Mitigating Thermal Stress in the Upper Delaware:
Toward a Lordville Thermal Relief Program

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Our Purpose Today

- To persuade the Decree Parties that a simple program of pulsed water releases from the NYC dams on the Delaware's headwaters can mitigate the most severe thermal stress to trout in the upper Main Stem -- without impacting water availability to any of the River's stakeholders.
- The concepts proposed today provide a foundation for a simple thermal relief program, are entirely compatible with the FFMP/OST framework, and can be implemented in the next release rules revision.

Part I. Introduction and Background

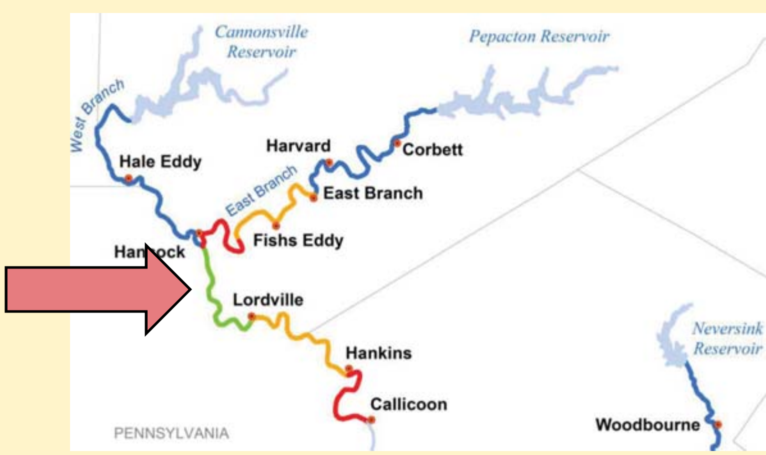
The Thermal Stress Issue

- During most summers there are days when water temperatures in the upper Main Stem of the Delaware rise above generally accepted levels for trout.
  - In recent years attempts have been made to alleviate thermal stress by pulsed releases from the NYC dams on the headwaters. These efforts and releases have been without a defined protocol or clear guidelines.
  - Prior to the FFMP, explicit thermal relief banks were employed at the discretion of the NYS-DEC, but they were not seen as effective by the fishing community.
- **OUR RESEARCH GOAL:** To design a science-based protocol for thermal relief releases that will:
  - be effective against severe thermal stress
  - use water efficiently
  - not increase water availability risk to the Delaware's other stakeholders.

Research Findings

- Using historical data, we have statistically estimated the magnitude of the thermal stress problem in the upper Main Stem, and the amount of cold water needed to mitigate the stress events.
- Our research shows that, in most summers, the most of the severe thermal stress problems at Lordville can be mitigated by pulsed releases of cold water -- within the current FFMP/OST water availability constraints.
- Thermal stress events can be anticipated and predicted by monitoring the water temperatures reported on USGS gage sites, and air temperature and other meteorological forecasts made by the National Weather Service.

Our Target: The Upper Main Stem from Hancock to Lordville



Source: Joint Fisheries White Paper, January 2010

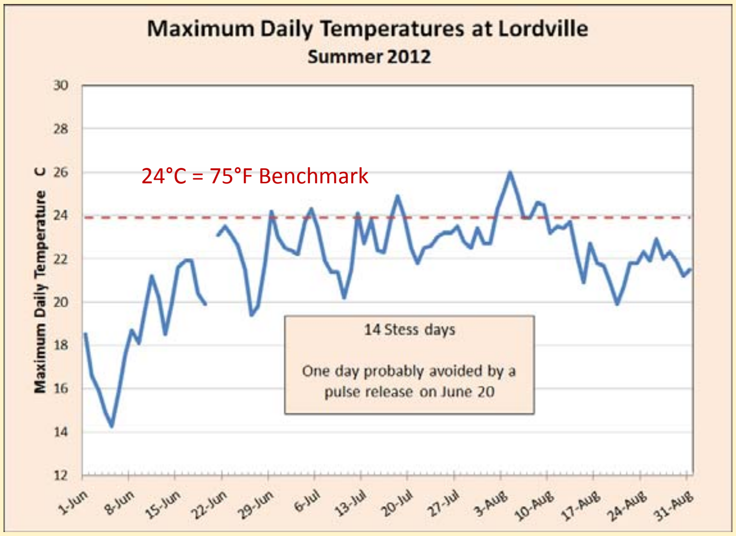
Working definition of (severe) thermal stress

- There is a large body of scientific literature on the impact of high water temperatures on trout, supporting a number of definitions of thermal stress . We adopt here the definition that trout are in 'severe thermal stress' whenever the daily maximum water temperature exceeds 75°F, that is, 23.9 C°.
- Use of this simple and conservative definition on the Delaware is supported by ample precedent:
  - DRBC Docket D77-20 CP (Revision 7), April 2004, Paragraph 4 - B
  - J. Douglas Sheppard, New York Reservoir Releases Monitoring and Evaluation Summary Report Sheppard Report, Technical Report 83-5, NYS-DEC, 1983
  - Mark Hartle, Preliminary Report on Trout Habitat -Water Temperature Relationships in the Upper Delaware Basin, PF&BC , SEF report the RFAC of the DRBC , August, 2010
  - John Pizzimenti, Lackawaxen River Thermal Decision Support System, Progress Report 2011

