GREAT LAKES FISHERY COMMISSION

Project Completion Report[1]

Fish Passage and Lamprey Exclusion Aspects at the Dow Dam, Chippewa River, Michigan

by:

Dr. Shouhong Wu

and

Chris Katopodis, P. Eng.

Freshwater Institute
Fisheries and Oceans Canada
501 University Crescent
Winnipeg, Manitoba
Canada, R3T 2N6

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1. Introduction

1.1 Report Objectives

The Dow dam is located in the Chippewa River (tributary to the Tittabawassee) near Saginaw, Michigan, USA. This dam frequently seems to function as a barrier to the migrations of most fish species, including walleye, smallmouth bass, white bass, channel catfish and sucker, but allows lamprey to pass and reproduce. The Great Lake Fisheries Commission (GLFC) currently spends about $165,000 annually on chemical lamprey control in the Tittawasse River and the Chippewa River ranks among the most productive streams in the Great Lakes for lampreys. The Dow Chemical Company (Dow) incurs costs in maintaining the dam and operating a trap, sort, and transfer facility at a fishway on one side of the dam. A long-term goal, shared by the GLFC and Dow, is to optimize operations and facilities at the dam by minimizing lamprey passage and maximizing passage of other fish species. The objectives of this report are to: a) use existing data to help explain anecdotal observations on passage of lamprey and other fish, b) examine the conditions under which lamprey and other fish may bypass the Dow dam, and c) develop strategies, examine ways, and recommend options for implementation and study to help achieve the above goal.

The benefits of achieving the goal of maximum fish passage and minimum lamprey passage would be substantial and far-reaching. If more walleyes and other fish passed above the dam, they would be able to spawn in an additional 12 miles of the Tittabawassee River, 47 miles of the Chippewa River, 33 miles of the Pine River, and 20 miles of the Big Salt River. These streams would not need to be exposed to lampricide again if lampreys were contained Downstream of the dam. More walleyes and other species that historically used the river above the dam would be naturally reproduced to benefit the Saginaw Bay fishery. Lamprey recruitment to Lake Huron would be reduced, thereby enhancing survival of game fish. The GLFC could eliminate the cost of lampricide treatment (3500 lbs on an annualized basis). These resources could be reallocated to other areas of the basin. Reduced reliance on lampricides in the sea lamprey control program would be a step forward in alleviating public concern about the discharge of chemicals in the Great Lakes (Ellie Koon, personal communication).

1.2 Historical background and anecdotal information

Ellie Koon, in a personal communication, provided the following historical and anecdotal information. In 1970, the Dow dam was converted from a hydraulically controlled structure to a concrete fixed-crest dam. The fishway was installed in 1971. In 1972, Mr. Howard Alexander of Dow reported that large numbers of sea lampreys were using the fishway, which continued for several years. Other fish reportedly did not use the fishway. In response to a US Fish and Wildlife Service Sea Lamprey Management (USFWS) request, the fishway was closed from March 1 to July 15 beginning in 1977, in an effort to reduce the number of lamprey passing upstream. Lamprey reproduction above the dam was not eliminated, but was greatly reduced.

In 1982, two drownings occurred in the plunge pool at the foot of the dam. In 1984, large rip-rap was installed below the dam, almost reaching the crest, and eliminating the plunge pool. In 1985, so many spawning lampreys bypassed the dam that the 1985 year-class of lampreys in the tributaries was by far the largest ever documented. In the ensuing years, Sea Lamprey Management personnel observed greater densities of faster-growing larvae in the Chippewa River than had been seen in any Great Lakes stream. In 1990, the fishway was closed permanently, but lampreys continued to bypass the dam in large numbers via the rip-rap. In 1993, Dow cooperated with the USFWS Sea Lamprey Management Program to install small portable lamprey traps at the dam. Results were promising, so in 1995 Dow (using their contractor, Sub-Lakes Diving Inc.) altered the fishway to provide a lamprey trap with a water flow to attract lampreys. It was very successful, capturing 1,700 adult lampreys that spring (out of an estimated total run of 10,300 lampreys).

The effectiveness of the fishway seems to be subject to small variations in entrance conditions. After the fishway was built, and since it was not used by fish other than sea lampreys, significant changes were made at the site: a) old photos show an elongated chute (a small Alaska steeppass fishway) at the entrance which has now been scrapped; b) installation of the rip-rap changed the hydraulic characteristics of the flow along the face of the dam; and 3) an area of rip-rap in front of the fishway has been excavated to help guide lampreys into the trap. In fact, employees of Sub-Lakes Diving, who operate the lamprey trap daily, report that thousands of white suckers now attempt to enter the trap, indicating that configuration changes since the ladder was first operated seem to have resulted in a facility that is more attractive to fish. However, anecdotal accounts from Sub-Lakes Diving, Inc. personnel suggest that even with improved entrance conditions, which attract large numbers of fish to the fishway, fish would probably not be able to pass through the upper end of the fishway. Reportedly, if the slide gate controlling water flow is open more than a few inches, such that fish could physically fit through the opening, the fishway floods. Serious design flaws with the fishway are suspected, and this is probably one of the contributing factors to its failure to pass fish.

1.3 Description of data provided

The information provided on the Dow dam may be organized as follows:

a) Design drawings for the Dow dam, fishway and rip-rap at the Downstream face of the dam. Photographs from a site visit (C. Katopodis July 10, 1996).
b) Water levels from a station 2000 ft Downstream the Dow dam. The data on water level elevations cover the period of March 1 to June 30 each year, from 1982 to 1995.
c) Water temperature data at the same station (2000 ft below the dam) and for the same period of the year (March 1 to June 30) but from 1988 to 1995.
d) The daily mean discharge at the same station (2000 ft below the dam) from October 1993 to September 1994. The monthly mean, daily maximum and minimum discharges for 58 water years (1936 to 1994).
e) Numbers of lampreys caught at the Dow dam fishway trap for three consecutive years. The lamprey trapping periods were April 28 to June 23 in 1993, April 29 to June 28 in 1994, and April 17 to June 16 in 1995.

A plan view of the Dow dam site is shown in Fig. 1. The dam was converted from a hydraulically controlled structure to a concrete fixed-crest dam in 1970. The crest of the dam is of Ogee shape (Fig. 2). The dam has a length of 265.12 ft (80.81 m) and a height of 6.5 ft (1.98 m). The dam crest elevation, DCE, is 595.12 ft (181.39 m), and the elevation at the foot of the dam is 588.62 ft (179.41 m). A view of the dam, vertical slot fishway installed on the west riverbank in 1971, and rip-rap installed in 1984 is provided by Fig. 3. A sketch of the fishway is shown in Fig. 4(a-c). The fishway consists of five pools, one with a length of 12.5 ft (3.81 m), another with a length of 9.0 ft (2.74 m), and the remaining three with a length of 10.0 ft (3.05 m). The inside width of the fishway is 9 ft (2.74 m). The width of the fishway slots is 1 ft (0.30 m). These dimensions are slightly different from those of a standard vertical slot fishway (design 1; 10 ft x 8 ft or 3.05 m x 2.44 m; Katopodis 1992). The slope of the fishway floor though is 1.94%, which is very low compared to about 10% for most vertical slot fishways for adult migrants. The elevation of the fishway exit floor, z_x, is 593.52 ft (180.90 m), which is 1.6 ft (0.49 m) lower than the dam crest, and extends 35.50 ft (10.82 m) upstream of the face of the dam. The elevation of the fishway entrance floor, z_f, is 592.38 ft (180.56 m), which is 2.74 ft (0.8 m) lower than the dam crest and extends 7.0 ft (2.13 m) downstream of the foot of the dam. The gate opening of the fishway is located in the middle of the upstream first pool. The opening is 4.0 ft (1.22 m) high. The elevation of the top edge of the opening, z_g, is 597.7 ft (182.24 m) which is 2.78 ft (0.847 m) above the dam crest.

2. Analysis of water levels and maximum velocities over the dam

2.1 Average daily maximum water levels downstream of the Dow dam

The average daily maximum water level at 2000 ft below the Dow dam is calculated from the available 14 year record (1982 to 1995). The results are plotted in Fig. 5. Based on the available information the lamprey migration time is considered to start on April 15. For convenience the period from March 1 to April 14, which is before lamprey migration, is referred to as Period 1. Similarly, the period from April 15 to June

30, during which lamprey migration occurs, is referred to as Period 2. The entire period from March 1 to June 30 is referred to as Period 3. The vertical broken line in Fig. 5 separates Periods 1 and 2. Fig. 5 shows that in general, the maximum water level at 2000 ft below the Dow dam is lower than the dam crest during lamprey migration, although it is usually higher than the dam crest before this migration starts.

2.2 *Frequency analysis for water levels downstream of the Dow dam*

Let us denote the maximum water level at 2000 ft Downstream of the dam as z_{2000} and the tailwater level at the foot of the dam as z_d. A water level frequency analysis was performed for z_{2000} for the Periods 1, 2 and 3 for the available 14 year record (1982 – 1995). For each period the frequency and cumulative frequency were calculated for different values of z_{2000}. A water surface slope of 0.01% was assumed for the river segment between the foot of the dam and 2000 ft downstream. Hence the tailwater level, z_d, was assumed to be z_{2000}+0.2 ft, and the frequencies for z_{2000} and z_d are the same. Table 1 lists the frequency and cumulative frequency for different z_d values with DCE denoting the dam crest elevation (595.12 ft). A comparison of column (6) with column (4) in Table 1 shows that for the same z_d, the cumulative frequency for Period 1 is much smaller than that for Period 2. This implies that the tailwater level is generally higher in Period 1 than that in Period 2, as is also indicated by Fig. 5.

The above frequency analysis results are plotted in Figs. 6-8. Also plotted in Figs. 6-8 are the elevations of the dam crest (DCE), dam foot and the fishway entrance floor (z_f). The dots in Figs. 6-8, which sometimes are accompanied by numbers, represent the estimated frequencies (bell shaped curves) or cumulative frequencies (S shaped curves) for tailwater levels by increments of 1 ft below or above the crest. For example in Fig. 6, the cumulative frequency that a tailwater level not higher than 2 ft below the crest is 16.1%, and increases to 34.0% for a tailwater level not higher than 1 ft below the crest. Similarly from Fig. 6, a tailwater level not higher than 1 ft above the crest has a cumulative frequency of occurrence of 67.0%.

Eq. (2) is plotted in Fig. 9 as the solid line, which demonstrates that the equation fits the data very well.

Eq. (2) is based on the daily mean discharge data provided for 1994. How well the 1994 data represent the long term hydrological trends was evaluated. Table 2 shows the results by comparing typical discharges for 1994 with corresponding values for the 58 year record (1936-1994). Note from column (4) in Table 2 that the ratio of monthly mean discharges is reasonably close to 1 (range 0.97 to 1.25). This indicates that the 1994 discharge data represent the long term average fairly well.

Based on the assumption mentioned above, the tailwater rating curve is obtained by shifting upwards the rating curve at 2000 ft downstream of the dam by 0.2 ft (broken line in Fig. 9) and is represented by the following equation:

$$Q=44(z_d - 587.2)^{2.09} \qquad (3)$$

2.4 Headwater rating curve

The headwater rating curve, a relationship between river discharge and water level upstream of the dam, was derived as shown in Table 3, using the above tailwater curve and the discharge capacity characteristics of the dam. In Table 3, column (1) lists tailwater levels (z_d) in 1 ft increments, from 5 ft below the dam crest to 2 ft above it (negative values) as shown in column (2). As calculated earlier (Table 1 and Fig. 6-8), columns (3) to (5) show the corresponding cumulative frequency that each tailwater level is equal to or lower than the value in column (1). In column (6), the daily mean discharge Q (cfs) is obtained from the tailwater rating curve. The unit width discharge q (in ft^2/s) is calculated in column (7), using the dam width of 256.25 ft. The upstream head over the dam crest, h_u, is calculated in column (8) by solving the Ogee weir free flow equation (Henderson 1966):

For Period 1 (March 1 to April 14), Fig. 6 demonstrates that in any given year there is a 53% chance for the tailwater level to be equal to or lower than the dam crest, or inversely a 47% chance for it to be higher than the dam crest. Note that Fig. 6 also shows that there is only an 8% chance that the tailwater level will be equal to or lower than the fishway entrance floor. For Period 2 (April 15 to June 30), Fig. 7 shows that in any given year there is an 83% chance for the tailwater level to be equal to the dam crest or lower; inversely there is only a 17 % chance for it to be higher than the dam crest. There is a 40% chance that the tailwater level will be equal to or lower than the fishway entrance floor. Similarly, for Period 3 (March 1 to June 30), Fig. 8 demonstrates that there is a 72% chance for the tailwater level to be equal to the dam crest or lower, or inversely a 28% chance for it to be higher than the dam crest. There is also a 28% chance that the tailwater will be equal to the fishway entrance floor or lower.

