Study of Water Level and Release Issues at Smith Mountain and Leesville Lakes

Smith Mountain Lake Association Board
Water Management Committee
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Background (slide 2)
As part of their license, every five years AEP must hold a public meeting to solicit comments on the performance of the project in maintaining lake levels and in providing flows necessary to protect instream beneficial uses. The current protocols that have been agreed to by all parties ensure that adequate water will be released to meet the biological needs downstream. An issue of concern is that low lake levels can cause triggers to be activated that reduce these releases. Understanding what causes low lake levels and making better predictions of their occurrence can reduce or even eliminate such reductions in downstream flows. Consequently, this analysis will focus on the lake level aspect with the goal of better predicting low lake levels and avoiding reductions in downstream flows.

A specific focus will be on trying to understand why the lake level fell so low in 2012 and whether that low level could have been avoided. In 2012, no triggers were called until the lake fell below 791 ft., necessitating significant reductions in Leesville releases at the end of the year. The figure shows actual SML lake levels for 2012. The remainder of these slides will use adjusted lake level, which is the level SML would be if all the water in Leesville above 600 ft. were pumped up to SML. Adjusted lake level is from an analysis perspective the easiest way to measure total water level changes in the two lakes (SML and Leesville) and does not imply anything about how the water is distributed between the two lakes.
Note: Adjusted lake level in the following analysis is calculated using the 2006 survey data for the Smith Mountain and Leesville lakes. It is assumed that surface area is directly proportional to lake level in the 790 to 795 ft. range for SML and the 600 to 613 ft. range for Leesville. This is equivalent to assuming that the lake bottom is a straight slope in these depth ranges. Integrating then gives lake volume as a quadratic in lake height. The water balance models described later then calculate changes in lake volume which can be converted to changes in lake height by solving this quadratic equation. The adjusted lake heights calculated this way do not exactly match the lake heights published by AEP, but the differences are always small, typically less than 1 inch. This is considered a negligible error at this point and is not further considered in this analysis.

Four Major Topics ae Addressed (3)
This analysis will focus on 3 major areas of interest: how well the current protocols that control Leesville releases and downstream flows can be met, identifying the major factors that control lake level and assessing whether the accuracy of the current predictive model can be improved. Finally, the significant analysis results will be presented and remaining issues and questions identified.

Trigger Points for Reducing Leesville Discharges (4)
The 3 trigger points that will lead to reduced Leesville discharges are shown here. Trigger 3, the lake falling below 791 ft adjusted height, can occur in 2 different ways. It can occur subsequent to a trigger 2 being called or it can occur simply by the lake falling below 791 ft. after September 30. This second condition does not have a probability associated with it and is what actually occurred in 2012; the current predictive model did not call either trigger 1 or 2 in 2012. As a side note, a trigger 1 event also implies at least a 20% probability of the second condition for trigger 3 will occur within 16 weeks.

Since the current protocols were adopted, Bedford has obtained a permit to withdraw drinking water from Smith Mountain Lake. As part of this permit, the Bedford Regional Water Authority is required to implement a number of actions if the lake falls below 791 ft, including projecting the Project water needs and available water supply for a ninety-day period from the date of the declaration of the Trigger 3 event, assessing vulnerability to the drought conditions and adjusting water usage, and inspecting water delivery system components..

Given the impact of a trigger 3 event on Bedford, it would seem appropriate to consider modifying the trigger point definitions to include a probability prediction for a trigger 3 (second condition) to occur.

Low Smith Mountain Lake Levels (5)
This slide shows the actual SML adjusted levels on a daily basis from 1995 to early 2013. Assuming the lake stays high through 2014, which it has, these data show trigger 1 levels occur approximately every 7 years and trigger 3 levels about every 4 years. The one caveat is that these results are based on the actual discharges from Leesville that occurred during those periods. Since the new protocols were accepted in 2010, the actual Leesville discharges may have been quite different. The subsequent slides will address the impact of these protocol discharges. A major emphasis in this analysis was to determine whether a trigger 1 or the 791 ft. criterion for trigger 3 could be either avoided or predicted with sufficient advance warning. Since the 790 ft. criterion for trigger 2 is lower than these levels, it is not explicitly addressed in this slide.

What Would a Perfect Predictive Model Do? (6)
A major difficulty in this analysis has been how to accurately predict inflow to the lakes. Fortunately, there is a simple way to avoid this issue and calculate the inflow that a "perfect predictive" model would have predicted. A basic water balance model would look at the difference between net inflow and Leesville discharges as the sole cause of changes in lake levels. Net inflow includes all inflow terms and all loss terms except for Leesville discharges. Since the lake level changes and the Leesville discharges for a 24 hour average are available daily from 1995 to early 2013, the net inflow can be calculated exactly (within measurement errors) on a daily basis. Since this net inflow represents exactly what happened, it also represents the output of a perfect predictive inflow model.

The calculations can then be done in reverse order to determine what lake level changes would have occurred for different discharges from Leesville. The protocol discharges for the Recreation Flows protocols are shown in the Table (based on the AEP attachment* to the final FERC order of April 19, 2011 and combining the recreation release minimums in Table 4 for June, July and August with the minimum Leesville discharges for September through December in Table 2). These discharge values are calculated using a 4 week month with the minimum discharge increases as specified in the tables and notes (e.g. the requirements for increased releases over weekends and holidays), then converting to an average hourly cfs value.

*Smith Mountain Project 2210 Appalachian Power Company Water Management Plan, June 2010

Effect of Protocol Discharges (7)
With the discharge protocols from the previous slide and the trigger points specified in this figure, the small blue squares show the lake levels that would have resulted. The trigger points specified in appendix B for the AEP Water Management Plan previously cited were used for 1998, 2001 and 2002. For 2008 and 2012, using actual Leesville discharges until the end of September and then going to the discharges shown in the previous Table would have resulted in the lake levels staying above 791 ft. as shown in the figure.

Minimum Lake Levels* vs Leesville Release (8)
This slide compares the actual minimum lake levels (at the end of the month) for various conditions. Column 1 shows the lake levels resulting from the actual Leesville discharges that occurred that year with the lake level falling below 791 ft. 3 times (in 2008, the minimum level occurred in mid-month and was only 1 inch above 791 ft). In column 2, the lake levels that would result from applying the Recreation trigger discharges based on the trigger dates identified in the previous slide are shown; all these minimum levels are above 791 ft. If we have an accurate predictive model that correctly calls trigger points, using the Recreation triggers in column 2 should avoid lake levels falling below 791 ft., except possibly in extreme drought conditions.

Column 3 shows the minimum lakes levels that would result from using the No Trigger Recreation Discharge levels from June to December. Except for 1998, the minimum lake level stayed above 791 ft., and frequently were even higher than the levels in column 2. 1998 was an exception because the actual Leesville discharges in June, July and August were all lower than the recreation limit of 650 cfs. Again lake levels below 791 ft. would still be possibly for extreme drought conditions. (a minor point worth noting is the actual minimum lake levels often occur in mid-month and these are end-of-month values, but the basic conclusions are still the same)

How Good are the Current Protocols? (9)
Based on the previous analysis, the recreation discharge protocols appear able to generally prevent the lake adjusted level from falling below 791 ft. under 2 IFS: (1) there is an accurate probability estimate of a trigger 3 being predicted with sufficient advance notice that preventive

measures can be effective and (2) the recreation discharge levels shown in the earlier slide are subsequently followed. As the previous table indicates, keeping the recreation "no trigger" discharges in effect the entire time from June on also generally keeps the lake level above 791 ft., but there is little margin for error in 2001 and the lake level does fall below 791 ft. in 1998.