Some Definitions and Key Data

- ***Thermal Stress Day:*** A day when the maximum daily river temperature exceeds 23.9 °C (75°F).
- ***Thermal Degree Day:*** The daily amount by which the river maximum temperature exceeds the stress benchmark of 23.9 °C (75°F). When cumulated, this is a measure of the amount of thermal relief needed.
- ***Thermal Cooling Day:*** The daily amount by which the river maximum temperature, when in stress, exceeds 23.4 °C (74°F). This is a more aggressive measure the amount of relief needed.
- ***Mitigation Period:*** June 1 to August 31
- ***Target Location:*** Lordville on the Upper Main Stem (USGS Gage 1427207)
- ***Data Used:*** USGS Gage records at key locations, River Master Weekly Reports, NYC-DEP data on reservoir operations, NWS historical weather data and forecasts at relevant stations. Note:
  - Lordville summer temperatures are only available from 1993 to 1995 and 2007 to 2012.

The Problem is real : Thermal stress at Lordville in 2012

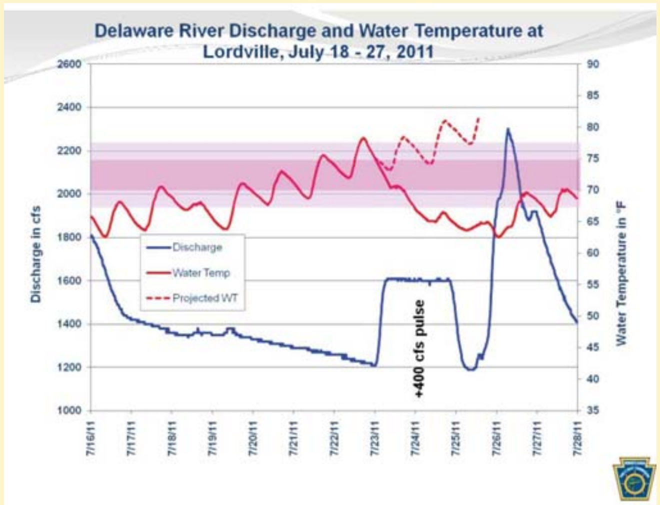


Date	Lordville Tmax	Stress Day?	Degree Days	Cooling Days
1-Jun	18.5	0	0	0
…	…	…	…	…
29-Jun	24.2	1	0.3	0.8
…	…	…	…	…
5-Jul	24.3	1	0.4	0.9
…	…	…	…	…
12-Jul	24.1	1	0.2	0.7
…	…	…	…	…
17-Jul	23.9	1	0	0.5
18-Jul	24.9	1	1	1.5
19-Jul	24.0	1	0.1	0.6
…	…	…	…	…
1-Aug	22.7	0	0	0
2-Aug	24.3	1	0.4	0.9
3-Aug	25.1	1	1.2	1.7
4-Aug	26.0	1	2.1	2.6
5-Aug	25.0	1	1.1	1.6
6-Aug	23.9	1	0	0.5
7-Aug	23.9	1	0	0.5
8-Aug	24.6	1	0.7	1.2
9-Aug	24.5	1	0.6	1.1
…	…	…	…	…
31-Aug	21.5	0	0	0
Total Summer 2012		14	8.1	15.1

Illustrating Our Stress Metrics
Summer 2012

- There were 14 stress days distributed across 5 stress events.
- There were a total of 8.1 degrees days and 15.1 cooling days.
- The worst day was August 4 when the temperature was 26.0°C, booking in 2.1 degree days and 2.6 cooling days
- The longest stress event lasted 8 days.

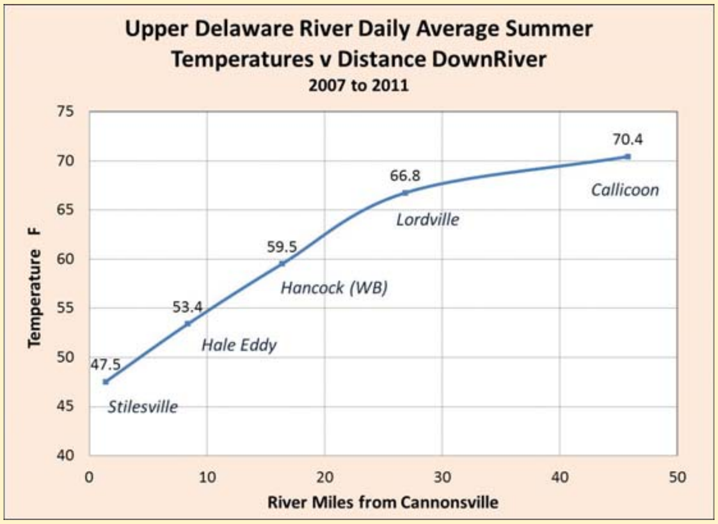
The Motivating Example of a Pulse Solution: The July 2011 stress event with a mitigating pulse



