB NUMBER ______
FILE NUMBER ______
SHEET ______ OF ______
BY ______ DATE ______
APP ______ DATE ______



VALVE DISCHARGE PATTERN AND IMPINGEMENT AREA FOR WATANA

FIGURE 6.1

FORM NO. 152 REV. 1

ACRES

Calculations

SUBJECT:

JOB NUMBER ______
FILE NUMBER ______
SHEET ______ OF ______
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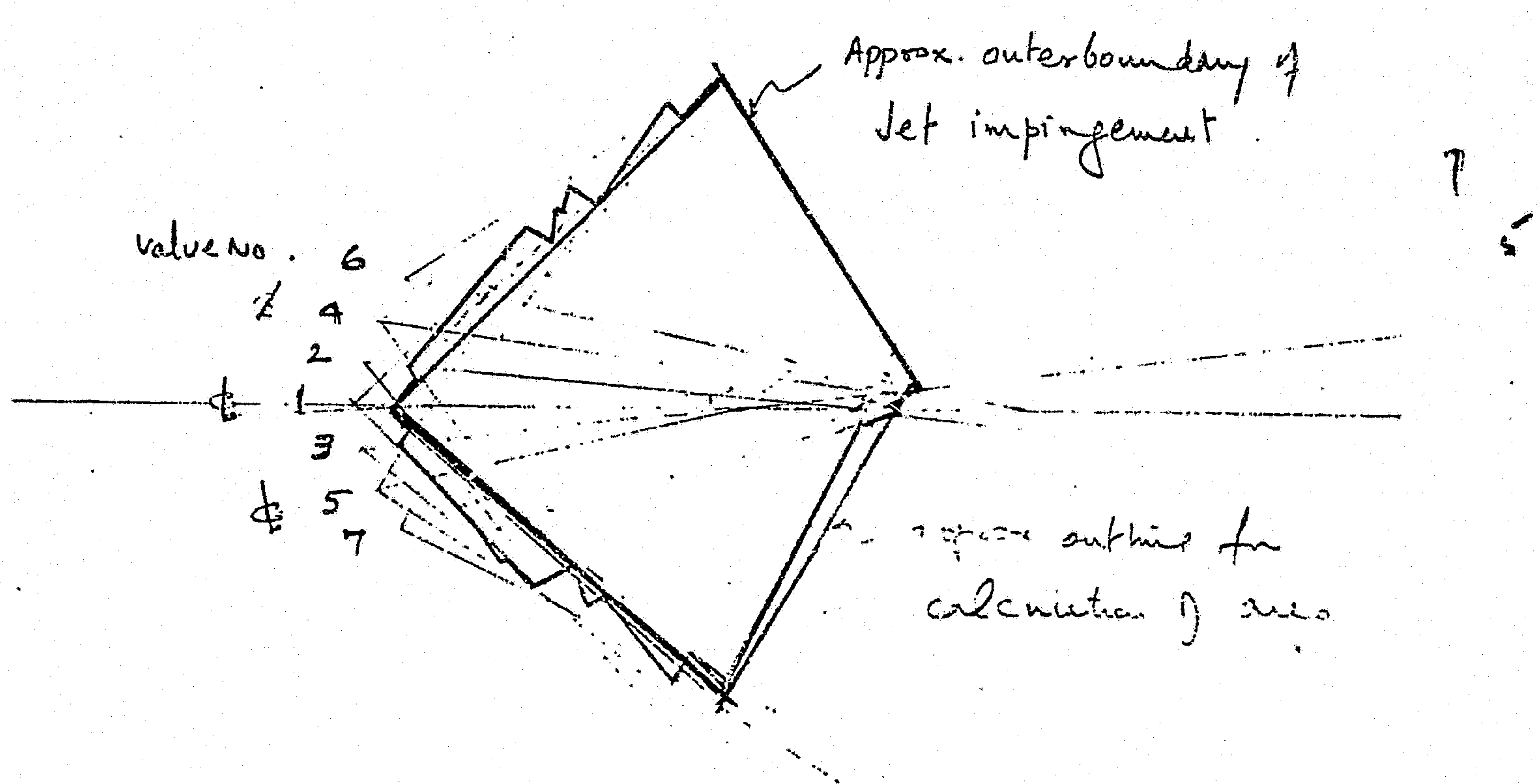
APP ______ DATE ______



Ref. Plate 52
vol. 3. Feasibility Report

0 100' 200'
scale.

When all 7 valves are operating.
total area of impingement $\simeq \frac{550 \times 630}{2} = 173250$ sf.

VALVE DISCHARGE PATTERN
IMPINGEMENT AREA FOR
DEVIL CANYON

FIGURE 6.2

FORM NO. 152 REV. 1

7 - CONCLUSIONS

1. The analyses described above indicate that the proposed fixed-cone valves would adequately prevent serious gas supersaturation in spill waters up to a recurrence interval of 1:50 years.

2. Several assumptions have had to be made in the analyses with respect to jet characteristics and its potential plunge into tailwater pool. Field test results available are only indicative of the valve performance. In particular, the configuration of the proposed valves set high above the tailwater pool and their free discharge with the atmosphere differ significantly from the Lake Comanche dam arrangement and the TVA test facility. In view of the nature of analyses and lack of precedence for the proposed valve arrangement, it is recommended that a physical model study be carried out to confirm the performance of the valves.

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LAKE COMANCHE
DISSOLVED NITROGEN STUDY

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June 1982

Nitrogen gas in the deep water of a reservoir may be slightly super-saturated due to the hydro-static pressure of the overlying water (Wetzel, 1975). Therefore water flowing from a dam with a deep intake may contain a super-saturated concentration of nitrogen. If this excess nitrogen gas is not rapidly released into the atmosphere, it may cause nitrogen gas bubble disease in fish residing below the dam outfall (Conroy and Herman, 1970).

A study was conducted at Lake Comanche Dam, Mokelumne River, California, to determine the efficiency of the Howell-Bunger Valve in removing super-saturated dissolved nitrogen (N_2) from the dam's tailwater.

The valves spray outfall water into concrete conduits before releasing the water to the stream. This was observed and photographed at Lake Comanche Dam on 28 May, 1982 ~~1981~~, at a flow of 4000 cfs into the Mokelumne River (see accompanying photos). This creates a turbulent and aerated flow with the purpose of facilitating nitrogen gas release to the atmosphere.

By sampling nitrogen gas in the reservoir near the intake, and at several locations below the outfall valves, the efficiency of the valve was obtained.

METHODS

In order to determine nitrogen gas concentrations at various depths in the reservoir, water samples were collected in Lake Comanche approximately 50 m from the dam directly over the river channel on 28 May 1982. A Van Dorn Bottle was lowered from a boat to collect water samples at depths of 0, 10, 20, 30, and 38.4 m. As reported by East Bay Municipal Utility District the dam intake was at a depth of 38.4 m (126 ft) at the time of the sampling.

Once taken aboard, each sample was poured with minimum turbulence into an airtight bottle and capped in a manner that left no air bubbles in the bottle. Bottles were placed in a cooler for transportation to the lab. Studies conducted by Steve Wilhelms of the Hydraulic Laboratory, U.S. Army Waterway Experiment Station, Vicksburg, Mississippi (personal communication) indicate that brief exposure of deep water samples to atmospheric conditions has little effect on nitrogen gas concentrations. However, he has found that periods of exposure to atmospheric air bubbles during transportation can cause significant changes in nitrogen gas concentrations, hence the need for removing all air bubbles before transportation. Excess water remaining in the Van Dorn Bottles was measured for temperature. The atmospheric pressure measured on site at the time of sampling was 753 mm.

At the tailwater below the dam, water was collected by immersing the sample bottles under the water and capping them in a manner that left no air bubbles in the bottles. Samples were taken at the outfall, 100 m below the outfall, and 200 m below the outfall. Water temperatures were taken at each of these locations. Bottles were placed in a cooler for transportation to the lab. At the time of sampling, the outfall flow was 4,000 cfs. The atmospheric pressure was 753 mm.

The water collected was analyzed for nitrogen gas (N_2) and oxygen (O_2) in a California State Certified Water lab using a Carle Model 8700 Basic Gas Chromatogram with a thermal conductivity conductor several hours after collection.