2.3 *Tailwater rating curve*

Fish passage conditions over the dam and through the fishway depend on headwater and tailwater levels as well as the discharge capacity characteristics of the dam. Headwater levels are not available, but can be calculated from river discharges, tailwater levels, and the dam discharge capacity. The daily mean discharge data provided at a station 2000 ft downstream of the dam and for the period from March 1 to June 30, 1994 were used to develop a relationship between discharge and tailwater level (rating curve). When discharge values were plotted against the corresponding maximum water elevations (Fig. 9) the following correlation was found:

$$\ln Q = 3.78 + 2.09 \ln(z_{2000} - 587) \qquad (1)$$

with a correlation coefficient R^2=0.95. In Eq. (1), Q is daily mean discharge (ft^3/s) 2000 ft below the dam, and z_{2000} (ft) is the corresponding water elevation. The constant 587 was found by trial and error. Eq. (1) can be reformulated as:

$$Q = 44(z_{2000} - 587)^{2.09} \qquad (2)$$

$$q=3.97(c/c_o)h_u^{1.5} \tag{4}$$

where c_0 is the Ogee weir discharge coefficient when h_u (ft) equals to the design head of the weir, and c is the coefficient when h_u is different from the design head. The design head, h_0 was found to be 3.3 ft by comparing the dam cross-sectional figure (B2-004-97128) with Fig. 248 from a design manual (US Bureau of Reclamation 1997). By digitizing Fig. 250 of the same manual, it was found that the ratio c/c_0 in Eq. (4) could be represented very well by:

$$c/c_o = 0.73 + 0.27(h_u/h_0)^{0.5} \qquad (0.2 < h_u/h_0 < 1.6) \tag{5}$$

Eq. (4) is valid when the weir flow is free from downstream submergence effect, which is the case here. The headwater elevation z_u is thus calculated as is shown in column (9) of Table 3. The dotted line in Fig. 9 shows the resulting headwater rating curve.

2.5 *Maximum water velocities over the dam for different elevations of rip-rap*

Maximum water velocity over the dam is one of the most important factors affecting fish passage over the dam. It depends on the water level drop across the dam (z_u-z_d) and rip-rap elevations. Table 3, column (10) shows the water level drop for several river discharges and water levels. In columns (11) to (15) the maximum water velocity over the dam, V_m (ft/s), is calculated for cases where the elevation at the top of the rip-rap is below the dam crest by different amounts. In these calculations, the head loss caused by the dam surface friction is neglected. The difference between the dam crest elevation and the rip-rap surface elevation is denoted as Δ. If the tailwater level z_d is less than or equal to (DCE-Δ), the rocks are not submerged and the maximum water velocity occurs at the rock surface level. In this case the maximum water velocity over the dam is calculated by converting the difference between headwater elevation and the rock surface elevation, $h_u+\Delta$ (potential energy), into kinetic energy:

$$V_m=[2g(\Delta + h_u)]^{0.5}. \qquad (z_d<=DCE-\Delta) \qquad (6)$$

If the tailwater level z_d is larger than (DCE-Δ), the rocks are all submerged. In this case the maximum water velocity over the dam is calculated by converting the water level difference across the dam, z_u-z_d (potential energy), into kinetic energy:

$$V_m=[2g(z_u-z_d)]^{0.5}. \qquad (z_d>DCE-\Delta) \qquad (7)$$

Fig. 10 displays the variation of maximum velocities V_m for different Δ values and tailwater levels at or below the dam crest (these correspond to the positive values on the abscissa). This figure shows that for a given Δ, V_m has a maximum value when the rip-rap is just submerged (DCE-z_d=Δ). Before reaching a maximum value, V_m increases as tailwater (z_d) increases. This is because headwater (h_u) increases as tailwater increases (Eq. 6). After a maximum value is reached, V_m decreases as tailwater increases. This is because the water level drop over the dam (z_u-z_d) decreases as tailwater (z_d) increases (Eq. 7). Fig. 10 also displays the results for tailwater levels above the dam crest (these correspond to the negative values on the abscissa). Note that as tailwater increases, maximum velocity decreases.

2.6 *Frequency of typical fishway water depths*

A minimum water depth is needed for a fishway to function properly and allow fish to migrate during low water levels. A frequency analysis of various water depths at the Dow dam fishway was conducted to assess its function, particularly in relation to minimum depth. The difference between tailwater level and the fishway entrance floor elevation is calculated in column (16) of Table 3. In Fig. 11, the cumulative frequency is plotted against this difference for Period 1, 2 and 3. A minimum depth of 2 ft was assumed as adequate for the vertical slot fishway and fish species at this site. Fig. 11 shows that during Period 1 (March 1 to April 14), there is a 40% chance that the minimum depth requirement is not met. Similarly for Period 2 (April 15 to June 30), in any given year there is a 76% chance that the minimum depth requirement is not met.

When the tailwater level is very low, say below the fishway invert, there can still be flow in the fishway as long as the gate is not closed. Although the depth at the fishway entrance is not adequate for most fish, this is not a problem for lamprey, which can swim upstream by attaching to the fishway floor. As mentioned earlier (Fig. 6), there is an 8% chance during Period 1, a 40% chance during Period 2, and a 28% chance during Period 3, that the tailwater level will be equal to or lower than the fishway entrance floor. The elevation of the top of the baffle at the fishway entrance is 597.9 ft, which is 2.79 ft above the dam crest. The chances for the baffle top to be submerged are 21.91%, 6.69% and 12.34% respectively in periods 1, 2 and 3. In conclusion, the fishway entrance floor was set too high for passage of fish other than lamprey and the elevation of the top of the baffle could be higher to accommodate early migrants, like walleye, more often.

The elevation of the fishway exit floor (z_x) is 593.52 ft, 1.60 ft below the dam crest and the fishway wall is 7 ft high at the exit. Columns (17), (3), (4), and (5) of Table 3 show that there is less than 2% chance that the flow depth at the fishway exit is less than 2.2 ft. There is very little chance that the fishway exit will be totally submerged either. Therefore the fishway exit elevation and fishway height were both properly designed.

The elevation of the top of the fishway gate opening, z_g, is 597.27 ft, which is 2.78 ft above the dam crest. The elevation difference between headwater and the top of the gate opening is calculated for different tailwater values and is plotted in Fig. 12. This figure shows that in Period 1 there is a 50% chance that the opening is not submerged (z_u-z_g<=0). The chances in Periods 2 and 3 are respectively 81% and 70%. When the opening is submerged fish swimming near free surface may hesitate to use the opening. Table 3 shows that the opening starts to be submerged when tailwater level reaches the dam crest or higher. Considering this factor, the gate opening was also designed fairly well.

3. Water temperature and fish swimming performance analysis

3.1 Water temperature analysis

Water temperature data were provided at the station 2000 ft downstream the Dow dam for 8 years (March 1 to June 30; 1988 to 1995). The average daily temperature, $\underline{T}$, is plotted against time in Fig. 13. The standard deviation, T_{sd}, is also plotted in the same figure. Fig. 13 shows that the average daily temperature increases almost linearly from March 1 to June 30. The following linear equation can be used to describe the variation:

$$\underline{T}(^{o}F)=31.84+0.376 * (\text{days from March 2}) \quad (8)$$

Eq. (7) is depicted in Fig. 13 by the straight line. For temperature units in ^{o}C, Eq. (8) becomes:

$$\underline{T}(^{o}C)=0.209 * (\text{days from March 2}) \quad (9)$$

According to Eqs. (8) and (9), the average temperature varies from 32°F to 48 °F (0~ 9°C) in Period 1 and from 48°F to 75°F (9~25°C) in Period 2.

A frequency analysis on the occurrence of various water temperatures near the Dow dam was performed and the results are presented in Table 4 and Fig. 14. Fig. 14 shows that in Period 1 there is a 98% chance that water temperature is equal to or lower than 52°F (11.1°C). In Period 2, there is a 95.6% chance that water temperature is higher than 47°F (8.3°C).

3.2 The possibility for lamprey and other fish to pass the dam by bursting

Fish swimming performance for different fish species was based on the data collected in the "Ichthyomechanics database" at the Freshwater Institute, Department of Fisheries and Oceans (DFO), and the results are listed in Table 5. These data are from fish endurance tests.

Lampreys are able to swim upstream by attaching to various surfaces at flow boundaries (Scott and Crossman 1973). Data from endurance tests, for the cases when lampreys are prevented from attaching, were analyzed. The lamprey fork length, L, represented in the database ranges from 0.15 to 0.59 m. According to Scott and Crossman (1973), 0.59 m is around the maximum length of this fish. In the database the testing temperature, T, ranges from 5 to 23°C. Similarly, the fish speed, U, ranges from 0.3 to 3.96 m/s and the endurance time, t, ranges from 0.8 to 2294 seconds. The following regression equation was derived, expressing the endurance time of lamprey as a function of fork length, temperature and speed:

$$\log t(\mathrm{sec}) = 6.58 + 2.34\,L(\mathrm{m}) + 0.046\,T(^\circ\mathrm{C}) - 6.44[U(\mathrm{m/s})]^{0.2} \qquad (10)$$

From Eq. (8) we can see that log t increases linearly with fork length and temperature but decreases as fish speed increases. If we denote flow velocity as V and lamprey swimming distance as S then:

$$S = t(U\text{-}V) \qquad (11)$$

For given L, T and V, the maximum swimming distance S_m can be obtained if U takes the optimum value U_0:

$$U_o = 0.178 + 1.284V \qquad (12)$$

In Tables 6, the results for lamprey bursting over the dam are summarized for a 0.6 m long lamprey swimming during the highest temperature of 25°C. These are conservative assumptions because if the largest fish cannot pass the dam under the highest temperature then no lamprey can pass the dam. It was further assumed that lamprey can reach the dam surface by attaching to the rip-rap when the tailwater level is lower than the rock surface. In Table 6, columns (1) to (5) are from Table 3. Column (6) is the length of the dam surface (S_D), which is measured from the top of the upstream vertical face of the dam to the rip-rap or the tailwater surface level, whichever is higher. The distance S_D is obtained from Fig. 2. Column (7) shows the required burst speed to pass the dam without attaching. Column (8) is the optimum speed calculated from Eq. (12). Column (9) shows the burst time calculated by Eq. (10). Column (10) shows the maximum burst distance calculated from Eq. (11). When the maximum burst distance is less than the dam surface length, lampreys fail to pass the dam. In some cases, even though the required burst speed is less than the optimum value, it is too high and out of the testing speed range, so it was assumed that lampreys were unable to pass the dam.

The following conclusions are formulated from Table 6, when tailwater levels are below the dam crest:

(1) If the rock surface level is just 1 ft below the dam crest, lampreys have a 34% chance to pass the dam by bursting, if they cannot attach.

(2) If the rock surface level is 2 ft below the dam crest or lower, lampreys cannot pass the dam without attaching when the tailwater is 1 ft below the dam crest or lower. The chances of this happening are estimated as 72%. Therefore, there is at most a 28% chance (100%-72%) that lampreys can pass the dam without attaching.

The swimming performance of some fish species other than lamprey from Table 5, were used to assess the passable conditions over the dam. It was assumed that fish could reach the dam surface only when the rip-rap is submerged. In Table 3, columns 11 to 15, the bold numbers represent the maximum surface water velocities when the rip-rap is just submerged. The values under the bold numbers in each column are for the cases when the tailwater level is above the rip-rap surface. Note that for tailwater levels 1 ft below the dam crest or lower, the water level drop across the dam is 2.9 ft (0.9 m) or higher, and even the lowest of these water velocities are 13.6 ft/s (4.2 m/s). Such water drops and high water velocities are beyond the range of salmonid capabilities (Table 5). They would probably stop even the largest salmon, let alone whitefish or walleye.

An appreciation of flow regimes for tailwater levels above the dam crest may be gained from a relevant study on sharp-crested weirs. For a sharp-crested weir, a high velocity layer forms near the free surface downstream of the weir when tailwater is at the crest level or higher (Wu and Rajaratnam, 1996). Below this surface layer, flow is very quiet. Although this phenomenon would probably occur with an Ogee weir (shape of the Dow dam), the combination of water levels, which may generate it, is not known. Furthermore, water velocity distributions from the water surface to the dam surface are not known for the entire range of flows and water levels. Lampreys and other fish that choose to swim near the water surface would encounter high velocities, which would impede passage over most flows. Those that choose to swim in the quiet flow area underneath the high velocity layer will encounter much lower velocities. In this case fish would only have to overcome a short distance of high velocities over the crest to pass the dam.

The last three rows of Table 3 summarize the frequency analysis results for water velocities over the dam for tailwater levels equal to or higher than the dam crest. This table shows that during the lamprey migration period (Period 2), there is a 17% chance for the maximum velocity to be lower than 12.0 ft/s (3.7 m/s). Since this velocity is below their highest burst speeds (Table 5), lampreys will probably be able to pass over the dam, unless stopped by other means, like a horizontal lip. Table 3 also shows that maximum water velocities of 7.9 ft/s (2.4 m/s) or higher, have a 75%, 92%, 86% chance of occurring in Period 1, 2 and 3, respectively. Note that these water velocities are much higher than the highest burst speeds of species like the whitefish (Table 5). In other words, even when tailwater levels are 2 ft above the crest weaker swimmers cannot pass the dam. Therefore, every year there are high chances that the Dow dam will stop the migrations of most fish.

