Small Dams and Habitat Quality in Low Order Streams

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Abstract:

It has long been known that large dams are major disruptions in the migration of anadromous fish to upstream reaches of a watershed. This study looked at the effects of small dams and culverts as they also present obstacles to the passage of native species, such as brook trout (Salvelinus fontinalis) in the Pawcatuck Watershed. Information was collected on the physical properties of dams and culverts in order to be able to assess their role in affecting fish passage. Preliminary hydraulic and fish behavioral studies were then related to the dam properties to assess the likelihood of fish passage obstruction. It is likely that many of the small dams and improperly functioning culverts can prevent migration of brook trout, especially during low flow periods. Properly designed and installed culverts and fishways need to be based on important biological factors, preferably with respect to the weakest swimmers of the species expected to migrate.

Temperature effects of dams on the Beaver River in Richmond was also examined. Data shows that it took up to 5 miles for the stream to recover from the warming effects downstream of a small dam.

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Small Dam Hydraulic Data and its Influence on Fish Passage

General

The methodology used in this portion of the study is primarily based on reports by Reiser and Peacock (1986) and Bell (1986). However, some modifications to the formulae described in the above reports were made in order to obtain preliminary estimates of certain parameters which were not directly measured due to logistic difficulties during the field work.

The basic approach used here involves an evaluation and comparison of leaping and swimming capabilities of certain salmonid species. It is known that brook trout do not jump out of the water and therefore all stream obstructions which require any degree of jumping ability for successful passage act as complete barriers to upstream migration of this species. However, another member of the salmonid family, the Atlantic salmon, has very strong jumping abilities. Rainbow trout and brown trout are also fairly good leapers. Of these two species the rainbow trout has the relatively stronger jumping ability. Since active restoration efforts for Atlantic salmon have been attempted for several years by the State of Rhode Island in parts of our watershed, it seems appropriate to briefly address the role of dams as obstacles to upstream migration of Atlantic salmon as well as a brown and rainbow trout. It is clear that downstream passage of salmon smolts and other salmonid species over dams of the size encountered in our watershed does not induce any significant mortality. Therefore, the downstream passage issue is not addressed in this report.

Methods

In order to establish the nature of fish passage problems likely to occur at a particular dam site, certain biological, physical and hydraulic parameters are required. In this study, the following definitions and notation were considered to be basic for assessments of the type reported herein:

HD = the head differential between the reservoir surface elevation and the top of the tail water (ft)
DC = critical depth of the dam crest (ft)
DT = tail water depth below the dam (ft)
VC = water velocity at the critical depth (ft per second)
VF = water velocity of the falling water as it enters the plunge pool (ft per second)
VT = water velocity in the tail water area (ft per second)

Each of these parameters (singly or in combination) can influence fish passage over a low dam. However, the values of HD, DC and DT relate directly to fish passage by jumping. Based on information provided in Bell (1986) it has been established that flow over a low dam or weir, such as those encountered in this study, can be estimated by:

$$Q = KL(DO) \qquad (1)$$

Where:

Q = flow in cubic feet per second (cfs)

L = length of weir (ft)
DO = water depth over weir (ft)
K = 3.5 (a parameter value considered suitable for observed data in our watershed)

Because information was available from published reports on maximum discharge (cfs) and weir length (ft), it becomes possible to estimate DO for various discharges using Equation 1. Most of our attention in this study has been focused on the main stem of the Pawcatuck River commencing at the first dam above the mouth at Potter Hill. Time limits and logistic difficulties prevented additional dam studies.

A reasonable approximation to the velocity of flow is obtained by solving the following expression:

$$VO = Q/LDO \qquad (2)$$

Where:
VO equals velocity in (ft per second) and Q, L and DO are as defined previously.