RESULTS

Location	Depth (m)	Temperature (°C)	N_2 (mg/l)	N_2 % Saturation	O_2 (mg/l)	O_2 % Saturati
Reservoir						
	0	22.0	14.9	101	9.2	105
	10	14.5	17.0	100	9.3	90
	20	13.2	17.3	99	10.0	94
	30	11.0	17.9	99	10.2	93
	38.4	10.0	18.5	101	9.3	82
Dam Tailwater						
At Valve	0	10.2	17.7	97	11.1	94
100 m downstream	0	10.5	17.3	95	11.2	98
200 m downstream	0	11.5	17.9	97	10.9	98

References

Conroy, D.A., and R. L. Herman. Textbook of Fish Diseases. 1970. T.F.H. Publications, Jersey City, New Jersey. 302 pp.

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APPENDIX B

SPILLS AT WATANA AND DEVIL CANYON DEVELOPMENTS

B.1 - OPERATION OF WATANA AND DEVIL CANYON COMBINED (Beyond Year 2002)

(a) Spill Quantities and Frequency

The monthly reservoir simulation studies calculate spill volumes as the flow required to be discharged from the dam to satisfy downstream requirements less the maximum turbine capacity, and does not restrict the turbine flow in relation to the actual energy demand of the system. Total energy production, as calculated, is the energy potential of the schemes. Usable energy is then calculated as the potential or the maximum energy demand, whichever is smaller. The turbine flows are not readjusted to the level of usable energy production. Tables B.1 to B.9 present selected results of the reservoir simulation studies which indicate this.

Tables B.10 to B.12 are developed from the reservoir simulation studies for adjusted turbine flows for two alternative generation patterns at Watana and Devil Canyon for the months of August and September when spills are most likely to occur. Alternative A assumes that whenever the potential energy generation from Watana and Devil Canyon developments is greater than the usable energy level, each development will share the usable energy generation in proportion to their average heads. However, in the months when Watana outflow, as simulated, is not sufficient to generate energy in proportion to its average head, Devil Canyon will make up this difference. This operation is required in such years when Devil Canyon is being drawn down to meet the minimum downstream flow requirements (years 1, 2, for example). Alternative B assumes that Devil Canyon would generate all the energy possible consistent with downstream flow requirements, and Watana would only operate to make up the difference in years when energy potential is greater than usable. This assumes that all the energy from Devil Canyon is useable as base load on a daily basis. Battelle load forecast (1981) tends to confirm this assumption for the year 2010. However, during earlier years, such operation may not be fully possible.

It may be readily seen from Tables B.10 to B.12 that frequency of continuous spills (24 hours) from the reservoirs in the months of August and September is significantly greater than presented by the reservoir simulation (Tables B.3 and B.6).

The analyses summarized in Tables B.10 to B.12 indicate that Devil Canyon would spill in 30 out of 32 years in August and 16 out of 32 years in September for the Case "C" operation which maintains a minimum instantaneous flow of 12,000 cfs in August at Gold Creek. For downstream discharge requirements greater than 12,000 cfs at Gold Creek, it is estimated that the frequency of spills may not be increased significantly. However, the volume of spills will be larger to make up for increased flow requirement. The above spill frequency is simulated for a system energy demand in the year 2010 (Battelle Forecast) and assumes that the entire demand is met by Watana and Devil Canyon developments where possible. The spills will be greater and more frequent in the years between 2002 (Devil Canyon commissioning) and 2010.

It may be seen that operation Alternative 2, which provides for maximum possible energy generation from Devil Canyon while Watana is allowed to spill, results in significantly reduced spill frequency from Devil Canyon. This type of operation is expected to be advantageous with regard to downstream water quality (see Section B.2).

Several intermediate distributions of generation between Watana and Devil Canyon is also possible. A recommended operation will be derived after finalizing the downstream flow requirements and the refined temperature modeling studies which are currently in progress.

(b) Spill Quality

(i) Spill Temperature

Figures B.1 and B.2 are extracts from the project Feasibility Report (7) and present simulated temperature profiles in the Watana and Devil Canyon reservoirs for the months June to September. Refinement of reservoir temperature modeling is currently in progress, but the differences between the revised profiles are not expected to be very significant from the ones presented here for these months.

Temperature of spill waters at Watana is expected to be close to that of power flow, and hence, it is not expected to create temperature problems downstream when Watana is operating alone (1993-2002) or when it spills into Devil Canyon. At Devil Canyon, however, spill temperature is expected to be close to 39°F compared to a power flow temperature of 48-49°F in August and 45°F in September. This is based on the conservative assumption that the temperature of spill water does not increase significantly while in contact with the atmosphere despite the highly diffused valve discharge. It is, therefore, considered prudent to keep the spill from Devil Canyon to a minimum to maintain as high a downstream temperature as possible during spills.

The operation Alternative 2 indicates that by operating Devil Canyon to generate as much as possible during these months and with Watana generating essentially to meet peak demands and spilling continuously when necessary, it would be possible to maintain downstream flow temperatures below Devil Canyon close to that of power flow.

During major floods (1:10 year or rarer frequency), there will be significant spills from Devil Canyon (see Tables B.10 and B.11) in addition to the power flow resulting in cold slugs of water downstream for a few to several days. It will be necessary to establish criteria for acceptability of lower temperatures for short durations in August and September in consultation with fisheries study groups and concerned Agencies. Currently, downstream water temperature analyses are being refined, and when the results are available, the above spill temperatures and duration should be reviewed to confirm downstream temperatures during normal power operation as well as flood events. If the projected temperature regime downstream is unacceptable, alternative means to remedy the situation should be considered. These may include provision of higher level intakes to several or all fixed-cone value discharges at Devil Canyon, multilevel power intake at Devil Canyon, limited operation of main overflow spillway (for floods 1:50 year or more frequent) to improve downstream water temperature without serious increase in nitrogen supersaturation, etc.

(ii) Gas Supersaturation

It does not appear (from Table 6.1) that there would be significant advantage in spilling from Watana as compared to spills from Devil Canyon in terms of gas concentration.

B.2 - OPERATION OF WATANA ALONE (1993-2002)

Before Devil Canyon is commissioned, Watana would operate alone, and spills required to maintain downstream flows will have to be made through the fixed-cone valves. Reservoir simulations indicate that, generally, spills would be of lower magnitude during this operation due to greater percentage of flow being used to generate usable energy.

It is believed that the river reach of some 30 miles between Watana dam and Devil Canyon would lessen the impact of spill temperature and gas concentration below Devil Canyon and would pose less problems, if any, compared to the case when Devil Canyon development is also commissioned.

