A Water Budget Assessment For Poland Spring in Hollis, ME

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1. Introduction

In the year 2000 Poland spring finalized and completed a water bottling plant in Hollis, Maine. At the time it was one of the largest bottling plants, capable of supplying almost a million cubic meters of water annually. Setting up a spring water bottling plant requires a permit application in the state of Maine. Part of the spring water permitting process required Poland Spring to create a groundwater flow model, which the DEP used to set a yearly extraction volulme. The Maine Department of Environmental Protection capped Poland Spring's water withdrawel to approximately 900,000 m^3 per year at the Hollis site (Poland Spring, 2014).

The Clear Spring watershed experiences a mean annual precipitation of approximately 9,150,000 m^3 (United States Geological Survey, 2020). The annual precipitation is generally much much higher than the amount of water Poland Spring is allowed to withdraw. However, precipitation alone is not the only important factor. Discharge, evapotranspiration, and groundwater flow are also important to consider.

Discharge is important because municipalities often source their water from surface sources (Maine Geological Survey, 2013). Similarly, evapotranspiration is important to consider because 30-40% of annual rainfall will be lost to it. Groundwater flow is the most difficult to characterize, but the movement of groundwater has a huge effect on the impact of groundwater withdrawel.

While Poland Spring did their own watershed analysis, and continues to maintain their own water resources, much of the information is not publically available. *Figure 1* shows groundwater elevation data and precipitation data published by a Poland Spring monitoring report from 2018.

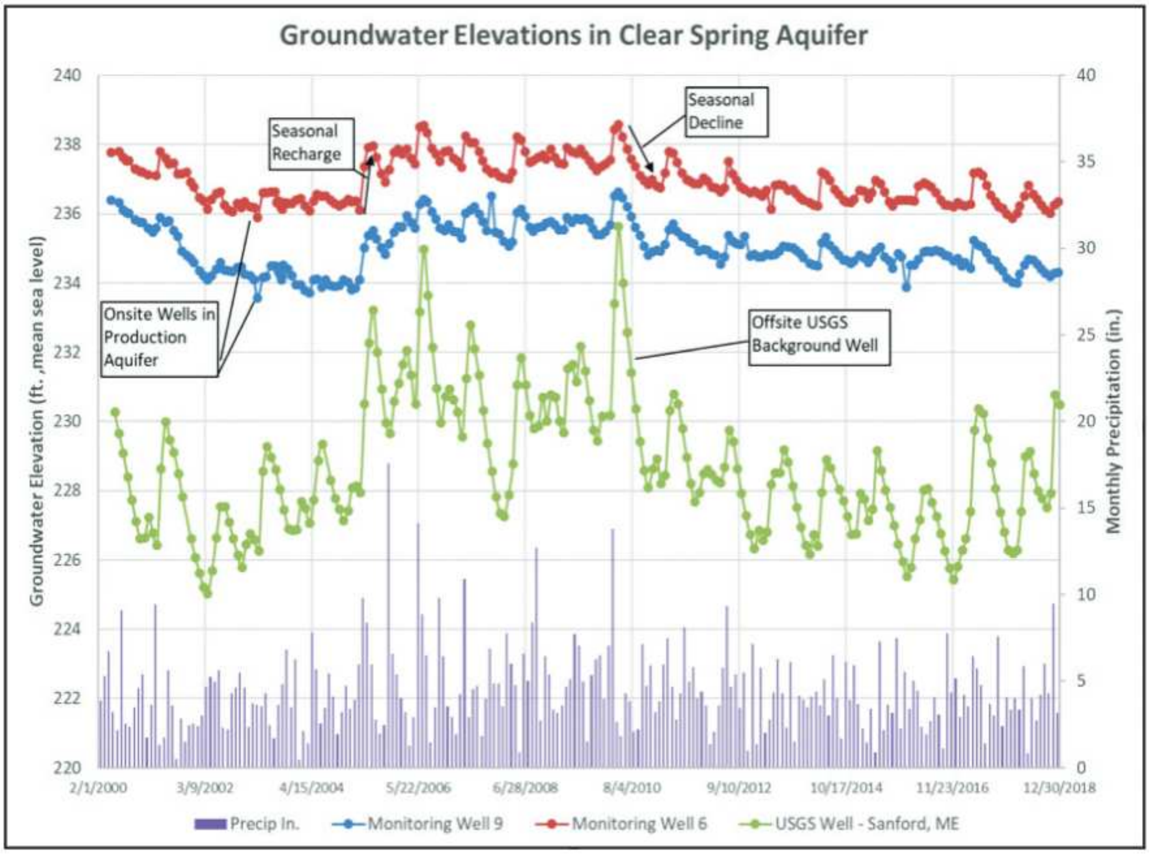

Figure 1: Groundwater elevations in the Clear Spring Aquifer from 2000 to 2018 (Poland Spring, 2018).