Of course, as mentioned earlier, the current protocols do not include a specific probability estimate of the lake falling below 791 ft. Moreover, in severe droughts, lake levels may still fall below 791 ft., but such events would likely be handled by AEP requesting a variance for Leesville discharges.

Major Factors Affecting Lake Levels: Ungaged Drainage Areas (10)
Inflows to the project are based on USGS streamflow measurements at the Rocky Mount, Roanoke and Sandy Level (for the Pigg River). These gaged areas cover 850 sq. miles, about 60% of the total drainage area above the Leesville dam. Total stream inflows into the lakes are estimated by extrapolating these 3 USGS measurements to cover the ungaged area of 624 sq. mi, with a different scaling factor used for each gage.

Low Lake Levels are a Summer/Fall Event (11)
This slide shows that if low lake levels, below 792 ft. occur, they always happen in late summer and lake levels typically don't start falling until June or July. These results suggest accurate predictions of future lake levels become most important in the June to December timeframe. The two low levels in January and February correspond to the 2001-2002 drought and represent a continuation of low levels from the 2001 fall rather than a new event in the January and February timeframe.

Key Terms in Water Balance Model (12)
A balance water balance model looks at the difference between inflows and outflows to calculate the change in SML adjusted height (the level SML would be if the water in Leesville above 600 ft. were pumped back to SML). The Hydrologics inflow estimate uses the 3 USGS gages. 40 cfs are added to the Roanoke streamflow to account for water withdrawals above that gage that are later returned to the river by the water treatment plant below the gage. These gage readings are then linearly scaled to account for the ungaged drainage areas. A 1.18 multiplying factor is then used to fit the post-dam streamflows to pre-dam conditions, and finally this scaled inflow is used in a cubic regression equation to minimize errors between observed lake levels and modeled lake levels in the 1995 to 2008 time period.

The discharge data from Leesville were based on measured Leesville discharges, but there is a question as to whether 24-hour averages are used for the Leesville discharge or a shorter period of only several hours in the Hydrologics model. The correct term for a water balance model is the 24-hour average, which we used. Precipitation on the lake surfaces constituted another inflow term (Hydrologics used Chatham data, we used an average between Rocky Mount and Bedford) and evaporation data from the lake surface was based on pan evaporation measurements (Hydrologics used Philpott Lake data; we used Claytor Lake data since we had the monthly measurements over the entire year; the evaporation difference between the two lakes in the summer is approximately 5 inches/month at Philpott vs. 4 inches/month at Claytor), not a great difference.

Finally there is a loss term attributed to groundwater losses, presumably through the lake beds. The actual nature of this loss term is an open issue that we feel warrants further investigation. Hydrologics estimates a loss term of about 300 cfs, based on the change in the USGS Alta-Vista gage between pre-dam and post-dam flows. We estimated the "groundwater loss" term by requiring conservation of volume of water between mid-2001 and April, 2013 using the Hydrologics linear inflow equation without the 1.18 scaling factor, resulting in a smaller loss around 140 cfs.

What Do Predictions 4 Months Ahead Look Like? (13)

The usual way to test a model is to run it ahead in time using actual data and compare the model calculations with the observed results. This "calibration" testing provides an assessment of (1) whether the important terms have been included in the model and (2) whether these important terms are correctly modeled. This slide shows the difference between the observed SML adjusted height vs. the modeled height using actual inflow and outflow data. The Hydrologics regression inflow is used in these calculations. The slide is titled "Predictions" because the model is started with the observed lake level, then run forward for 4 months using the actual inflow and outflow data, and the resulting calculated adjusted height then compared to the actual observed lake height. 4 months is used since that is about the same as the 16-week prediction time for calling a trigger 1.

The differences between calculated and observed are shown in green as inches on the right-hand scale. The average absolute difference is 7.1 inches, but a number of large differences lasting several months of ± 30 inches are seen. A positive difference corresponds to a model under-prediction of lake level; a negative difference corresponds to a model over-prediction of lake level. For illustration, a 24 inch difference in lake level corresponds to a 683 cfs difference in inflow or outflow lasting a month or a 20,500 cfs difference lasting for 1 day. The large 24 inch positive spike in May 2012 is particularly interesting in light of the subsequent drop in lake level in 2012 and will be discussed in detail later.

Hydrologic Model Fits to Calibration Data (14)

The Hydrologics water balance model also shows similar differences and durations between calculated and observed adjusted lake levels (however, note the difference in vertical scale between this figure and the previous one). A key question for the accuracy of predicting trigger points then became what was causing these large deviations. Was it a missing term or was one of the terms in the water balance equation not accurately handled?

Typical Model Values (cfs) (15)

This table shows the typical sizes of the terms in the water balance model in both summer and winter. The dominant terms are clearly inflow and outflow, while rain and evaporation largely cancel one another. However, during very heavy rain events, inflows can go much higher, to 10 to 20 thousand cfs for short periods, with corresponding larger Leesville releases to keep the lakes from overflowing the spillways.

Factors that were Examined (16)
A number of factors were examined as possible explanations for the observed large deviations. Wind surges or seiches are the result of prolonged high winds causing the water to pileup on one of the down-wind shores. The bank effect was perhaps the largest of these factors and one of the more interesting. As the water level rises, part of the water soaks into the lake banks, resulting in a lake level lower than the model prediction. As the water level falls, the reverse process happens. Part of the water stored in the lake bank flows out into the lake, resulting in a higher lake level than the model predicts. However, none of these factors appeared to be able to produce lake level differences larger than a few inches, well under the 30 inch deviations that were seen earlier. The bank effect may be the one exception since the magnitude of the effect depends on how much water can seep into the surrounding banks and no studies could be found for the magnitude of this effect in humid climates. The impact on trigger points from the bank effect is that a model would predict lower lake levels than actually would occur, thereby potentially calling trigger points unnecessarily early.

The remaining factors– the inflow equation and localized rainfall events– did show a correlation with lake levels and will be discussed in more detail in the following sides.

Testing Drainage Area Scaling (17)
As stated earlier, the Hydrologics inflow model, as well as the earlier Hunt and Meade inflow model, start with the assumption that inflows from the areas downstream of the 3 USGS gages can be estimated by scaling using the ratio of drainage areas. This validity of this assumption is fairly easy to test for the Roanoke River because there are so many gages on it. The Hydrologics scaling equation also adds 39.4 cfs back to the Roanoke River gage to account for water withdrawals to support Salem and Roanoke above the gage. It is assumed this water addition represents the water added back to the Roanoke River by the wastewater treatment plant downstream from the Roanoke gage, thereby better estimating the water actually flowing into the lakes. This slide shows the ratio of observed values of Roanoke River streamflow at the Roanoke gage (corrected for the 39.4 cfs withdrawal) to the streamflow at the Glenvar gage which lies upstream, at the edge of the Roanoke urban development. The horizontal axis in the month of the year and the red triangles are the streamflow ratios for each of the years for that month.

The solid black line is the drainage area ratio for the 2 gages, 1.53. If the streamflows scaled by drainage area and the regions above and below the gages were uniformly affected by the other factors such as meteorological events, the data points should all fall on or near the black line. However, the data show considerable variability from year to year and generally tend to lie above the drainage ratio line, especially during the late summer/early fall period. Because urban areas have more impervious surface area than rural areas, higher runoff might be expected in urban areas. There are also some research papers that suggest the groundwater that does get recharged in urban areas often leaks into storm water drainage pipes and then into the river, further increasing streamflow in urban areas. Since the Glenvar drainage area is more rural in comparison, it may not be surprising that the Roanoke gage reads higher than the drainage area calculation would suggest.