Water flowing over a low dam passes through a point of minimum specific energy. At this point a depth known as critical depth DC occurs. This parameter is estimated from the following:

$$DC = \text{cube root of } (QQ/g) \qquad (3)$$

Where:
Q = flow in ft per second per foot width
g = acceleration to gravity (32.2 ft per second squared)

The velocity at critical depth (VC) can be calculated as in Equation 2:

$$VC = Q/LDC \qquad (4)$$

The velocity at the plunge pool (VF) can be determined from:

$$VF = \text{square root of } (2gHD) \qquad (5)$$

The tail water velocity is given by:

$$VT = Q/WTDT \qquad (6)$$

Where:
VT = tail water velocity (ft per sec)
WT = stream or channel width (ft)
DT = depth of tail water in stream or channel (ft)

Biological Considerations

It has been established for West Coast salmonids that burst speeds for a few seconds range from about 8 to 12 body lengths per second (Bell, 1973). Maximum burst speeds are expected to be utilized in attempting passage over low head dams such as are found in our watershed. It is evident that maximum burst speeds of salmonid fishes vary greatly among species as is shown in Table 1. Even within species, it has been shown that wild fish swam about 30% faster than similar sized hatchery fish (Bainbridge, 1960). It is generally recognized that there are variations in swimming ability within a species, and that there are many factors, including size of adult fish and physical factors which affect jumping ability. However, it seems prudent to establish reasonable limits and to also provide preliminary information related to fish passage procedures. Table 1 in Reiser and Peacock (1997) reports on original data from other authors and also summarizes available information regarding the swimming ability of adult salmonid fishes. We repeat some parts of this table and contribute additional values related to brook trout in our Table 1. It is evident that, of the species considered, only the Atlantic salmon has the ability to successfully leap over dams listed in Table 2, and this is possible only under specific conditions which will be indicated later.

An attempt has been made to obtain reasonable estimates of the heights of dams encountered in the Wood-Pawcatuck watershed area. The primary dam type encountered in our study can be defined as an L shaped weir. The hydraulic properties of this type of dam can be estimated from the equations which have been described previously. Some results from this study are presented in Table 2. This table includes some basic information on these dams which has been provided by the Rhode Island Department of Environmental Management.

Table 1.
Swimming Speeds of Selected Salmonid Species of Fishes

Author and Species	Prolonged Speed (ft/sec)	Sustained Speed (ft/sec)	Burst Speed (ft/sec)	Maximum Jump Height (ft)
Bell (1986) Atlantic Salmon	0-4.2	4.2-12.7	12.7-26.5	10.9
Bell(1986) Brown trout	0-2.2	4.6-13.7	6.2-13.7	2.5
Bell (1986) Rainbow t.	0-2.0	2.6-6.4	6.4-13.5	2.8
Bell (1986) Brook t. (3-5 inches)	0-2.0	---	---	
Peake et al (1997) Brook t. (10 inches)	---	2.8-3.2	5.12	
This Study Brook t. (6 inches)	---	1.9-2.1	5.02	

Table 2.
Selected Properties of Dams Located in the Wood-Pawcatuck Watershed

Dam	Length (ft)	Estimated Height (ft)	Max Discharge (cu ft/sec)	Storage acre ft
Potter Hill	112	10	5457	240
Bradford Pond	200	10	---	---
Shannock Mill	148	8	1265	17
Horseshoe Falls	121	9	1067	207
Kenyon Mill	358	8	300	36

Culverts in Low Order Streams

General

Although the major objectives of this study involved small dams and water quality at lower order streams in the Wood-Pawcatuck watershed, several culverts were found at streams visited by our investigators. It was evident from a preliminary examination that some of these culverts are or could become unsuitable for migration by certain indigenous fishes. Included in these is the brook trout (Salvelinus fontinalis) during its spawning migration, which usually occurs under low flow conditions. Improper design and installation of culverts can be an important factor in impeding unrestricted movement during migration periods for this species and possibly others. It should be recognized that the brook trout does not attempt to leap over obstacles in contrast to the Atlantic salmon which has remarkable leaping abilities. In addition, the brook trout appears to be the weakest swimmer among other salmonid fishes which have been tested for swimming ability (Peake et al, 1997).