Although Poland Spring does publish groundwater elevation data from their wells, they do so only in these monitoring reports without accompanying raw data. Poland Spring publishes similar discharge data, though once again they do not provide the raw data. Poland Spring also does not collect or publish evapotranspiration data. Precipitation data is already publically available from the National Oceanic and Atmospheric Administration.

The most important point to be taken from *Figure 1* is that according to Poland Spring's data, the groundwater level in their wells has hardly changed in twenty years. There have been fluctuations spanning roughly five years, but the wells have always remained within 234-236 ft (71.3-71.9 m) above sea level. However the long-term groundwater data alone does not account for the short-term withdrawal effect during wet and dry periods. The goal of this study is to produce a more expansive water budget analysis for the Clear Spring watershed in Hollis, Maine.

2. Methods

The town of Hollis is located about thirty kilometers west of Portland, in southern Maine. Poland Spring wells in the area intercept water from Clear Spring, located in the Killick Pond and Wales Pond Brook watershed, outlined in *Figure 2*.

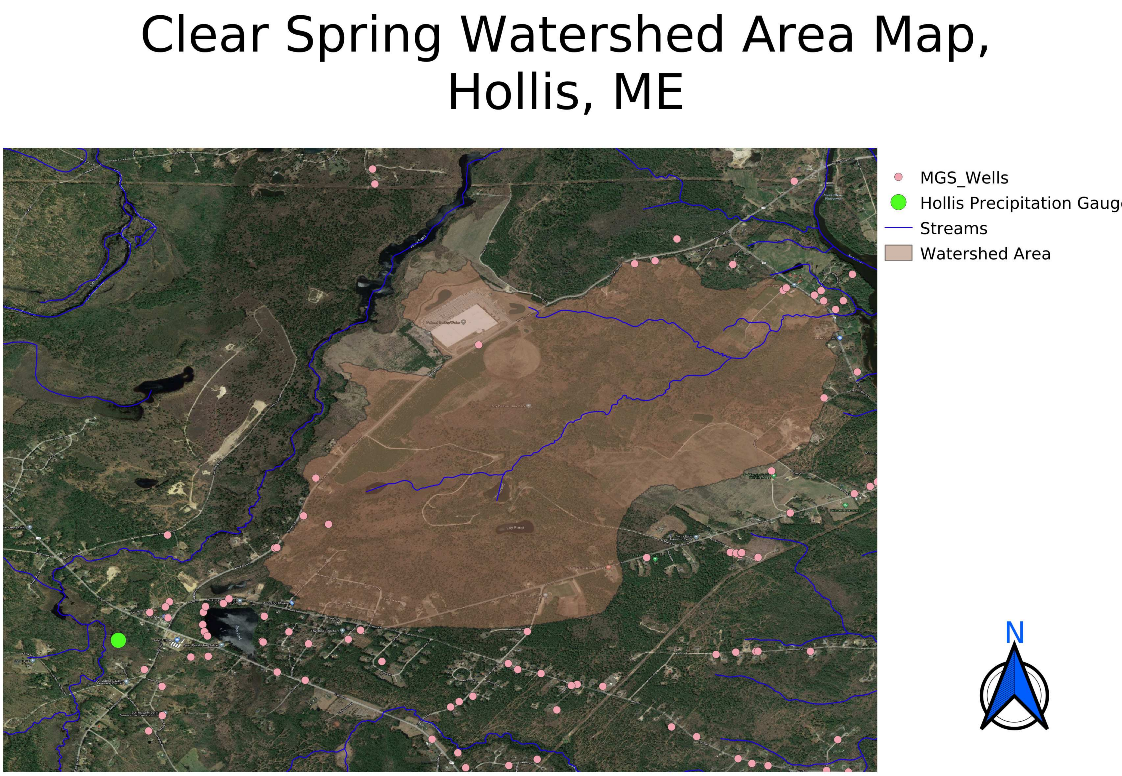

Figure 2: Map of Killick Pond and Wales Pond Brook Watershed. The watershed has an area of approximately 8.029 km^2. Maine Geological Survey wells are represented by the pink dots. Not pictured are the USGS groundwater monitoring well in Sanford, ME, the USGS discharge guage in East Sebago, ME, and climate stations located in Sanford, ME and Durham, NH.