The situation is further complicated by the number of reservoirs that supply water for Salem and Roanoke and Roanoke County. To some degree, it appears these reservoirs are filled in the winter period when streamflows are higher and then used to supply drinking water in the summer period. As a result, the effect is more a time-shifting of water withdrawals from the Roanoke River rather than a constant withdrawal rate. There are also a number of groundwater wells in the Roanoke area that can supply drinking water that will later become an addition to the Roanoke River flow into the lake, but do not constitute an actual withdrawal. These effects may also help explain why the Roanoke streamflow gage drainage ratio is so much higher during the late summer/early fall period.

If these explanations are correct, there are implications to using the Roanoke gage to scale for the downstream drainage, since much of the area from the Roanoke gage to SML is more rural in character. Doing a drainage area scaling is basically assuming the urban drainage characteristic of the Roanoke gage also applies to the downstream area, potentially resulting in an over-prediction of the Roanoke River inflow into SML.

The use of the Niagara streamflow gage further down the river may resolve some of the issues discussed above. Although this gage does lie just downstream from the Niagara dam and would be affected by releases from that dam, it still should be a good representation of the Roanoke River streamflow actually reaching the lake. Any short-term effects from fluctuations in Niagara dam releases would also average out over time.

(Observed-Model) Differences vs Inflow (Regression) (18)

Nonlinear regression fits are often used to minimize errors between fitted and actual data after all the important factors have been included in the model. However, the non-linear regression can obscure the effects of any other factors that have not already been included in the model. We looked for any correlations or trends between the Hydrologics regression inflow and the other factors such as bank effect mentioned earlier, but were unable to detect any clear trends. This slide shows one example comparing the Hydrologics regression inflow plotted against the difference between observed and modeled adjusted lake level, using the regression inflow in the model calculations. Although the height differences seem spread equally between positive and negative values, with no clear trend with inflow levels, there is still a wide spread in the results, with differences ranging from over 20 inches to almost -15 inches. The groundwater correction made in the model to conserve volumes over the 12 year period (2001-2013) was 377 cfs, the same order of magnitude as the 300 cfs cited by Hydrologics.

(Observed-Model) Differences vs Inflow (Linear) (19)

This slide shows the same calculations in the 2001-2013 time period except now using the Hydrologics linear equation, including the 1.18 multiplier, rather than the regression equation. There is now a clear trend in the results, with the model inflow generally too high and the error becoming larger and larger as the model flow increases. All the other terms in the water balance equation, including the groundwater correction of 377 cfs were kept the same to avoid mixing multiple effects.

Height Difference vs. 0.81*Hydrologics Inflow (Linear) (20)
This slide shows the effect of removing the 1.18 factor. Actually a slight over-correction was made to better visually fit the data trend, dividing the Hydrologics linear flow by 1.23 factor rather than the 1.18. The strong linear trend seen in the previous slide is gone and the groundwater correction has dropped to about 81 cfs*. This drop can be attributed to the fact that reducing the inflow rate by a 1.23 factor also reduces the need for a large groundwater loss to conserve volume over the 12 year period. Note the reduction in horizontal scale as well, with the peak flow dropping from about 5300 cfs to around 4300 cfs, again because of the 1.23 factor reduction in inflow.

The 1.18 multiplying factor appears to have been introduced to allow the use of both pre-dam and post-dam streamflow data in the statistical predictions.** However, this same reference also suggests the dam may have changed the geo-hydraulics in the area. As discussed later in the section on issues, we agree the dam may have changed the geo-hydraulics in several different ways. Given the uncertainties of how the dam may have changed the flows, the issues section further discusses possible alternative ways to achieve improved statistics without having to combine pre-dam and post-dam data. Consequently, the remaining analysis will be conducted using the Hydrologics linear streamflow scaling without the 1.18 multiplying factor, unless otherwise noted.

∗ The calculations in the remaining analysis will reduce the linear flows by only 1.18 rather than 1.23, increasing the groundwater loss from 81 cfs to ~ 142 cfs

** From "Flood and Drought Management Low Flow Operating Protocol Report", March 2008, Figure 2

SML 2012 Lake Levels vs Leesville Discharge (21)
The previous analysis suggested the 1.18 factor gives an inflow from the Roanoke, Blackwater and Pigg rivers that is too high for the post-dam period. Since the Blackwater gage has data from only late-1976, the subsequent analyses will focus on only the 1977 to 2012 time period and use the Hydrologics linear fit for inflow without the 1.18 multiplying factor. The question of whether the Niagara gage is a better choice for estimating Roanoke River inflows to the lake is also left as an issue to be addressed at a later time. The next question was whether localized rainfall could explain the large deviations between observed and "predicted" lake heights.

We focused on the 2012 time period for exploring the reason for these large deviations since we were especially interested in explaining the latter drop in lake level in 2012. This slide shows the observed adjusted lake level on a daily basis from April through July vs. Leesville discharges. From April to mid-May, there is a steady trend downwards in lake level corresponding to increased Leesville discharges. This behavior was the result of a faulty downstream gage that caused more water than necessary to be released from Leesville to maintain downstream flows.

However, this problem was fixed by mid-May, several days before the sudden, large increase in lake level, over 1 ½ ft, in mid-May. At the time of that large increase in lake level, the Leesville discharge was fairly constant.

Observed vs. Linear Model Adjusted Height vs. Rain (22)

In this slide, the same SML adjusted height data from the previous slide is reproduced together with the rain, averaging Rocky Mount and Bedford rain data. This slide clearly shows the large increase in lake level occurred at the same time that the precipitation level peaked to 1.8 inches. The water balance model output is also shown, using the Hydrologics linear inflow without the 1.18 multiplying factor and starting with the actual lake level on April 1 and running the model through July without updating with observed lake levels.

The model follows the actual lake level decrease caused by the abnormally high Leesville discharges quite well, even handling the spiking discharges from Leesville, up to the time of the high rain event. At that point, the model predicts only about an 8 inch rise from the rain event, 16 inches short of what was actually observed. After that, the model output still tracks the actual lake level trends, but remains about 16 inches below the actual level.

Inches of Rain on May 13-16, 2012 (23)

This slide shows what actually happened in rainfall in that mid-May period. A large number of meteorological gages had been installed throughout the area after the 2010-2011 time period, allowing a clearer picture of the rain distribution. Inches of rain are shown in red, with the location of the gage at the center of each white box. The dashed area shows a fairly intense rain event, with rain totals of 6 to 8 inches, well above the 2 inches shown elsewhere. Most of this area of intense rain also lies in the ungaged area below the Rocky Mount and Roanoke gages, shown in blue. Calculating the volume of excess rain in this dashed area and assuming it all flows into the lakes (this is equivalent to assuming the other 2 inches of rain has saturated the near-surface ground so all the excess rain is runoff) gives an additional lake level increase of about 18 inches over what would be assumed from the USGS streamflow gages, close to the size of the lake level rise that was actually seen.

Major Factors Affecting Lake Level (24)

The conclusion from the previous analysis is that heavy, localized rain events appear to be the primary explanation for the major, sudden changes in lake level. If the predictive model is re-started after the rain event with the new, higher, lake level, its future predictions should correctly reflect the actual lake height. Had this re-starting been done in the previous example after May 16, the model would have been indicating a lake height about 16 inches higher and would have correctly tracked the future changes in lake height. Since the current predictive model is re-run every three days, there should be no significant effect on predictive accuracy as a result of localized, heavy, rain events. Although the meteorological data is not as dense for the earlier, large deviations seen in slide 13 (e.g. in 2003 and 2005), the limited rainfall data available are at least consistent with the observed deviations in lake level.