Courtesy Mark Hartle, PF&BC

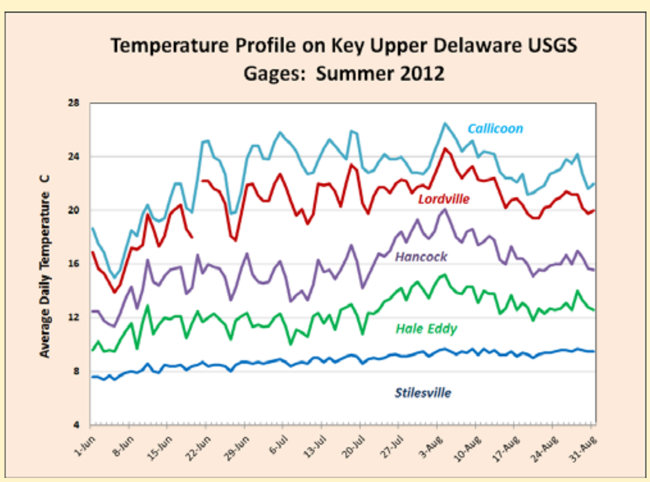
Understanding the Hydro-thermodynamics of the Upper Delaware

Upper Delaware Thermodynamics:
Downriver Warming



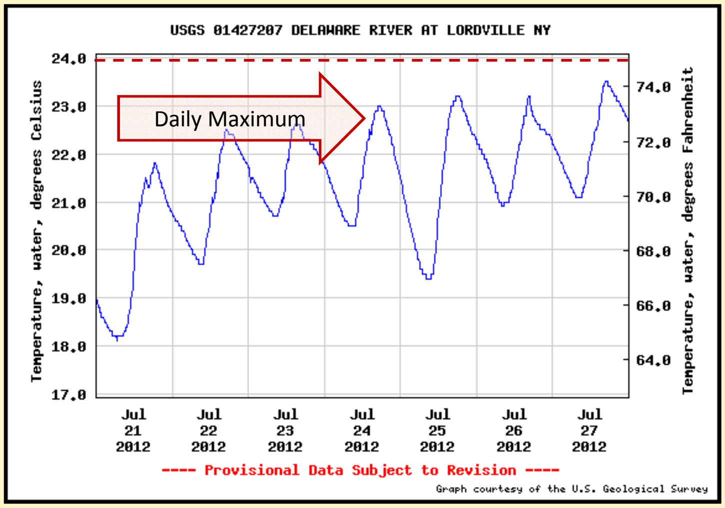
Upper Delaware Thermodynamics:
Variation Over the Summer

Cold water from the Cannonsville and Pepacton warms as it flows down river. Warmer water joins the flow from tributaries such as the Beaverkill, Oquaga Creek , etc. . The result over the summer is:



Upper Delaware Thermodynamics:

Diurnal Fluctuations at Lordville



Thermal Stress Mitigation Efforts in 2012

- **Stress conditions were predicted for June 20 , June 29, July 5 and August 3.**
  - The June 20 pulse of about 311 cfs-days appears to have been effective in avoiding a stress situation – as compared to the rising temperatures over the same period at Fishs Eddy.
  - The June 29 and July 5 mitigation requests were not acted on. In each case the system went into stress on that day.
  - A serious stress condition was forecasted on August 3, which then developed and persisted between August 1 and August 7. We estimate that this 8-day event could well have been mitigated by a multi-day pulse of about 1200 total cfs-days. On August 1 reservoir storage stood at 82 % capacity, well inside the normal (L2) level.
  - Four of the five actual stress events of the summer of 2012 were anticipated! One was missed due to forecasted precipitation not occurring .

- **Background Conditions in 2012**: During the entire summer reservoir storage was well within the normal (L2) range. Releases generally followed the FFMP/OST & Rivermaster guidelines. Stress conditions at Lordville were concomitant with a hotter than average summer -- July highs were about 6°F above normal.

The Pulse Release Concept, History and Our Research Goal

- Provision for thermal relief releases was explicitly part of Rev 7 (¶ 4-A,B).
- Since the 2007 implementation of the FFMP, according to the River Master, there were 4 distinct thermal stress releases.
- The 800 cfs-days pulse made in July of 2010 appears to have worked -- partially.
- The 311 cfs-days pulse made on June 20 appears to have worked.
- The requested pulses on June 29, July 5 and August 1 were denied, and stress events occurred – the most serious being the 8 day-long event that began on August 1 .
- ***Question:*** *Can an algorithm be designed to determine when and how much water to pulse to mitigate thermal stress at Lordville?*

Our Research Plan

1. Quantify the magnitude of the thermal stress problem at Lordville
2. Estimate the statistical impact of Cannonsville and/or Pepacton releases on Lordville temperatures; then estimate how much water is needed to ameliorate a thermal stress event.
3. Develop a <u>predictive</u> statistical model of thermal stress events at Lordville.
4. Develop and test an explicit stress relief protocol, algorithm, decision support system that can be integrated into the FFMP/OST program.

Part II. The Magnitude of the Thermal Stress Problem at Lordville

How bad has the temperature problem been at Lordville?

- **Multiple Metrics:**
  - How many thermal stress days, degree days, cooling days are there in a month, a summer, or a season?
  - How many thermal stress episodes (periods of consecutive days of stress) are there?
  - How long do such stress episodes last?
  - When in stress, how high do the temperatures get above the benchmark?
  - When are stress events most likely to occur: May, June, July, August, September?