Watershed budget analysis is derived from the following equation:

$$\frac{ds}{dt} = P + GW_{in} - Q - ET - GW_{out} - Q_{PS} \pm \delta \tag{1}$$

where $\frac{ds}{dt}$ is the change in storage, P is the precipitation in the watershed, GW_{in} is the flow of groundwater into the watershed, GW_{out} is the flow of groundwater out of the watershed, Q is the discharge flowing out of the watershed, ET is the evapotranspiration of the watershed, Q_{PS} is the human usage of water in the watershed (i.e., withdrawel from Poland Spring), and δ is the unaccountable residual. Calculations were performed for the 2016 and 2018 water years, which were a dry year and a wet year, respectively. 2016 had a particularly dry summer and 2018 had a particularly wet summer.

2.1. Precipitation and Discharge

Daily precipitation data was sourced from a precipitation gauge located in Hollis, ME (GHCND:USC00173862), which is displayed in the map in *Figure 2*. Sub-hourly discharge data was sourced from a USGS discharge gauge located in East Sebago, ME (USGS 01063310). Discharge data was provided by USGS in cubic feet per second; these numbers were converted to mm by dividing by the watershed area. All other stations used in this study recorded hourly data. Discharge data and other records were integrated to produce daily values for calculation with precipitation data.

2.2. Evapotranspiration

For calculating evapotranspiration, hourly data was sourced from NOAA stations located in Sanford Regional Airport, ME (LCD WBAN64709) and Durham, NH (CRN Durham 2 N). It is important to note that none of the sites listed are within the watershed, as there are no climatological monitoring stations located in the immediate area. The stations chosen are the closest ones available: roughly 20 km northeast (Sanford) and 20 km southwest (Durham).

As the majority of the watershed is vegetation (instead of open-water), the Penman-Monteith equation was used to calculate evapotranspiration. First, several inputs for the Penman-Monteith equation needed calculation:

$$\Delta = \frac{2508.3}{(T_a + 237.3)^2} \exp\left(\frac{17.3T_a}{T_a + 237.3}\right) \tag{2}$$

where T_a is the air temperature in $°C$.

$$K = K_{in}(1 - \alpha) \tag{3}$$

where K_{in} is the measured input shortwave radiation energy and α is the surface albedo.

$$L = \varepsilon_s(2.7e_a + 0.245T_a - 45.14) - \varepsilon_s \sigma T_s^4 \tag{4}$$

where ε_s is the surface emissivity, e_a is the near-surface vapor pressure, σ is the Stefan-Boltzmann constant, and T_s is the surface temperature. Temperatures for *Equation 4* are in Kelvin.

$$\lambda_v = 2.50 - 2.36 \times 10^{-3} T_w \tag{5}$$

where T_w is the surface temperature in °C.

$$\gamma = c_a \frac{P}{0.622} \lambda_v \tag{6}$$

where c_a is the specific heat capacity of freshwater.

$$e_a^* = 0.611 \exp\left(\frac{17.3T_a}{T_a + 237.3}\right) \tag{7}$$

Additionally, the Penman-Monteith equation requires the calculation of values known as *f-values*. The purpose of f-values is for calculation of the time-varying leaf conductance C_{leaf} and the canopy conductance, C_{can}. First, the absolute humidity deficit, $\Delta\rho_v$, is calculated as:

$$\Delta\rho_v = \frac{m_v}{RT_a}(e_a^* - e_a) \tag{8}$$

where m_v is the molar mass of water vapor in $\frac{g}{mol}$ and the air temperautre is in Kelvin. Next the functional relationship between leaf conductance and the absolute humidity deficit is calculated as

$$f_\rho = \begin{cases} 1 - 66.6\Delta\rho_v & \text{for } \Delta\rho_v < 0.01152 \frac{kg}{m^3} \\ 0.233 & \text{for } \Delta\rho_v > 0.01152 \frac{kg}{m^3} \end{cases} \tag{9}$$

Next the functional relationship between leaf conductance and incident solar irradiance, K_{in} was calculated.

$$f_k = \begin{cases} \frac{12.78K_{in}}{11.57K_{in}+104.4} & \text{for } K_{in} < 86.5 \frac{MJ}{m^2 day} \\ 1 & \text{for } K_{in} > 86.5 \frac{MJ}{m^2 day} \end{cases} \tag{10}$$

Then the functional relationship between leaf conductance and air temperature (in °C) was calculated.

$$f_T = \begin{cases} \frac{T_a(40-T_a)^{1.18}}{691} & \text{for } T_a < 40°C \\ 0 & \text{for } T_a < 0°C \text{ or } T_a > 40°C \end{cases} \tag{11}$$