Under the assumption that heavy rain events are randomly distributed over the entire drainage area and since the gaged and ungaged portions of the drainage area are roughly equal (actually a 60/40 ratio), heavy rain events should occur above the gages roughly as often as below. A rain event entirely above the gages will lead to higher model predictions than the lake actually reaches, while a rain event entirely below the gages will lead to the model under-predicting lake heights. For rain events that cover both gaged and ungaged areas, the two effects will tend to cancel one another. A reasonable assumption at this time is that there will **not** be a significant bias toward under-or over-prediction of lake heights that needs to be corrected.

As described earlier in slide 16, a number of other factors were also examined as possible explanations for the observed large deviations. Wind surges or seiches are the result of prolonged high winds causing the water to pileup on one of the down-wind shores. The bank effect was perhaps the largest of these factors and one of the more interesting. As the water level rises, part of the water soaks into the lake banks, resulting in a lake level lower than the model prediction. As the water level falls, the reverse process happens. Part of the water stored in the lake bank flows out into the lake, resulting in a higher lake level than the model predicts. However, none of these factors appeared to be able to produce lake level differences larger than a few inches, well under the 30 inch deviations that were seen earlier. The bank effect may be the one exception since the magnitude of the effect depends on how much water can seep into the surrounding banks and no studies could be found for the magnitude of this effect in humid climates. The impact on trigger points from the bank effect is that a model would predict lower lake levels than actually would occur, thereby calling trigger points unnecessarily early.

Can Predictive Accuracy be Improved ? (25)
In terms of improving predictive accuracy, an early hypothesis was that better accounting for ground water in the predictive model would lead to better predictive accuracy. In temperate, humid climates like the eastern US, there is a clear annual cycle in the ground water flow. In the winter, some faction of the rainfall, on the order of 10% on the average, flows directly off into the streams. The reminder soaks into the ground and seeps down, replenishing the sub-surface groundwater. Some of this groundwater can remain at shallow depths in the ground and can flow out into the streams and lakes, while some portion can continue seeping down into cracks and fissures in the bedrock to become deeper groundwater. Since the flow of rainwater into the shallow groundwater region typically occurs faster than this groundwater can flow out into the streams and lakes, the winter period constitutes a groundwater recharge period.

With the advent of the growing season in the spring and summer, the plants generally transpire most of the rainfall that is not direct runoff back into the atmosphere. Groundwater recharge ceases and the remaining shallow groundwater continues to flow out into the streams and lakes at an exponentially decreasing rate. In the early part of the summer, this groundwater flow can be a significant portion of the entire streamflow, and it can be the dominant portion in a low rainfall summer.

The USGS McCabe model is a publically available model on the Internet that models this fairly simple picture of groundwater. For this region, the McCabe model suggested that groundwater recharge generally ceases by April or May. An estimate of the amount of groundwater available at the end of May with a subsequent exponential decrease may then provide an estimate of the groundwater component of streamflow though the summer.

The current predictive model for lake level uses historical streamflow data to predict future streamflows and the probability of specific trigger points occurring. Historical streamflow also implicitly includes historical groundwater flow which was set by the historical rainfall in the previous winter of that year. However, the actual groundwater flow during the current summer should be determined by the prior winter's recharge and should be a calculable quantity, not a statistical variable from historical data.

The initial idea for improving predictive accuracy was to replace historical groundwater flows with estimates of the actual groundwater flows for the current year. This would be done by first using a groundwater model to calculate the winter groundwater recharge for each year in the historical data and then predict the summer groundwater flow for that historical year. Then a prediction for the current year, say 2012, would use the same groundwater model to calculate the recharge in the 2011-2012 winter and then predict the summer 2012 groundwater flow. This 2012 summer groundwater flow would then be used to replace the summer groundwater flow for each historical year, and these modified historical streamflows would be used to predict the probability of specific trigger points occurring.

Where do we get Groundwater Flows? (26)
Testing this groundwater hypothesis requires some way of estimating the magnitude and timing of the winter groundwater recharge and its contribution to the summer streamflow. One way to make this estimate is by a groundwater model, and there are many such models from which to choose. However, as a general rule, the simpler models that are easy to use and require easily available data are likely to be too inaccurate, while the more accurate groundwater models are typically much more labor- and data-intensive. At the time of this analysis, we had the USGS McCabe model available to us which gave a general indication of the timing and magnitude of the winter groundwater recharge, but we felt it was too inaccurate to give streamflow estimates that were sufficiently accurate for making the correction described previously (discussed in the 2013 Ferrum College presentation). While we had access to other, more sophisticated groundwater models such as the Sacramento model used by the National Weather Service, there was insufficient time to get them installed, running and verified in time for the public comments to AEP deadline.

The other widely used way to calculate baseflow (or groundwater flow) is to use a digital filter to separate the low frequency baseflow from the higher frequency direct runoff from rain events. Again there are numerous digital filters available. The one used here is the Eckhardt filter which is available as part of the USGS Web-Based Hydrograph Analysis Tool (WHAT). The Eckhardt filter was first run on the daily streamflow data to separate the base flow from the faster direct runoff flow. The faster runoff flow was then examined to determine rainfall peaks in the time period around the end of May. The rough rule that the effect of direct runoff disappears D days after a rainfall peak, where $D = A^{0.2}$ and A is the drainage area in sq. mi., was then used to identify periods relatively unaffected by direct runoff. For the Roanoke, Blackwater and Pigg gages, this time varies from about 2.5 to 3.3 days.

2008 Roanoke Summer Groundwater Flow (27)
We tested this use of digital filters by first examining a year when there was an actual drought with very low summer rainfall. 2008 was such a year. The continuous blue line shows the 2008 streamflow at the Roanoke gage for 2008. The narrow peaks represent streamflow peaks from local rains and from early May to late June there was very little rain, as evidenced by the largely exponential decay of the streamflow and lack of narrow peaks. The flow is plotted on a logarithmic vertical scale since exponential decay follows a straight line on such a log-linear plot.

We ran the Eckhardt filter* using an exponential decay value, α, and baseflow index (BFI) based on data in a USGS paper.* The BFI represents the ratio of groundwater streamflow to total streamflow. The Eckhardt filter gives baseflow at time t, b(t) in terms of streamflow at time t, y(t) and baseflow at the previous time, b(t-1), using the following equation:

$$b(t) = Ab(t-1) + By(t)$$

where the coefficients A and B are given in terms of α and BFI. Direct rain runoff is then given by the difference between y(t) and b(t). To give the starting transients a chance to dieoff by the start of 1977, we started the filter in 1976.

We then used the 3-day rule mentioned earlier to find a point closest to May 31 that was free from direct runoff and took the value of the baseflow at that time as an estimate of the groundwater streamflow from the winter groundwater recharge. We finally exponentially decayed that value in time to estimate groundwater streamflow through the rest of the summer. The result is shown as the red dashed line which very closely follows the streamflow decay to about the first of July, when rain runoff effects again became evident. If we back-extrapolate, the filter output also follows the streamflow very well to about early May.

The conclusion from this example is that recharge groundwater runoff appears to fairly well describe the actual streamflow decay during low rainfall periods in the late spring-early summer, late May through June. By the end of July, however, the groundwater flow is becoming negligible, representing only about 20% of the total streamflow or less.

