Morgan's Water Budget Model

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Executive Summary

Since the development of the Deep Creek Watershed Management Plan, Morgan France has been advocating the development of a 'water budget' approach for allocating the waters of Deep Creek Lake equitably among its stakeholders. MDE and DNR have declined to develop such a model. There has been considerable confusion as to how to go about its development and what it would entail. After many discussions with Morgan, this note attempts to express his thought processes in the form of a model and examine it against historical information published in Brookfield's annual reports. The basic conclusions is that **it is possible** to construct such a model.

Introduction

After many iterations with Morgan France, especially during the last few weeks (March 2017), I got his blessing that I understand his approach. And I must say, it actually makes sense. It is not a water budget in the traditional sense as one reads the literature, but it is a water budget. However, I've taken a slightly different approach to implementing it than Morgan has with his Excel spreadsheets, but the result is essentially the same.

In this note I explain the theory, the process as it applies to Deep Creek Lake, the implementation of a version of it with "R" [5, 6], and tests performed against several years of historical data.

The results seem reasonable but they also expose a number of 'political' rather than scientific issues that need to be dealt with, to make this a tool for daily use.

This paper only deals with the scientific issues, leaving the possible political aspects to a separate paper.

For the record, my previous report about water budgets can be found here [1, 2].

Morgan's Approach

Morgan has always talked about 'what goes out must come in,' not necessarily the other way around (that's my take). The crux of the problem and approach to the water budget is the MDE water permit under which Brookfield must legally operate. This is permit #GA1992S009 (08), dated 11 June 2011 [4], the number in parenthesis referring to the version number since it's inception in 1994. From here on I will refer to it as 'the Permit.'I have reported the evolution of the permit in a separate paper [3].

The Permit is all about how the waters leaving the lake are partitioned into 'mandatory' and 'discretionary' releases. The Permit is made up of 24 conditions.

The only way that water can physically leave Deep Creek Lake lake is via releases through the hydroelectric facility (lake water evaporation, most of the snowmaking capabilities at the Wisp and water for the ASCI white water recirculating facility are exceptions, but these quantities are small and are not talked about in the permit; it is not entirely clear how much of that water usage eventually evaporates, returns to the lake or goes directly into the Youghiogheny watershed).

A mandatory release is what must be satisfied as written in the Permit, particularly Condition 19, and discretionary releases are releases through the hydroelectric plant at the will of Brookfield, the owner/operator of the facility, to generate power and hence as much income as possible. Their only mandate is that the lake levels stay between the rule bands as specified in the permit. Note that each release generates power, perhaps not at the optimal price point.

Consider the lake water level on a given date. It should (must) be between the upper and lower rule bands somewhere, as dictated by the Permit.

Between the lake level and the lower rule band there is a certain amount of water available to allocate for whatever needs are coming up. Ideally that water should satisfy all of the needs, but in all likelihood it won't. As time progresses and water is removed from the lake by the various demands, new water comes in via rain, streams flowing into the lake, and groundwater. The lake is a dynamic system, and at any time, there is a balance between what's in the lake , what's coming into the lake and what's removed from the lake.

So what are the activities that remove water from the lake? As has been mentioned, except for evaporation, they are all specified in the Permit. They are:

1. Power generation by Brookfield - They are entitled to generate power as long as the lake levels stay between the rule bands. This entitlement is specified in terms of a total amount of water per year and an average daily amount of water that can be removed from the lake.
2. White water releases - These are specified in the permit, specific days, times, and amounts. Condition 19 in the permit provides those details. Most of the verbiage in the Permit is about defining a schedule for releases for use by the white-water rafting community. Note that such releases also produce power for Brookfield! Note also that these releases are 'mandatory' provided the rule bands are not violated. Actually the only rule band that matters is the lower rule band.
3. Temperature Enhancement Releases - These are not specified as releases to be conducted at certain times and dates, but they are controlled by a protocol, an analysis procedure that must be conducted daily during the summer months in order to decide whether a release is to be conducted or not. The purpose of these releases are to control the water temperature of the Youghiogheny to be less than 25°C at the Sang Run River bridge so as to enhance the survival chances of trout. Note that these releases produce power for Brookfield. The protocol currently mandates these releases to occur at 11 am.
4. Bypass flow - to keep to Youghiogheny River at a minimum flow. The basic purpose is to have water in the Youghiogheny river at all times, so that fish can survive and white-water rafting can be conducted.
5. A mandatory 'wicket gates' losses of 9cfs. Wicket gate losses are expensive to fix. Therefore they have been artificially made mandatory to complement the bypass flow condition. There is no verifiable way to measure this flow that I know of, although one can be easily and inexpensively implemented a measurement system.
6. Evaporation - This is not a 'need,' but is an important water-loss[7]. This water-loss cannot be controlled and is dependent on weather conditions around the lake.

So Morgan's water budget analysis focusses on how to distribute the water that is currently available among the six 'needs' identified above. If these can be satisfied then we're 'home free.'

If they can't be satisfied then we must define some process of prioritizing water allocation and/or curtailment. This is most likely a 'political' problem and will not be considered here.

Just to offer a few teasers, however, one approach would be that 'need 1' is cut out first. The water budget analysis is redone and if it works proceed with its implementation.

If the remaining needs cannot be satisfied after curtailing 'need 1,' then 'need 2' could be cut in some way. Because 'need 6' is not controllable, it will happen no matter what, and could be estimated. 'Need 3' would probably be used only in desperation, whatever that means, because, clearly, you don't want to kill the trout! More on the options and potential changes to the Permit are discussed in a separate paper.

When water is removed from the lake some groundwater recharge takes place. There is no model to compute this recharge, and as it turns out, we don't need to model it. The amount coming into the lake, to attempt to replace what is taken out of the lake, is a function of the past weather conditions, including recent rainfall; sometimes there is more, other times there is less. But, streams keep flowing and groundwater keeps entering the lake.

So the basic idea is to compute how much water we have available on a given day to dole out to the various needs, address those needs as best as we can, and if there is insufficient water then deal with how to curtail the needs.

To find out what one has available is to look at today's water level and compute how much volume one can dole out by computing what's in the lake between the current water level and the lower rule band. After all, we cannot go below the lower rule band!

One can repeat the analysis steps outlined above on a daily basis, allocating the instantaneous amounts of water available to all of the six needs identified above.

This process is actually fairly simple to implement, requiring minimal computational and data resources.