The soil moisture deficit $\Delta\theta$ is necessary for calculating the functional relationship between leaf conductance and soil moisture deficit, f_θ, and is calculated from the soil moisture fraction Θ and the estimated field capacity Θ_{fc} and the soil thickness h as follows:

$$\Delta\theta = \begin{cases} (\Theta_{fc} - \Theta)h & \text{for } \Theta < \Theta_{fc} \\ 0 & \text{for } \Theta > \Theta_{fc} \end{cases} \tag{12}$$

f_θ is then calculated as:

$$f_\theta = \begin{cases} 1 - 0.00119\exp(0.81\Delta\theta) & \text{for } \Delta\theta < 8.4cm \\ 0 & \text{for } \Delta\theta > 8.4cm \end{cases} \tag{13}$$

The time-varying leaf conductance C_{leaf} is calculated by multiplying these f-values together with the input maximum leaf conductance C^*_{leaf}.

$$C_{leaf} = C^*_{leaf} f_K f_\rho f_T f_\theta \tag{14}$$

Then the canopy conductance is calculated as

$$C_{can} = k_s \times LAI \times C_{leaf} \tag{15}$$

where k_s is the shelter factor and LAI is the leaf area index. The Penman-Monteith equation was then ready to be calculated:

$$ET = \frac{\Delta(K + L) + \rho_a c_a C_{at} e^*_a (1 - H)}{\rho_w \lambda_v (\Delta + \gamma(1 + \frac{C_{at}}{C_{can}})} \tag{16}$$

where ET is the estimated evapotranspiration in $\frac{m}{d}$, Δ is the slope of the curve of saturation vapor pressure with respect to air temperature in $\frac{kPa}{°C}$, K is the net incoming short-wave solar radiation flux in $\frac{MJ}{m^2 * day}$, L is the net incoming longwave radiation energy in $\frac{MJ}{m^2 * day}$, γ is the psychometric constant in $\frac{kPa}{°C}$, K_e is the evaporation coefficient in $\frac{s * kPa}{d}$, ρ_w is the density of fresh water in $\frac{kg}{m^3}$, λ_v is the latent heat of vaporization in $\frac{MJ}{kg}$, U is the windspeed in $\frac{m}{s}$, and H is the relative humidity as a non-dimensional fraction. The total evapotranspiration was then calculated. *Table 1* shows the values of the constants used in this study.

Table 1: Constants used for calculation of evapotranspiration (Dingman, 2015).

Constant	Value
α	0.069
z_m	$10\ m$
z_o	$0.9\ m$
z_d	$6.5\ m$
c_a	$10^{-3}\ \frac{MJ}{kg°C}$
K_e	$1.26 \times 10^{-3}\ \frac{s}{kPa \times day}$
ρ_w	$1000\ \frac{kg}{m^3}$
ε_s	0.95
σ	$4.90 \times 10^{-9}\ \frac{MJ}{m^2K^4day}$
m_{da}	$28.97\ \frac{g}{mol}$
m_v	$18.016\ \frac{g}{mol}$
R	$8.31\ \frac{J}{molK}$
h	$100\ cm$
c^*_{leaf}	$100\ \frac{m}{s}$
k_s	0.5
Θ_{fc}	$1.016\ cm$

2.3. Storage and Groundwater flux

Without access to sufficient monitoring wells, groundwater flux was impossible to account for in this study. For calculation, groundwater flux was assumed to be net zero. In reality, the groundwater flow is most likely not zero for such a small watershed. It was, however, possible to account for change in storage using a nearby USGS groundwater monitoring well in Sanford, ME (USGS 432310070393301). Hourly groundwater level data was converted to change in storage using the following equation:

$$\frac{ds}{dt} = \frac{dE}{dt} \times \phi$$

where $\frac{dE}{dt}$ is the time-order derivative of the groundwater elevation and ϕ is the porosity of the aquifer.

2.4. Poland Springs Withdrawel

The daily withdrawal from Poland Springs was estimated from the annual withdrawal limit of 900,000 m^3. The withdrawal rate was first converted to mm by dividing by the watershed area, then divided by 365.25 days to estimate a constant daily withdrawal rate. In reality, the withdrawal rate will fluctuate just like other parameters, but Poland Spring does not publish its daily withdrawal metrics and so that information cannot be ascertained.

3. Results

The water budget equation total inputs and outputs are outlined in *Table 2* for each studied water year. Interestingly, 2016 had a higher positive change in storage than 2018 even though 2018 was considered wetter than 2016. However, the total precipitation for 2018 was greater than 2016, and the Palmer Drought Index, used by the United States Drought Monitor, uses recent precipitation to determine drought level.