* "Estimated Hydrologic Characteristics of shallow Aquifer Systems in the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces Based on Analysis of Streamflow Recession and Baseflow", A.T. Rutledge and T.O. Mesko, USGS paper 1422-B, 1996. From those data, we calculated decay constants, α, of -0.02867, -0.02208 and -0.02022 for the Roanoke, Blackwater and Pigg, respectively, and estimated values for BFI of 0.627, 0.705 and 0.624 for the Roanoke, Blackwater and Pigg, respectively. Technically, we actually used the Boughton filter, which has the same form as the Eckhardt filter and whose constants can be determined from the Eckhardt constants. (See "Technical note: Analytical sensitivity analysis of a two-parameter

recursive digital filter baseflow separation filter" K. Eckhardt, Hydrology and Earth Sciences, vol 16, pp 451-455, 2012)

2012 Roanoke Summer Groundwater Flow (28)
This slide shows the previously described digital filter methodology applied to the Roanoke gage for 2012. The period when the filter baseflow matches the streamflow is roughly mid-May to mid-June, after which rain events begin to dominate, as seen by the spiky behavior in streamflow.

2012 Pigg Summer Groundwater Flow (29)
These are the same results for the Pigg, with apparently more localized rain events in the May-June time period than seen for the Roanoke.

2012 Blackwater Summer Groundwater Flow (30)
Finally the same results for the Blackwater. Interestingly, the Eckhardt decay curve follows the streamflow more closely well into August, with the exception of the large rain event in mid-June. This behavior was not seen in the Roanoke and Pigg cases.

Linear Scaled May Baseflow (31)
We then used the May 31 baseflows for the Roanoke, Blackwater and Pig Rivers together with the Hydrologics linear scaling equation (without the 1.18 factor) to get an estimate of the linear scaled baseflow going into the lake for each year from 1977 to 2012. While the 2012 scaled baseflow at approximately 700 cfs is not the lowest baseflow, it is at the top of in the lowest 1/3 (i.e., 2/3 of the years have a higher groundwater baseflow at the end of May), This is consistent with earlier results from the McCabe model that suggested the groundwater recharge in 2012 had actually occurred earlier than normal, with the result that much of the groundwater had flowed out by the beginning of the summer.

The red squares are the years when the AEP Water Management Report said the predictive model would have called a trigger 1. While many of these predicted events do coincide with low baseflow years, not all of them do (e.g., 1983, 1998). However, just because a predictive model says there is a 20% or greater chance of falling below some lake level doesn't mean that event will actually occur, and vice-versa.

Low Lake Level vs. Groundwater Deficit/Surplus (32)
The impact of groundwater flows on lake level is somewhat more difficult to calculate. The approach adopted here was to obtain an estimate by using an exponential falloff rate of 0.025/day and extrapolating the May 31 groundwater flow from the previous slide back to mid-May to get an estimate of average monthly flow. This back extrapolation amounted to multiplying the May 31 groundwater flow in the previous slide by a factor of 1.5. This mid-May flow with its exponential falloff is then integrated forward in time to get the total volume of water associated with this groundwater flow. The same calculation is then done using the median groundwater flow in the 1977-2012 period. The volume difference between the flow in any year from the median is then calculated and converted to a height difference by dividing

the volume difference by the surface area of the lake. The result is the horizontal graph shown above. Since the median groundwater flow is computed from 1977-2012 data, but we only have adjusted lake levels from 1995 on, there is no requirement that there are equal number of data points above and below 0 ft. in the figure (in the figure, 11 data points are below 0 ft. and 7 data points are above 0 ft.).

As stated above, this calculation provides only an estimate of the effect on lake level and assumes: (1) the digital filter provides a good estimate of the groundwater flow from the winter recharge, and (2) the decline of this groundwater flow can be described by a single exponential falloff factor. Plotting the resulting groundwater height deficit against lowest lake level further assumes that Leesville discharges and rainfall totals are the same every year for this period of time, which they are not. There is no clear trend in the figure between groundwater deficits and low lake levels, and this lack of clear correlation is attributed to year-to-year variability in rainfall and Leesville discharges.

The other point to be taken from this figure is the groundwater deficits are typically only about 2 to 3 ft. at the most, not enough to account for the really low lake levels of 791 ft. or less (recall from slide 11 that the lake level generally is around 795 ft in May, so a lake level below 791 ft. implies a 4 ft. drop), and sometimes low level levels occur with positive groundwater deficits. Moreover, the 2012 groundwater deficit is only about 1.2 ft., not nearly enough to account for the drop of over 4 ft. seen in the actual 2012 lake level by early December.

2012 Adjusted Lake Level vs. Inflows (33)
We are now in a position to examine possible causes of the 2012 low lake level and the impact of winter groundwater recharge on summer lake levels. This slide shows the lake level in blue against the linear calculation of streamflow (inflow) in red and the groundwater baseflow in green. The green baseflow line (extrapolated back to mid-month to allow direct comparisons with the monthly average streamflow) tracks the falloff rate for the streamflow (red line) in June-July and the steep drop in lake level for the same period. So the decay of winter groundwater for 2012 may account for a significant part of the early 1-2 ft drop in lake level, based on the 1.2 ft. deficit shown in the previous slide, from 795 ft to between 794 and 793 ft. in this early time period. However, low groundwater flow in 2012 clearly can't account for the continued drop to under 791 ft. By July-August, the baseflow component has become a small fraction of the total streamflow, around 20% or less.

2012 Adjusted Lake Level vs. Rainfall (34)
This slide proposes a likely answer to what caused the continued drop in lake level in 2012. The observed adjusted lake level at the end of each month is again shown by the solid blue line. The dip in April followed by the increase at the end of May is caused by the faulty downstream gage, resulting in abnormally high Leesville discharges, following by the localized, heavy rain event in mid-May. Following that, the lake level stays high in June, then starts a steady decline that ends with a trigger 3, second condition, called in early December.

The red dashed line shows the rain deficit each month from the historical average while the green dashed line shows the cumulative deficit. From May to November, the total deficit is a little over 8 inches. A deficit of 8 inches of rain over 1474 sq. mi. with a direct runoff of 10% concentrated in a 35 sq. mi. lake corresponds to a height deficit of 2.8 ft, which is a large fraction of the 4 ft lake level decrease seen between May and November.

Two Factors Caused 2012 Low Lake Levels (35)
The conclusions expressed in the two previous slides are summarized here. It would seem these two factors, low baseflow at the start of the summer and a rainfall deficit that continued throughout the summer and fall, acted together in succession to produce the 4 ft. drop in lake level seen in 2012.

Although the influence of summer groundwater flow from winter recharge rapidly decreases in a month or so and appears able to change lake levels by only about 1 to 2 ft. or so, being higher or lower depending on whether the groundwater flow is larger or smaller than normal, the effect can be long-lasting. A characteristic of water balance models is after any event which causes a significant change in lake level, that change in lake level persists far into the future, assuming all subsequent events remain the same. In other words, if low summer groundwater flow in June-July causes a 1 ft. drop in lake level, the lake will still be 1 ft. lower by the end of the year, everything else being the same. Looked at another way, had 2012 summer groundwater flow been closer to the normal level, the lake would have been about 1 ft. higher in December and trigger 3 (second condition) would not have occurred. By the same argument, had the heavy local rain event not occurred in mid-May, the lake would have almost 2 feet lower by December, with the result that a trigger 1 would almost certainly have been called before then.

Can Predictive Accuracy be Improved? (36)
So far the emphasis has been on understanding and calibrating water balance models to determine the important factors controlling lake level and how accurately lake levels can be "predicted" using known data. Actually predicting lake levels into the future requires a prediction for all of the terms in the water balance model. Historic data can be used for the rainfall and evaporation, and these are not major terms, except for the occasional heavy localized rainstorm. Moreover, these two effects partially compensate each other, as seen earlier, and re-initializing the predictive model should eliminate any bias introduced by local, heavy storms. The "groundwater loss" is considered to be a constant loss term by virtue of how it is derived, so it is basically a constant. The real issue for accurate predictions becomes how future streamflows are predicted and what values are assumed for Leesville discharges.