The following brief discussion of culverts in relation to small streams in our watershed area is very limited in scope and detail since it was not specifically included in the project proposal. However, the importance of culverts was clearly recognized during the execution of this project. Excellent reviews of culverts, design criteria and effectiveness for various species of fishes are currently available. Some examples of such documents include the following: Behlke (1991), Behlke et al (1991), Behlke et al (1993), Chestnut (2002) and Webb (1973).

Brook Trout Swimming Performance

Some review and analysis of swimming performance data is considered necessary in order to provide a criterion based on empirical data for the design of suitable fish passage facilities. These facilities include fishways as well as culverts. Properly designed and installed culverts and fishways need to be based on important biological factors, preferably with respect to the weakest swimmers of the species expected to migrate. In this instance we suggest that the brook trout is the appropriate target species for our watershed. Migrating brook trout held back by obstructions may fail to reproduce successfully due to their inability to find suitable substrate sizes as well as other conditions required for natural spawning. Any effort to implement a successful fish passage facility should be based on the best available information. The objectives of this portion of our study include searching for and analyzing available literature, studying the local conditions, and providing basic information on swimming speeds. Special attention is given to the brook trout, which is still found in local low order streams.

The swimming behavior of fish can be divided into three broad categories which include sustained, prolonged, and burst speeds. Sustained swimming occurs at relatively slow speeds and utilizes red muscle fibers which are fuelled by energy derived from aerobic metabolism (Beamish, 1978). This permits swimming for long periods of time (200 minutes or more) without fatigue. Sustained swimming occurs at a speed of about 2-4 body lengths per second. Burst swimming involves white muscle fibers which utilize energy from anaerobic processes in order to obtain high speeds for short periods up to about 10 to 15 seconds. Burst speeds involve movement at about 8-12 body lengths per second. Prolonged swimming involves a spectrum of velocities between burst and sustained. This involves both red (aerobic) and white (anaerobic) muscle tissues.

Peake et al (1997) provide a relatively recent evaluation of swimming performance of some salmonid fishes, including the brook trout. We have utilized the published information related to the brook trout from these studies for this section of the report. The model for estimating the swimming and or holding speed (S; meters per second) that a brook trout of a given fork length (C; Centimeters), at a given temperature (Y; degrees Centigrade) can maintain for any prescribed period of time (Z) expressed in log transformed minutes. This equation is described as follows:

$$S = ao + a1X + a2Y + a3Z \qquad (1)$$

Equation (1) is a multiple linear regression equation where ao is the model intercept and a1, a2, and a3 are regression coefficients derived from a least squares analysis of observed experimental data. The derived regression coefficients in the brook trout equation apply to a fork length range of (7.1-40.5 cm) and a temperature range of (12.7-20 degrees centigrade) and a variable time period expressed in seconds.

In this section we illustrate an application of the above regression equation to a culvert designed to pass all brook trout (6 in. or approximately 15 cm in fork length) at an estimated water temperature of 13 degrees centigrade (55 degrees Fahrenheit) for a period of 15 seconds as follows:

$$S\ (\text{m/sec}) = -0.039 + 0.051X + 0.0153Y - 0.135Z = 0.922\ \text{m/sec}\ \text{ or } 3.02\ \text{ft/sec}$$

The parameters for this regression are from Peake et al (1997) Table 1- brook trout prolonged and burst speed. From this analysis it is suggested that a brook trout of 6 in. in fork length at a temperature 55 degrees Fahrenheit could maintain its position at a culvert water velocity of 3.02 ft/sec but would be unable to negotiate the culvert at this or any higher velocity. However, if the flow in the culvert was 2 ft per second for example, then the trout could move about (3.023 -2 times 15 seconds) or about 15 m (approximately 50 ft.) in the culvert before becoming fatigued. For those interested in further details, the reader is referred to Peake et al (1997). Obviously, it is possible to utilize the above equation with other input variables to account for size changes, temperature changes and/or time changes as well as sustained travel speeds

Tentative Suggestions and Comments:

Detailed design procedures for culverts are available in the publications cited previously. However, some preliminary suggestions are provided herein to provide guidance for an initial assessment of culverts in our area.