Statistics of Thermal Stress Days at Lordville:
An Overview of 9 Seasons

	May				June				July			
	Days	Stress Day	Degree Days	Cooling Days	Days	Stress Days	Degree Days	Cooling Days	Days	Stress Days	Degree Days	Cooling Days
1993	31				30	1	0.9	1.4	31	6	4	7
1994	31				30	5	5	7.5	31	12	9.2	15.2
1995	31				30	8	5.3	9.3	31	12	12.7	18.7
2007	31	1	0.1	0.6	29	1	1.1	1.6	31	5	3	5.5
2008	31				30	8	9.6	13.6	31	9	9.6	14.1
2009	31				30				31			
2010	31	4	4.6	6.6	30	2	0.3	1.3	31	15	18.3	25.8
2011	31				30				[illegible]	3	2.2	3.7
2012	31				29	1	0.3	0.8	[illegible]	5	1.7	4.2
Total	279	5	4.7	7.2	268	26	22.5	35.5	279	67	60.7	94.2
Average	31.0	2.5	2.4	3.6	29.8	3.7	3.2	[illegible]	31.0	8.4	7.6	11.8
Percent		1.8%				9.7%				24.0%		

	August				September				Annual			
	Days	Stress Days	Degree Days	Cooling Days	Days	Stress Days	Degree Days	Cooling Days	Days	Stress Days	Degree Days	Cooling Days
1993	31				30				153	7	4.9	8.4
1994	31				30				153	17	14.2	22.7
1995	31	3	1.3	2.8	30				153	23	19.3	30.8
2007	31	3	0.8	2.3	30				152	10	5	10
2008	31	1	0.1	0.6	30				153	18	19.3	28.3
2009	31				30				153	0	0.0	0.0
2010	31	1	0	0.5	30	2	0.7	1.7	153	24	23.9	35.9
2011	31				28				151	3	2.2	3.7
2012	31	8	6.1	10.1					122	14	8.1	15.1
Total	279	16	8.3	16.3	238	2	0.7	1.7	1343	116	96.9	154.9
Average	31.0	3.2	1.7	3.3	29.8	2.0	0.7	1.7	149.2	12.9	10.8	17.2
Percent		5.7%				0.8%				8.6%		

For each month of each year we record the number of days with data, the number of stress days, the total degree days, and the total cooling days.

During summers (June July August) there were 109 stress days , 91.5 degree days and 146 cooling days out of the 826 days in the record. Lordville was in stress 13% of the time -- about 12 days per summer. July is the toughest month with about 7.6 days on average (24%) .

Summary of Summer Stress at Lordville

Lordville Thermal Stress: 9 Summers Between 1993 and 2012

	Days	Stress Days	Degree Days	Cooling Days
1993	92	7	4.9	8.4
1994	92	17	14.2	22.7
1995	92	23	19.3	30.8
2007	91	9	4.9	9.4
2008	92	18	19.3	28.3
2009	92	0	0.0	0.0
2010	92	18	18.6	27.6
2011	92	3	2.2	3.7
2012	91	14	8.1	15.1
Total	826	109	91.5	146
Average		12.1	10.2	16.2
Percent		13.2%		