4. Recommendations

4.1 Modification to the Dow dam

The above analysis demonstrates that if the rip-rap surface is at least 2 ft below the dam crest, and lampreys could not attach, then the chances of them passing the dam are reduced to 28%. For lampreys not to attach either the dam surface needs to be covered with a special material or a horizontal lip needs to be placed along the dam crest, as shown in Fig. 15. For the special non-attaching material to be effective, it would have to cover the entire length of the dam surface to at least 2 ft below the crest, in the vertical direction. The horizontal lip will also help a strong surface flow to form when tailwater is equal to or above the dam crest and would act like a short velocity barrier, improving the chances of stopping lamprey. The design of the lip has to consider the following two factors:

(1) The lip downstream edge should be high enough from the dam surface so that lampreys cannot cross it when tailwater is below the dam crest. The suggested minimum lip height is 1 ft and this corresponds to a minimum lip width of 2.5 ft.

(2) If the lip is wide enough lampreys may not be able to swim across it and the lip will provide even better chances to stop them.

In Table 7, the lengths of the largest lampreys to be stopped by lips of different widths at different temperatures are estimated. It is assumed that the lamprey bursting speed limit is 4 m/s and that lampreys start to burst at the downstream edge of the lip. Table 7 shows that when tailwater level is equal to the dam crest level and the lip is 3.5 ft wide, no lampreys can pass if the water temperature is lower than 71°F (22°C; 1°C lower than the highest recorded temperature in Period 2). As pointed out earlier, there is an 83% chance for the tailwater to be equal to or lower than the dam crest. Therefore, with a 3.5 ft wide lip there is at least an 83% chance in any year that lampreys cannot pass the dam. If the lip is 2.5 ft wide lampreys can pass if water temperature is higher than 64°F (18°C; after May 26). Table 7 also shows that to completely stop lampreys when the tailwater level is 1 ft or 2 ft above the dam crest, the horizontal lip has to be 13 ft or 26 ft wide, respectively. This table indicates that even with such wide lips, there is still a 12% or 8% chance, respectively, that lamprey can go over the dam. It is also interesting to note that increasing the dam height and adding a short lip would improve the chances of stopping lamprey. Table 1 though indicates that the dam crest would have to be raised by about 5 ft before the chances of stopping lampreys are increased to 95%.

In conclusion, covering the dam surface with a special non-attaching material or adding a 2.5 ft wide horizontal lip would stop lampreys 72% of the time. On the other hand, if a 3.5 ft wide horizontal lip is added, it would stop lampreys 83% of the time. A combination of raising the dam crest and placing a lip would further increase the chances of stopping lampreys.

4.2 Modification to the fishway

It was pointed out earlier that the fishway exit elevation was properly designed while the fishway entrance elevation was set too high for fish passage under most water levels. There is adequate space to replace the existing fishway with a similar one but with a steeper floor slope to accommodate fish passage conditions at the full range of water levels. In Table 8, the cumulative frequency for the depth at the invert to be less than 2 ft in different periods for different entrance elevations is estimated. The current fishway slope is just 1.94%. If the slope is increased to 7.04% the fishway entrance will be 3 ft lower. In Period 1 the chances that the depth at the entrance will be less than 2 ft, will be reduced from 40% to 2%. In Period 2, it will be reduced from 76% to 20%. These conditions could be improved further by lowering the fishway entrance floor even more.

The current fishway is not a problem for lampreys but is a problem for other fish. A replacement fishway will not enhance lamprey passage but will greatly increase the passage of other fish. Since lampreys and other fish will use the fishway, necessary measures are needed to deal with the lamprey passing through the fishway. Manual sorting, lamprey traps, or a lamprey barrier within the fishway that allows other fish to pass, offer potential solutions.

4.3 Suggested experimental studies

The possible solutions to the fish passage and lamprey control concerns at the Dow dam need further investigation, before their feasibility is established. A set of controlled experiments, complemented by field studies, would be required to arrive at the best alternative for this site. The flow regime and velocity distributions over the Dow dam Ogee weir for the range of headwater and tailwater levels at the site, may be investigated through hydraulic modelling. The effects of various rip-rap elevations and horizontal lip widths on the flow structure and velocity distributions need to be tested. Tests with lamprey barriers incorporated within a vertical slot fishway may also be conducted. Testing of these alternatives with lamprey and other fish is possible with the use of the mobile Ichthyohydraulics Flume. This research facility is a collaborative effort between the Freshwater Institute (Fisheries and Oceans Canada), and the Department of Civil and Environmental Engineering of the University of Alberta. This flume was used recently to test a fish guidance system (louvers). Further field observations on the migration timing of several fish species will also be needed for a more complete analysis and assessment of alternatives. The results from some of these studies would be applicable for similar situations with other dams around the Great Lakes and the GLFC may wish to consider research funding for them.

5. Notations

The following notations are used in the current report:

c	discharge coefficient when h_u is different from h_0
c_0	discharge coefficient when $h_u = h_0$
DCE	the Dow dam crest elevation (595.12 ft)
h_0	Ogee dam design head (3.3 ft used)
h_u	dam upstream head
L	fish fork length
Q	daily mean discharge
q	unit dam width discharge

R	correlation coefficient
S	fish swimming distance
S_D	dam surface length in flow direction
S_m	maximum distance fish can swim
$\underline{T}$	average daily water temperature
t	fish swimming time
T	water temperature
T_{sd}	standard deviation of daily water temperature
U	fish swimming speed
U_o	optimum fish bursting speed
V	mean water velocity
V_m	maximum water velocity
z_{2000}	maximum water level at station 2000 ft below the Dow dam
z_d	tailwater level downstream of the Dow dam
z_f	the fishway entrance floor elevation (current value=592.38 ft)
z_g	the elevation of the top of the fishway gate opening (597.27 ft)
z_x	fishway exit floor elevation (593.52 ft)
z_u	headwater elevation
Δ	height between dam crest and rip-rap surface

6. Acknowledgement

The Great Lake Fisheries Commission and Dow Chemical financially supported this research project.

7. References

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Table 1 Summary of frequency analysis on maximum tailwater levels at the Dow dam (based on data from 1982 to 1995)

z_d	DCE-z_d	Period 1: 3/1~4/14		Period 2: 4/15~6/30		Period 3: 3/1~6/30	
		Frequency	Cumulative frequency	Frequency	Cumulative frequency	Frequency	Cumulative frequency
(ft)	(ft)	(%)	(%)	(%)	(%)	(%)	(%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
589.12	6	0.00	0.00	0.00	0.00	0.00	0.00
590.12	5	0.00	0.00	1.89	1.89	1.18	1.18
591.12	4	1.91	1.91	13.38	15.27	9.12	10.31
592.12	3	3.99	5.90	18.85	34.12	13.33	23.64
593.12	2	10.21	16.11	20.64	54.76	16.77	40.40
594.12	1	17.86	33.97	17.44	72.20	17.59	58.00
595.12	0	18.98	52.95	10.84	83.03	13.86	71.86
596.12	-1	14.04	66.99	5.28	88.31	8.53	80.39
597.12	-2	7.50	74.48	3.68	91.99	5.09	85.49
598.12	-3	4.63	79.11	1.70	93.69	2.78	88.27
599.12	-4	5.26	84.37	1.79	95.48	3.08	91.35
600.12	-5	4.63	89.00	1.51	96.98	2.67	94.02
601.12	-6	3.35	92.34	0.66	97.64	1.66	95.68
602.12	-7	2.55	94.90	0.47	98.11	1.24	96.92
603.12	-8	1.12	96.01	0.66	98.77	0.83	97.75
604.12	-9	1.59	97.61	0.75	99.53	1.07	98.82
605.12	-10	1.28	98.88	0.28	99.81	0.65	99.47
606.12	-11	1.12	100.00	0.19	100.00	0.53	100.00

DCE: dam crest elevation (595.12 ft)

z_d: tailwater level

Table 2 Comparison of typical discharges for 1994 with those for the 58 year record (1936-1994)

Month	monthly mean for 1994 (cfs)	58 year monthly mean (cfs)	58 year mean/ 1994 mean	1994 maximum daily (cfs)	58 year maximum daily (cfs)	58 year maximum daily /1994 maxmum	1994 minimum daily (cfs)	58 year minimum daily (cf/s)	58 year minimum daily / 1994 minimim daily
(1)	(2)	(3)	(4)=(3)/(2)	(5)	(6)	(7)=(6)/(5)	(8)	(9)	(10)=(9)/(8)
March	3990	3949	0.99	9740	10660.00	1.09	1740	1027	0.59
April	3010	3768	1.25	6860	8096.00	1.18	962	969	1.01
May	1829	2124	1.16	4260	5573.00	1.31	667	567	0.85
June	1397	1361	0.97	5010	5270.00	1.05	314	355	1.13

Table 3 Water level drop across the Dow dam and maximum flow velocity

tailwater elevation	how much tailwater level below dam crest	cumulative frequency (%)			daily mean discharge	unit dam width discharge	head over crest	headwater elevation	water level drop across dam	maximum flow velocity downstream the dam					depth at fishway entrance	depth at fishway exit	depth above fishway gate opening
z_d (ft)	DCE-z_d(ft)	3/1 ~ 4/14	4/15 ~ 6/30	3/1 ~ 6/30	Q(cfs)	q (ft^2/s)	h_u(ft)	z_u(ft)	z_u-z_d(ft)	V_m(ft/s)					z_d-z_f (ft)	z_u-z_x (ft)	z_u-z_g (ft)
(1)	(2)=DCE-(1)	(3)	(4)	(5)	(6) rating curve	(7)=(6) / DW	(8)	(9)=(8)+ DCE	(10)= (9)-(1)	(11) (Δ=5')	(12) (Δ=4')	(13) (Δ=3')	(14) (Δ=2')	(15) (Δ=1')	(16) = (1)-z_f	(17) = (9)-z_x	(18) = (9)-z_g
590.12	5	0.0	1.9	1.2	413	1.56	0.60	595.72	5.60	**18.98**	17.20	15.21	12.93	10.14	-2.26	2.20	-1.55
591.12	4	1.9	15.3	10.3	765	2.88	0.89	596.01	4.89	17.73	**17.73**	15.81	13.62	11.01	-1.26	2.49	-1.26
592.12	3	5.9	34.1	23.6	1229	4.63	1.20	596.32	4.20	16.43	16.43	**16.43**	14.34	11.88	-0.26	2.80	-0.95
593.12	2	16.1	54.8	40.4	1810	6.82	1.52	596.64	3.52	15.05	15.05	15.05	**15.05**	12.74	0.74	3.12	-0.62
594.12	1	34.0	72.2	58.0	2508	9.45	1.87	596.99	2.87	13.58	13.58	13.58	13.58	**13.58**	1.74	3.47	-0.28
595.12	0	53.0	83.0	71.9	3325	12.54	2.22	597.34	2.22	11.96	11.96	11.96	11.96	11.96	2.74	3.82	0.08
596.12	-1	67.0	88.3	80.4	4263	16.07	2.59	597.71	1.59	10.12	10.12	10.12	10.12	10.12	3.74	4.19	0.45
597.12	-2	74.5	92.0	85.5	5323	20.07	2.97	598.09	0.97	7.91	7.91	7.91	7.91	7.91	4.74	4.57	0.83

DCE: 595.12 ft, dam crest elevation

DW: 265.25 ft, dam width

z_f: 592.38 ft, floor elevation of fishway entrance

z_x: 593.52 ft, floor elevation of fishway exit

z_g: 597.27 ft, elevation of the top of gate opening

(6): $Q=44*(Z_d - 587.2)^{2.09}$

(8): solve $q=3.97(c/c_0)h_u^{1.5}$ where $(c/c_0)=0.73+0.27(h_u/3.3)^{0.5}$

(11)~(15): $V_m=[2g*\min(\Delta+h_u, z_u-z_d)]^{0.5}$ where $g = 32.15\ ft/s^2$

Δ=dam crest elevation - rock surface elevation

Table 4. Frequency analysis on daily water temperature at the Dow dam

T(°C) (1)	T(°F) (2)	cumulative frequency in period 1 (%) (3)	cumulative frequency in period 2 (%) (4)	cumulative frequency in period 3 (%) (5)
0	32	3.2	0	1.0
2.8	37	40	0	12.2
5.6	42	67.6	0	20.6
8.3	47	89.6	4.4	30.4
11.1	52	98	15.3	40.5
13.9	57	99.6	28.1	49.9
16.7	62	99.6	45.5	62.0
19.4	67	100	66.8	76.9
22.2	72	100	86.8	90.8
25.0	77	100	97.7	98.4
27.8	82	100	100	100

Table 5. Regression equations for burst swimming of different fish species (data from DFO Ichthyomechanics database)