1) Determine the swimming capabilities of the design fish.
2) Determine or define swimming behavior when in the culvert.
3) Design culverts to pass fish without overextending swimming capabilities of the design species.
4) Field studies conducted elsewhere have demonstrated the value of relatively large culvert corrugations (Behlke et. al, 1991). In general, studies to date suggest that culvert corrugations should be a least a five centimeters (2 in.) in amplitude to provide optimum passage conditions.
5) Perching is thought to be an important consideration in the design and analysis of culverts in our watershed area. Perching refers to the tendency to create a falls or cascade at a culvert outfall. Although proper design and installation of culverts should avoid this kind of fault, it is also possible to correct it after installation. It is suggested that one of the more effective ways to eliminate perching is to build small rock dams below the outfall in order to raise the outfall basin water level to a value which eliminates the fall or cascade. Another possible approach is to build an apron which is negotiable by the species of concern.
6) It is also possible to reduce culvert barrel velocity by placing rocks or other velocity reducing devices into the culvert. Obviously, reduction of the grade of the culvert is helpful if this can be accomplished with reasonable effort.

In summary, it is strongly recommended that WPWA and cooperating agencies develop a project which involves a comprehensive inventory and assessment of culverts in our watershed area with a view toward minimizing the delays to successful migration by the species of concern. This project should include precise culvert locations, culvert type, culvert length, velocity of flow, wetted perimeter at outfall, and culvert slope as well as indications of its effectiveness.

Beaver River Temperature studies

Summer water temperatures are a very important consideration for salmonid fishes in of our watershed area. For example, there is substantial evidence to indicate that physiological effects of high water temperatures adversely affect fish locomotion. Therefore, it seems prudent to consider the effects of dam impoundments on downstream water temperatures as well as the effects of stream canopy and stream width and depth on temperature changes over time or space.

The recent availability of low-cost data loggers (I buttons) for water temperature measurement over time has permitted us to plan and execute a study to examine changes in maximum summer stream water temperatures as a function of distance from the head water source. The specific null hypothesis to be tested is that there are no significant differences in maximum daily water temperatures as a function of distance from the source located near the origin of the stream. This particular study represents only a small portion of the interesting results which were obtained by examination of simultaneous time series of data from several stations located in a flowing stream.

The Beaver River is one of the more important streams in our watershed area. It is a location for intensive fishing effort and it contains an indigenous native brook trout population. Our interest was an estimating temperature effects of a small dam as well as recovery to normal conditions or changing water temperature as related to distance from the source location. Seven sites were selected for this study. They include the following stations in the Beaver River, all located in the Town of Richmond:

B4	Above New London Tpk./Dawley Road (below small dam)
B6	Above Old Mountain Road
B8	Above Hillsdale Road
B10	Above pool on Decoppet Estate, east of Hillsdale Road
B13	Below Rt. 138 bridge
B14	Below School House Road
B15	Below Shannock Hill Road

Note that the first station was located just below a small dam, approximately four ft. high, and the rest of the above stations were located in relatively free flowing water conditions.

Table 3 summarizes the results obtained from analysis of the data from maximum water temperatures during each day for the period of July 28th through August 6th. It has been found from prior temperature studies that this period includes virtually all maximum summer water temperatures encountered. The 70 data points resulting from seven stations with maximum temperatures for 10 days are shown in the upper part of Table 3. A one-way analysis of variance (AOV) using these data was conducted. The results of the one-way AOV shown in Table 3 clearly indicate significant differences among the seven stations. A test for homogeneity of variance (middle of Table 3) indicated that there was homogeneity among the sample variances. This is an important assumption to test when applying the AOV procedure. Finally, the bottom part Table 3 shows the results of an all pairwise comparisons test. These results, indicating 3 separate groups, are the most interesting part of the total analysis conducted with the data.