Implementation

The implementation process, to be described below, is based on the following assumptions:

1. At the time the calculations are performed it will be assumed that we have no knowledge of future rainfall or the amount of groundwater entering into the lake. These two assumptions are automatically corrected when we do the next analysis the next day. If, during the next day, it rains let it rain and groundwater recharge takes place always. Hence, the lapse of time between the two analysis automatically adjusts the lake level by additional groundwater flows and any possible rain and its impact on groundwater flows.
2. There is a time-volume release schedule for white-water rafting that is specified in the Permit, the mandatory releases. This schedule also contains curtailment criteria should the water budget be unable to satisfy all demands. A few are specified in the Permit, such as when the lower rule band can or cannot be violated.
3. There is a TER release protocol for the conditions specified in the Permit. For water budget analyses, this may be some statistical schedule based on past experiences. This may be a combination of modeling, let's say for the next 10 days, to which is added statistical information for the remainder of the three months for which the TER is supposed to be evaluated according to the permit. There are several options available for a predictive capability which will be discussed later in the paper.
4. Modeling is only needed from April 15 to October 15.

The 'water budget' model can be defined by the following steps:

1. Obtain the current lake level reading from the existing gage. (NOTE: There needs to be a redundant gage at another location!)
2. Compute the available volume of water based on the current value of the lower rule band. The current volume is based on the stage-storage relationship previously defined as a result of bathymetric work performed in 2012. See another of my reports [xx]
3. Compute the daily water needs based on the white-water schedule defined in the Permit. Estimate the amount of evaporation and remove it from the available water volume. This can only be grossly estimated, although, with a little effort, a more accurate relationship can be developed for the lake.

4. Estimate the number of TERs that may be required. This can be done in a simple manner, using long range forecasts or statistically based on historic data. This results in some pseudo mandatory releases.
5. If there is still volume available, then Brookfield is allowed to generate power, with whatever schedule is dictated by their PJM contract or their own internal procedures.
6. The algorithm can be revisited every day. This would automatically incorporate any water coming into the lake via rain and/or groundwater.

As described above, the main forecasting model requires the following sub-models:

1. A revised TER protocol, because its error rate is too large.
2. A white water release protocol. Already spelled in the Permit, but may require tuning.
3. A water evaporation model. Not expected to be a significant contributor, but could impact allocations during hot and dry seasons.

The next section discusses the implementation of the water budget model as described above.

Implementation.

To see how things work out with the proposed approach I will discuss the analysis methodology with past results. Specifically the model will be developed with data from 2011 and tested with data from 2012 and 2013.

First, let's see what the lake levels were during 2011 and how they related to the existing rule bands.

The daily average lake levels were obtained from the "deepcreekscience.com" website, a site that I created to collect all kinds of verifiable information about Deep Creek Lake. That data in turn was extracted from Deep Creek Hydroelectric annual reports.

The first few lines of the 2011 lake level data file are shown below:

1/1/2011	2457	0.04	2455.00	2457.90
1/2/2011	2457	0.1	2455.00	2457.90
1/3/2011	2457.1	0	2455.00	2457.90
1/4/2011	2457.1	0	2455.00	2457.90
1/5/2011	2457.1	0	2455.00	2457.90
1/6/2011	2457	0.03	2455.00	2457.90
1/7/2011	2457.1	0.08	2455.00	2457.90
1/8/2011	2457.1	0.35	2455.00	2457.90
1/9/2011	2457.2	0.03	2455.00	2457.90
etc.				

with the columns indicating the day of the year, average daily lake-level (ft AMSL[1]), daily rainfall (inches), lower rule band value (ft AMSL) and upper rule band value (ft AMSL).

The daily levels and rule bands are plotted in Figure 1. Although for some period of time the lake levels were close to the lower rule band, the year, in general was relatively wet. Exceeding the upper rule band is only in issue in the winter time. Brookfield would like to keep a margin between the height of the spillway and the lake level in case of accumulation of wind driven ice that may case severe damage to the spillway, should ice be carried over the spillway.