Fish (1)	Fish family (2)	Fork length L(m) (3)	Temperature T(°C) (4)	Speed u(m/s) (5)	Time t(sec) (6)	Equation (7)
Lamprey	Petromyzon	0.15~0.51	5~15	0.3~0.6	13.5~2294	log t(sec) = 6.58 + 2.34 L(m) + 0.046 T(°C) - 6.44 u(m/s)$^{0.2}$
		0.45~0.55	6~10	1~1.5	4~127	
		0.39~0.59	9~21	1.11~3.65	1~99.4	
		0.43~0.48	11.5~23	1.52~3.96	0.8~5	
Coho salmon	Samonidae	0.475~0.75	10~12.5	0.914~3.048	8~897	log t(sec) = 1.99 + 0.104T(°C) - 0.469u(m/s)
Steelhead trout		0.61~0.82	10	1.219~3.048	49~502	
Pink salmon		0.448~0.552	20	1.16~2.38	72~30600	
Sockeye salmon		0.438~0.565	18	1.22~2.37	120~25500	
White fish		0.31	5~12	0.55~1.02	96~2358	log t(sec) = 5.16 + 0.088T(oC) - 4.21u(m/s)

Table 6. Estimates of maximum bursting swimming speeds and distances for 0.6 m lampreys under T=25°C (77°F)

tail water level below dam crest	cumulative in period 2 (%)	rock surface below dam crest	maximum water velocity	maximum water velocity	dam surface length	required burst speed to pass dam	optimum burst speed	burst time	maximum burst distance	burst result
DCE-z_d (ft)	cumulative (%)	Δ (ft)	V_m(ft/s)	V_m(m/s)	S_D(ft)	u(m/s)	u_o(m/s)	t(sec)	S_m(ft)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
5	1.9	1	10.14	3.09	4.00	3.26	4.15	9.48		pass
4	15.3	1	11.01	3.36	4.00	3.60	4.49	6.51		pass
3	34.1	1	11.88	3.62	4.00	4.00	4.83	4.33		pass
2	54.8	1	12.74	3.88	4.00	4.35	5.16	3.11	too large u	failed
1	72.2	1	13.58	4.14	4.00	4.90	5.49	1.92	too large u	failed
5	1.9	2	12.93	3.94	5.53	4.80	5.24	2.09	too large u	failed
4	15.3	2	13.62	4.15	5.53	5.51	5.51	1.19	5.28	failed
3	34.1	2	14.34	4.37	5.53	5.79	5.79	0.96	4.49	failed
2	54.8	2	15.05	4.59	5.53	6.07	6.07	0.79	3.84	failed
1	72.2	2	13.58	4.14	4.00	4.90	5.49	1.92	too large u	failed

Table 7 Length of the largest lamprey to be stopped by lips of different widths at different temperatures

cumulative(%)	z_d -DCE (ft)	V_m (ft/s)	lip width (ft)	lip height (ft)	u_o (<=4) (m/s)	time (sec)	T(°C) <=25	T(°F) <=77	L_m(m) <=0.6
83.0	−0	11.96	3.50	1.71	4.00	3.01	22	71	0.60
83.0	0	11.96	3.00	1.29	4.00	2.58	25	77	0.50
83.0	0	11.96	3.00	1.29	4.00	2.58	20	68	0.60
83.0	0	11.96	2.50	1.00	4.00	2.15	25	77	0.47
83.0	0	11.96	2.50	1.00	4.00	2.15	18	64	0.61
88.3	1	10.12	13.00	1.71	4.00	4.33	25	77	0.60
88.3	1	10.12	3.50	1.71	4.00	1.17	26	79	0.34
88.3	1	10.12	3.50	1.71	4.00	1.17	20	68	0.45
88.3	1	10.12	3.50	1.71	4.00	1.17	15	59	0.55
88.3	1	10.12	3.00	1.29	4.00	1.00	25	77	0.33
88.3	1	10.12	3.00	1.29	4.00	1.00	20	68	0.43
88.3	1	10.12	3.00	1.29	4.00	1.00	15	59	0.52
.88.3	1	10.12	3.00	1.29	4.00	1.00	11	52	0.60
88.3	1	10.12	2.50	1.00	4.00	0.83	25	77	0.29
88.3	1	10.12	2.50	1.00	4.00	0.83	20	68	0.39
88.3	1	10.12	2.50	1.00	4.00	0.83	15	59	0.49
88.3	1	10.12	2.50	1.00	4.00	0.83	10	50	0.59
92.0	2	7.91	26.0	1.71	3.27	9.19	25	77	0.60
92.0	2	7.91	3.50	1.71	3.27	1.24	25	77	0.22
92.0	2	7.91	3.50	1.71	3.27	1.24	20	68	0.32
92.0	2	7.91	3.50	1.71	3.27	1.24	15	59	0.42
92.0	2	7.91	3.50	1.71	3.27	1.24	10	50	0.52
92.0	2	7.91	3.00	1.29	3.27	1.06	25	77	0.20
92.0	2	7.91	3.00	1.29	3.27	1.06	20	68	0.29
92.0	2	7.91	3.00	1.29	3.27	1.06	15	59	0.39
92.0	2	7.91	3.00	1.29	3.27	1.06	10	50	0.49
92.0	2	7.91	2.50	1.00	3.27	0.88	25	77	0.16
92.0	2	7.91	2.50	1.00	3.27	0.88	20	68	0.26
92.0	2	7.91	2.50	1.00	3.27	0.88	15	59	0.36
92.0	2	7.91	2.50	1.00	3.27	0.88	10	50	0.46

Table 8 Cumulative frequency for z_d-z_f≤2ft for different elevations of fishway entrance floor

z_f(ft)	note	slope (%)	cumulative for period 1 (%)	cumulative for period 2 (%)	cumulative for period 3 (%)
592.38	current level	1.94	40	76	62
591.38	1 ft lower	3.64	20	60	45
590.38	2 ft lower	5.34	8	40	28
589.38	3 ft lower	7.04	2	20	14
588.38	4 ft lower	8.74	0	5.5	4

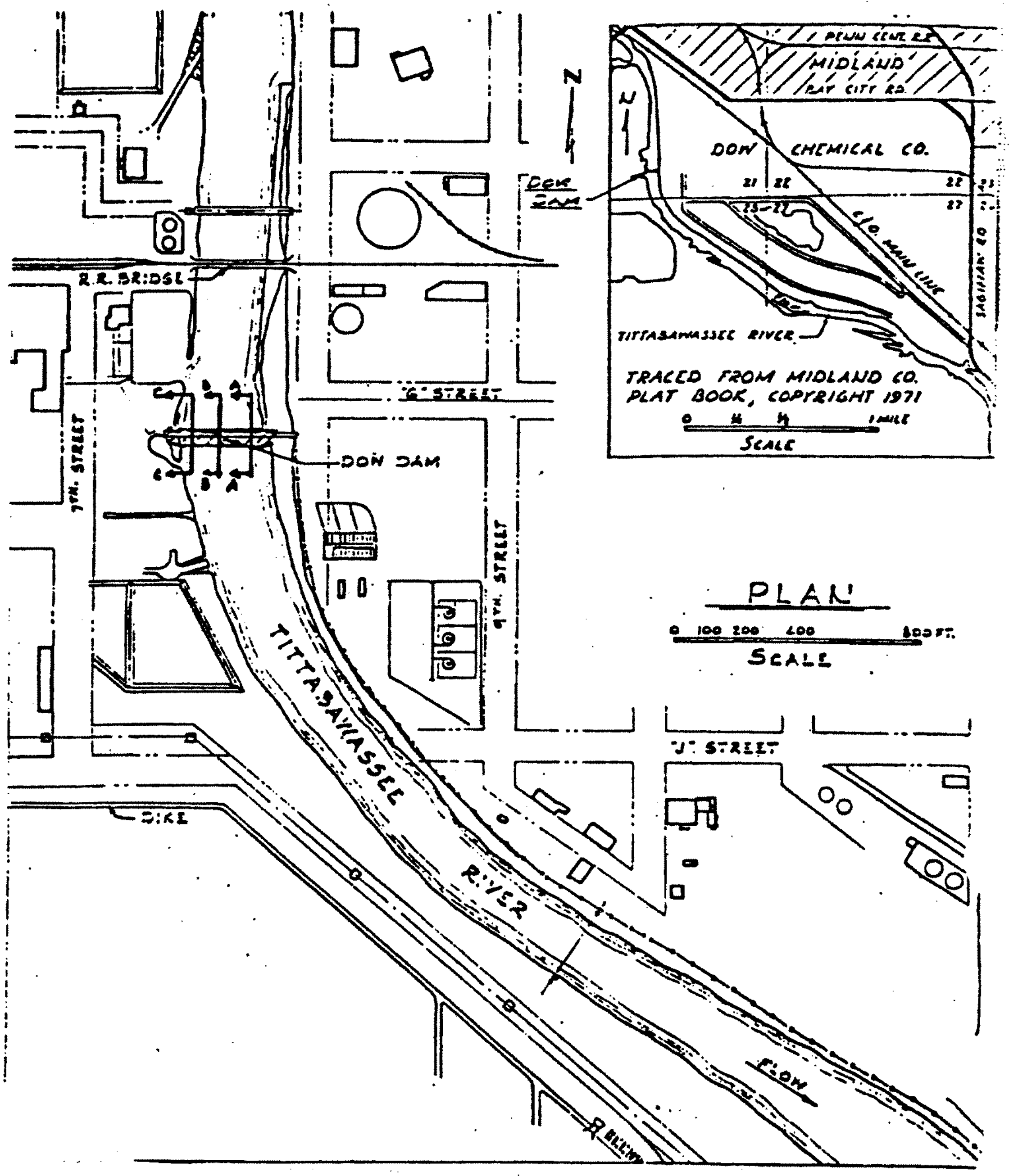

Fig. 1 Plan view of the Dow dam site

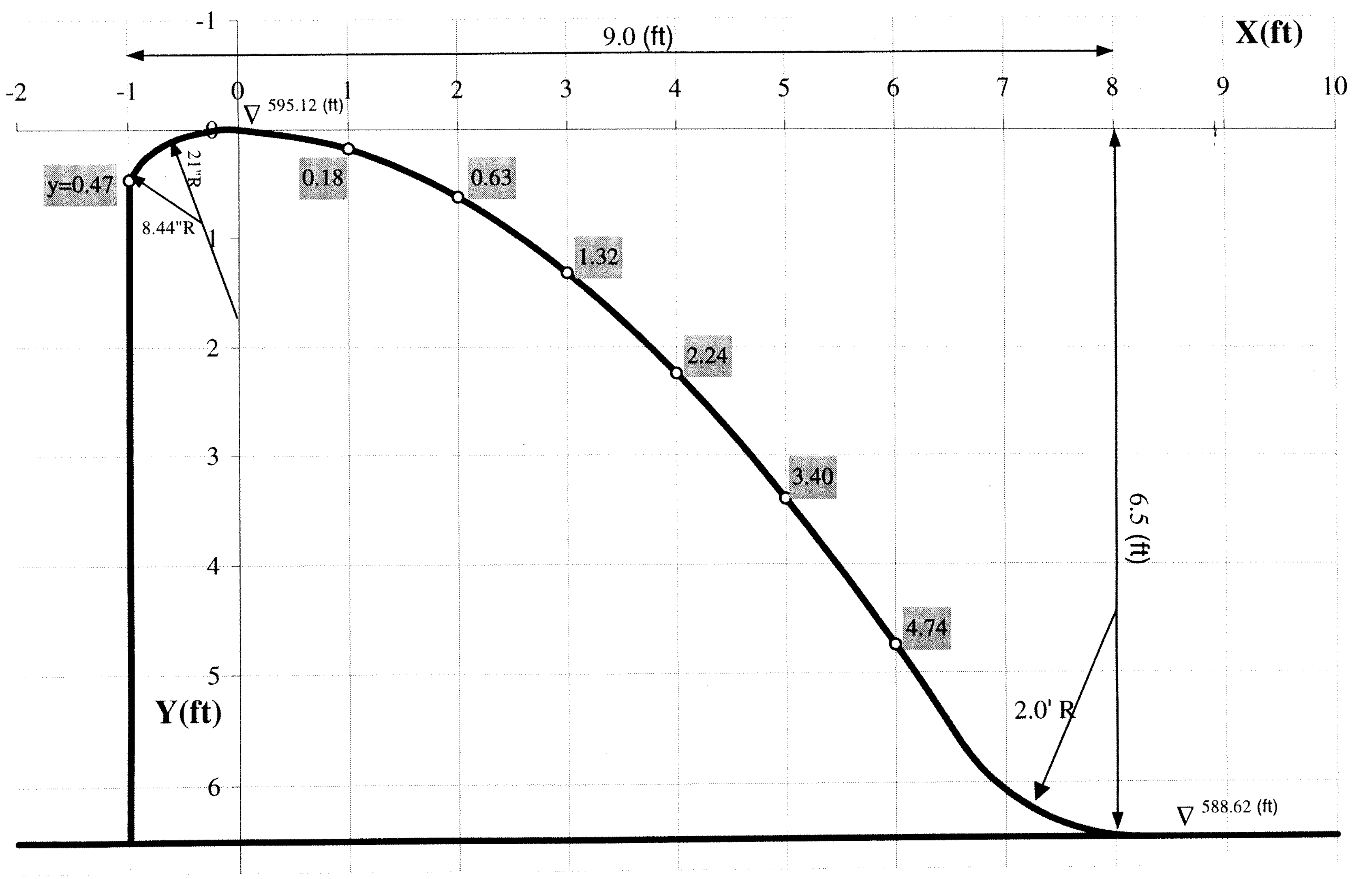

Fig. 2. Dow dam cross section (Ogee weir type)