Hydrologics uses historical streamflow data to generate a series of synthetic streamflows which are then used to project lake levels forward in time and calculate the probability of the lake level hitting a trigger point. Technically, the model they describe appears to be an autoregressive model where next month's stream flow is a linear combination of several prior month's streamflow and an error term*. For statistical reasons, the model uses the natural logarithm of streamflow rather than streamflow directly. They determine the appropriate linear multipliers for each month of the year for all years in the historical record using a linear least squares fit, and then the errors for each year of that month. This error or noise term is calculated as the difference between the average predicted flow and the actual flow for that month for each year in the historic record. They include the possible effect of correlations in the errors from month-to-month by doing forward predictions using only error data from the same year. This extrapolation procedure replicates the procedures described in Hirsch's 1981 paper.**

The other major parameter in a predictive model is the value used for Leesville discharges in the future months. Hydrologics has stated they calculate a release from Leesville needed to meet the Brookneal minimum flow requirements using an estimate of the additional inflows between the Leesville dam and the Brookneal gage, a drainage area of 930 sq. mi. and they have provided us the methodology and equations that they use for making these predictions. We have made these calculations for the Leesville discharge for the June to December period for each of the low lake years (1998, 2001, 2002, 2008 and 2012) and found the required release from Leesville has always been less than the minimum release required under the current protocols, and generally significantly less. According to the methodology, when this occurs the minimum required Leesville releases discussed earlier are used for making predictions.

Consequently, in the predictive runs in the following slides, it is assumed the predictions are made using the Recreation "no trigger" releases shown earlier in slide 6. We also used the two previous months in determining the coefficients for the autoregressive model since the lagged correlation coefficients of streamflows fell off significantly after a 2 month lag (e.g., June flows are estimated using a linear combination of April and May flows).

* "Using Streamflow Forecasts to Improve Real-time Drought Management", B.J. McCrodden, D.P. Sheer and D. Randall, 2008 , http://www.hydrologics.net/publications.html
** "Stochastic Hydrologic Model for Drought Management", R.M. Hirsch, Journal of the Water Resources Planning and Management Division, pp 303-313, 1981

Leesville Monthly Average Releases (37)
The next issue is what values to use for Leesville discharges in a predictive. Since the new protocols were adopted in 2010, it is not clear the earlier historical data for Leesville discharges are appropriate for use in a predictive model. This slide shows the average monthly discharges from Leesville for 2010, 2011 and 2012 compared to the Recreation No Trigger Discharges shown in green on the lower curve. It is clear that the actual discharges always exceed the minimum allowed levels, particularly in the later parts of 2010 and 2011. These higher discharge levels in 2010 and 2011 can be traced back to rainfall and inflow surpluses in those periods, though it is not clear why the Leesville discharges had to increase since both of these periods were characterized by low lake levels (see slide 5).

As discussed in the previous slide, the current predictive model apparently uses the minimum discharges in calculating future lake levels. However, since the actual discharges have always exceeded those minimum levels, predicted levels will always be higher than the actual lake levels. The question is by how much. The next two slides examine this question for predictions using the minimum levels (the solid green line), the average value for the 2010 to 2012 period (the solid black line) and the actual discharge that occurred in 2012 (the dashed red line).

Probability a Trigger 1 will Occur in 2012 (38)
Using the model previously described, this slide shows the probability that the lake level will fall below 790.5 ft in the next four months in 2012, starting with the June-July-August-September period. If the recreation release protocols are followed, the probability never gets close to the 20% point for a trigger 1, potentially explaining why a trigger 1 was never called in 2012. On the other hand, if the historic average for actual Leesville discharges for recent years are used in the predictive model, the results are very different. The historic Leesville discharges are limited to the years 2010 to 2012 since it was considered likely that the actual Leesville discharges had changed to match the new trigger protocols. In this case with historical discharges, a trigger 1 occurs at the beginning of the ASON time period, with a probability of 30%, well above the 20% threshold. For comparison, if the actual discharges that would be released in 2012 were known in advance, the predicted result would be the green line shown in the middle. Unfortunately, such advance knowledge is not available.

Probability Lake will Fall below 791 ft. in 2012 (39)
This slide shows the same calculations except the probability is now that the lake level will fall below 791 ft. within the next 4 months in 2012. Again, following the recreation release protocols, the lake level has little chance of falling below 791 ft. Using the recent historical discharge data ,however, changes the picture significantly. Now the probability is over 35% by the start of the JASO time period, a month earlier than the previous slide. This is well in advance of the October deadline shown earlier when the release protocols needed to be adopted to keep the lake level above 791 ft. However, as noted earlier, there is no probability value set in the current trigger protocols for calling a trigger 3 (second condition). Again the results for the actual 2012 discharge data are also shown, although such advance knowledge would not be available at the time. The probabilities of falling below 791 ft. are between 15 and 20%, although the current triggers do not contain a probability level for the occurrence of this event.

Discharge vs Linear Flow (40)
The previous two slides showed the probability of low lake levels increased significantly if actual Leesville discharge values rather than the minimum values were used in the predictions. This behavior raises the question of how Leesville discharges vary with inflow levels. Even though the discharge protocols did change in 2010, it is instructive to examine the relationship between inflows and Leesville discharges from 1977 on. This slide shows the relationships for each of the 4 month periods from June on, using the Hydrologics linear inflow equation without the 1.18 multiplier. The inflows and discharges are shown as cfs-days, taking the monthly average flow in cfs and multiplying by the number of days in the month, in effect giving the total volume of inflow and discharge that occurred over that 4 month period.

In all four periods, there is a very clear linear trend between higher inflows and higher discharge levels, with the red line in each case being a linear least squares fit to the actual data. Since the current predictive model uses synthetic streamflows that do cover higher inflow periods, it would appear that the Leesville discharges during those periods should also be higher to reflect this relationship and more accurately predict the expected lake level. Using the minimum discharges instead would appear to over-predict future lake levels and potentially miss predicting low lake levels and calling triggers, as suggested by the two previous slides. Unfortunately, it is not obvious right now how the actual Leesville discharges should be adjusted in order to be correctly paired with the synthetic inflows.

November 2012 Lake Level Predictions (41)
There are two issues to be examined. First, does using the linear scaling relationship shown in the previous slide to match Leesville discharges to the synthetic inflow provide a more accurate prediction of lake level? Second, does using the linear scaling relationship change whether a trigger point would have been called in 2012?

The histograms shown above provide a positive answer to the first question. The top histogram shows the August-September-October-November (ASON) lake level predictions for the years 1977 to 2011, using the linear synthetic streamflows and the minimum no trigger discharges from Leesville. The lake level predictions at the end of November are binned, with the bin label representing the upper bin limit (e.g., the 791 ft bin represents all lake level predictions falling between 790 ft and 791 ft). The actual lake level at the end of November in 2012 was actually 790.7 ft, shown by the black arrow. Lake levels well in excess of 797 ft occur in these simulations since no spillway limitations were imposed. We did examine the effect of limiting adjusted lake level to 795 ft, assuming any higher water levels could not occur because of spillway overflow, and the results were largely unchanged. Although all the data points in the histogram in the 796 ft bin and above are now compressed to the 795 ft bin, still only one predicted lake level lies in the 790-791 ft bin that was actually reached in 2012. Not unexpectedly, using the minimum discharge levels with synthetic inflows produces predicted lake levels much higher than actually reached.