Table 2: Total values for each water year. ΣdS is the total change in storage, ΣQ is the total discharge, ΣP is the total precipitation, ΣET is the total evapotranspiration, and $\Sigma\delta$ is the total residual. All results are in mm. The residuals in the table take the Poland Spring extraction volume into account.

Water Year	**ΣdS**	**ΣQ**	**ΣP**	**ΣET**	$\Sigma\delta$
2016	87.6	671	1104	62.1	-171
2018	66.6	528	1230	68.3	-457

The residual was negative for both 2016 and 2018, suggesting that there was unaccounted water exiting the watershed in both years (*Equation 1*). Results are broken down visually for both water years in *Figure 3* and *Figure 4*. *Figure 5* and *Figure 6* show the cumulative results, respectively. Even though 2016 had a greater total discharge, *Figure 3* and *Figure 4* show that the discharge for 2018 was more evenly spread through the year. In 2016 there was a substantial dry period during the summer months from June to even late September. Additionally, the precipitation during that period was more sporadic and rarely exceeded 25 mm, in contrast to the same time in 2018. The change in storage responds to increases in discharge by going negative. That suggests that the USGS monitoring well that was chosen was well-suited to substitute for an on-site well. As would be expected, the evapotranspiration remained about the same for both water years.

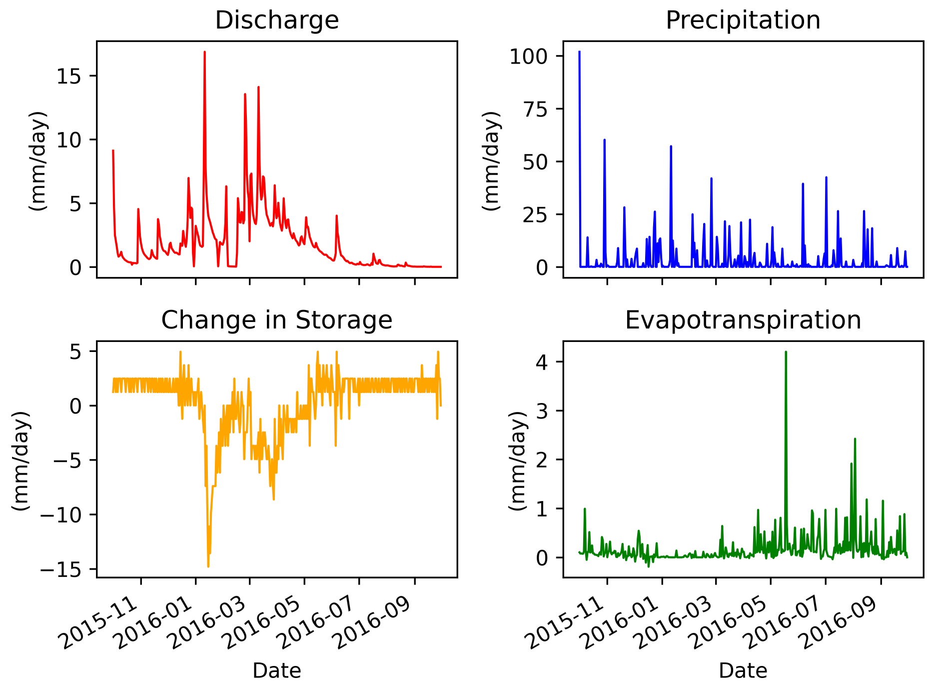

Figure 3: Daily discharge, precipitation, change in storage, and evapotranspiration for the 2016 water year. X-axis values are shared by charts in the same column.