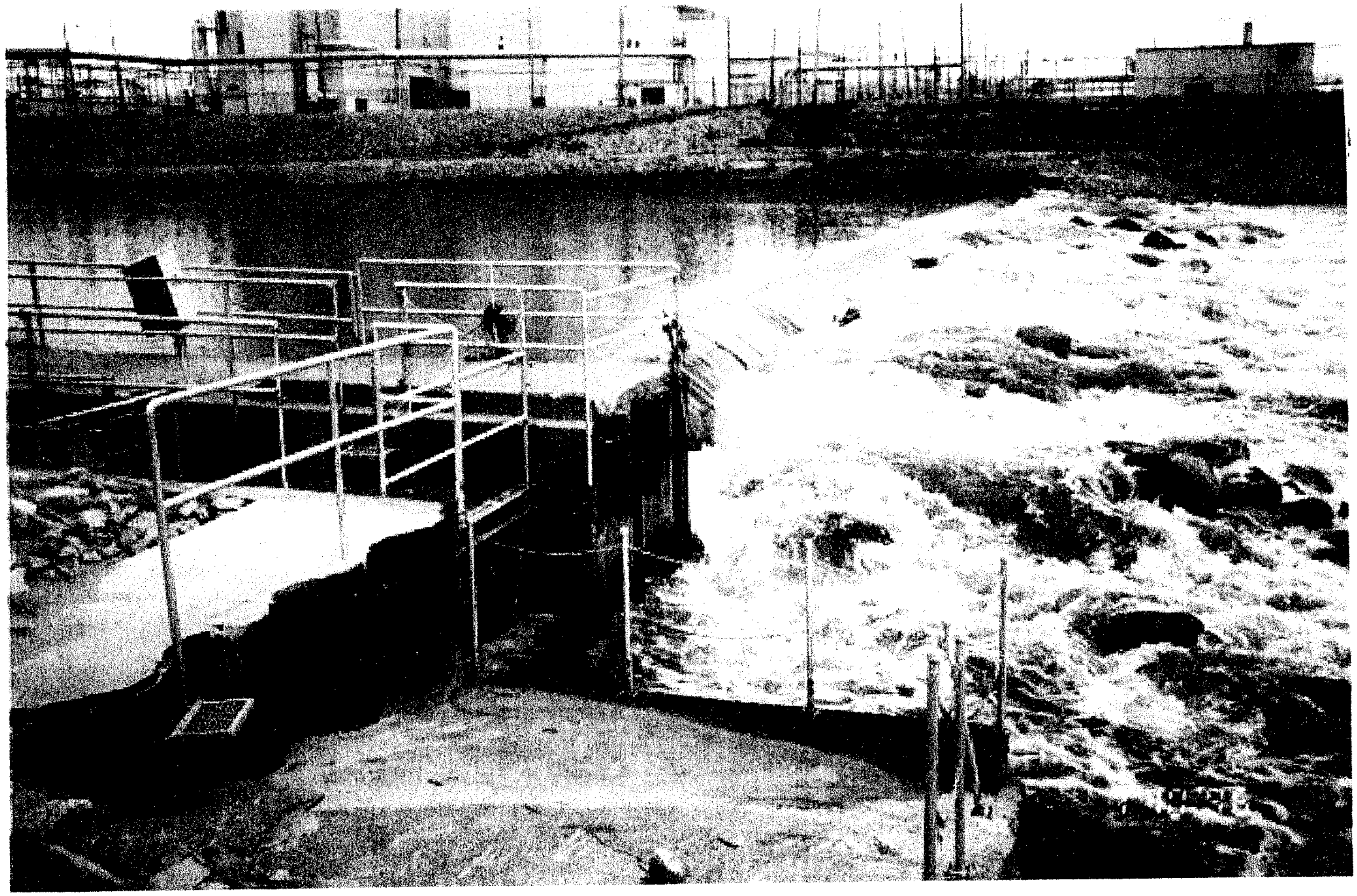

Fig. 3 View of Dow dam, fishway and rip-rap

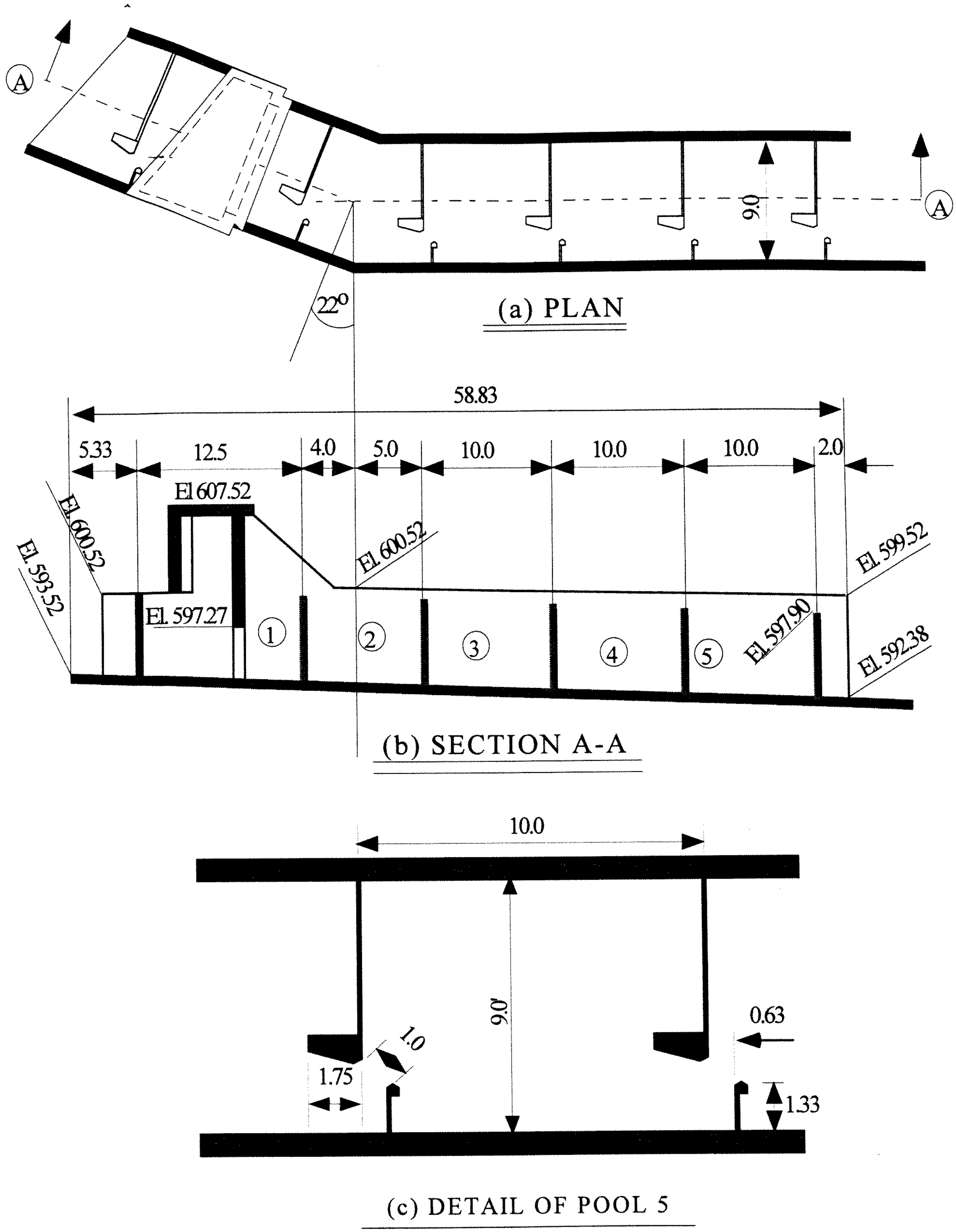

Fig. 4(a-c) Sketch of the vertical slot fishway of the Dow dam

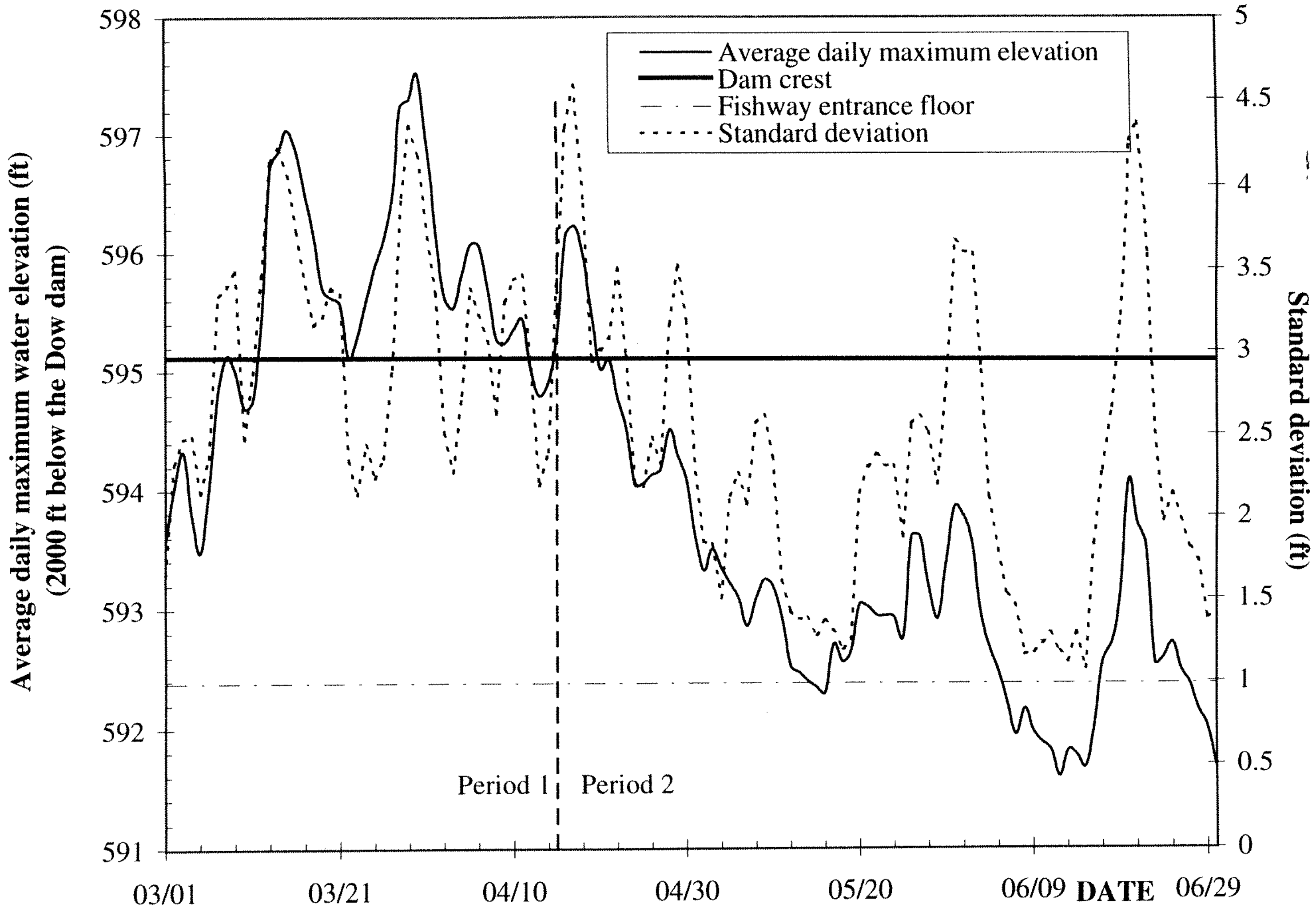

Fig. 5. Average daily maximum water level at 2000 ft downstream of the DOW dam
[Based on 14 years of record (1982-1995) from March 1 to June 30]