Table B.1 Watana Monthly Inflow

RESERVOIR 1

INFLOW (CFS)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	4719.9	2083.6	1168.9	815.1	641.7	569.1	680.1	8655.9	16432.1	19193.4	16914.6	7320.4
2	3299.1	1107.3	906.2	808.0	673.0	619.8	1302.2	11649.8	18517.9	19786.6	16478.0	17205.5
3	4592.9	2170.1	1501.0	1274.5	841.0	735.0	803.9	4216.5	25773.4	22110.9	17356.3	11571.0
4	6285.7	2756.8	1281.2	818.9	611.7	670.7	1382.0	15037.2	21469.8	17355.3	16681.6	11513.5
5	4218.9	1599.6	1183.8	1087.6	803.1	638.2	942.6	11696.8	19476.7	16983.6	20420.6	9165.5
6	3859.2	2051.1	1549.5	1388.3	1050.5	886.1	940.8	6718.1	24881.4	23787.9	23537.0	13447.8
7	4102.3	1588.1	1032.6	816.9	754.8	694.4	718.3	12953.3	27171.8	25831.3	19153.4	13194.4
8	4208.0	2276.6	1707.0	1373.0	1189.0	935.0	945.1	10176.2	25275.0	19948.9	17317.7	14841.1
9	6034.9	2935.9	2258.5	1480.6	1041.7	974.3	1263.4	9957.8	22097.8	19752.7	18843.4	5978.7
10	3668.0	1729.5	1115.1	1081.0	949.0	694.0	885.7	10140.6	18329.6	20493.1	23940.4	12466.9
11	5165.3	2213.5	1672.3	1400.4	1138.9	961.1	1069.9	13044.2	13233.4	19506.1	19323.1	16085.6
12	6049.3	2327.8	1973.2	1779.9	1304.8	1331.0	1965.0	13637.9	22784.1	19639.8	19480.2	10146.2
13	4637.6	2263.4	1760.4	1608.9	1257.4	1176.8	1457.4	11333.5	36017.1	23443.7	19887.1	12746.2
14	5560.1	2508.9	1706.9	1308.9	1184.7	883.6	776.6	15299.2	20663.4	28767.4	21011.4	10800.0
15	5187.1	1789.1	1194.7	852.0	781.6	575.2	609.2	3578.8	42841.9	20082.6	14048.2	7524.2
16	4759.4	2368.2	1070.3	863.0	772.7	807.3	1232.4	10966.0	21213.0	23235.9	17394.1	16225.6
17	5221.2	1565.3	1203.6	1060.4	984.7	984.7	1338.4	7094.1	25939.6	16153.5	17390.9	9214.1
18	3269.8	1202.2	1121.6	1102.2	1031.3	889.5	849.7	12555.5	24711.9	21987.3	26104.5	13672.9
19	4019.0	1934.3	1704.2	1617.6	1560.4	1560.4	1576.7	12826.7	25704.0	22082.8	14147.5	7163.6
20	3135.0	1354.9	753.9	619.2	607.5	686.0	1261.6	9313.7	13962.1	14843.5	7771.9	4260.0
21	2403.1	1020.9	709.3	636.2	602.1	624.1	986.4	9536.4	14399.0	18410.1	16263.8	7224.1
22	3768.0	2496.4	1687.4	1097.1	777.4	717.1	813.7	2857.2	27612.8	21126.4	27446.6	12188.9
23	4979.1	2587.0	1957.4	1670.9	1491.4	1366.0	1305.4	15973.1	27429.3	19820.3	17509.5	10955.7
24	4301.2	1977.9	1246.5	1031.5	1000.2	873.9	914.1	7287.0	26859.3	16351.1	18016.7	8099.7
25	3056.5	1354.7	931.6	786.4	689.9	627.3	871.9	12889.0	14780.6	15971.9	13523.7	9786.2
26	3088.8	1474.4	1276.7	1215.8	1110.3	1041.4	1211.2	11672.2	26689.2	23430.4	15126.6	13075.3
27	5679.1	1601.1	876.2	757.8	743.2	690.7	1059.8	8938.8	19994.0	17015.3	18393.5	5711.5
28	2973.5	1926.7	1687.5	1348.7	1202.9	1110.8	1203.4	8569.4	31352.8	19707.3	16807.3	10613.1
29	5793.9	2645.3	1979.7	1577.9	1267.7	1256.7	1408.4	11231.5	17277.2	18385.2	13412.1	7132.6
30	3773.9	1944.9	1312.6	1136.8	1055.4	1101.2	1317.9	12369.3	22904.8	24911.7	16670.7	9096.7
31	6150.0	3525.0	2032.0	1470.0	1233.0	1177.0	1404.0	10140.0	23400.0	26740.0	18000.0	11000.0
32	6458.0	3297.0	1385.0	1147.0	971.0	889.0	1103.0	10406.0	17323.0	27840.0	31435.0	12026.0
AVE	4513.1	2052.4	1404.8	1157.3	978.9	898.3	1112.6	10397.6	22922.4	20778.0	18431.4	10670.4

Table B.2 Watana Power Flows . Case 'C' Operation

POWERHOUSE FLOW (CFS)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	5676.3	8474.4	11285.3	8391.9	7294.9	6363.2	5436.6	6551.7	5399.7	4546.3	5553.9	4900.3
2	6234.5	7324.0	9102.0	8384.7	7326.2	6551.2	5554.2	7959.3}{_				
^r}{_>aRr									6844.1	4830.3	6576.8	13051.6
3	7568.3	9549.1	11617.4	8851.3	7494.2	6366.9	5457.6	6409.6	7389.9	5719.7	6135.3	10801.3
4	8881.8	10527.8	11397.6	8395.7	7264.9	6365.6	5846.8	9241.8	8943.8	4991.6	6326.2	8208.5
5	7194.3	8978.6	11300.2	8664.5	7456.3	6367.8	5404.4	7775.0	7269.2	4579.7	5917.9	7900.3
6	6834.6	9430.1	11665.9	8965.1	7703.7	6345.9	5648.4	6627.3	7933.7	6692.3	13289.8	13447.8
7	7077.7	8967.1	11155.0	8393.7	7408.0	6336.3	5422.2	8265.3	10712.1	8844.4	12744.0	13194.4
8	7183.4	9655.6	11823.4	8949.8	7842.2	6330.4	5719.3	7209.1	9352.7	6001.2	6328.7	14301.6
9	8803.9	10526.1	11738.1	9694.2	7694.9	6357.9	6051.0	7144.7	7949.2	5316.5	6441.1	5471.6
10	6643.4	9108.5	11231.5	8657.8	7602.2	6324.0	5417.5	7119.7	6419.8	4845.6	10300.0	12466.9
11	8140.9	9592.5	11788.7	8977.2	7792.1	6339.2	5861.9	8408.6	5632.4	4525.4	6138.6	12284.9
12	8931.7	9803.0	11622.3	9624.0	7958.0	6338.8	7139.7	8649.0	9142.5	5839.0	7837.0	10146.2
13	7613.0	9645.4	11876.8	9185.7	7910.6	6343.1	6468.3	7749.1	10656.2	9961.3	17662.2	12746.2
14	8535.5	9887.9	11825.3	8885.6	7837.9	6375.6	5475.6	9351.6	8663.7	8862.3	11618.3	10600.0
15	8162.5	9166.1	11311.1	8428.7	7434.8	6369.1	5452.9	5539.1	10761.9	9863.7	9051.8	7524.2
16	7734.6	9747.2	11186.7	8439.8	7425.9	6382.8	5820.5	7576.7	7810.9	6420.2	6734.3	16225.6
17	8196.6	8944.3	11320.0	8637.2	7637.9	6315.1	6179.7	6642.3	8515.5	4506.3	6003.3	5612.0
18	6245.2	8581.2	11238.0	8679.0	7684.5	6316.6	5591.2	8196.3	9716.6	6866.1	16260.0	13672.9
19	6994.4	9313.3	11820.6	9194.4	8213.6	6568.2	6751.4	8306.3	10193.5	7156.7	5880.7	6015.5
20	6110.4	8733.9	10870.3	8196.0	7260.7	6371.4	5736.1	6933.8	5800.2	4270.8	9821.8	5667.0
21	6385.6	7578.3	9136.9	8137.8	6651.3	6918.7	5961.7	4892.9	3431.4	5330.1	8283.8	4603.1
22	6198.0	7402.9	9021.9	8090.4	6616.0	6883.7	5897.4	5180.5	3262.7	6756.4	7536.6	4348.9
23	6163.2	7240.4	11277.0	9247.7	8144.6	6373.8	6480.1	9618.4	10679.2	7464.2	8595.5	10955.7
24	7276.6	9356.9	11362.9	8608.3	7653.4	6372.6	5581.6	7128.3	7541.5	4985.5	6715.3	5525.7
25	6196.2	7329.3	9516.4	8363.1	7343.1	6549.4	5595.7	8226.2	5565.6	3776.7	8232.6	4036.2
26	6243.9	7361.3	8813.6	7831.3	6351.8	6584.6	5620.6	8257.3	9538.8	7327.3	6402.3	12681.6
27	8654.5	8980.1	10992.6	8334.6	7396.4	6347.4	5564.0	6716.2	6784.5	4972.5	7569.4	5330.5
28	6157.1	7202.2	8673.1	8290.9	7856.1	6461.9	6023.4	6879.2	10725.5	7084.7	7247.5	10613.1
29	8769.3	10024.3	11855.3	9395.5	7920.9	6305.1	6541.2	7726.7	6311.4	4789.8	5470.6	5025.6
30	6096.7	7236.4	8767.4	7906.2	7708.6	6578.8	6007.2	8289.4	8874.4	7527.5	7878.1	9096.7
31	9099.8	10930.5	11921.9	9273.2	7886.2	6342.9	6415.4	7252.5	8524.9	8036.5	10151.7	11000.0
32	9082.6	11038.5	11501.4	8723.7	7624.2	6339.9	5799.2	7356.0	6092.8	7212.3	19391.0	12026.0
AVE	7346.5	8988.6	10944.3	8681.2	7543.7	6421.8	5872.6	7474.4	7895.0	6247.0	8846.7	9361.9