Figure 1

[1] AMSL = Above Mean Sea Level

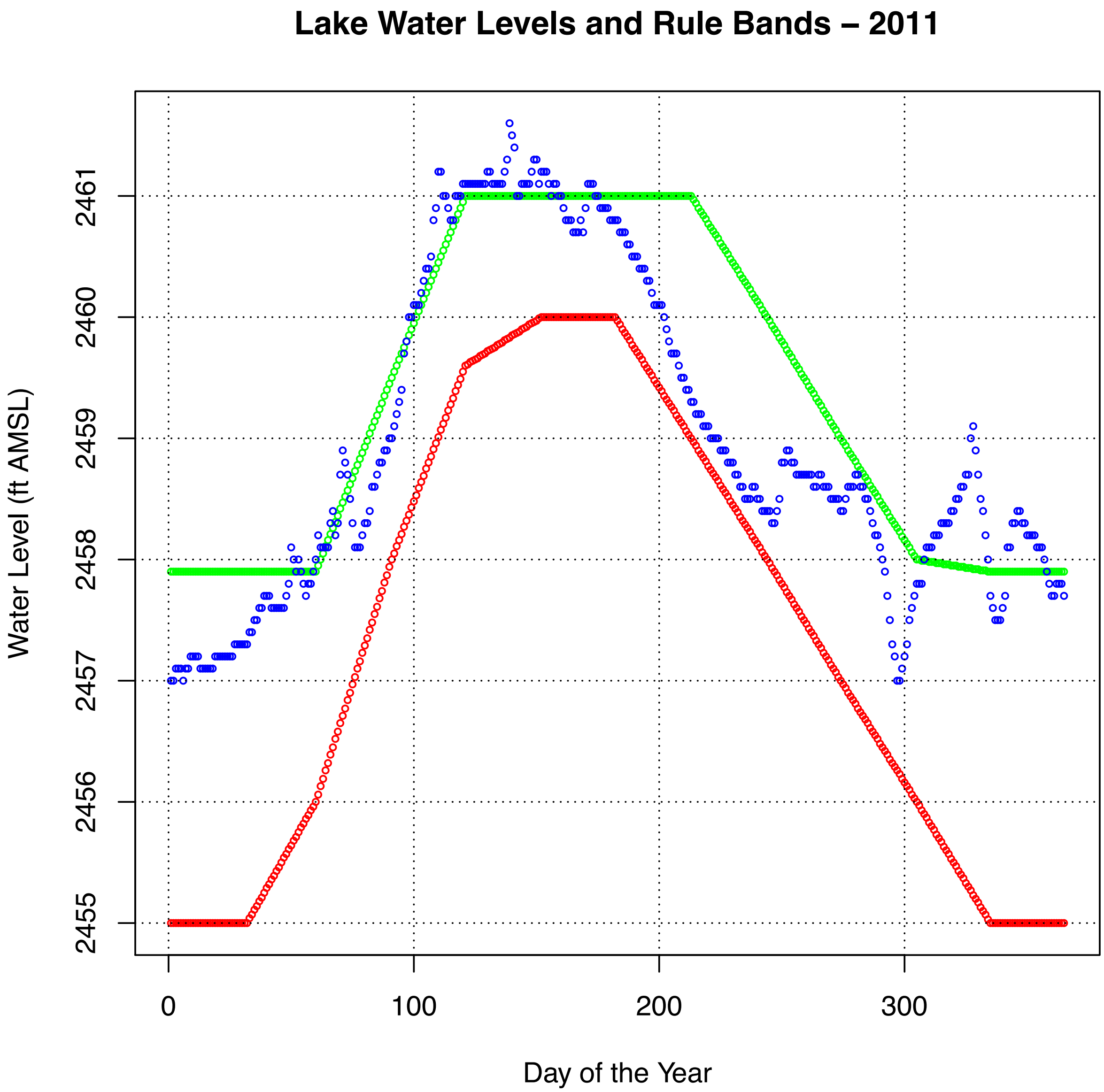
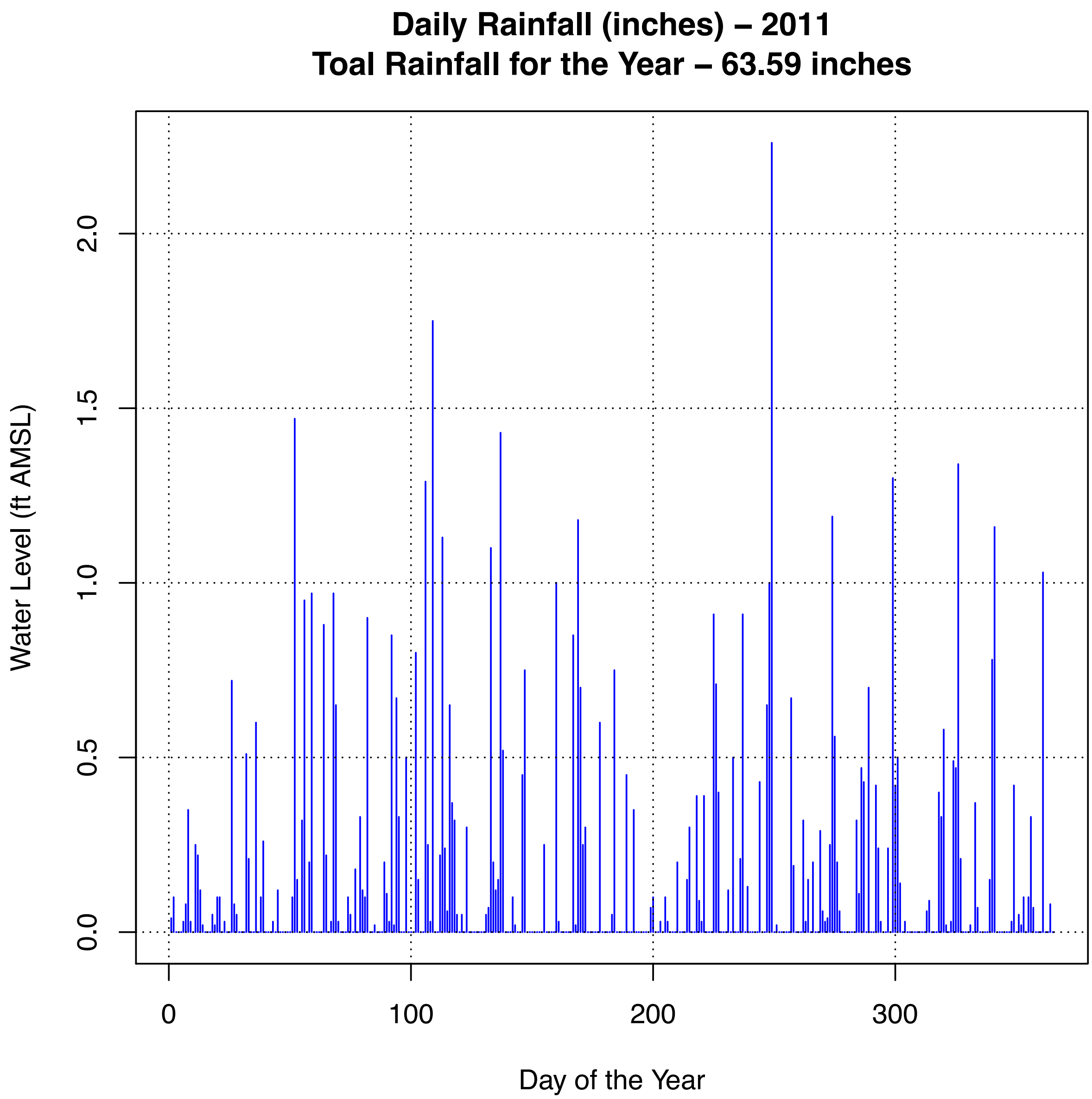


Figure 2 shows the daily rainfall for the year. While this information is not used in the methodology, it is of interest to see historically what is going on.

The total rainfall for that year is noted in the heading of the figure, namely 63.59 inches, considerably wetter than the average rainfall for Garret County, often quoted as to be around 48 or 49 inches. This one of the reasons that the upper rule band is violated in Figure 1.

While not important to the eventual methodology, it's important to note that rainfall is relatively uniformly distributed during the year, at least in this year.

Figure 2



The next step is to develop the various mandatory release schedules. The white-water release schedule is specified in the Permit. It's in terms of when and how long. The Permit data has been converted into a file that is easily processed. Below are the first few lines of the white-water release file:

The next data file to be used is the TER release file. It's easy to use past data since we have the actual release dates and durations. For a predictive model a

```
# The following are the scheduled white-water releases for 2011
# as specified under Condition 19 in Permit GA92S009 (08)
# These are standard releases
# They are subject to certain conditions specified in the Permit
#
Date                Start               End
# April -All Fridays after April 14 (1000 HR to 1300 HR)
4/22/2011           1000                1300
4/29/2011           1000                1300
# May - First two Mondays (1000 HR to 1300 HR)
5/2/2011            1000                1300
5/9/2011            1000                1300
# May - First three Fridays (1000 HR to 1300 HR)
5/6/2011            1000                1300
5/13/2011           1000                1300
5/20/2011           1000                1300
# May - First Saturday (1000 HR to 1300 HR)
5/7/2011            1000                1300
etc…
```

combination of forecast TERs and statistical information is probably the way to go. Here are the first few lines of the historical TER data file for 2011:

```
# The TER data were extracted from the 2011 Annual Report
# The data show the date and the start and end times of the release
# File Name: ter_2011.txt
# REF: 2011DCHydro.pdf, p.5
# NOTE: These data are in addition to the white water releases
# NOTE: Some of TER releases also serve as white-water releases.
Date                     Start                    End
6/8/2011                 12:30                    17:15
6/9/2011                 11:00                    17:00
6/30/2011                14:15                    15:15
7/31/2011                14:00                    15:00
7/6/2011                 14:00                    18:00
7/7/2011                 12:30                    14:30
etc…
```

There is one other mandatory data file to be derived from the annual report. This is the bypass data file. This information is also variable, because it depends on the flow conditions in the Youghiogheny river. The historical data as reported in the annual report are, as with the TERs, actual occurrences. In a predictive model the current day's reading is clearly available, but future demands must rely on some kind of combination of forecasting and statistical data.