In summary, from this analysis it is evident the null hypothesis was rejected and that there were significant differences among stations. Bartlett's test confirms the legitimacy of this statement by demonstrating that a major AOV assumption was satisfied. Finally the Tukey all pairwise comparison test indicated three groups for the seven variables. Firstly, the source station near the origin had the highest summer temperature. Secondly, the next three stations (B6, B8 and B10,) were similar and with lower temperatures than at the source. This indicates a non significant decline within the three stations. Thirdly, some temperature increases were indicated among stations B13, B14 and B15. From this analysis it is evident that the small dam near the source increased the original water temperature by about 4-5 degrees C. A distance of about 5 mi. was required in this instance to bring the water temperature to an estimated value of about 17 degrees centigrade. Only in the 6th and 7th miles (1 to 2 mi. downstream from the lowest observed temperature) was it possible to detect temperature increases. This example clearly demonstrates the effects of small dams on temperature and on the distance to recovery under these observed conditions.

Figure 1 illustrates a scatter plot of the average maximum water temperature (Y axis) versus the distance from the source station (B4). It is evident that the recovery of the stream to its expected temperature occurred at a distance of about 5 miles. Note also the increase in temperature with increasing distance from the source occurred after about five miles.

A second related study of dam effects was conducted between two stations-namely B2 and B3, also on the Beaver River. Figure 2 illustrates the late spring to late summer maximum water temperatures for five stations. Our major interest lies in a comparison of the results for station B2 located at the Decoppet Estate and B3, the bypass station in the stream passing around the impoundment. Visual inspection of the two station data suggests that the B2 station at the dam had the highest maximum temperature and the bypass stream (B3) had a lower temperature over the entire study period. Since these data are suggestive of a dam effect, it was decided to do a somewhat more critical statistical examination of a portion of the data. Specifically, the temperature maxima for 10 days (July 28th-August 6th) at these two stations were subjected to a formal statistical analysis. The data and the results obtained are illustrated in Table 4. The results of the one way AOV in this case were not significant at the 0.05 alpha level. Bartlett's test rejected the assumption of equality of variances. Therefore this test was followed by a paired t test, shown at the bottom of Table 4. It is evident from this analysis that the null hypothesis of no differences in maximum daily temperature between the two stations was rejected and significant differences in daily temperature maximum were obtained. This material further confirms the fact that low dams and small impoundments have a measurable effect by increasing summer temperatures of the impounded water. It is also clear from this study that the effect of a dam under some conditions may adversely affect the stream for a considerable distance. These data suggest that when possible dam removal is the most successful way to permit unrestricted passage as well as maintaining water temperatures at lower values than those found in the impoundments.

Overall Conclusions

From our preliminary examination of dam properties in a portion of our watershed area, it seems possible to make some initial observations and suggestions. This analysis suggests that the presence of dams in the study area of this report may not be a complete barrier to the return of some migrating adult Atlantic salmon under specified conditions. This statement is made based on the assumption that a pool depth of 8 ft. is or could be made available at the base of each of these dams and that other conditions such as flow, aeration, and temperature are adequate. It is also evident that the existing dam heights preclude successful upstream passage by both brown and rainbow trout as well as brook trout.

We contend that fish passage facilities to be constructed in this watershed should be designed to facilitate passage of the weakest swimmer among the species of interest. In this case, it is suggested that the brook trout is a reasonable candidate for this purpose. Usually this facilitates passage of stronger swimming species. However, it is recognized that some of the stronger swimmers may also have other specific requirements. A careful and extensive study of culverts and other obstructions to free passage should be made in order to aid in successful fish restoration and other management related activities. An ecologically significant temperature rise occurs in impoundments created by small dams in our watershed area. An example of this is the increase in some predator species resulting from warmer water conditions. This problem merits further study in order to permit adequate stream restoration for some migrating fish species.