Worst Summer

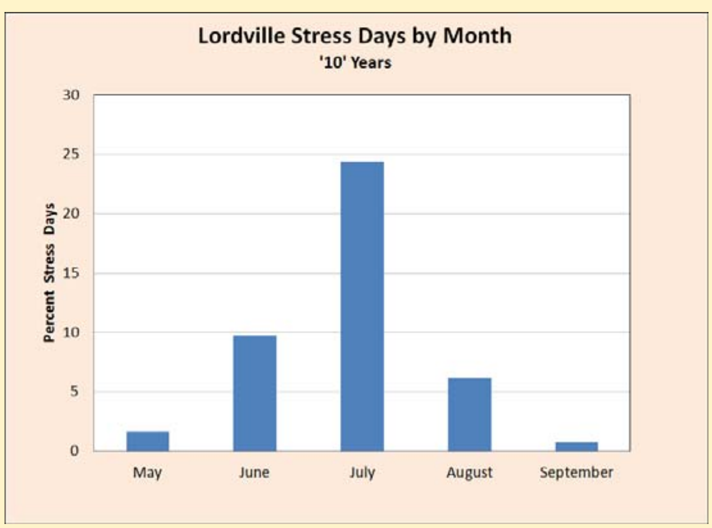
Average Summer

Stress Events: Sequences of Successive Stress Days

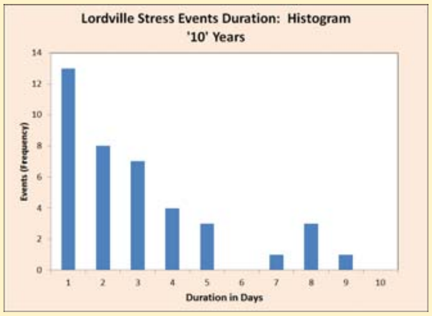
Stress Incident	Start Date	Duration (Days)	Sum of Tmax	Max Tmax	Degree Days	Tmax on First Day
1	6/14/93	1	24.8	24.8	0.9	24.8
2	7/7/93	4	99.1	25.5	3.5	24.3
3	7/13/93	2	48.3	24.3	0.5	24.3
4	6/16/94	5	124.5	26.0	5.0	24.0
5	7/4/94	1	24.0	24.0	0.1	24.0
6	7/6/94	9	223.0	26.0	7.9	24.5
7	7/20/94	1	24.0	24.0	0.1	24.0
8	7/22/94	1	25.0	25.0	1.1	25.0
9	6/3/95	2	48.0	24.0	0.2	24.0
10	6/6/95	3	72.5	24.5	0.8	24.0
...	...	...	...	...	...	...
24	7/2/08	1	24.5	24.5	0.6	24.5
25	7/7/08	4	99.7	25.7	4.1	24.9
26	7/15/08	4	100.5	26.1	4.9	24.1
27	8/6/08	1	24.0	24.0	0.1	24.0
28	5/26/10	3	75.3	25.6	3.6	25.6
29	5/31/10	2	48.8	24.9	1.0	24.9
30	6/5/10	2	48.2	24.2	0.4	24.2
31	7/5/10	8	203.5	27.1	12.3	25.5
32	7/15/10	4	99.0	25.6	3.4	24.8
33	7/27/10	3	74.3	25.5	2.6	24.2
34	8/31/10	3	72.4	24.5	0.7	23.9
35	7/21/11	3	73.9	25.7	2.2	24.2
36	6/29/12	1	24.2	24.2	0.3	24.2
37	7/5/12	1	24.3	24.3	0.4	24.3
38	7/12/12	1	24.1	24.1	0.2	24.1
39	7/17/12	2	48.8	24.9	1.0	23.9
40	8/2/12	8	197.3	26.0	6.1	24.3

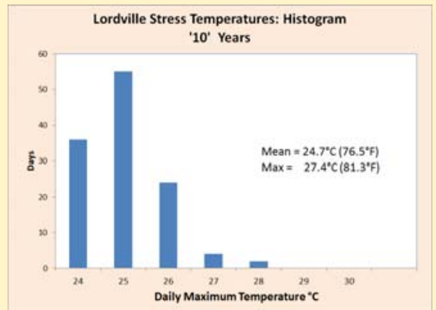
- **The 109 stress days cluster into 40 stress 'events'.**
- **Average event duration was 2.5 days, and the maximum was 9 days.**
- **Average maximum temperature when in stress was 25.0°C (77°F).**
- **The maximum maximum temperature was 27.4° C (81°F).**

Thermal stress frequency is very low in May and September; It peaks in July



Most stress events are short (1 day) but there are some quite long ones.





Most stress days were of 'moderate' intensity -- less than 1°C above the benchmark, but some were more intense.

Summary Findings on Thermal Stress at Lordville

- There were about 12 stress days in an average summer; one summer (1992) had none; the worst summer (1995) had 23. Recent Years: The summer of 2010 had 18 stress days, 2011 had 3 and 2012 had 14.
- Stress days cluster in July --24% of July days, compared to the summer-wide average of 13.2%. There are few stress days in May (2%) or September (1%).
- The average maximum temperature when in stress was 24.7°C (76.4°F) the highest maximum temperature was 27.4 °C (81.3°F).
- The average summer had about 10 degree days, and 16 cooling days. The worst summer had 19 degree days and 31 cooling days.
- Stress events averaged 3 days in duration with a maximum of 9 days. They averaged 3 degree days in magnitude. The worst event (9 days in duration) had 12 degree days and had a maximum water temperature 27.4 ° C

The Bottom Line, Thus Far

- The average summer had about 12 stress days, 10 degree days, and 16 cooling days.
- The worst summer had 23 stress days , 19 degree days and 31 cooling days.
- ***Now on to Part III***: How much water would it take to mitigate such stresses?

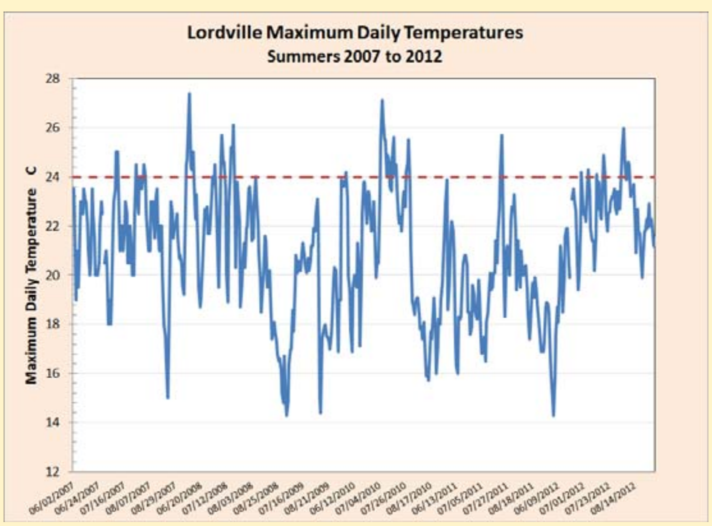
Part III. Estimating the Impact of Reservoir Releases on Lordville Temperatures

The Research Challenge

- Build a statistical model that can estimate the impact of a pulse release from Cannonsville or Pepacton on water temperatures at Lordville.
  - Such a model must include other key determinates of Lordville water temperatures.
  - There are serious gaps in available data. In particular, the Lordville gage was out of commission for years, the Cooks Falls gage no longer records temperatures and there is no temperature gage at Downsville.
  - Although thermal releases were made in the prior to the FFMP, neither NYS-DEC, nor NYC-DEP nor the RiverMaster have good records of such.