As quoted from the 2011 annual report "…when flows in the Youghiogheny River were less than 26 cfs. Flow data were obtained from the U.S. Geological Survey (USGS) recording at the Oakland gage, direct readings from the Oakland gage, or from the tailrace gage at the Deep Creek Station, per guidance provided in the protocol. Valve openings (see Appendix C) were determined from Table 3 of the protocol and were based on station operating status."

It is not clear that the bypass setting is adjusted daily, but it is assumed to be such in the present analysis. Here are the first few lines of the 2011 bypass file:

```
# Bypass Valve Settings data extracted from the 2011 Annual Report
# File Name: bypass_2011.txt
# REF: 2011DCHydro.pdf
# Bypass values and % open of bypass valve
Date            Valve
7/22/2011       22
7/23/2011       30
7/24/2011       32
7/29/2011       23
etc…
```

What is shown is the date and the valve setting. The setting is a function of the amount of flow at the Oakland USGS flow gage.

The valve setting has been correlated with the amount of flow that is bypassed using data from several annual reports and is discussed in one of my notes {8]. The data from these reports have be fitted to a simple linear equation, giving the flow as a function of valve setting as follows:

$$Q = -13.8197 + 0.7215 \times V$$

Q = bypass flow, cfs

V = valve setting, %

The one remaining mandatory release is the 9 cfs through the wicket gates. This is a constant flow year-around, because this is wicket gates leakage, a flow that can only be stopped with expensive repairs to the turbines.

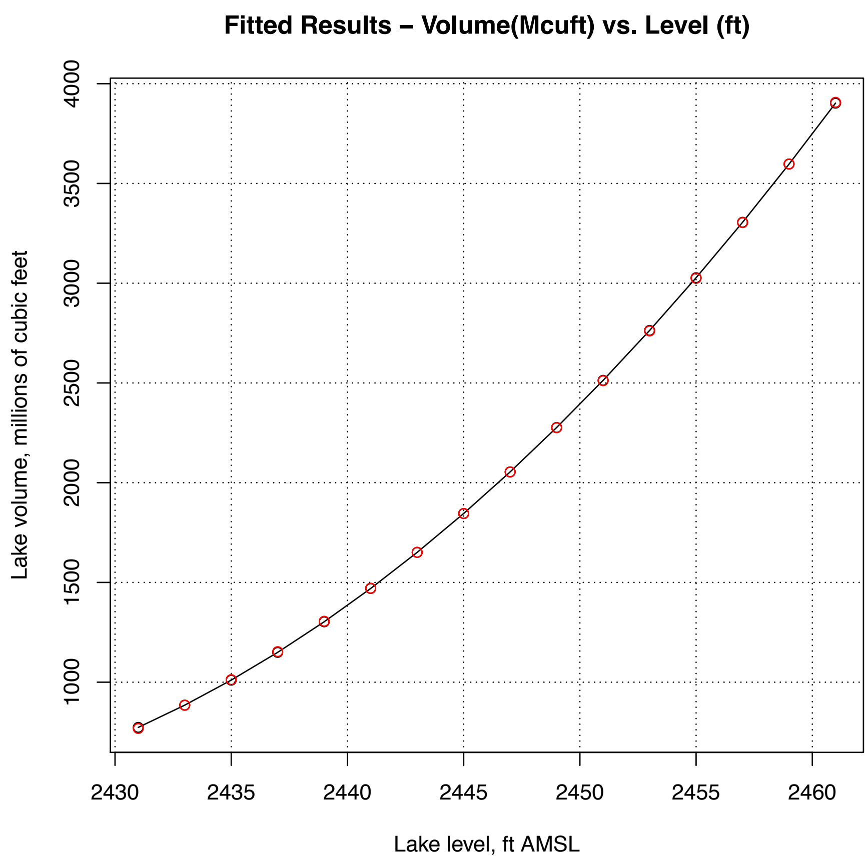
For now evaporation from the lake surface will be ignored.

All of these mandatory flow releases are now cast into a consistent set of total mandated daily demands. The unit of flow that will be used in the following discussions is acre-feet/day. Note that one acre-foot = 43,560 cubic feet.

One last item must be defined: the amount (volume) of water available in the lake between a given lake level and the lower rule band.

In an analysis performed a number of years ago, while defining the bathymetry of the lake, the stage-volume relationship was also determined. I wrote a report on that analysis [9]. Since only the upper part, say the top 10ft to 15ft, are of interest, an equation has been cited to the bathymetry derived data. The resulting curve is shown in Figure 3, showing that the lake is not a cylinder.

Figure 3



The resulting equation, obtained from a regression analysis using "R" functions, can be stated as follows:

$$V1 = 10113728 - 8372.327 \times H + 1.732756 \times H \times H$$

$V = V1 \times 1.0e{+}06/43560$

Where: H = lake level, ft AMSL

V = Lake volume, acre-feet

To find the available volume between a given lake level and the lower rule band one just computes the volumes at these two elevations, with the difference being the available lake water.

In the following graphs all *y*-axis values are cast in terms of acre-feet of water volume. This is because traditionally, in civil engineering circles, volumes of reservoirs have been stated in these terms because they are of sensible magnitudes. At the same time these quantities are easy to display on graphs.

Putting it all together one gets the results for the year 2011 described in the following set of figures..

First the white-water releases. Figure 4 shows the water volume required, in acre-feet, for the days specified in the Permit.

I'm sure you note the peak. This is specified in the permit for the "Annual Team Friendsville Upper Youth Race," an extended 6-hour release. Normally the releases are only for 3 hours.