Table B.3 Walawe Monthly Spills

SPILLS (CFS)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2755.0	0.0
AVE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	86.1	0.0

Table E.1 Walana Monthly Energy Potential

ENERGY FROM RESERVOIR 1 (GWH)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANN
1	221.9	318.0	429.3	312.2	240.6	228.3	185.8	230.5	187.4	169.0	213.2	185.0	2921.2
2	243.1	273.5	345.4	312.0	241.6	235.0	189.9	281.0	239.2	180.8	253.8	495.4	3290.8
3	297.2	358.7	441.9	329.3	247.1	228.5	186.7	224.2	256.2	214.8	238.2	411.5	3434.3
4	348.9	395.6	433.5	312.4	239.6	228.4	200.0	327.4	314.9	187.7	244.5	311.9	3544.8
5	282.5	337.3	429.8	322.4	245.9	228.5	184.8	274.6	254.4	171.2	228.7	300.8	3260.9
6	268.4	354.2	443.7	333.6	254.0	227.8	193.3	232.8	276.4	252.2	517.5	512.8	3666.7
7	277.9	336.8	424.3	312.3	244.3	227.4	185.4	292.2	377.8	336.6	498.5	503.1	4016.7
8	282.1	362.7	449.7	333.0	258.6	227.3	195.7	254.3	328.2	226.4	245.9	545.0	3708.9
9	345.9	395.5	446.8	361.0	253.7	228.2	207.1	252.0	278.1	199.7	249.9	208.5	3426.4
10	260.9	342.1	427.2	322.1	250.7	226.7	183.3	251.2	224.0	181.3	399.5	475.4	3546.7
11	319.7	360.3	448.4	334.0	257.0	227.6	200.6	297.4	196.3	168.1	236.2	466.5	3511.9
12	350.8	368.3	449.8	358.2	262.4	227.7	244.5	306.0	321.7	220.2	304.7	386.9	3801.1
13	299.0	362.2	451.8	341.8	260.9	227.8	221.4	273.6	378.9	384.5	694.2	486.0	4381.9
14	335.2	371.4	449.8	330.6	258.5	228.8	187.3	331.3	304.9	336.0	571.8	411.8	4117.5
15	320.5	344.4	430.2	313.6	245.2	228.5	186.4	193.6	379.6	379.7	354.6	286.9	3663.2
16	303.7	366.1	435.5	314.0	244.9	229.1	199.1	267.4	273.4	241.8	262.1	618.7	3745.9
17	321.9	336.0	430.6	321.4	251.9	226.7	211.5	233.4	297.2	169.1	231.6	213.1	3244.3
18	245.2	322.3	427.5	322.9	253.4	226.7	191.3	289.7	341.9	259.8	633.5	521.4	4035.7
19	274.7	349.8	449.6	342.1	270.8	235.9	231.2	293.7	359.1	271.1	228.9	229.1	3536.1
20	240.0	328.1	413.5	304.9	239.4	228.6	196.2	244.4	200.9	157.1	365.7	203.2	3121.9
21	234.8	265.6	323.7	281.1	202.8	228.4	186.4	158.1	116.9	184.7	296.9	162.1	2641.5
22	225.6	258.1	319.1	279.7	202.2	228.0	185.0	165.6	105.1	240.0	280.9	158.7	2648.0
23	239.6	270.6	428.5	344.1	268.6	228.9	221.9	341.0	378.7	284.0	335.2	417.8	3758.9
24	285.7	351.5	432.2	320.3	252.4	228.7	191.0	250.4	262.6	186.3	258.0	208.8	3227.9
25	241.8	273.9	361.3	311.2	242.1	234.6	191.2	290.5	194.1	140.2	312.6	150.2	2943.7
26	240.8	271.9	331.2	288.8	208.1	235.2	191.4	290.2	334.4	277.3	249.5	483.4	3402.3
27	339.9	337.3	418.1	310.1	243.9	227.8	190.3	236.6	236.6	185.5	290.5	200.6	3217.2
28	238.6	267.5	328.2	308.2	259.1	232.0	206.1	242.2	377.3	260.0	282.5	404.7	3415.4
29	344.4	376.5	451.1	349.7	261.2	226.5	224.0	272.8	220.2	178.6	209.6	188.5	3302.9
30	236.2	269.0	331.8	293.9	254.2	236.1	205.5	292.9	311.6	284.6	307.3	346.9	3370.0
31	357.4	410.6	453.6	345.1	260.1	227.8	219.6	255.8	298.6	304.0	396.4	419.5	3948.4
32	356.8	414.8	437.5	324.6	251.4	228.3	198.4	259.5	212.4	271.1	756.0	458.6	4169.3
AVE	286.9	336.0	414.5	321.6	247.7	229.2	199.8	262.7	276.2	234.8	342.1	355.4	3507.0

Table B.5 Devil Canyon Power Flows Case C Operation

POWERHOUSE FLOW (CFS)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	6714.6	8793.5	11458.9	8528.1	7388.9	6464.1	7436.8	6562.3	7436.2	8363.4	10940.6	6149.8
2	6587.4	7447.9	8923.1	7913.3	6437.6	6628.5	5756.6	5581.7	8304.7	8585.9	10860.0	11307.8
3	8203.6	9918.0	11873.9	9060.5	7596.4	6460.1	7410.6	8845.9	8026.9	8470.5	10727.2	10293.7
4	10113.7	11010.3	11666.8	8576.4	7398.8	6461.6	7874.9	10138.6	12704.7	8564.0	10597.0	8149.3
5	6996.7	9300.3	11503.5	8800.9	7582.9	6459.0	7470.7	9540.0	10980.6	8374.1	9971.6	8219.9
6	7812.3	9885.8	11984.4	9225.9	7928.4	6483.4	7693.4	6475.1	11134.2	9117.2	13763.2	13763.2
7	7629.8	9167.6	11323.0	8498.5	7546.3	6494.2	7449.6	9466.8	13763.2	12225.1	13763.2	13763.2
8	8217.2	10152.8	12103.0	9160.0	8042.1	6500.8	7761.6	7682.3	12493.1	8379.6	10849.2	13763.2
9	10205.5	11187.3	12378.0	10012.1	7865.4	6470.1	8101.3	7211.8	10264.9	8463.1	10679.8	5938.8
10	6630.1	7603.1	11487.3	8893.7	7832.3	6507.9	7530.0	9055.7	9627.9	7970.4	13763.2	13763.2
11	9042.6	10001.7	12127.9	9263.0	7993.4	6490.9	7888.2	8343.2	7108.8	8339.3	10476.1	11848.1
12	10053.3	10241.8	12279.2	10062.6	8246.8	6646.7	9458.5	9217.5	13427.7	8879.8	11061.4	10623.9
13	8441.3	9923.1	12095.1	9372.8	8066.6	6486.6	8502.7	6732.5	13763.2	11508.2	13763.2	13763.2
14	9289.6	10075.0	12012.4	9072.7	8040.6	6450.4	7388.3	9925.7	12094.4	12483.3	13763.2	11777.2
15	8980.2	9464.4	11503.5	8554.7	7553.4	6457.7	7418.6	7670.5	12132.6	11706.9	11145.8	8265.1
16	8725.9	10024.1	11277.2	8502.1	7482.0	6442.4	7780.9	7053.5	10708.2	9380.0	10669.3	13763.2
17	9478.4	9286.8	11594.8	8855.5	7840.6	6517.8	8338.8	6457.9	13022.3	9256.2	10414.6	5594.3
18	6489.9	7809.7	11481.3	8934.7	7921.5	6516.2	7673.5	8252.0	12801.1	9962.0	13763.2	13763.2
19	7567.2	9582.5	12046.1	9428.0	8431.9	6786.5	8844.1	8637.8	13763.2	9944.9	10920.5	5909.9
20	6444.5	7253.0	10704.7	8263.4	7335.0	6455.0	7774.2	6225.8	6788.8	9714.3	11604.6	6202.5
21	6849.0	7703.1	9237.6	8258.5	6757.9	7016.4	6021.9	6078.1	6351.3	8062.2	10672.8	5822.5
22	7175.2	7988.3	9409.3	8312.1	6782.2	7033.4	6069.9	5751.2	6680.9	8571.6	10405.9	5696.0
23	6721.1	7565.7	9040.0	7932.2	6909.1	6667.6	8618.6	11597.8	13763.2	9360.4	11364.1	10206.1
24	7620.5	9533.8	11503.4	8716.6	7781.2	6453.7	7332.5	5913.4	10074.8	8901.8	11188.1	6152.0
25	6631.1	7437.5	8885.4	7868.1	6399.1	6601.6	5672.9	6786.2	7551.7	10230.6	11037.0	5620.1
26	6661.9	7506.3	9023.4	8024.3	6583.7	6815.1	5866.1	4914.7	13152.2	10084.9	10941.6	12038.9
27	9985.2	9232.0	11124.3	8473.6	7529.4	6481.9	7643.8	7258.4	9604.1	8892.6	11497.7	6082.3
28	6736.0	7667.2	9133.1	8054.9	6547.8	6712.1	5798.5	6296.2	13763.2	9117.9	11131.2	9519.0
29	9918.2	10589.8	12240.5	9692.0	8178.2	6529.0	8608.2	6364.3	7451.0	8639.0	10936.5	5973.4
30	6825.1	7615.8	9004.2	7977.8	6503.6	6642.3	5707.7	5464.0	9787.5	10078.6	10646.7	9828.7
31	9849.8	11367.2	12162.4	9458.7	8036.2	6486.9	8464.7	6665.3	11379.9	11298.5	12347.7	12342.0
32	9870.6	11447.3	11670.4	8863.7	7742.2	6467.9	7812.6	6801.7	8205.8	10608.3	13763.2	13493.0
AVE	8077.1	9180.8	11070.6	8769.1	7508.8	6565.2	7480.3	7467.7	10566.0	9454.2	11544.8	9668.6