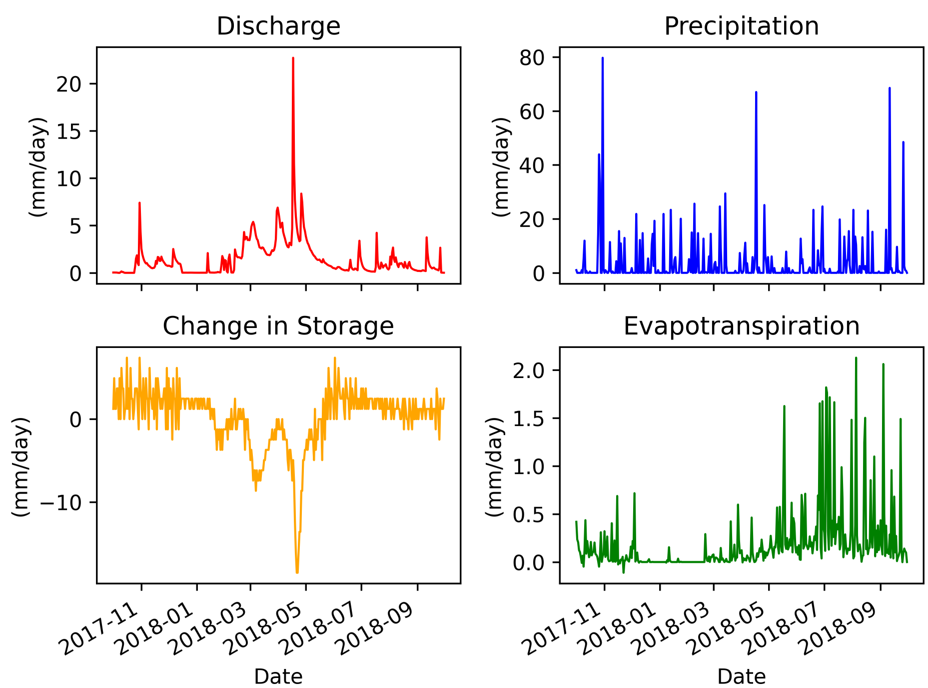

Figure 4: Daily discharge, precipitation, change in storage, and evapotranspiration for the 2018 water year. X-axis values are shared by charts in the same column.

The cumulative discharge further illustrates the summer drought in 2016 by showcasing the "flatlining" of the discharge. The cumulative discharge increases until around May 2016, when the cumulative discharge increases at a slower and slower rate. Eventually the cumulative discharge stops increasing. In contrast, the cumulative discharge keeps increasing during the summer in 2018, though at a slower rate than it did in the spring of 2018.

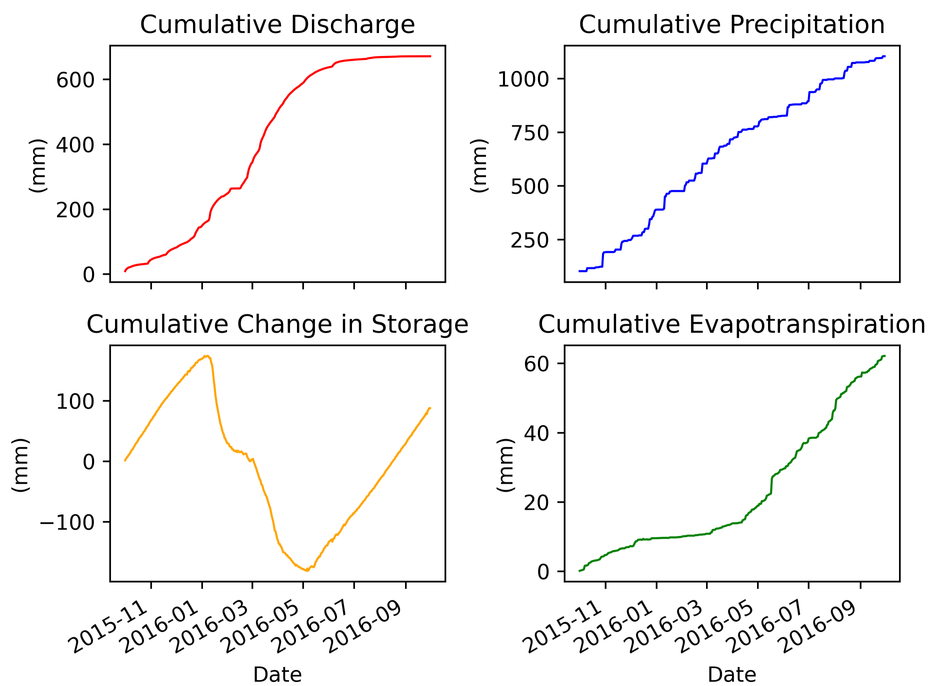

Figure 5: Cumulative daily discharge, precipitation, change in storage, and evapotranspiration for the 2016 water year. X-axis values are shared by charts in the same column.