Figure 4

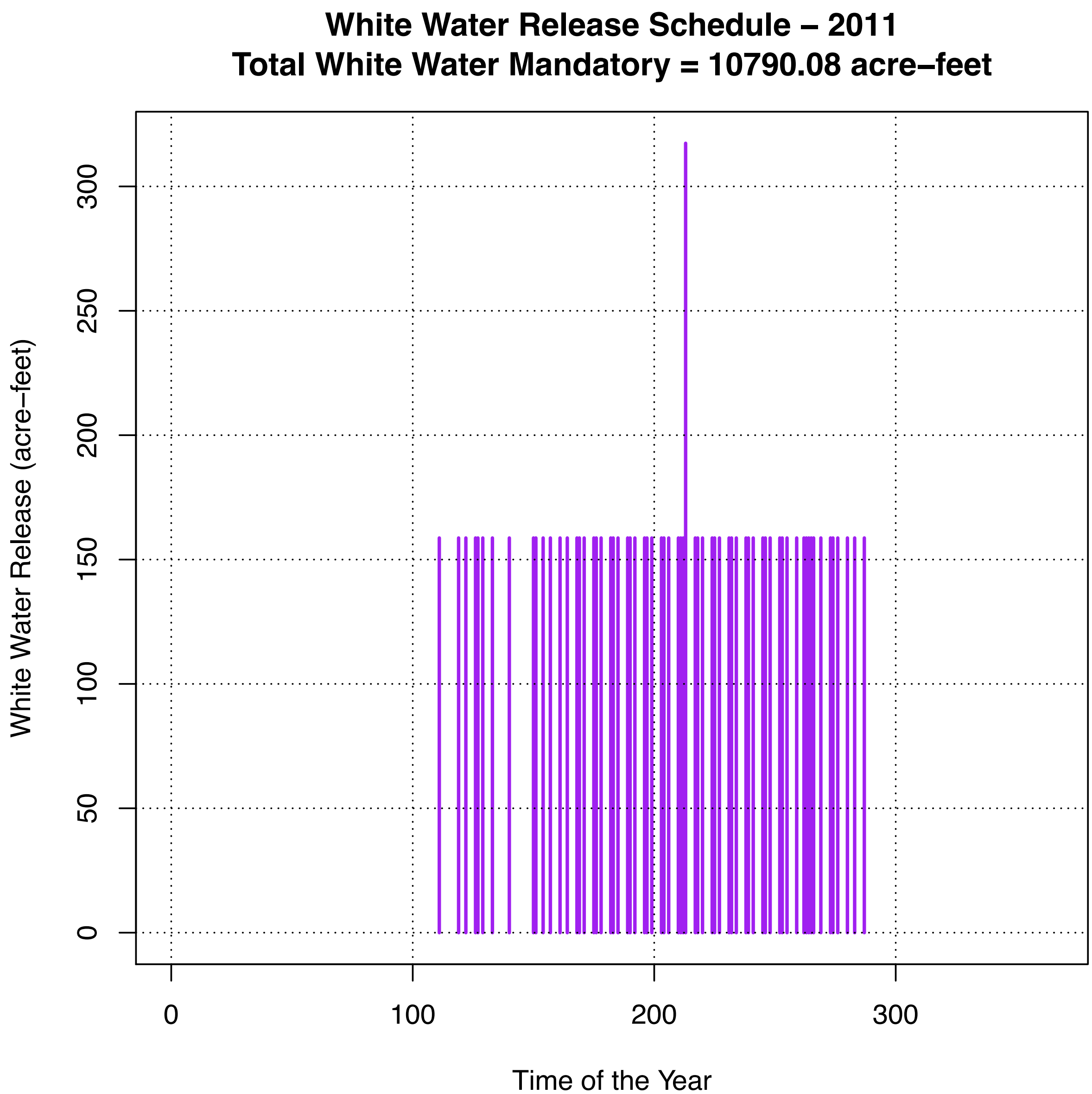


Figure 5 shows the water volumes associated with the TERs.

Figure 5

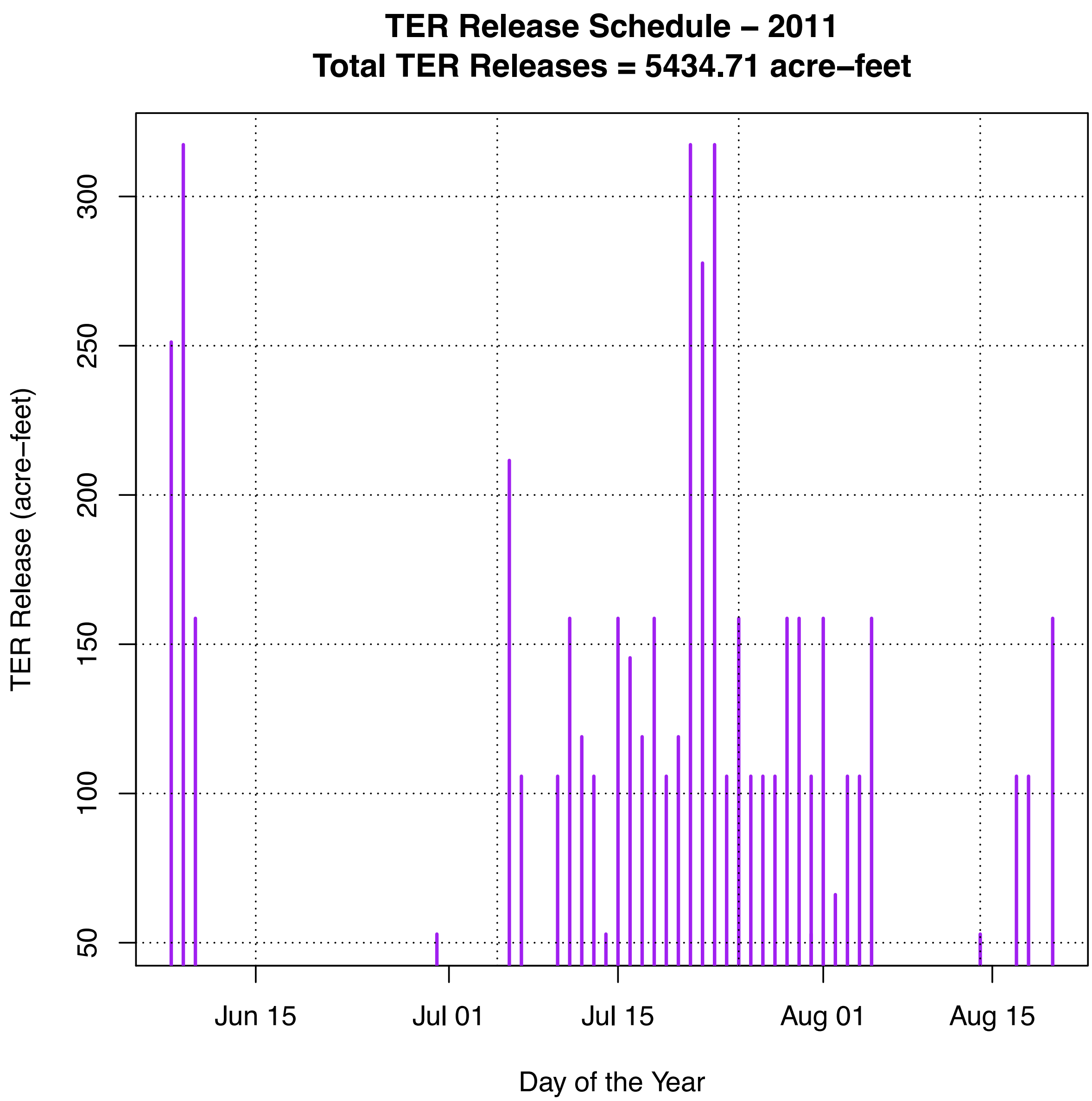


Figure 6 shows the bypass flow schedule. This is also mandated in the permit, and is a function of the Youghiogheny flow at Oakland. Hence it can vary