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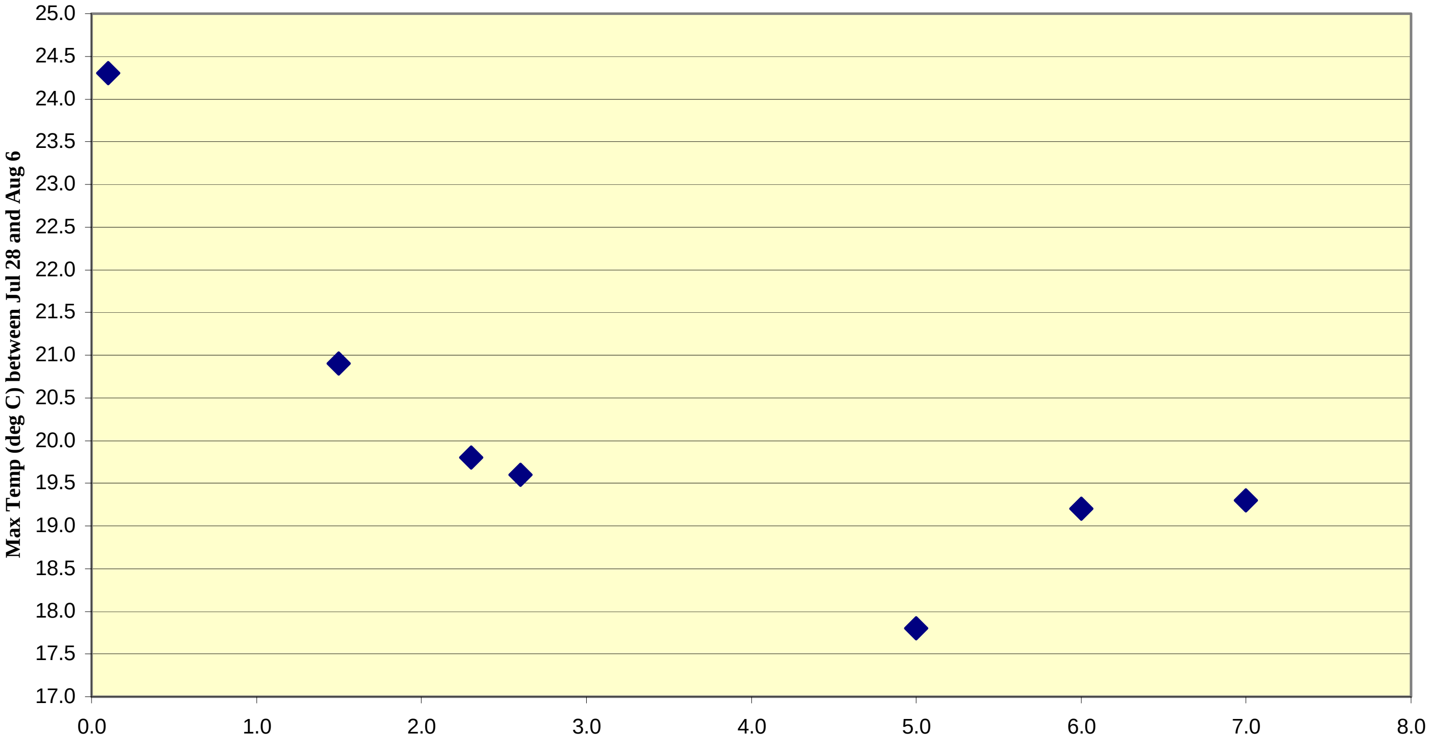
Figure 1.
Beaver River Summer Maxima 2004