The lower histogram shows the results of running the same simulations, using the greater of either the minimum no trigger Leesville discharge or the scaled discharge using the linear scaling relationship from the previous slide. All of the predicted lake levels now fall in a much narrower range, from 790.5 ft to 793 ft, with the large majority falling between 792 and 792.5 ft. The predicted levels are clearly much more accurate, now falling much closer to the actual 790.7 ft level reached at the end of November, 2012. So using the linear relationship seen in the previous slide between inflows and Leesville discharges does produce more accurate lake level predictions.

However, the answer to the second question is in the negative. Although the lake level predictions are now more accurate, they are still about 1 to 2 ft. higher than the actual level reached at the end of November of 790.7 ft. Examining the lower histogram shows there is a 0 % chance of calling a trigger 1 at the beginning of August, which requires a prediction of a 20%

chance of falling below 790.5 ft. These results suggest that other factors in addition to predictive accuracy are important in determining whether the lake level will fall below a trigger point.

Lowest Lake Level vs. Rainfall Surplus/Deficit (42)
Since the rainfall deficit in the second half of 2012 seems to be the primary reason for the resulting low lake level in 2012, a logical question is whether there is a correlation between rainfall surplus or deficit and the resulting lowest lake level. The slide shows the lowest lake level that was reached in the June to December timeframe for each year from 1995 to 2012, plotted against the rainfall deficit or surplus from the historical average for that year, equally weighting rainfall at Roanoke, Rocky Mount and Bedford. As was done with groundwater, rainfall surplus or deficit from the historical average is converted to a change in lake level, assuming a 10% runoff factor, and plotted as the horizontal axis of the figure. Even though the data show considerable scatter, there does appear to be a clear trend with the lowest lake levels corresponding to a significant rainfall deficit.

This behavior suggests that seasonal precipitation predictions might provide another indicator for the possibility of low lake levels occurring by the end of the year. It turns out that the NOAA Climate Prediction Center (CPC) makes such predictions for the next 3 months on a monthly basis, with more frequent updates as appropriate.

Lowest Lake Level vs. Rainfall and Groundwater Surplus/Deficit (43)
Before examining the NOAA CPC predictions, it is worth comparing the effects of groundwater surplus/deficits against those for rainfall on lake level. This figure shows the Groundwater and Rainfall Surplus/Deficits for the 1995-2012 period for 5 ranges of lowest lake level. With two exceptions, lake levels are above 792 ft. for all years with a rainfall surplus, regardless of the groundwater surplus or deficit value. The lowest lake levels, less than 791 ft., all occur for rainfall deficits. In the lower left quadrant of the figure, groundwater deficits appear to combine with smaller rainfall deficits to produce low lake levels. However, twice the lowest lake level occurs in the upper left quadrant, where the increased rainfall deficit seems to dominate over the groundwater surplus. Although other factors such as Leesville releases also affect these results, the figure suggests that groundwater and rainfall deficits may reinforce one another, but the rainfall deficit in the June-December time period is the primary factor leading to low lake levels.

U.S. Seasonal Drought Outlook (44)
This slide shows the predictions made by the NOAA Climate Prediction Center for 3 of the periods in 2012. Each prediction was released on the first date shown in the time period. In particular, the Jul 5- Sep 30 prediction in the center, released on Jul 5, suggested that drought development in the Roanoke area was likely, with existing drought areas predicted to the south and west of the Roanoke area. While the Roanoke area never became a drought region in that year, the proximity of drought areas would suggest the likelihood of reduced rainfall in nearby regions such as the SML/Leesville drainage areas. Moreover, as shown in slide 34, it doesn't

require a major rainfall deficit, but only about 1 inch/month shortfall on a continuing basis to create a significant drop in lake level.

Recommendations (45)

The previous analysis results indicate that changing what the predictive model uses for future Leesville discharges can increase the accuracy of the predictions of lake levels in the summer-fall time period. Currently the model calculates an assumed Leesville discharge by estimating inflow between Leesville and Brookneal and calculating a Leesville release that would be needed to meet the Brookneal minimum flows. In the June to December period, this guidance becomes equivalent to following the minimum releases required by the current protocols. However, the actual Leesville discharges are typically higher than these minimum discharges. It is recommended that the historical average discharge values since the new protocols were adopted in 2010 be used instead. It is recognized that sometimes historical Leesville discharges in the post 2010 period from June to December are significantly higher than the minimums because of higher inflow levels; how to properly correct for such instances is an issue that is discussed on the next slide.

The analysis also suggests maintaining closer adherence to the minimum discharges for Leesville as specified in the Water Management Plan will help avoid reaching a trigger 3 condition. However, it is recognized that this can be operationally difficult for 2 reasons: the difficulty in accurately measuring Leesville discharges within a few cfs and the consequences for AEP of falling below the required minimums. However, these difficulties may possibly be mitigated since the need to stay near the minimum discharge protocols is necessary only in the years when a significant rainfall deficit is expected for a long period of time (see the Issues slide).

We also believe the trigger protocols need to include a probabilistic prediction for lake levels dropping below 791 ft., but this is primarily an issue for the Bedford Regional Water Authority to address. Since the Bedford Regional Water Authority would be most affected by such a trigger 3 event, it seems appropriate that they would be the party to request such a change and choose the appropriate probability value.

We request that the Department of Environmental Quality renew the AEP permit for the next 5 years and review our recommendations and issues for accuracy, feasibility and completeness (DWQ).

Finally, we believe the preceding analysis has raised many issues and questions that are identified in the next two slides. As a result, we feel that it is important the predictive model performance continue to be monitored and assessed over the next 5 years and the gains offered by possible improvements, described in the next slide on Issues, be evaluated (SMLA)

Issues (46)

This analysis has also identified a number of issues that we believe need to be addressed over the next five years. Low rainfall deficits appear to be a major factor in explain low lake level events and may be a good advance indicator of such occurrences. These rainfall deficit/low lake events appear to occur only about once every 5 years and the drought predictions published by the NOAA Climate Prediction Center (CPC) may help identify those years in advance. The feasibility of using these predictions as an indicator of low lake years should be examined. If a good advance indicator of low lake years can be found, it is only for those years that AEP would need to stay as close as possible to the minimum Leesville discharges specified in the Water Management Plan.

The importance of summer groundwater flow to later lake levels is still an open issue and needs to be examined further. There are a number of groundwater models available that may give better estimates of the winter groundwater recharge and its contribution to the summer groundwater flow into the rivers. The Sacramento model may be particularly interesting since it is currently used by the National Weather Service and allows two groundwater flow components, each with its own decay rate. We also have concerns that the digital filter separation method used in this analysis may still include too much of an effect from rainfall events, in addition to allowing only a single decay rate for the baseflow portion.

The possible interaction between rainfall deficit and groundwater deficits deserves further examination. Based on the very limited data we have been able to examine, it appears that moderate deficits for both rainfall and groundwater can be additive, leading to lower lake levels, near or lower than the trigger points. However, the groundwater deficit alone is limited in effect, causing a lake drop of only around 2 ft, while rainfall deficits can have a much larger effect. The result appears to be that large rainfall deficits can even override groundwater surpluses, leading to low lake levels that can cause activation of trigger points. If this linkage is correct, groundwater deficits, which are known by the end of May, may serve as an early warning indicator for the potential of a low lake level year.