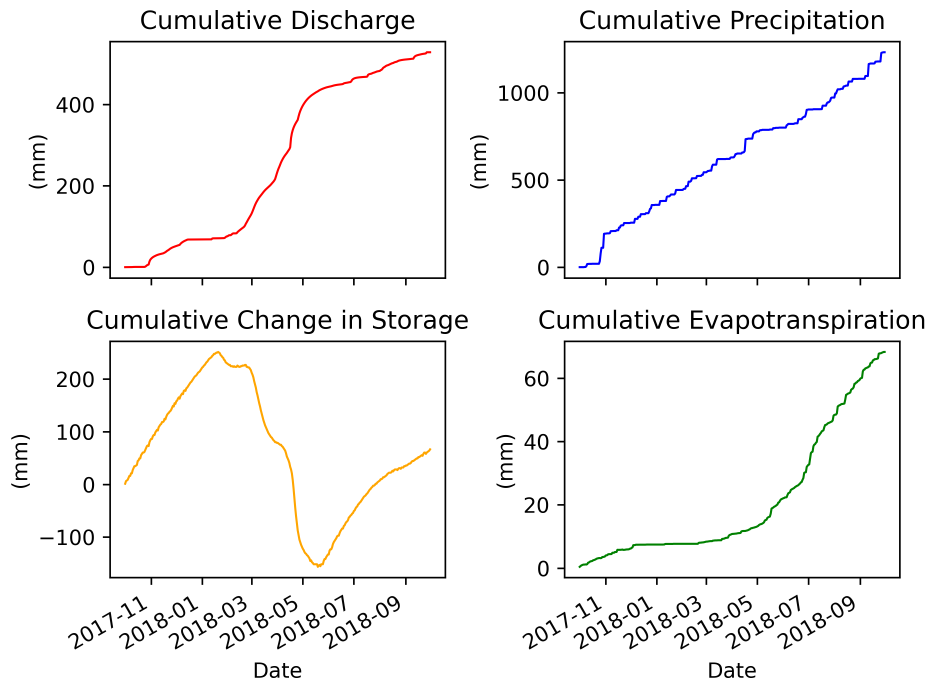

Figure 6: Cumulative daily discharge, precipitation, change in storage, and evapotranspiration for the 2018 water year. X-axis values are shared by charts in the same column.

There is unaccounted water in this water budget. *Figure 7* and *Figure 8* show the cumulative residuals for each water year, both with and without the Poland Spring withdrawal volume taken into account. The residual for the 2016 water year stops increasing in magnitude around May 2016, which is during the dry summer period. The 2018 water year has a residual that, except for a smaller period during May 2018 to July 2018, tends to keep increasing in magnitude.

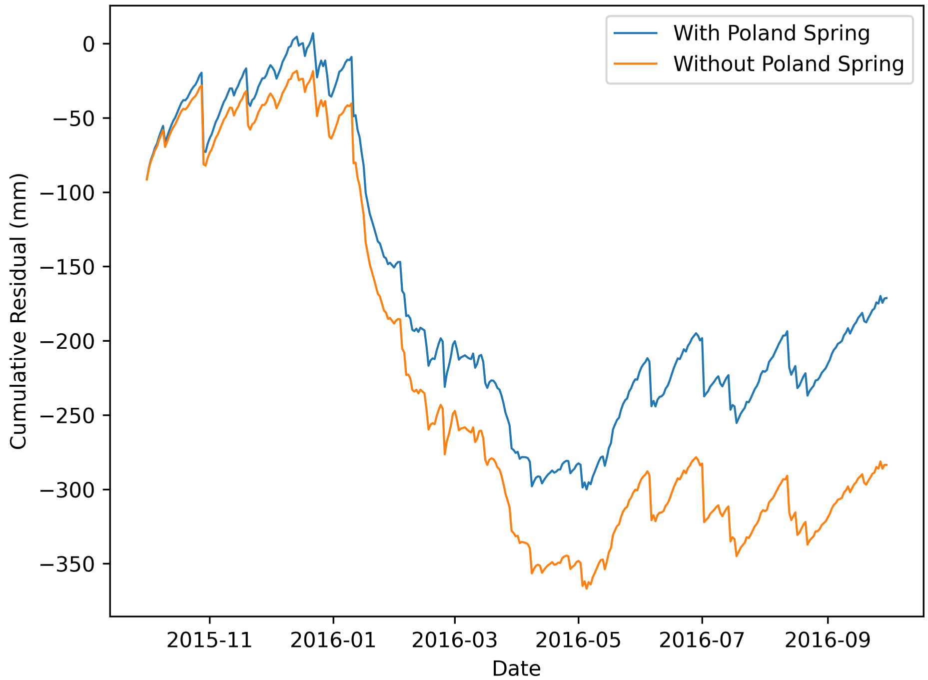

Figure 7: Cumulative residual for the 2016 water year, with Poland Spring and without Poland Spring withdrawals.