Distance (miles from source area)
The stations are: B4, B8, B10, B13, B14, B15 from left to right

Figure 2
Beaver River, Impoundment on Decoppet Estate

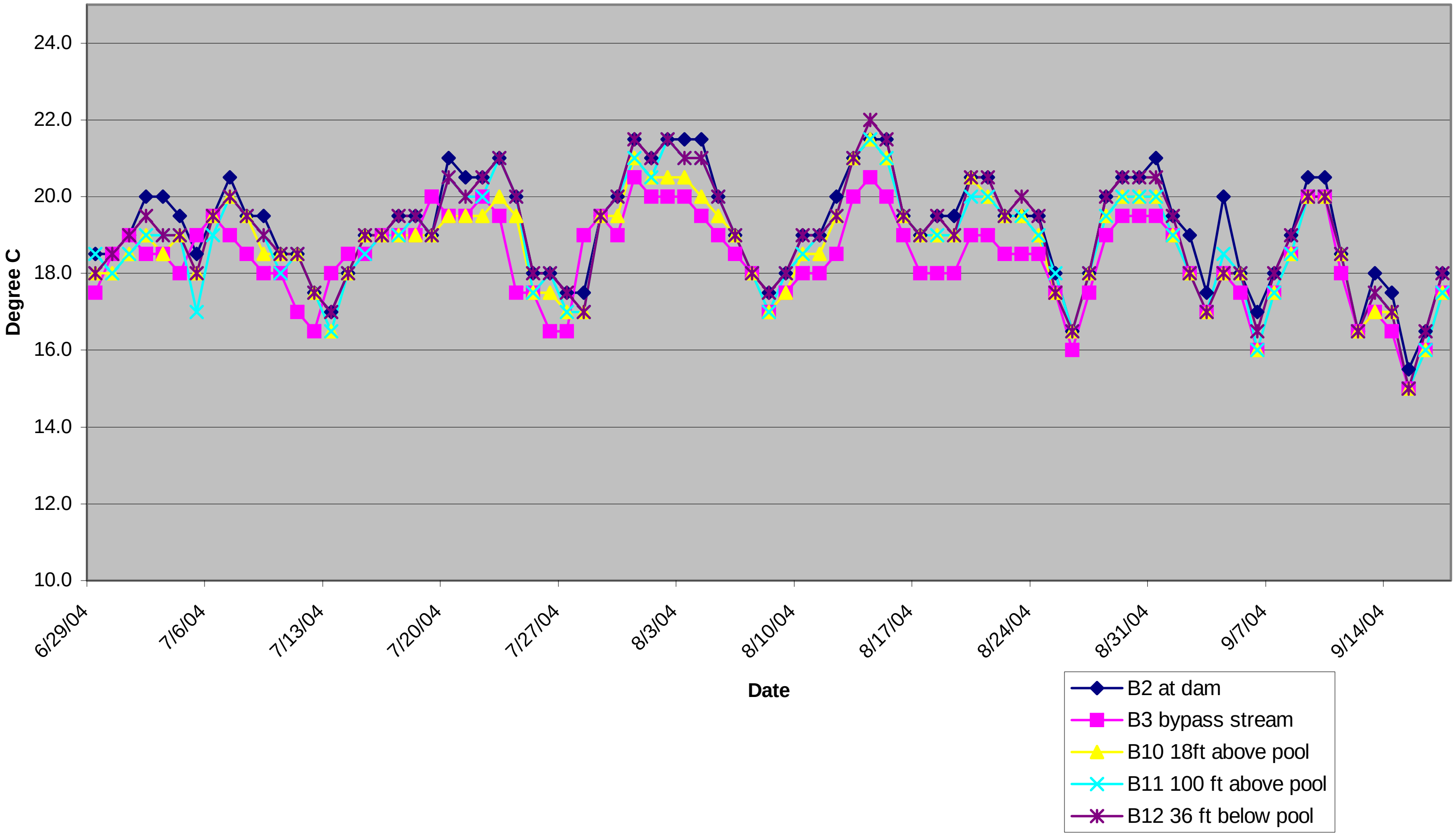


Table 3
Beaver River Summer Maximum Temperatures 2004 by Station

CASE		B4	B6	B8	B10	B13	B14	B15
1	22.5	17.5	17	17	15	15.5	16.5	
2	22.5	21.5	19.5	19.5	17.5	19	19	
3	23	21.5	20	19.5	18	19.5	19.5	
4	24.5	21.5	21	21	19	21	20.5	
5	25	21	20.5	20.5	18.5	19.5	20	
6	25.5	22.5	21	20.5	18.5	21	20	
7	25	22	20.5	20.5	18	19.5	20	
8	26	21.5	20	20	18	20.5	19.5	
9	26.5	20	19.5	19.5	17.5	18	19	
10	22.5	20	19	19	17	17.5	18.5	

Each case (1-10) refers to daily maximum stream temperatures at seven locations commencing on July 28 and ending on Aug. 6. This time period includes all previous records from our data collections. Stations are listed at increasing distances from left to right from the source area.

One-Way AOV for: 84 B6 B8 B10 B13 B14 B15

Source	**DF**	**SS**	**MS**	**F**	**P**
Between	6	260.121	43.3536	24.1	0.0000
Within	63	113.325	1.7988		
Total	69	373.446			
Grand Mean	20.107	CV 6.67			

	Chi-Sq	*DF*	*P*
Bartlett's Test of Equal Variances	3.34	6	0.7647

Cochran's Q 0.2330

Largest Var / Smallest Var 2.3784

Component of variance for between groups 4.15548

Effective cell size 10.0

Variable	**Mean**
B4	24.300
B6	20.900
B8	19.800
B10	19.700
B13	17.700
B14	19.100
B15	19.250

Observations per Mean 10