Another issue is the impact of correlations between inflows to the lakes and the Leesville discharges. Guidance to stay near the minimum discharges specified in the protocols without considering the inflow levels is equivalent to assuming the inflows and Leesville discharges are statistically independent, which they are not. While the inflows are totally controlled by natural events and the Leesville discharges are, to an extent, controlled by human decisions, the two factors are not as independent as this might suggest. The correlation between monthly inflows, using the linear Hydrologics inflow equation, and monthly Leesville discharges from 1977 to 2012 is 0.96. Limiting the months of interest to only June through December for the same 36 year period drops the correlation to only 0.93. A high correlation value, near 1, typically suggests that that the discharge values are largely determined by the inflow values. Of course, it is not surprising that the Leesville discharge is very closely related to the inflow level. For high inflows, high discharges are required to keep the lakes from overflowing the spillways. During low inflow periods, typically June through December, Leesville discharges are also reduced, in part because of lower release protocols and probably in part to keep the lakes sufficiently full to generate electricity when needed. The question is to what degree this correlation must be accounted for when using historic streamflows in a statistical predictive model. For example, a few high rain months with the associated higher inflows occurring late in the year can bias the post-2010 Leesville discharges higher than normal. This higher discharge level can then result in calculating a higher probability for a trigger than actually exists, while a compensating effect during low rain/inflow months cannot occur because of the discharge minimums. Some further analysis is needed to determine if this behavior represents an important bias and, if so, how to correct for it.

Alternate methods for generating synthetic streamflows should also be considered. The current method used by Hydrologics apparently relies on historical streamflow data to calculate the random noise terms and pre-dam and post-dam records are combined to generate a larger historical database to do this. However, questions about the Alta Vista gage have been raised by several investigators and this gage has been key in linking pre- and post-dam streamflow records. Making this linking has also been the reason for the approximately 300 cfs groundwater loss term introduced by Hydrologics, as well as the 1.18 multiplier for post-dam streamflow. There may be alternative approaches for calculating synthetic streamflows that avoid these difficulties. Specifically, it appears that a major advantage of synthetic streamflows is that once estimates for the variance of the noise term and the coefficients for the streamflows are determined, any number of synthetic streamflows can be generated by using a random number generator for the noise term. Moreover, doubling the amount of data for determining these variances and coefficients typically only reduces the error by a factor of $1/2^{½}$. It's not clear if this roughly 30% increase in accuracy is worth the additional uncertainties introduced by trying to combine pre-dam and post-dam data, for the reasons discussed below. We also understand one reason Hydrologics wants the larger historical record is to deal with possible correlations between the errors from month-to-month that they have found necessary in modeling drinking water supply reservoirs. However, since SML/Leesville is primarily designed for pump-back power generation rather than a water supply reservoir, this month-to-month error correlation may not be significant. One way to examine this issue is to look at how random the month-to-month error sequences are for each year in the post-dam period.

The addition of 40 cfs to the Roanoke gage to account for upstream water withdraws for Roanoke and Salem should be reconsidered. This 40 cfs addition presumably is intended to account for the water treatment plant releases back to the Roanoke River below the Roanoke gage. However, the limited data available that we have found on those treatment plant releases suggest the average release from the water treatment plant is close to 58 cfs* and the releases may come as major surges. Moreover, much of the Roanoke and Salem water appears to come from reservoirs that are filled during the winter season, and there are also a number of groundwater wells used for water in the Roanoke area. All of these factors suggest an appropriate correction may be more complicated than simply adding 40 cfs to the Roanoke flow on a monthly basis.

The use of the Niagara gage rather than the Roanoke gage should also be considered. This gage lies below the water treatment plant and thereby avoids the 40/57 cfs issue just discussed. There is also some evidence that gages in urban areas like the Roanoke gage can display an urban bias because of different rain runoff characteristic of urban areas. Extrapolation of an urban gage streamflow to rural downstream areas may then produce erroneous results. Moreover, the Roanoke gage in the center of Roanoke can capture only a portion of this urban bias while the Niagara gage captures the full amount. Eric Anderson, a retired Hydrologist from the National Weather Service, has also examined the various USGS gages and developed a set of gage combinations that avoids using gages like the Roanoke and the Niagara gage, both of which may have urban biases, to extrapolate to the ungaged drainage area. His scaling uses the Niagara gage, but does not extrapolate it to predict downstream flow, avoiding the urban area extrapolation issue discussed earlier. He has also developed scaling equations for other gage combinations as well to cover the entire period from 1930 to the present time. His papers are available upon request.

We believe the groundwater loss term should also be re-evaluated. We have been unable to find any papers or other research that suggest such a large loss term for lakes or reservoirs. The few papers that address the issue also suggest that the inflow of sediment to the lake or reservoir should gradually seal the cracks and fissures, slowly reducing any groundwater loss. One factor supporting the concept of the groundwater loss term is the effect of the dam on local geology; specifically, the higher water level behind the dam will produce greater hydrostatic pressure on the old river beds and the higher water levels may find new leaks in the mountain around the sides of the dam. However, the dam has also produced other changes as well. In particular, the dam has added a 35 sq. mi. lake surface for evaporation that did not exist before. While the water balance models currently see the rain falling on the lake as effectively having a 100% direct runoff, so local rainfall largely offsets evaporation, particularly during the summer, this may not be true. The sides of the lake down to the old river beds are fairly steep slopes, and direct rain runoff can be much higher on slopes, 30% or more. The result is the dam has added a major evaporation term, 4 inches/month or about 100 cfs in the summer, and it is not clear all of the rain falling on the lake surface represents new runoff that did not exist before the dam. In short the dam may also have introduced a new net loss term from evaporation that can be on the order of several tens of cfs. This is a substantial part of the 140 cfs loss that is seen with the linear inflow term for the water balance model. The dam may also have affected the groundwater flow from the Franklin and Bedford counties into the lake region by raising the overall water table.

Finally, the water balance model also assumes evaporation losses depend only on the month of the year. It is well known that other factors such as wind speed, air and water temperatures and humidity profiles above the water surface all affect evaporation rates. There is the possibility that hot, drought-prone, summers may also have higher evaporation rates than assumed here, further exasperating the problem of low lake levels.

*
http://www.westernvawater.org/85256a8d0062af37/vwContentByKey/N2628UFG962PLESEN

Questions (47)

Hydrologics has been extremely helpful in providing a description of their methodologies and many of the equations they use for calculating the various terms in their predictive model. However, we are not sure we are properly replicating their methods with actual data--- are we using the same data, are we implementing their methodology in the correct way, are we using the right techniques to determine parameter coefficients, etc. For problems of this complexity, the uncertainties can compound quickly. Consequently, it would be extremely helpful if we had a copy of the actual predictive calculations currently being used. Specifically, the actual terms and coefficients for the synthetic streamflow model, the evaporation and rainfall terms and the inflow calculations for pre-1977, before the Blackwater gage was installed would be extremely useful.

Finally, the post-1995 data suggest there is a clear correlation between rainfall deficit and low lake level years, suggesting NOAA CPC drought predictions may provide another early warning for the occurrence of a low lake level event. In addition, groundwater deficits can possibly act together with moderate rainfall deficits to produce low lake levels, near or below the rigger points. Consequently, it would be very informative to see whether this trend occurs in the earlier years after the dam was installed. Access to the AEP adjusted lake heights for the period 1967 to 1994 would allow these issues to be examined.

SMLA Says Thanks to: (48)

Finally we would like to recognize and thank all the participants for their support in this effort. The results of this analysis, the recommendations and the issues have been reviewed by The Smith Mountain Lake Board, the Smith Mountain Lake Council and the Tri-County Lakes Administrative Commission (TLAC). These results, issues and recommendations have also been shared with Hydrologics, Appalachian Electric Power and the Bedford Regional Water Authority.