Table E.6 Devil Canyon Monthly Spills

SPILLS (CFS)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	949.2	226.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	914.2	0.0	2437.2	2732.6
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	970.7
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	963.2	1566.4
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1555.6	0.0	6253.7	1004.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2564.2	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2879.9
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6685.3	1965.0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	188.4	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1416.5	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1216.2	0.0	0.0	0.0
29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12217.9	0.0
AVE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	165.3	0.0	1002.2	354.5

Table E.7 Devil Canyon Monthly Energy Potential

ENERGY FROM RESERVOIR 2 (GWH)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANN
1	217.8	276.1	371.7	276.6	216.5	209.7	230.5	210.2	233.4	268.3	337.9	177.9	3026.5
2	196.0	214.4	266.1	237.7	176.7	202.9	170.5	175.9	260.7	274.7	336.9	344.3	2856.9
3	266.1	311.3	385.1	293.9	222.5	209.5	229.7	276.2	245.7	274.8	342.4	318.0	3375.2
4	328.1	345.6	378.4	278.2	216.8	209.6	244.1	324.8	398.8	274.5	331.1	247.7	3577.6
5	225.4	291.9	373.1	285.5	222.2	209.5	231.6	305.6	344.7	268.7	315.4	254.4	3327.8
6	253.4	310.3	388.7	299.2	232.3	210.3	238.5	207.4	349.5	295.7	446.4	432.0	3663.8
7	247.5	287.8	367.3	275.6	221.1	210.6	230.9	303.3	432.0	396.5	446.4	432.0	3851.1
8	266.5	318.7	392.6	297.1	235.6	210.8	240.6	246.1	392.2	271.5	344.9	423.9	3640.5
9	331.0	351.2	401.5	324.7	230.4	209.9	251.1	231.0	322.2	272.5	336.5	179.3	3441.4
10	208.8	235.9	372.6	288.5	229.5	211.1	233.4	290.1	302.2	258.2	445.8	432.0	3508.1
11	293.3	313.9	393.4	300.4	234.2	210.5	244.5	267.3	223.1	267.6	328.6	363.5	3440.4
12	326.1	321.5	398.3	326.4	241.6	215.6	293.2	295.3	421.5	288.0	355.2	330.0	3812.7
13	273.8	311.5	392.3	304.0	236.3	210.4	263.6	215.7	432.0	373.3	446.4	432.0	3891.3
14	301.3	316.2	389.6	294.3	235.6	209.2	229.0	318.0	379.6	404.9	446.4	369.7	3893.9
15	291.3	297.1	373.1	277.5	221.3	209.4	230.0	239.5	371.4	379.7	360.4	258.6	3509.3
16	283.0	314.6	365.8	275.8	219.2	209.0	241.2	225.9	336.1	304.3	342.5	427.6	3545.0
17	307.4	291.5	376.1	287.2	229.7	211.4	258.5	206.9	408.8	265.4	327.8	170.4	3341.1
18	207.3	243.6	372.4	289.8	232.1	211.3	237.9	264.3	401.8	323.1	446.4	432.0	3662.2
19	245.4	300.8	390.7	305.8	247.0	220.1	274.2	276.7	432.0	322.6	346.5	178.9	3540.7
20	203.6	224.4	346.7	268.0	214.9	209.4	241.0	199.4	213.1	304.6	348.3	178.6	2951.9
21	203.8	221.8	274.8	245.7	181.6	208.8	173.4	180.8	182.9	239.9	317.5	167.6	2598.7
22	213.5	230.0	280.0	247.3	182.3	209.3	174.8	171.1	192.4	255.0	309.6	164.0	2629.2
23	200.0	217.8	274.6	249.2	200.5	216.3	267.2	371.5	432.0	3[illegible]3.6	364.6	316.9	3414.2
24	247.2	299.2	373.1	282.7	228.0	209.3	233.5	189.4	316.3	283.3	341.0	177.1	3180.2
25	197.3	214.2	265.9	237.8	176.7	203.3	169.1	214.5	237.1	320.8	331.2	161.8	2729.6
26	198.2	216.1	268.5	238.7	176.9	202.8	168.9	152.8	412.9	327.1	348.4	370.9	3082.2
27	323.9	289.8	360.8	274.8	220.6	210.2	236.9	232.5	301.5	283.0	350.5	175.1	3259.7
28	200.4	220.8	271.7	240.7	179.6	206.1	173.0	199.6	432.0	295.8	355.2	294.0	3068.8
29	321.7	332.4	397.0	314.4	239.6	211.8	266.8	203.9	233.9	276.0	334.8	172.0	3304.3
30	203.1	219.3	267.9	237.5	176.8	201.9	168.4	171.9	306.8	326.9	344.7	307.9	2933.1
31	319.5	356.8	394.5	306.8	235.4	210.4	262.4	213.5	357.2	366.5	400.5	387.4	3811.0
32	320.2	359.3	378.5	287.5	226.8	209.8	242.2	217.9	257.6	344.1	446.4	423.6	3713.8
AVE	256.9	283.0	353.2	279.7	216.9	209.7	229.7	237.5	330.1	303.5	364.9	296.9	3361.9