Figure 6

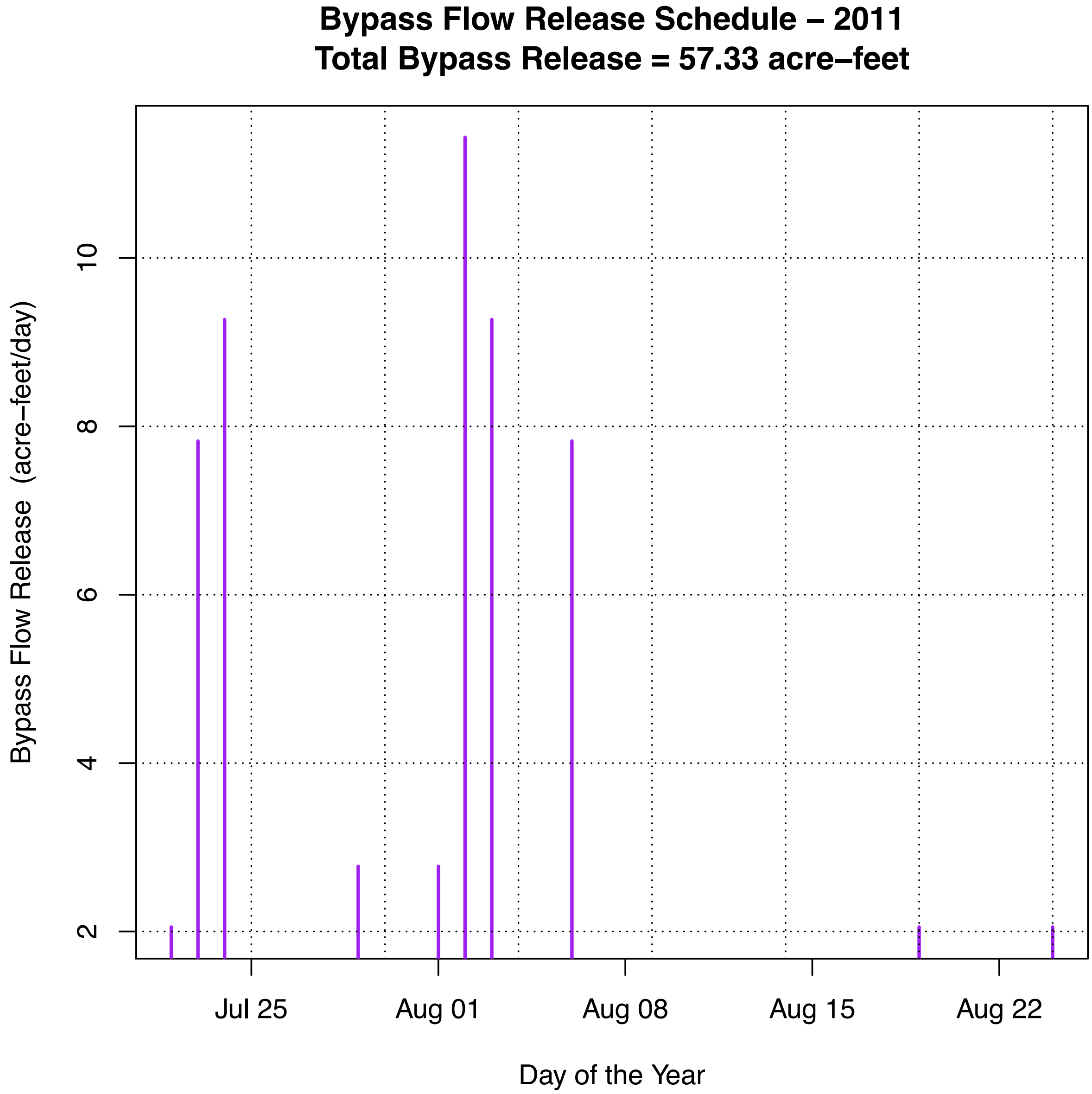
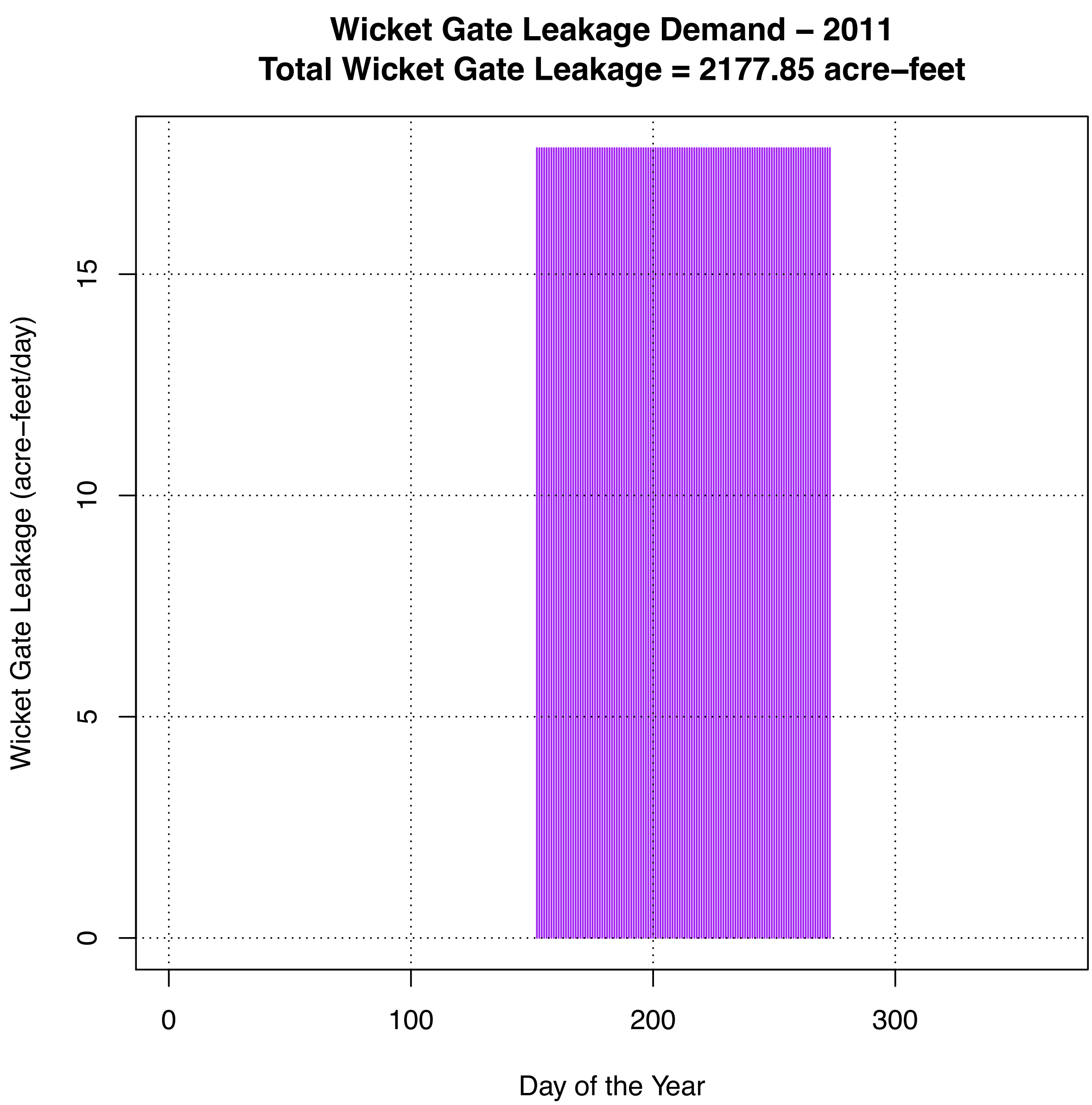