Standard Error of a Mean 0.4241

Std Error (Diff of 2 Means) 0.5998

Tukey HSD All-Pairwise Comparisons Test

Variable	**Mean**	**Homogeneous Groups**
B4	24.300	A
B6	20.900	B
B8	19.800	B
B10	19.700	B
B15	19.250	BC
B14	19.100	BC
B13	17.700	C

Alpha 0.05 Standard Error for Comparison 0.5998

Critical Q Value 4.307 Critical Value for Comparison 1.8266

There are 3 groups (A, B, etc.) in which the means are not significantly different from one another.

Table 4.
Beaver River Impoundment and Bypass Comparison, Decoppet Estate

CASE	B2	B3
1.	17.5	19.0
2.	19.5	19.5
3.	20.0	19 .0
4.	21.5	20.5
5.	21.0	20.0
6.	21.5	20.0
7.	21.5	20.0
8.	21.5	19.5
9.	21.5	19.5
10.	19.0	18.5

One-Way AOV for: B2 B3

Source	DF	SS	MS	F	P
Between	1	4.0500	4.05000	3.48	0.0785
Within	18	20,9500	1.16389		
Total	19	25.0000			

Grand Mean 20.000 CV 5.39

	Chi-Sq	DF	P
Bartlett's Test of Equal Variances	5.56	1	0.0184

Cochran's Q	0.8461
Largest Var / Smallest Var	5.4961
Component of variance for between groups	0.28861
Effective cell size	10.0

Variable	*Mean*
B2	20.450
B3	19.550

Observations per Mean	10
Standard Error of a Mean	0.3412
Std Error (Diff of 2 Means)	0.4825

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Paired T Test for B2 -B3

Null Hypothesis:	difference = 0
Alternative Hyp:	difference <> 0
Mean	0.9000
Std Error	0.3317
Mean -HO	0.9000
Lower 95% CI	0.1497
Upper 95% CI	1.6503
T	2.71
DF	9
P	0.0239

Cases Included 10   Missing Cases 0