Table B.8 Total Monthly Energy Potential
Watana + Devil Canyon

TOTAL ENERGY PRODUCED (GWH)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANN
1	439.7	594.0	800.9	588.8	457.0	438.0	416.4	440.7	420.9	437.3	551.1	363.0	5947.8
2	439.1	488.0	611.6	549.7	418.3	437.8	360.4	457.0	499.9	455.6	590.7	839.7	6147.6
3	563.3	670.0	827.0	623.2	469.7	438.0	416.4	500.5	501.9	489.5	580.6	729.5	6809.5
4	677.0	741.2	811.9	590.5	456.3	438.0	444.1	652.2	713.7	462.2	575.6	559.5	7122.4
5	507.9	629.2	802.9	607.8	468.0	438.0	416.4	580.2	599.1	439.9	544.1	555.3	6588.8
6	521.8	664.5	832.4	632.8	486.3	438.1	431.8	440.2	625.9	547.9	964.0	944.8	7530.5
7	525.4	624.6	791.6	587.9	465.4	438.0	416.4	595.4	809.9	733.2	944.9	935.2	7867.7
8	548.6	681.4	842.3	630.1	494.2	438.1	436.3	500.4	720.3	497.9	590.8	969.0	7349.3
9	676.9	746.6	848.3	685.7	484.2	438.1	458.2	483.0	600.3	472.2	586.5	387.8	6867.8
10	469.7	578.0	799.8	610.6	480.1	438.0	418.8	541.2	526.2	439.5	845.4	907.4	7054.8
11	613.0	674.2	841.8	634.4	491.1	438.1	445.1	564.6	419.4	435.7	564.8	830.0	6952.3
12	676.9	689.7	848.1	684.6	504.0	443.3	537.7	601.3	743.2	508.2	659.9	716.9	7613.7
13	572.8	673.7	844.1	645.8	497.2	438.2	485.0	489.3	810.9	757.8	1140.6	918.1	8273.2
14	636.5	687.6	839.4	624.9	494.0	438.1	416.4	649.3	684.6	740.9	1018.2	731.5	8011.4
15	611.8	641.4	803.3	591.1	466.4	438.0	416.3	433.2	750.9	759.4	715.0	545.5	7172.5
16	586.8	680.8	791.3	589.8	464.1	438.0	440.3	493.4	609.6	546.0	604.6	1046.3	7290.9
17	629.3	627.5	806.6	608.6	481.6	438.1	470.0	440.3	706.0	434.4	559.4	383.6	6585.4
18	452.6	565.9	799.8	612.7	485.5	438.1	429.2	554.1	743.7	582.9	1079.9	953.4	7697.9
19	520.1	650.6	840.3	647.9	517.9	456.0	505.3	570.4	791.1	593.7	575.4	408.0	7076.8
20	443.5	552.5	760.2	573.0	454.3	438.0	437.2	443.8	414.0	461.6	713.9	381.8	6073.8
21	438.6	487.4	598.5	526.8	384.4	437.2	359.8	338.9	299.7	424.6	614.4	329.8	5240.1
22	439.1	488.1	599.1	527.0	384.5	437.3	359.8	336.7	297.4	495.1	590.5	322.7	5277.2 FIRM
23	439.6	488.5	703.2	593.2	469.1	445.2	489.1	712.5	810.7	587.6	699.8	734.6	7173.1
24	532.9	650.7	805.3	603.0	480.3	438.1	424.5	439.8	578.8	469.6	599.1	385.9	6408.0
25	439.1	488.0	627.2	549.0	418.9	437.9	360.3	505.1	431.2	461.0	643.9	312.1	5673.3
26	439.0	488.1	599.6	527.6	385.0	438.0	360.3	443.1	747.2	604.4	597.9	854.3	6484.5
27	663.7	627.1	778.9	584.9	464.5	438.0	427.3	469.1	538.1	468.5	641.0	375.7	6476.9
28	439.0	488.3	599.9	548.9	438.6	438.1	379.1	441.7	809.3	564.8	637.7	698.7	6484.3
29	666.1	708.9	848.1	664.0	500.8	438.2	490.8	476.6	454.1	454.6	544.4	360.5	6607.2
30	439.3	488.3	599.7	531.4	431.0	438.0	373.9	464.8	618.4	611.5	652.0	654.8	6303.1
31	676.9	767.4	848.1	651.9	495.5	438.2	482.0	469.3	655.8	670.5	796.9	806.9	7759.4
32	677.0	774.1	816.0	612.1	478.2	438.1	440.6	477.4	470.0	615.2	1202.4	882.1	7883.2
AVE	543.8	618.9	767.7	601.2	464.6	438.9	429.5	500.2	606.3	538.2	707.0	652.3	6868.9

Table B.9 Total Usable Energy in Year 2010
Watana + Devil Canyon.

TOTAL USABLE ENERGY (GWH)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	ANN
1	439.7	594.0	800.9	588.8	457.0	438.0	416.4	440.7	420.9	437.3	550.6	363.0	5947.2
2	439.1	488.0	611.6	549.7	418.3	437.8	360.4	457.0	499.9	455.6	550.6	576.0	5843.8
3	563.3	670.0	827.0	623.2	469.7	438.0	416.4	500.5	501.9	489.5	550.6	576.0	6626.0
4	677.0	741.2	811.9	590.5	456.3	438.0	444.1	543.1	532.8	462.2	550.6	559.5	6807.3
5	507.9	629.2	802.9	607.8	468.0	438.0	416.4	543.1	532.8	439.9	544.1	555.3	6485.4
6	521.8	664.5	832.4	632.8	486.3	438.1	431.8	440.2	532.8	520.8	550.6	576.0	6628.0
7	525.4	624.6	791.6	587.9	465.4	438.0	416.4	543.1	532.8	520.8	550.6	576.0	6572.5
8	548.6	681.4	842.3	630.1	494.2	438.1	436.3	500.4	532.8	497.9	550.6	576.0	6728.6
9	676.9	746.6	848.2	685.7	484.2	438.1	458.2	483.0	532.8	472.2	550.6	387.8	6764.2
10	469.7	578.0	799.8	610.6	480.1	438.0	418.8	541.2	526.2	439.5	550.6	576.0	6428.5
11	613.0	674.2	841.8	634.4	491.1	438.1	445.1	543.1	419.4	435.7	550.6	576.0	6662.6
12	676.9	689.7	848.1	684.6	504.0	443.3	537.7	543.1	532.8	508.2	550.6	576.0	7094.9
13	572.8	673.7	844.1	645.8	497.2	438.2	485.0	489.3	532.8	520.8	550.6	576.0	6826.0
14	636.5	687.6	839.4	624.9	494.0	438.1	416.4	543.1	532.8	520.8	550.6	576.0	6860.1
15	611.8	641.4	803.3	591.1	466.4	438.0	416.3	433.2	532.8	520.8	550.6	545.5	6551.3
16	586.8	680.8	791.3	589.8	464.1	438.0	440.3	493.4	532.8	520.8	550.6	576.0	6664.5
17	629.3	627.5	806.6	608.6	481.6	438.1	470.0	440.3	532.8	434.4	550.6	383.6	6403.3
18	452.6	565.9	799.8	612.7	485.5	438.1	429.2	543.1	532.8	520.8	550.6	576.0	6507.1
19	520.1	650.6	840.3	647.9	517.9	456.0	505.3	543.1	532.8	520.8	550.6	408.0	6693.5
20	443.5	552.5	760.2	573.0	454.3	438.0	437.2	443.8	414.0	461.6	550.6	381.8	5910.5
21	438.6	487.4	598.5	526.8	384.4	437.2	359.8	338.9	299.7	424.6	550.6	329.8	5176.3
22	439.1	488.1	599.1	527.0	384.5	437.3	359.8	336.7	297.4	495.1	550.6	322.7	5237.3
23	439.6	488.5	703.2	593.2	469.1	445.2	489.1	543.1	532.8	520.8	550.6	576.0	6351.1
24	532.9	650.7	805.3	603.0	480.3	438.1	424.5	439.8	532.8	469.6	550.6	385.9	6313.5
25	439.1	488.0	627.2	549.0	418.9	437.9	360.3	505.1	431.2	461.0	550.6	312.1	5580.0
26	439.0	488.1	599.6	527.6	385.0	438.0	360.3	433.1	532.8	520.8	550.6	576.0	5860.8
27	663.7	627.1	778.9	584.9	464.5	438.0	427.3	469.1	532.8	468.5	550.6	375.7	6381.2
28	439.0	488.3	599.9	548.9	438.6	438.1	379.1	441.7	532.8	520.8	550.6	576.0	5953.9
29	666.1	708.9	848.1	664.0	500.8	438.2	490.8	476.6	454.1	454.6	544.4	360.5	6607.2
30	439.3	488.3	599.7	531.4	431.0	438.0	373.9	464.8	532.8	520.8	550.6	576.0	5946.5
31	676.9	767.4	848.1	651.9	495.5	438.2	482.0	469.3	532.8	520.8	550.6	576.0	7009.4
32	677.0	774.1	816.0	612.1	478.2	438.1	440.6	477.4	470.0	520.8	550.6	576.0	6830.8
AVE	543.8	618.9	767.7	601.2	464.6	438.9	429.5	481.7	497.6	487.5	550.2	501.2	6382.9