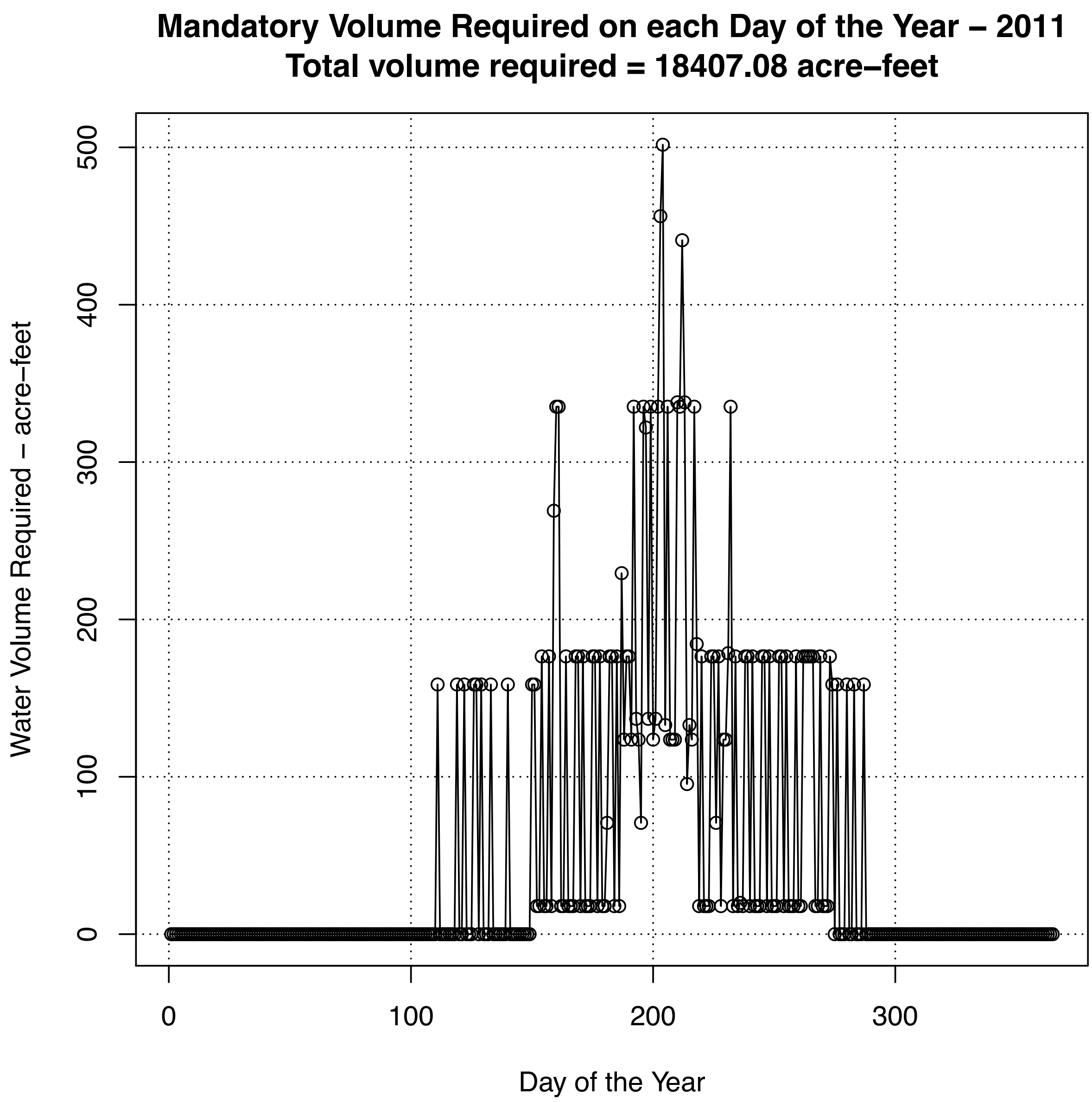
Figure 7 shows yet another required flow, namely leakage through the wicket gates. It is specified as a requirement in the Permit. However, I don't believe that they (Brookfield) have much choice. This is 'natural' leakage because the wicket gates, which basically function to control the flow through the turbines, are wearing out and are very expensive to repair or replace.

Figure 7



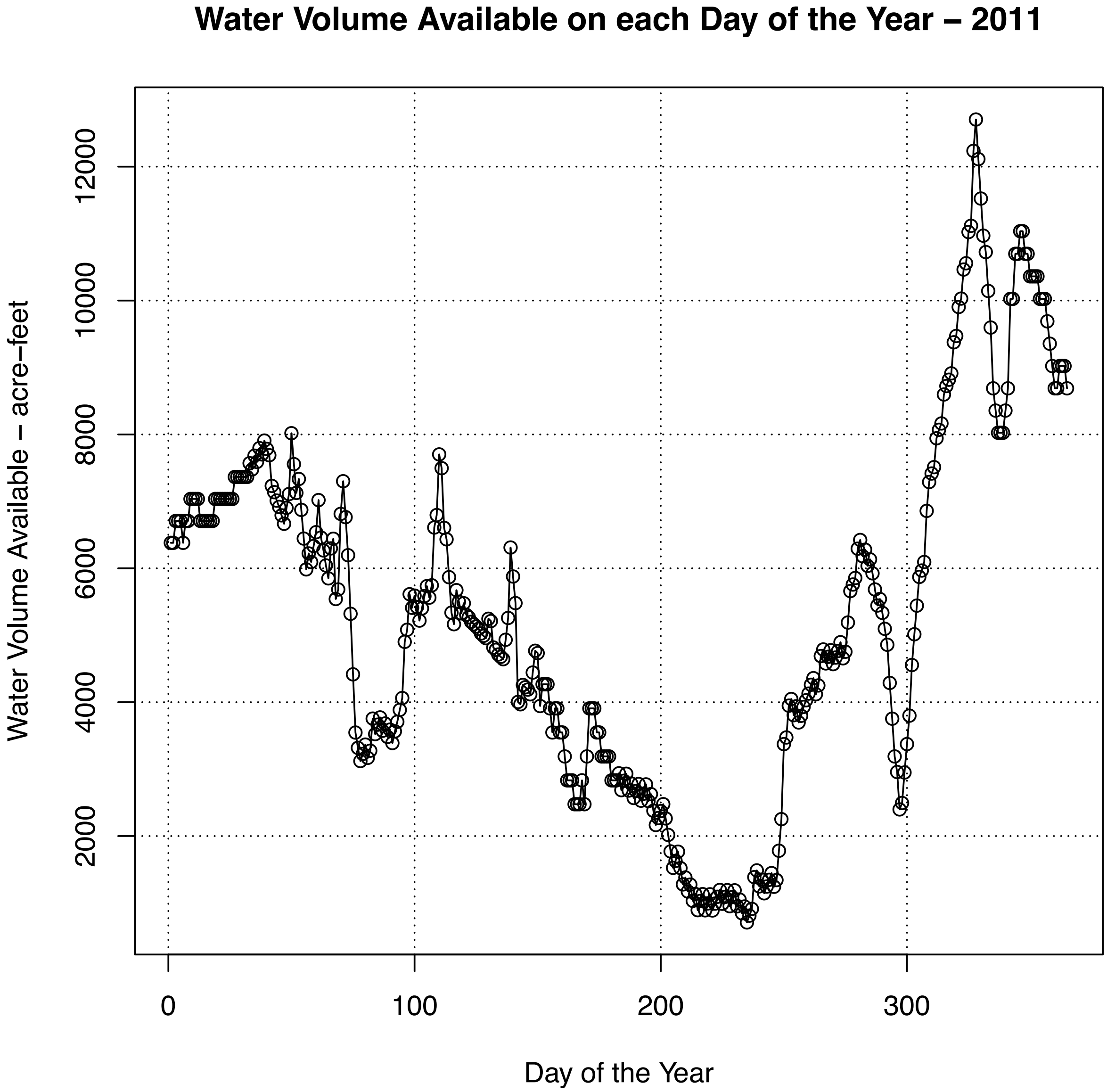
And the final result for all of the demands together is shown in Figure 8. This is basically the sum of Figures 4, 5, 6 and 7.