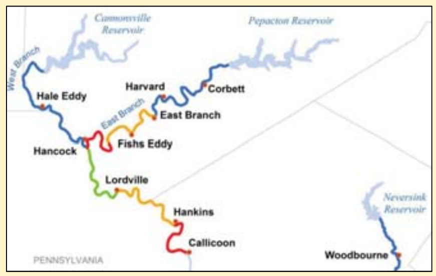
The Research Challenge:

Find an equation, including reservoir releases, that explains this 5 year long temperature pattern at Lordville.

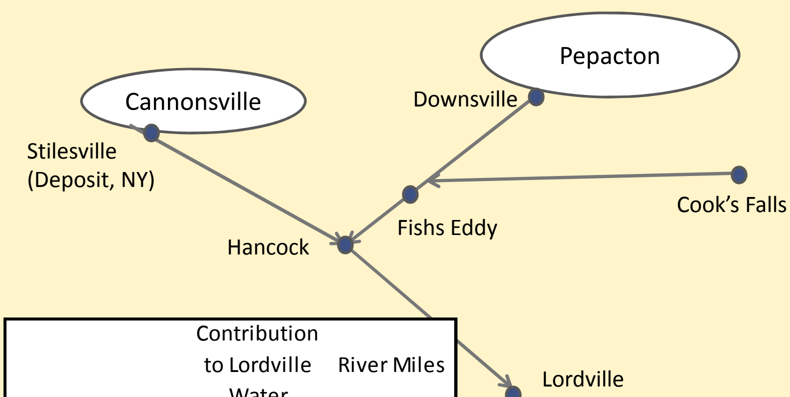


Principal factors determining water temperatures at Lordville

- Regional ambient air temperature, solar radiation, relative humidity and precipitation on that day and preceding days.
- Release quantities and temperatures on that day and preceding days from Cannonsville and Pepacton.
- Flow quantity (discharge) and temperature from the Beaverkill on that day and preceding days.
- Flow quantity (discharge) and temperature at Lordville on preceding days.



Upper Delaware Schematic & Basic Facts



	Contribution to Lordville Water	River Miles
Cannonsville	31%	27
Pepacton	14%	42
Beaverkill	30%	35
Other Tributaries	25%	-

Physics Rules!!

- The water at Lordville is a mixture of releases from Cannonsville and Pepacton, water from the Beaverkill, and water from other tributaries . As it flows down river this water gains or loses heat to the environment depending on atmospheric conditions. The dynamic transition toward heat balance determines water temperatures at Lordville.
- Hydo-thermodnamic theory describes these processes quite well via sets of partial differential equations. Since we do not have the data to calibrate such complex models, we use linear approximations – of considerable accuracy.

$$\frac{\partial T}{\partial t} = -\frac{\partial (QT)}{A\partial x} + \frac{\partial}{A\partial x}\left(EA\frac{\partial T}{\partial x}\right) + \frac{H_f}{\rho c_p D} + S_b$$

Type equation here.

Contributions to Water 'Heat' Content at Lordville

(The heat of water flowing past a point on the river ≈ Temperature × Flow Rate)

- Heat at Stilesville ~ modulated during its 27 mile passage to Lordville
- Heat at Downsville ~ modulated during its 42 mile passage to Lordville
- Heat at Cooks Falls on the Beaverkill ~ modulated during its 35 mile passage to Lordville
- Heat entering the River from other tributaries ~ modulated during their passages to Lordville

The Role of Fishs Eddy

Temperatures at Downsville and Cooks Falls on the Beaverkill are not available . The East Branch and the Beaverkill join above the Fishs Eddy USGS gage – the data from the Fishs Eddy gage becomes their surrogate in our analysis.

- Heat at Fishs Eddy ~ modulated during its 21 mile passage to Lordville
  - Heat at Downsville ~ modulated during its 21 mile passage to Lordville
  - Heat at Cooks Falls on the Beaverkill ~ modulated during its 15 mile passage to Lordville

A Simple and Accurate Model for 'Heat' Content of Water at Lordville

The regression equation is
LordvilleHeat = 3393 + 1.34 StilesvilleHeat + 1.28 FishsEddyHeat + 18.4 Deposit max AirTemp

Predictor	Coef	SE Coef	T	P	VIF
Constant	3393	3730	0.91	0.36	
StilHeat	1.34	0.128	10.50	0.000	1.037
FishHeat	1.28	0.012	107.4	0.000	1.040
DepoTmax	18.44	46.46	0.40	0.692	1.055

S = 6986.6   R-Sq = 96.1%   R-Sq(adj) = 96.1%

The remarkable accuracy of this model explains why our model for calibrating the impact of Cannonsville releases on Lordville temperatures works so well. (Physics rules!!)