FORECAST DEMAND ENERGY (GWH)

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	
677.0	777.6	848.2	773.8	732.5	662.2	590.4	543.1	532.8	520.8	550.6	576.0	7784.9

Table B.10 Potential Spill from Devil Canyon in August

Year Simulated	Energy Potential GWh	Reservoir Operation A: Usable energy at Watana and Devil Canyon is proportional to overall heads			Reservoir Operation C: Maximum possible generation of usable energy at Devil Canyon		
		Usable energy Yr 2010 - GWh	Turbines @ cfs	Spill cfs	Usable energy Yr 2010 - GWh	Turbines @ cfs	Spill cfs
1	337.9	337.4	10925	16	337.9	10941	0
2	336.9	296.8	9567	1293	336.9	10860	0
3	342.4	312.4	9727	740	342.4	10727	0
4	331.1	306.1	9797	800	331.1	10597	0
5	315.4	315.4	9972	0	315.4	9972	0
6	446.4	250.3	7716	6992	446.4	13763	949
7	446.4	249.7	7698	8502	446.4	13763	2437
8	344.9	304.7	9584	1265	344.9	10849	0
9	336.5	300.7	9535	1135	336.5	10683	0
10	445.8	251.0	7738	6988	445.8	13763	763
11	328.6	314.4	10023	453	328.6	10476	0
12	355.2	249.1	7760	3304	355.2	11064	0
13	446.4	247.0	7678	12339	446.4	13763	6254
14	446.4	249.7	7698	8629	446.4	13763	2564
15	360.4	249.0	7702	3444	360.4	11164	0
16	342.5	262.1	8165	2504	342.5	1066[illegible]	0
17	327.8	319.0	10135	279	327.8	10415	0
18	446.4	250.2	7715	12733	446.4	13763	6685
19	346.5	321.7	10139	782	346.5	10720	0
20	348.3	245.0	8191	3414	348.3	11605	0
21	317.5	253.7	8528	2144	317.5	10673	0
22	309.6	269.7	9065	1341	309.6	10406	0
23	364.6	242.6	7748	3616	364.6	1136[illegible]	0
24	341.0	292.6	9600	1588	341.0	111[illegible]	0
25	331.2	243.1	8102	2935	331.2	11037	0
26	348.4	301.1	9456	1486	348.4	10[illegible]2	0
27	350.5	260.1	8532	2966	350.5	1147[illegible]	0
28	355.2	268.1	8402	2729	355.2	11131	0
29	334.8	334.8	10936	0	334.8	10937	0
30	344.7	249.8	7716	2931	344.7	10647	0
31	400.5	247.7	7705	4642	400.5	12343	0
32	446.4	250.1	7712	13269	446.4	13763	12218

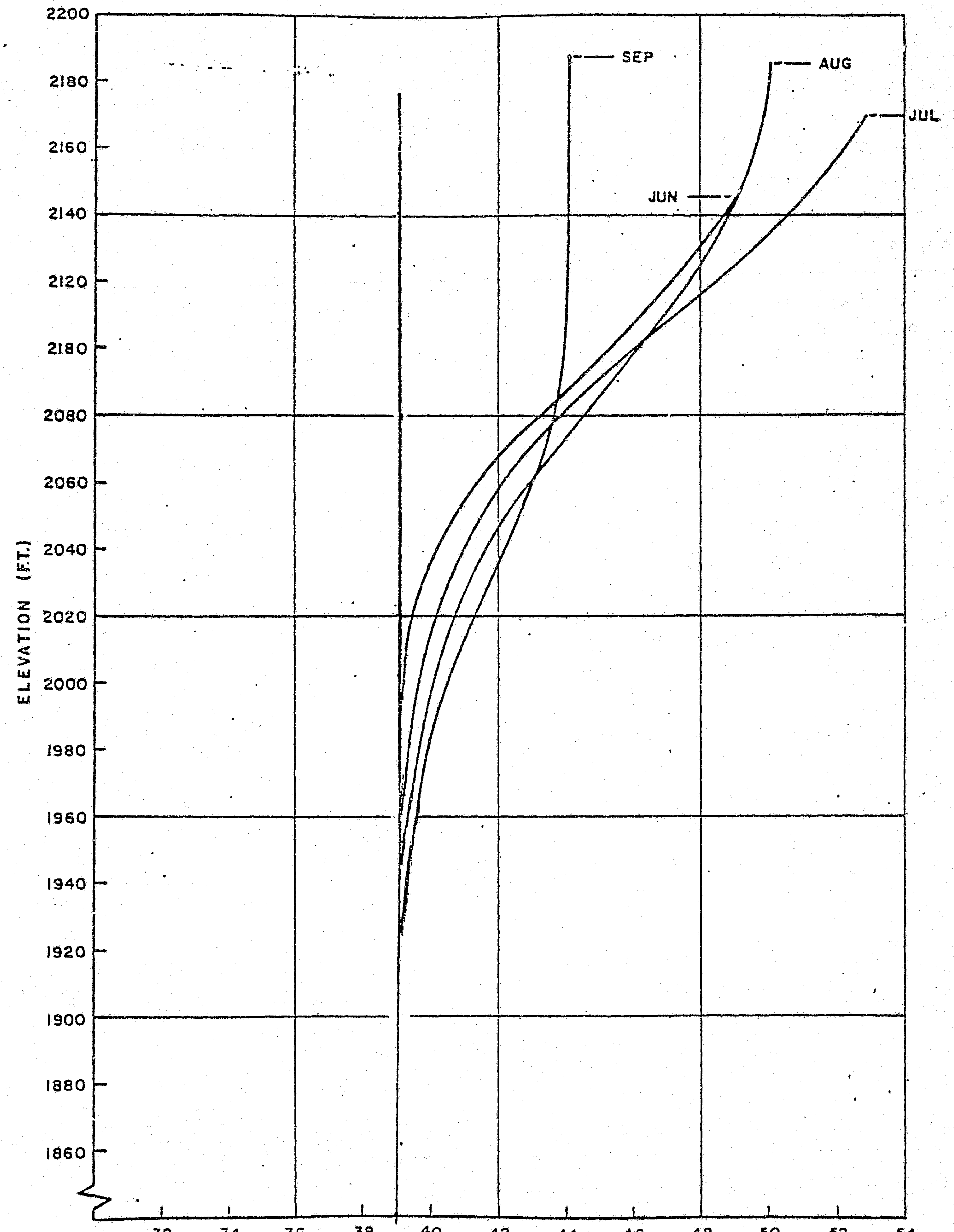
Table B.11 Potential Spill from Watana in August