Figure 8



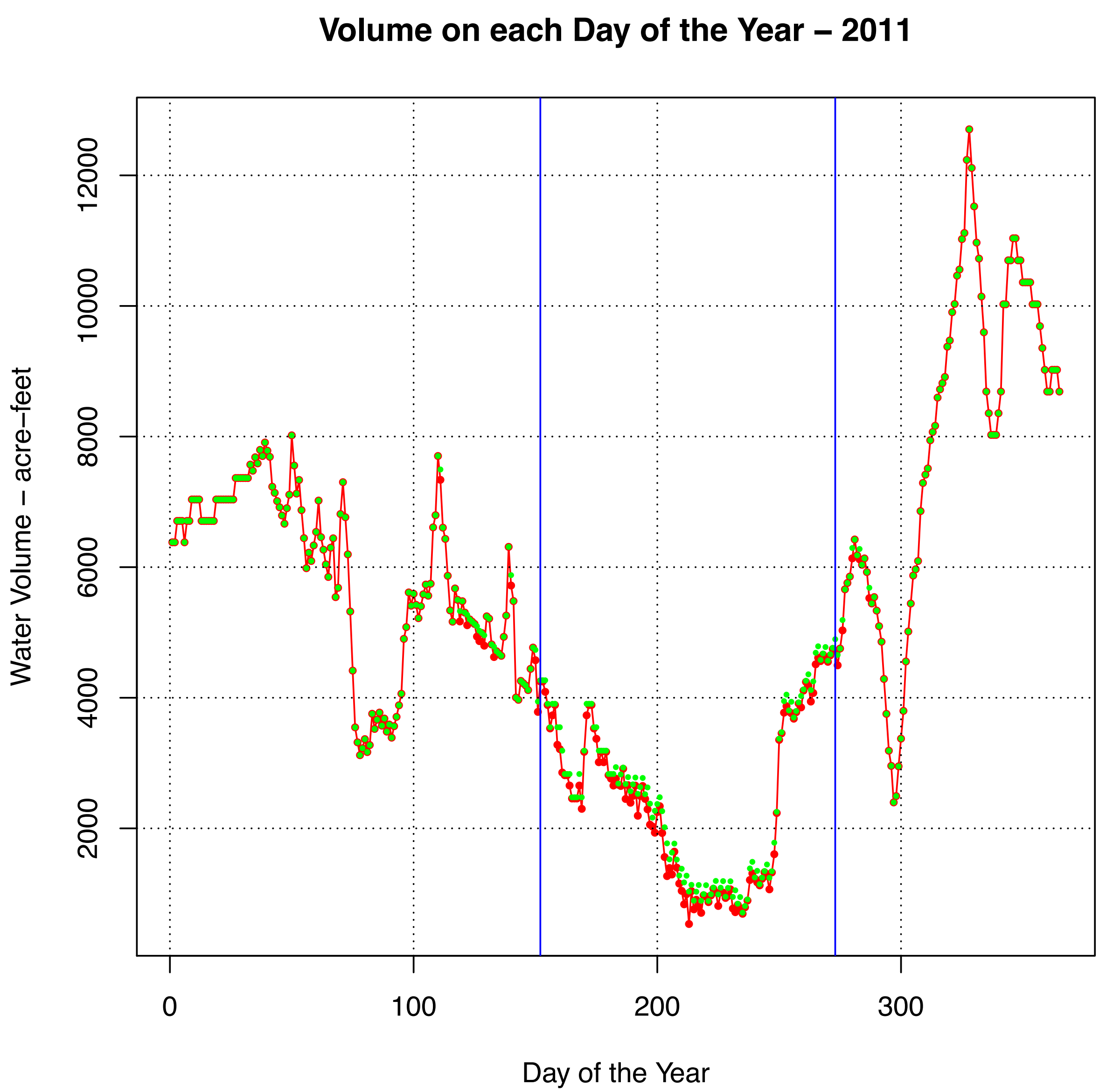
The total daily water volume available is shown in Figure 9. These are the result of calculations whose methodology are described earlier in this paper.

Figure 9



The next graph would normally show the difference between the daily available volume and the daily demand volume. However, the two curves look almost the same so both, available and demand have been plotted on the same graph and are shown as Figure 10. The green dots are the available volume numbers, while the red dots are the net remaining volumes, meaning daily available minus daily demand.

Figure 10



Discussion

Do NOTE, the discretionary releases have not been taken into account. That will make the curves look different before the first and after the vertical blue lines in Figure 10 (day 152 and 273). In between these two lines there are no discretionary releases because plenty of power is made via the mandatory releases.

The reason the discretionary releases have not been taken into account is because they are not available from the literature. They can be reconstructed from the USGS river flow gage data but has not been done. They are not going to change the basic issues that exist during the Permit period, from day 152 to day 273, April 15 through September 15.

PLV: 4/2/2017

Revised:

List of References

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9. P. Versteegen, stage volume reference, DCL161, Stage-Storage Diagram - August 30, 2013