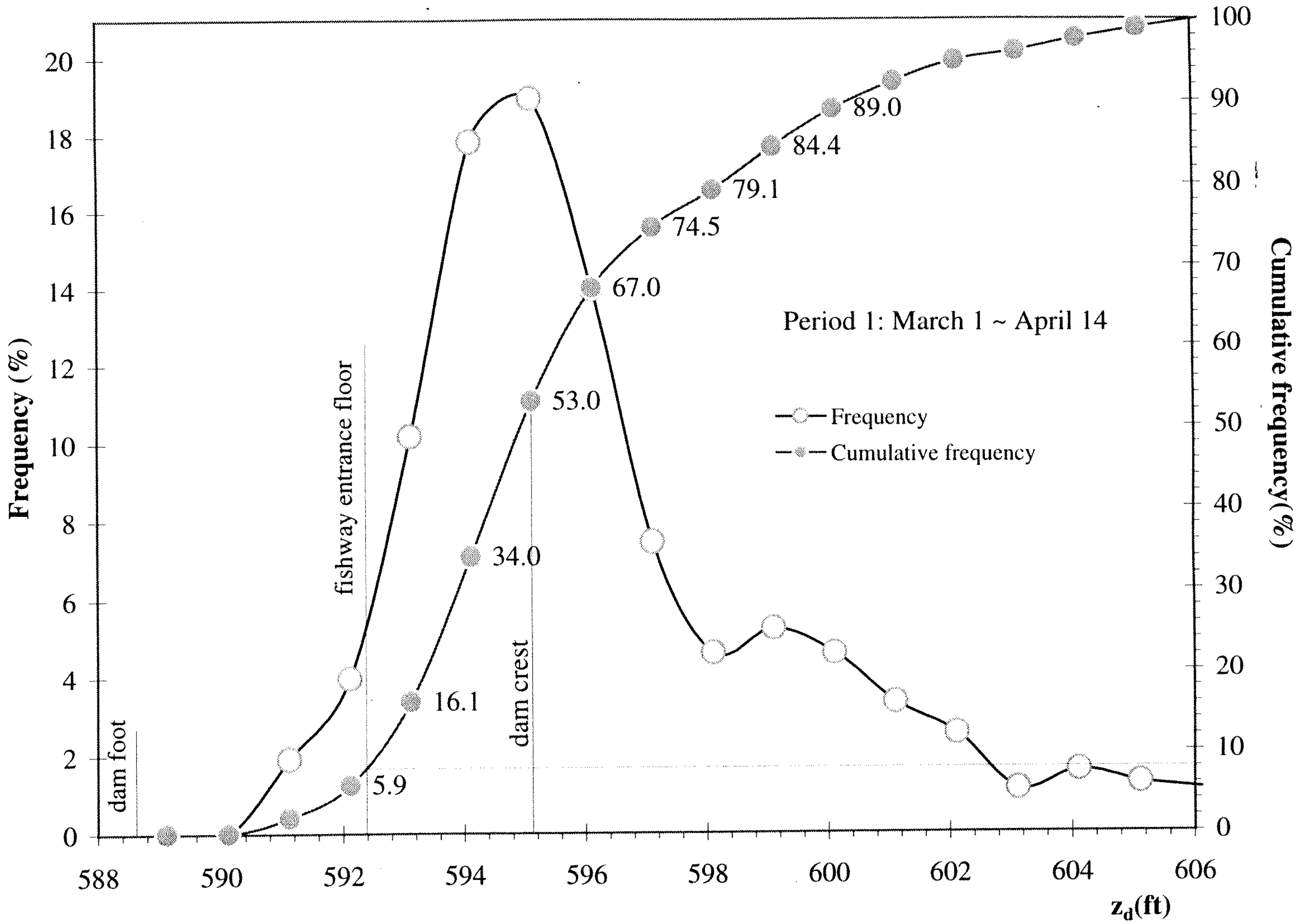

Fig. 6. Frequency and cumulative frequency for maximum tailwater at the Dow dam from March 1 to April 14 [Based on 14 years of record (1982-1995)]

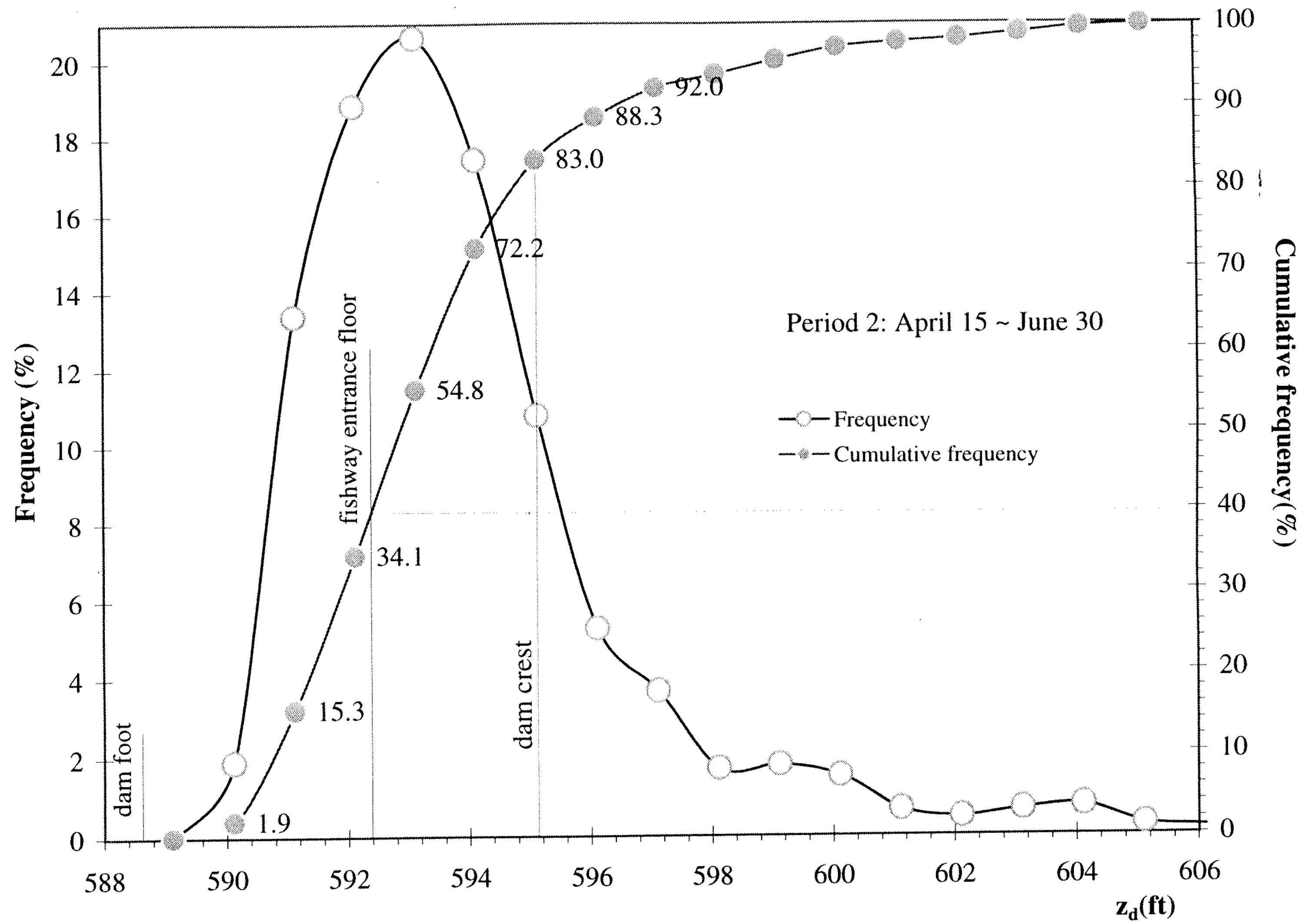

Fig. 7. Frequency and cumulative frequency for maximum tailwater at the Dow dam from April 15 to June 30 [Based on 14 years of record (1982-1995)]

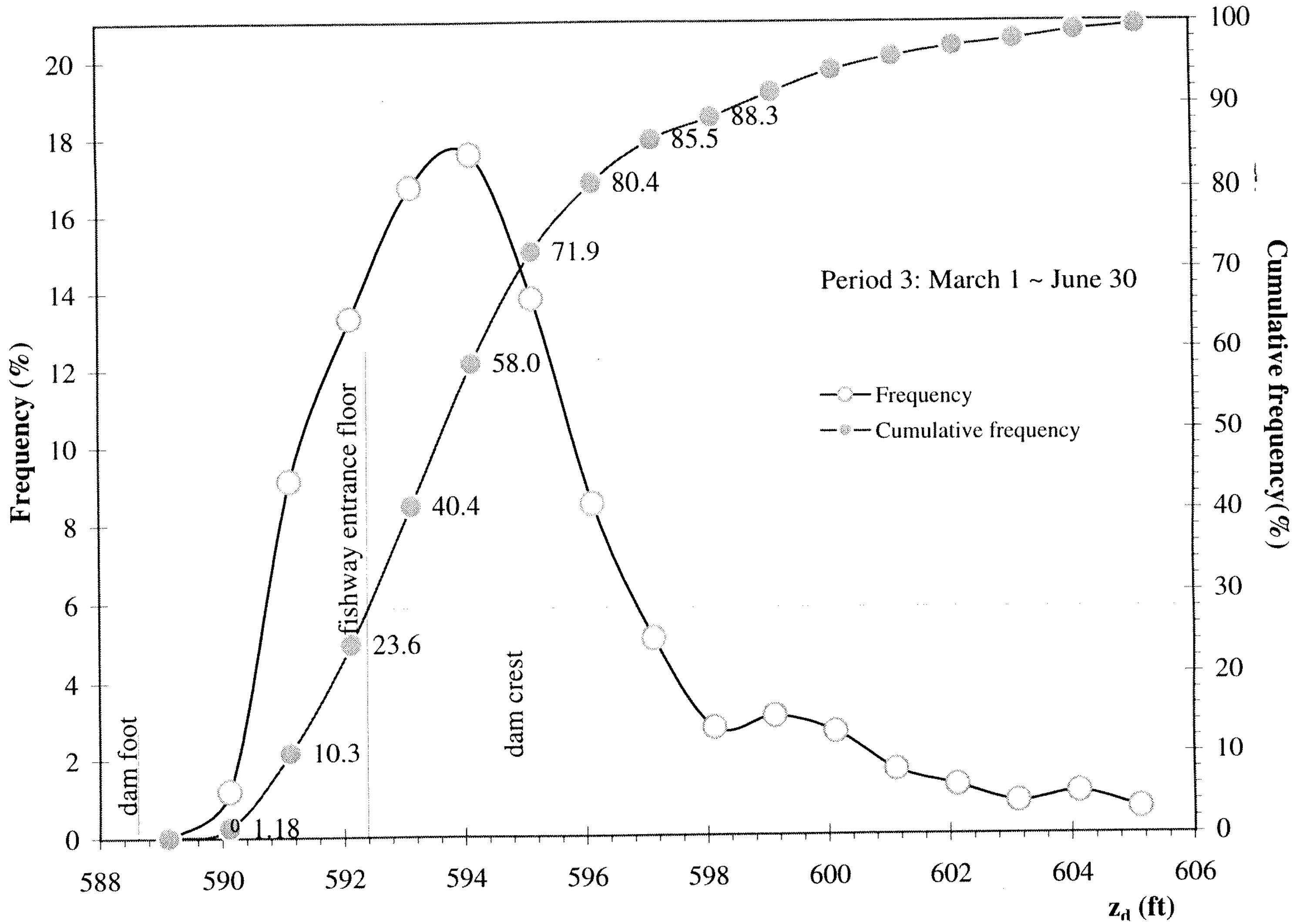

Fig. 8. Frequency and cumulative frequency for maximum tailwater at the Dow dam from March 1 to June 30 [Based on 14 years of record (1982-1995)]