Year Simulated	Energy Potential Gwh	Reservoir Operation A — Usable energy at Watana and Devil Canyon Proportional to average heads: Usable Energy Yr. 2010 — Gwh	Turbine Q cfs	Spill cfs	Reservoir Operation B — Maximum possible generation of usable energy at Devil Canyon: Usable energy Yr. 2010 Gwh	Turbine Q cfs	Spill cfs
1	213.2	213.2	5553	0	212.7	5540	13
2	253.8	253.8	6576	0	213.7	5537	1039
3	238.2	238.2	6135	0	208.2	5362	773
4	244.5	244.5	[illegible]	0	219.5	5679	647
5	228.7	228.7	5918	0	228.7	5912	0
6	517.5	300.3	7715	5575	[illegible]	2677	10613
7	498.5	300.9	7692	5072	104.2	2634	10100
8	245.9	245.9	[illegible]	0	205.7	5214	1035
9	249.9	249.9	6441	0	[illegible]	5518	923
10	399.5	299.6	7724	2576	104.8	2702	7598
11	236.2	236.2	6139	0	222.0	5770	362
12	304.7	301.5	7755	82	195.4	5023	2811
13	694.2	301.6	7673	9989	104.2	2651	15011
14	571.8	300.7	7692	6926	104.2	2664	11954
15	354.6	301.6	7699	1353	190.2	4855	4197
16	262.1	262.1	6734	0	208.1	5347	1387
17	231.6	231.6	6003	0	222.8	5775	228
18	633.5	300.4	7710	8550	104.8	2983	14117
19	228.9	228.9	[illegible]	0	204.1	5243	637
20	365.7	304.8	8186	1636	202.3	5433	4337
21	296.9	[illegible]	[illegible]	0	233.1	6504	[illegible]
[illegible]	280.9	280.9	7527	0	241.0	6466	1071
[illegible]	335.2	332.0	7745	851	[illegible]	4770	2975
[illegible]	258.0	258.0	6715	0	207.6	5455	1260
[illegible]	312.5	307.5	8101	132	211.2	5775	2326
[illegible]	249.5	247.5	[illegible]	0	202.2	5188	1214
[illegible]	290.5	290.5	7569	[illegible]	207.1	5214	2355
[illegible]	282.5	282.5	7242	0	195.4	5015	2253
[illegible]	209.6	209.6	5471	0	209.6	5471	0
[illegible]	307.3	300.8	7711	167	205.9	5278	2433
[illegible]	316.4	300.7	7701	2451	155.1	3844	3427
[illegible]	756.0	300.5	7708	14438	104.2	2673	19473

Table B.12 Potential Spills from Devil Canyon in September

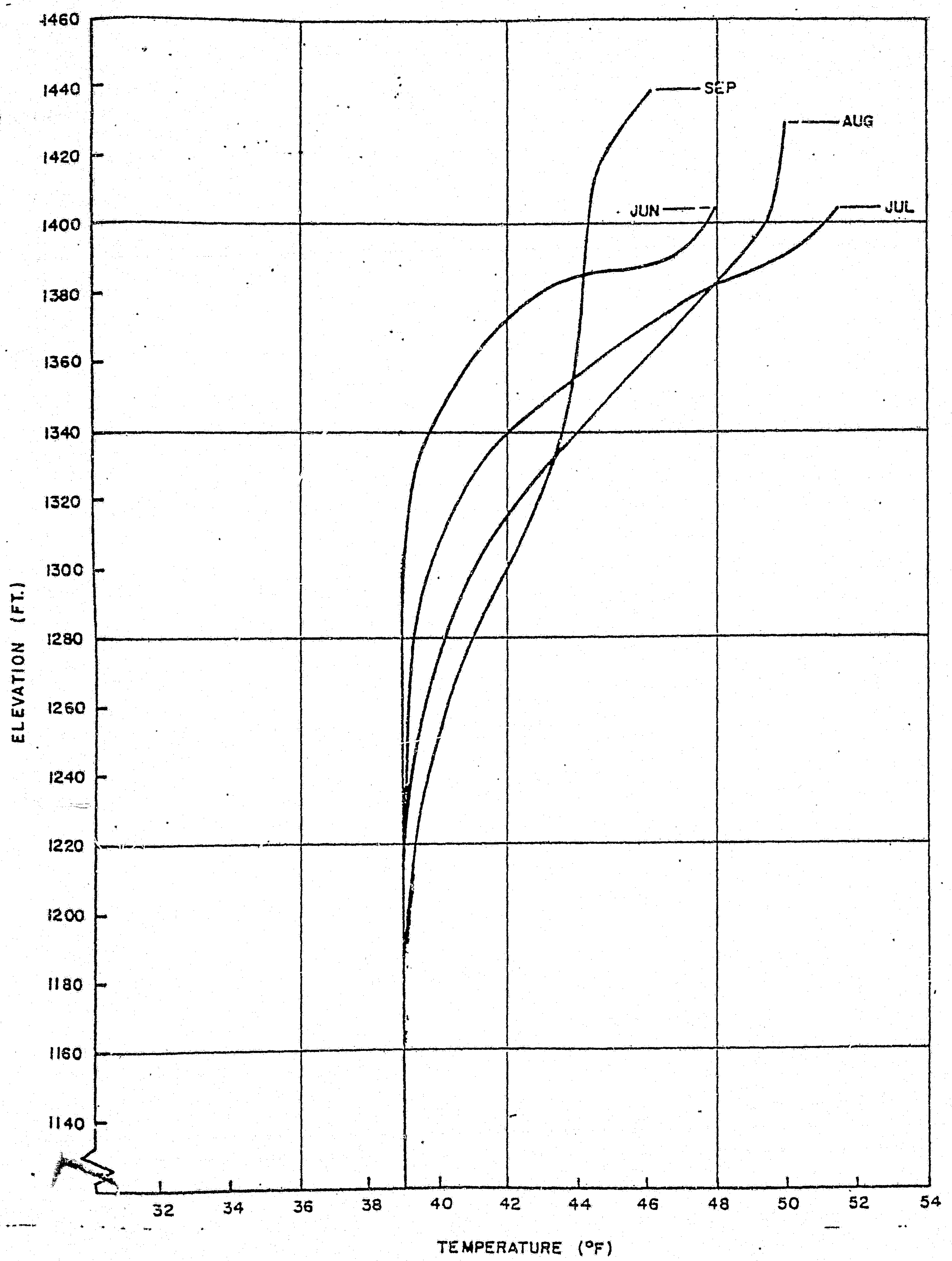
Year simulated	Energy Potential Gwh	Reservoir Operation A: Usable energy at Watana & Devil Canyon proportional to ave. ... heads			Reservoir Operation B: Maximum possible generation of usable energy at Devil Canyon[1]		
		Usable energy to 2010 Gwh.	Turbine Q cfs	Spill cfs	Usable energy 2010 Gwh.	Turbine Q cfs.	Spill cfs
1	177.9	177.9	6150	0	177.9	6150	0
2	344.3	245.0	8047	3261	344.3	11308	0
3	318.0	246.5	7979	2315	318.0	10294	0
4	247.7	247.7	8149	0	247.7	8149	0
5	254.4	254.4	8220	0	254.4	8220	0
6	432.0	248.6	7920	6067	432.0	13763	226
7	432.0	248.6	7920	8576	432.0	13763	2733
8	423.9	246.1	7990	6743	423.9	13763	971
9	179.3	179.3	5939	0	179.3	5939	0
10	432.0	248.6	7920	7409	432.0	13763	1566
11	363.5	246.1	8021	3827	363.5	11848	0
12	330.0	247.2	7[illegible]	2575	[illegible]	[illegible]	0
13	432.0	248.6	7920	6847	[illegible]	13763	1004
14	369.7	248.6	7919	3858	[illegible]	11777	0
15	258.6	258.6	8265	0	258.6	8265	0
16	427.6	247.2	7927	8686	427.6	13763	2880
17	170.4	323.6	5594	0	170.4	5594	0
18	432.0	248.6	7920	77[illegible]	432.0	13763	1965
19	178.9	178.9	5710	0	178.9	5910	0
20	178.6	178.6	6202	0	178.6	6202	0
21	167.6	167.6	5823	0	167.6	5823	0
22	164.0	164.0	5696	0	164.0	5696	0
23	316.9	247.1	7958	[illegible]	316.9	10206	0
24	177.1	177.1	6152	0	177.1	6152	0
25	161.8	312.1	5620	0	161.8	5620	0
26	370.9	246.1	7982	4051	370.9	[illegible]	0
27	175.1	175.1	6082	0	175.1	6082	0
28	296.0	246.4	7178	1541	[illegible]	9519	0
29	172.0	172.0	5973	0	172.0	5975	0
30	307.9	248.3	7926	1902	[illegible]	9829	0
31	387.4	[illegible]	7920	4422	387.4	12842	0
32	423.6	[illegible]	[illegible]	5574	423.6	[illegible]	0

1 Assumes potential energy as usable on a daily basis



WATANA RESERVOIR TEMPERATURE PROFILE

AVERAGE YEAR CONDITIONS JUNE THROUGH SEPTEMBER



DEVIL CANYON RESERVOIR TEMPERATURE PROFILE

AVERAGE YEAR CONDITIONS JUNE THROUGH SEPTEMBER

FIGURE B.[illegible]