Our Regression Approach to Estimating Reservoir Release Impact on Lordville

- Regression permits us to simultaneously measure the impact of many variables on Lordville temperatures
- We did a series of linear regressions of available Lordville summertime maximum daily temperatures against the following 'causal factors'.
- Data imitations necessitated some workarounds.
- Variables used: Stilesville flows and temperatures, Fishs Eddy flows and temperatures, Binghamton precipitation and temperatures, Deposit precipitation and temperatures.
  - All variables were also lagged by 1 day. (Cannonsville to Lordville 24 miles, about 12 hours flow time, Fishs Eddy to Lordville about 17 miles, about 8 hours.)
  - Logarithmic, quadratic and interaction models were tested
  - Data used for summers (June, July, August) of 2007 to 2012, excluding days on which Cannonsville or Pepacton were spilling: 498 data points over 5 summers.

Our Main Findings

- Simple lagged models worked best.
- Cannonsville water has a substantially higher impact on Lordville than does Pepacton water*.
- A 100 cfs Cannonsville release reduces Lordville maximum daily temperature the next day by about 0.47 °C (0.85°F). *It takes about 221 cfs to lower Lordville 1°C* (It takes 118 cfs to lower it by 1°F)
- This result is highly statistically significant and appears to be very robust (does not depend on the particulars of the regression model.)

* The lack of a temperature gage at Downsville constrained our analysis on this question. The finding is consistent with the fact that Pepacton is 42 miles from Lordville and contributes 14% of Lordville's water. The figures for Cannonsville are 27 miles and 31% , respectively.

Typical Supporting Regression Result:

Regression Model with yesterday's Stilesville flow and yesterday's Deposit max air temperature, and today's Fishs Eddy maximum water temperature

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The regression equation is
LordTmax = 4.72 - 0.00473 StilFloLag + 0.0995 DepTmaxLag +
0.500 FishTmax

498 cases used, 4 cases contain missing values

Predictor         Coef     SE Coef       T      P    VIF
Constant        4.7235     0.5169     9.14  0.000
StilFloLag    -0.00473    0.00017   -27.37  0.000  1.109
DepTmaxLag     0.09952    0.00882    11.28  0.000  1.894
FishTmax       0.49958    0.02154    23.20  0.000  1.891

S = 0.984521   R-Sq = 85.2%   R-Sq(adj) = 85.1%

Analysis of Variance
Source           DF        SS      MS       F      P
Regression        3   2759.97  919.99  949.15  0.000
Residual Error  494    478.82    0.97
Total           497   3238.79
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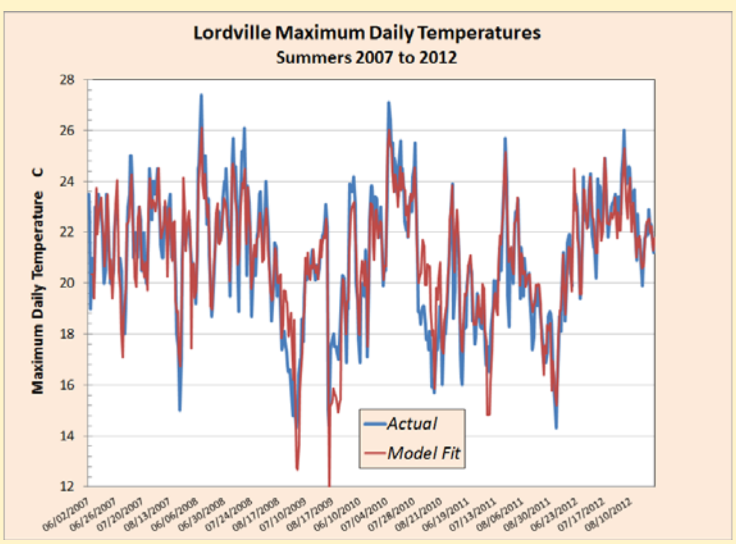
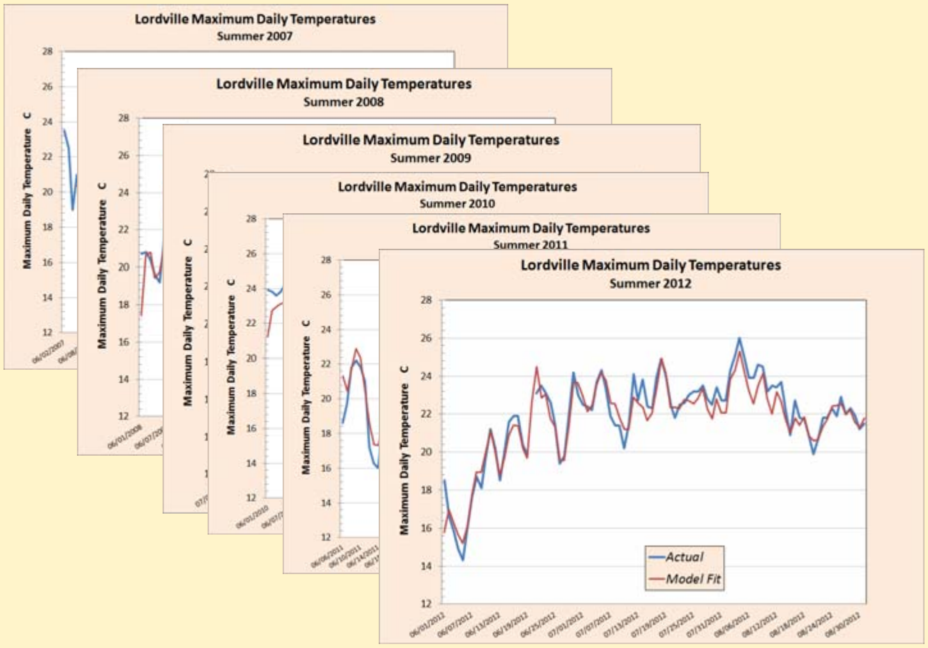
The Model's Overall Fit during Five Summers:

Model with yesterday's Stilesville flow and yesterday's Deposit max air temperature, and today's Fishs Eddy maximum water temperature

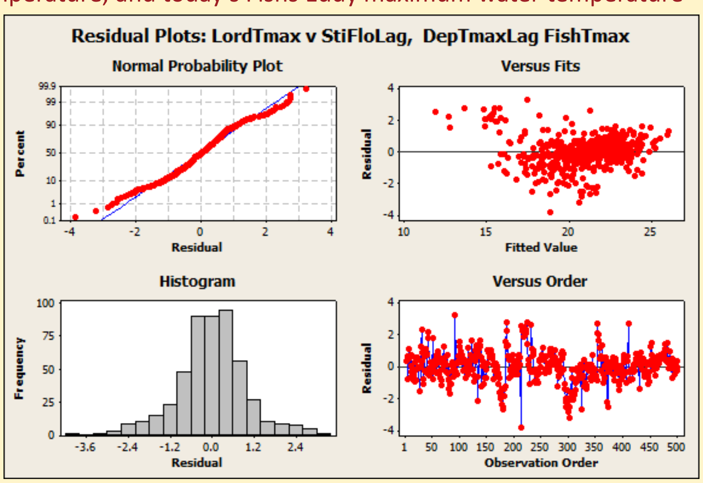


Good Model Fits in Individual Years



More Evidence of the Validity of the Regression Model: Residual Plots:

Model with yesterday's Stilesville flow and yesterday's Deposit max air temperature, and today's Fishs Eddy maximum water temperature



The Bottom Line:

- Our regression analysis indicates that a 100cfs additional release from Cannonsville will decrease Lordville maximum and average temperatures by about 0.47°C, that is about 0.85°F. Thus, a reduction of 1°C would take about 211 cfs, a reduction of 1°F would take about 118 cfs.
- Estimates were made under FFMP operations and flow regimes from some 500 days of data from the summers of 2007 to 2012.
- Every indication is that these results are reliable. The model appears to be quite robust -- a variety of regression models, at different flow rates, applied to different time horizons give essentially the same values.
- But, these results are 'averages' over many conditions, and are 'linear' regression models. Some thermodynamic phenomena on rivers can be nonlinear. Experimentation to validate these findings is recommended.

Conclusion: Thermal relief is feasible at Lordville within the parameters of the current FFMP/OST)

- The model indicates that a 1°C lowering at Lordville requires about 211 cfs release from Cannonsville on the prior day. Combining these estimates with our statistics on the extent of thermal stress at Lordville gives

	Degree Days C	Water Needed (cfs Days)
Average Summer	10.2	2,152
Worst Summer	19.3	4,072
	Cooling Days	
Average Summer	16.2	3,418
Worst Summer	30.8	6,499

- Our worst historical case required 6499 cfs days. There are 9,423 cfs-days of water in the IERQ which the DRBC can use to support "extraordinary water needs." Thus thermal relief appears feasible at Lordville in most summers, even in an extreme summer.

What's Next?

- Continuation of our research:
  1. Development of a forecasting model for Lordville water temperatures.
  2. Development of a thermal relief algorithm based on the results of the completed work to date and the results of steps 1 above. We aim for a procedure similar to what is now successfully implemented on the Lackawaxen by PPL under PF&BC jurisdiction.
- We urge the Implementation of an experimental thermal relief program for Lordville in the upcoming FFMP/OST revision based on these results and the ability of the PF&BC and NYS-DEC to forecast thermal stress events.
- A principal goal, in addition to providing stress mitigation next summer, should be to conduct experiments to validate these estimates of the cooling effect of Cannonsville releases on Lordville temperatures.

Related Data Issues for Immediate Action

- This work has again shown, the importance of accurate and complete data in Delaware release program design and evaluation. The following missing data are vital to continued progress:
  - Downsville: no temperature gage
  - Cooks falls: no temperature gage
  - Junction of the East and West Branches: no gage at all
- Transparency: To date, neither the DRBC, nor the decree parties, nor the USGS *Water Smart* project, nor any stakeholders have an 'OASIS' model that describes current Delaware operations. Everyone is flying blind. Delaware operations are too important to be a black box.
- FFMP/OST updates are not posted and archived or announced in a well defined process.
- River Master reports are posted (in pdf format) in a fashion that makes their use in analysis extremely cumbersome.