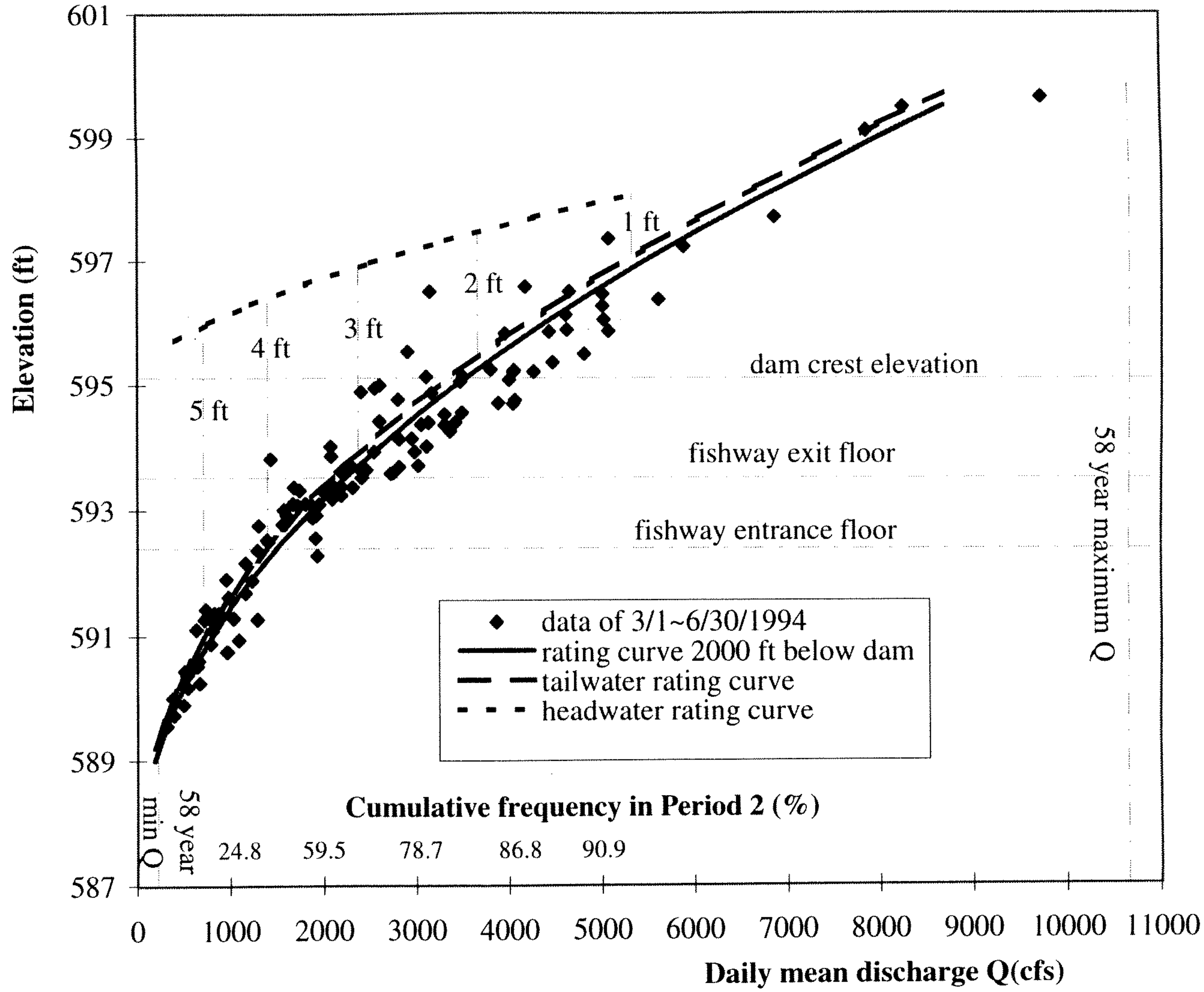

Fig. 9. Discharge rating curves of headwater, tailwater and 2000 ft downstream of the Dow dam

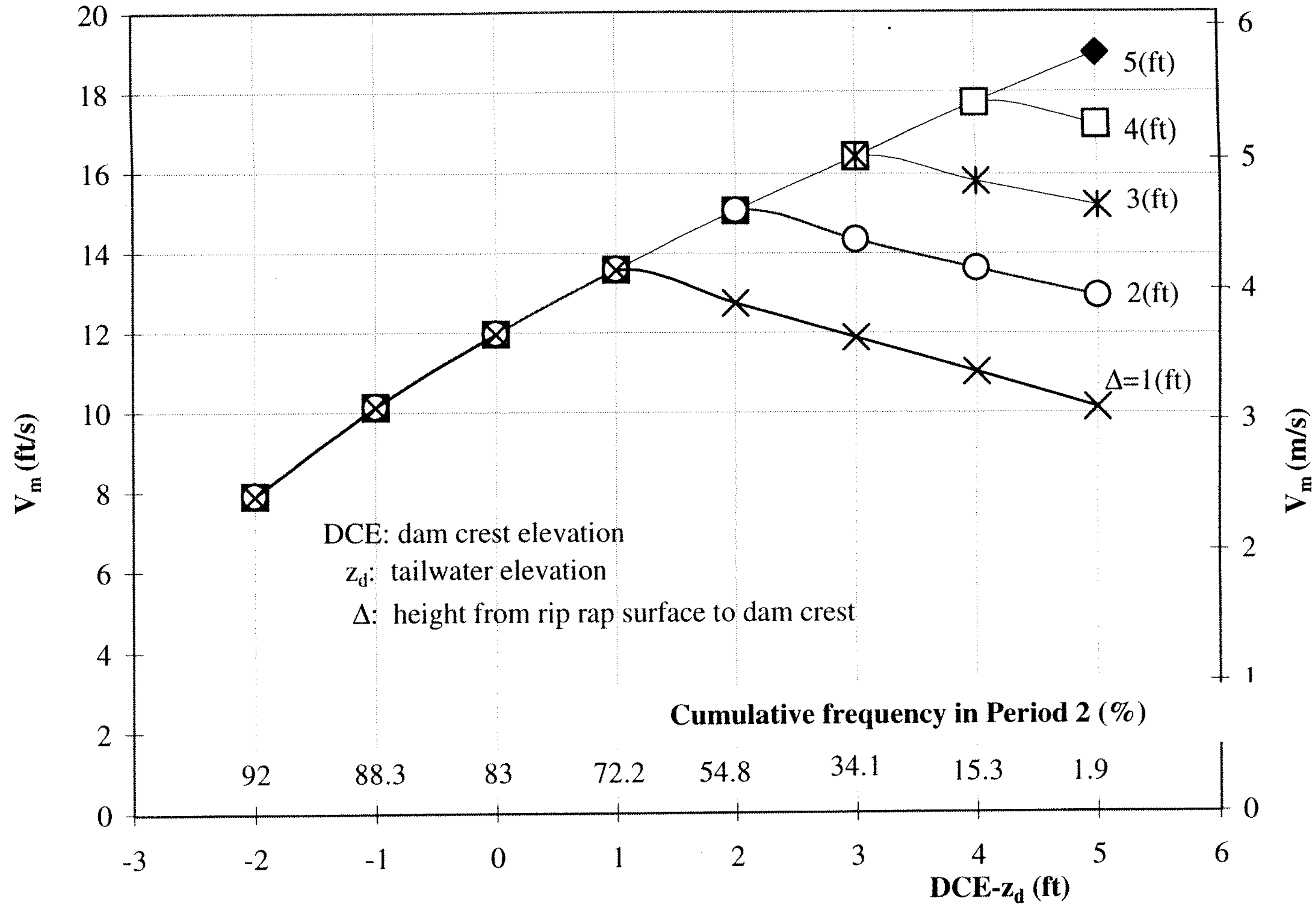

Fig. 10. Variation of maximum flow velocity with elevation difference between dam crest and tailwater surface for different rip-rap elevations [Calculation based on 14 years of water level record (1982-1995) and 1 year discharge record (1994)]

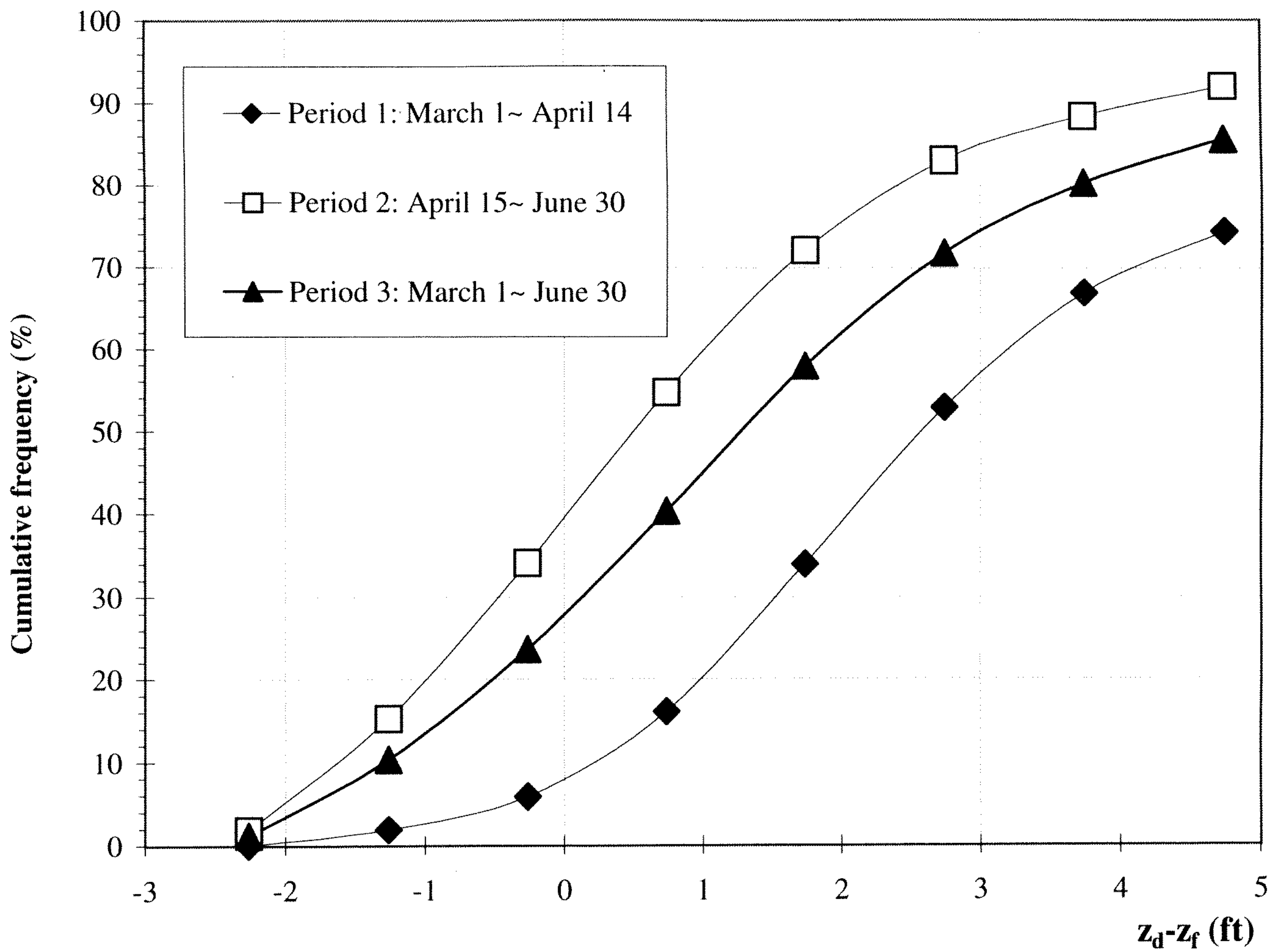

Fig. 11. Cumulative frequency for elevation difference between tailwater surface and fishway entrance floor [Based on 14 years of record (1982-1995)]

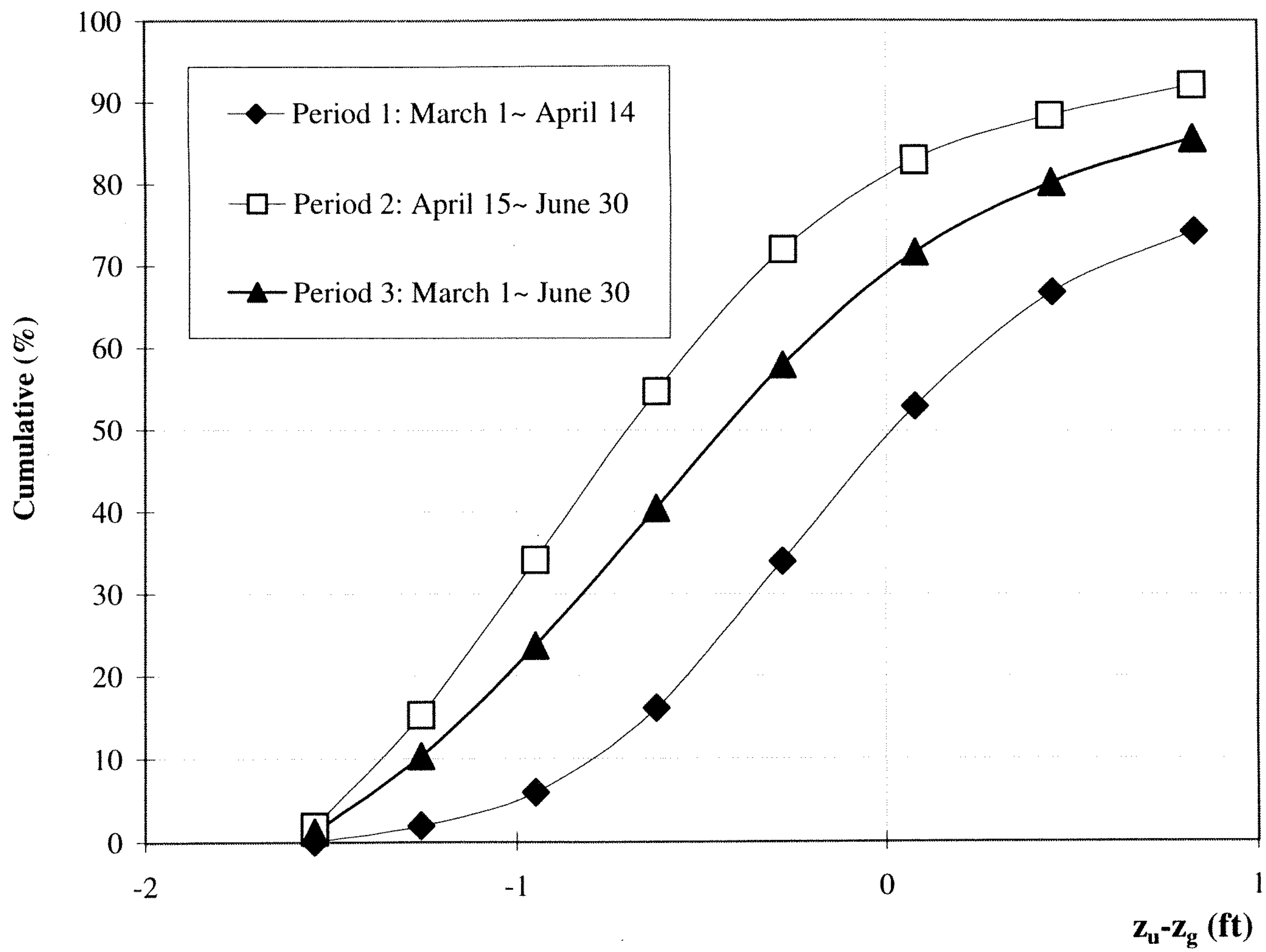

Fig. 12. Cumulative frequency forelevation difference between headwater and the elevation of the top of the fishway gate opening [Calculation based on 14 years of water level record (1982-1995) and 1 year discharge record (1994)]