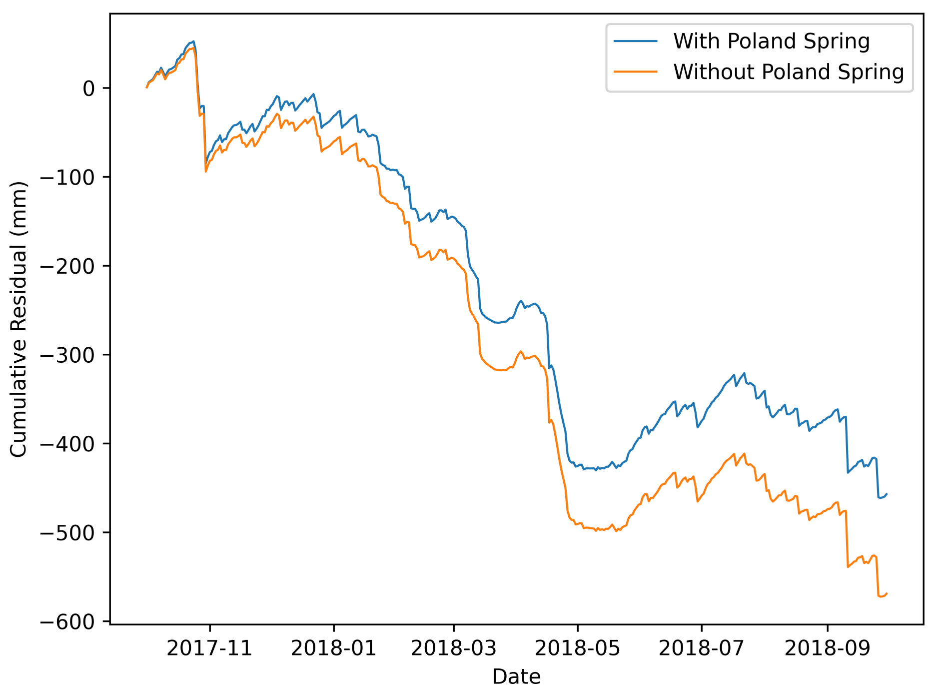

Figure 8: Cumulative residual for the 2018 water year, with Poland Spring and without Poland Spring withdrawals.

4. Discussion

The residual for the 2018 water year was higher in magnitude than that of the 2016 water year. That suggests that there was more unaccounted water leaving the watershed in 2018 than in 2016. There are a few explanations for why that could be, the first being that 2016 had lower overall precipitation, especially during the summer, than 2018. Secondly, 2016 had a higher discharge, which accounts for more of the water leaving the watershed. Paradoxically, 2018 had more precipitation, less discharge, and less change in storage than 2016, despite not experiencing drought. It is important to emphasize again that the drought in 2016 was focused during the summer season in 2016 in New England.

The main culprit for the residual is most likely groundwater flow. The Clear Spring watershed is only about 8 square kilometers, making it a fairly small watershed. It is very possible that groundwater flows out of this watershed into other watersheds nearby, detracting from any change in storage in the groundwater. In order to verify this, monitoring wells would have to be drilled in the watershed, Poland Spring would need to allow access to their own monitoring wells, or Poland Spring would need to publish their own monitoring data. Regardless, the groundwater flow is an important component for such a small watershed.

Still, without the groundwater component, it is possible to interpret these findings with respect to Poland Spring's impact on the watershed. *Figure 7* and *Figure 8* both show that without Poland Spring withdrawing water, there would be about 100 mm of extra water either remaining in the watershed or being discharged through surface streams every year. However, even during the dry year of 2016, the cumulative change in storage was not substantially effected by Poland Spring, as both 2016 and 2018 had net positive changes in groundwater storage despite Poland Spring extraction.

Just as there is likely to be groundwater flowing out of the aquifer, there is also likely to be groundwater flowing into it. In fact, groundwater flow into the aquifer is the best explanation for how Poland Spring's extraction could have no noticeable effect on the change in storage of the aquifer. If that is the case, then the town of Hollis may not notice the true impact of Poland Spring; the imapct will simply be punted to other watersheds. If the effect is distributed, then it may be dampened enough such that no one would notice. This is more reason for Poland Spring to either continually monitor groundwater flow, allow someone else to monitor groundwater flow, or for Maine DEP to require it.

The findings in this study show that Poland Spring appears to have no noticeable impact on the Clear Spring watershed. However, more extensive groundwater studies are necessary to alleviate future concerns regarding groundwater withdrawal, specifically groundwater flow studies. The implications of these findings and future findings are particularly important for the residents of Hollis, Maine, as many of them rely on groundwater wells for their homes. Furthermore, the true impact of Poland Springs withdrawal in Hollis may not be felt by Hollis itself, but could be shared by neighboring aquifers or towns located downstream of Hollis. Therefore, it is vitally important for both Poland Springs' business interests (that they may keep operating their bottling plant with community trust) and nearby residents that there be public access to groundwater monitoring data within the watershed.

References

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