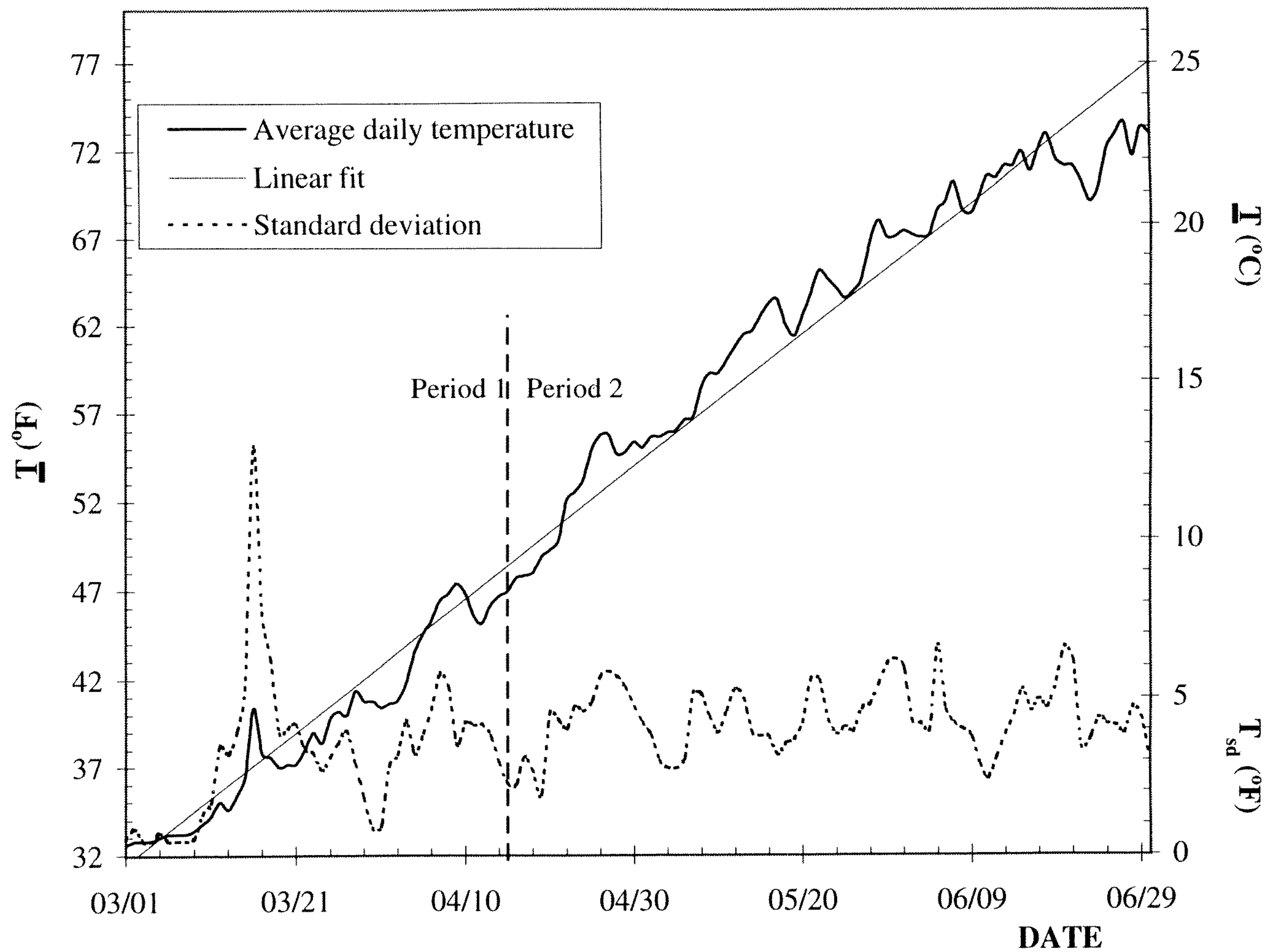

Fig. 13 Average daily temperature 2000 ft downstream of the Dow dam
[Based on 7 years of record (1988-1995) from March 1 to June 30]

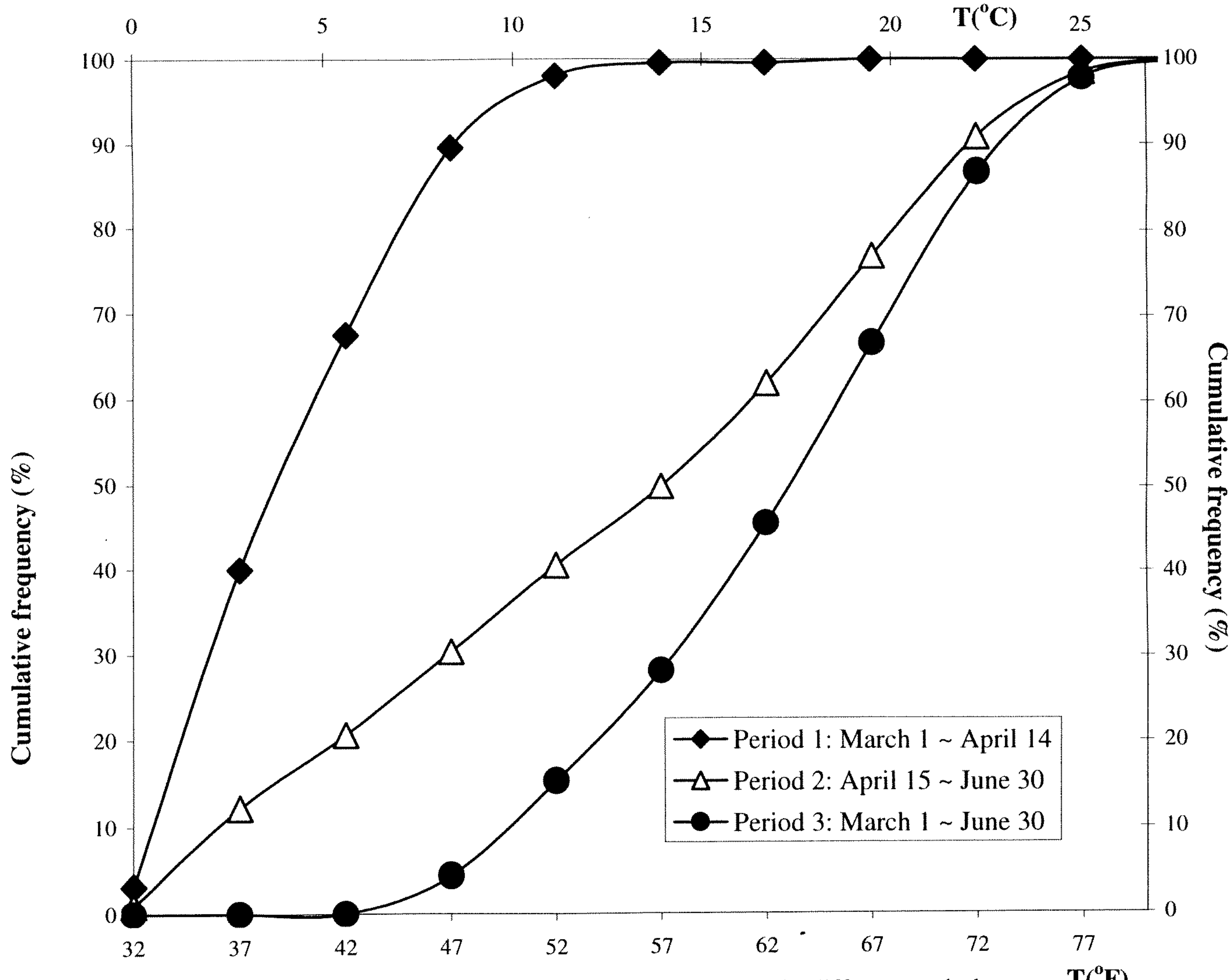

Fig. 14. Cumulative frequency for temperatures in different periods
[Based on 7 years of record (1988-1995)]

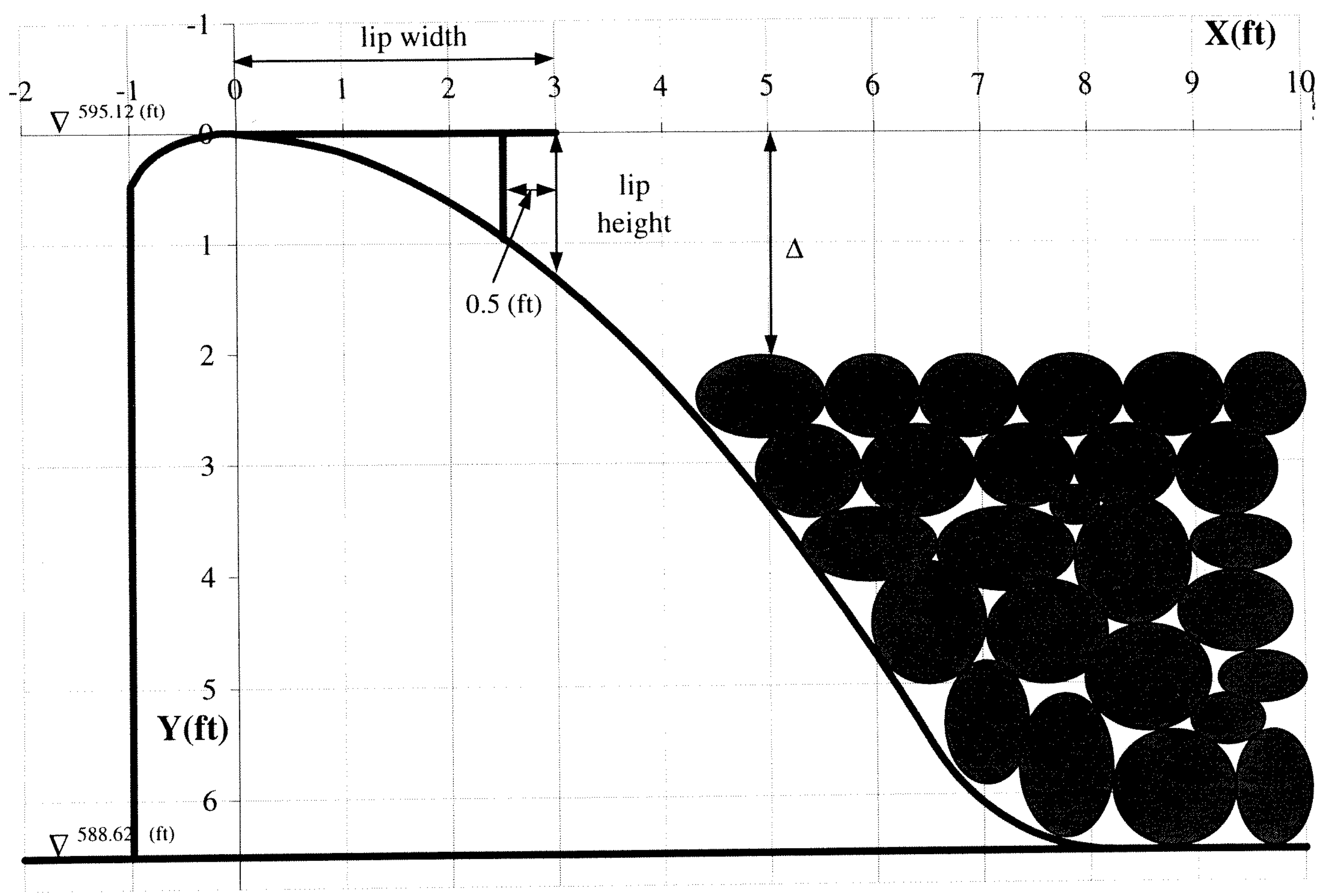

Fig. 15. Cross section of the Dow dam showing the rip-rap and suggested horizontal lip