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The Impact of Local Climate Change on Drinking Water Quality in a Distribution System

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Abstract: In this study, air temperatures were collected between 1985 and 2016 and compared to water temperatures in four locations in the distribution system of Pasadena Water & Power (PWP) that received imported surface water between 2001 and 2016 and from the purveyor of imported water. The concentration of chloramine residual and nitrite concentrations were collected between 2001 and 2016 these five locations. The results indicate that the median nighttime temperature of the period 2009 - 2016 was 1.6 °C warmer than the period of 1985 - 2000 and 0.5 °C warmer than the period 2001 - 2008. The median water temperature in the four distribution system samples increased by 0.8 °C to 1.4 °C depending on the location over the study period ($p<0.001$). The median chloramine concentration fell significantly ($p<0.001$) at three distribution system locations and the nitrite concentrations increased significantly at all four distribution system locations.

Keywords: Local Climate Change, Nitrification, Monochloramine, Temperature

1. Introduction

Research the impact of Anthropogenic Climate Change (ACC) on drinking water has focused entirely upon changes in water temperature, microbiology, and chemistry in source waters (Delpha et al 2009). There has been no research to date on the impact of ACC on treated drinking water in the distribution system of a water purveyor. In the previous research, it has been

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shown that ACC has been occurring in the City of Pasadena. Records showed that air temperatures had increased on average 2.8 ºC in the daytime between the decades of 1911-1920 and 2011-2016 and 6.1 ºC in the nighttime. The daytime temperatures increased the most in January and the least in June while the nighttime temperatures increased uniformly all year around. This change in air temperatures has been shown to affect stream flow (Kimbrough 2017) and thus water supply (Kimbrough 2018). This general rise in air temperatures can have a variety of impacts on drinking water utilities, including water resources. Changing rainfall patterns, evapotranspiration rates, and customers' demand, could be influenced by changing water temperatures (Miello et al. 2014). However, it is not unreasonable to imagine that water temperature in all parts of the distribution system would increase as atmospheric temperatures increase. This could have a number of important water quality implications. At higher water temperatures, disinfectant residuals decay more rapidly and bacteria growth is enhanced (Ndiongue, et al. 2002, Michalak 2016). **The purpose of this study is to determine if the increases in atmospheric temperatures are in fact affecting water temperatures and microbiological stability in the distribution system of Pasadena's Water & Power Department (PWP).**

2. Pasadena Water and Power

The City of Pasadena, incorporated in 1886, has owned and operated a public water system (PWS) since 1914 after purchasing a number of privately held water companies. PWP operates a number of wells and has not used local surface water directly for the last 30 years, although it does divert local stream flow into percolation basins for groundwater recharge (Kimbrough 2017 a). PWP also receives imported surface water from both the Colorado River Aqueduct (CRA) and the California State Water Project (SWP) after it is treated by the Metropolitan Water District of Southern California (MWDSC). The SWP is a system of dams, conveyances, and pumping stations spanning 1,000 km (600

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miles) stretching almost the entire length of California from Lake Shasta in the north to Lake Silverwood in the south. The CRA takes water from Lake Havasu and moves it 389 km (242 miles) to Lake Matthews and then an additional 44 km (30 miles) to the F. E. Weymouth Treatment Plant (WTP). There the plant may blend the CRA and SWP water or treat 100% of either and then deliver the effluent to PWP and other agencies.

Imported surface water purchased from WTP must first enter the PWP system through one of three reservoirs, Sunset, Jones, or Eagle Rock. Sunset Reservoir has a capacity of 57 million liters (ML - 15 million gallons (MG)) and consists of a blend of WTP water and local well water. Jones Reservoir has a capacity of 189 ML (50 MG) and during the study period only held WTP water until late 2015 when some local well water was introduced and blended. Eagle Rock is considerably smaller at a volume of 3.6 ML (0.95 MG) and only uses WTP water. The WTP is 40 km (25 miles) from the Sunset Reservoir with a detention time of one to two days depending the on the time of year. Jones Reservoir is 5 km (3 miles) closer to the WTP than is Sunset and Eagle Rock Reservoir is about 5 km further away. These reservoirs are made primarily of concrete and steel with the water in contact with concrete walls. The distribution system is summarized in Figure 1.

All of the water purchased from MWDSC by PWP contains monochloramines so the Division of Drinking Water (DDW) of the State Water Resources Control Board (SWRCB) has required PWP to routinely sample different parts of its distribution system as part of a nitrification control plan for water temperature, total chlorine residual, and nitrite since 2001. The “Nitrification Monitory and Action Plan” (NMAP) dictates where PWP tests for indicators of nitrification and what PWP must do when those indicators are present. As a result, the PWP database consist of thousands of water temperature data points from several locations between 2001 and 2016.

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3. Hypothesis

The hypothesis of this study was that the temperature of the water in PWPs distribution system has been increasing due to increasing atmospheric temperatures during the study period. This has resulted the gradual decrease of monochloramine residual and an increase in bacterial nitrification where residence times are longest.

3.1 Proposed Mechanism

The three reservoirs identified above where WTP water enters PWP's distribution system are made primarily of concrete and steel which can absorb heat by direct absorption of sunlight and through conduction of heat from the air to the outside surfaces. This in turn can heat the water in the reservoirs before it leaves. Pipes in the distribution system can likewise warm as the surrounding ground is warmed in the same fashion that the reservoirs warm. As the temperature of the air increases over the years, the temperature of the water in reservoirs, pipes, and water would warm as well. Moreover, the further that the water has to move from the point of entry to the reservoirs, the more the temperature will increase.

3.2 Nitrification

The decay of monochloramines releases ammonia, which can be consumed by Ammonia Oxidizing Bacteria (AOB) which releases nitrite (NO2) and Utilization Associated Products – (UAP). AOBs can also co-metabolize monochloramines which also produce NO2 UAP. UAP can react with chloramines outside the cell wall, which reduces the concentration of chloramines. This process of nitrification can result in the complete loss of chloramine residual, which can allow pathogenic and non-pathogenic bacteria to grow. Thus, nitrification is process water purveyors must work hard to prevent.

3.3 Expected Results

If ACC is in fact warming both the local air temperature and the water temperatures in the distribution system of PWP, two parallel trends should be observed;

3.3.1 As temperatures in the water distribution system increase over time the concentration of monochloramine should decrease and nitrite concentrations should increase.

3.3.2 The above pattern should be more visible in the parts of the distribution furthest from the entry point into the distribution and less visible in the nearer points.

There is an important caveat to this hypothesis and expected results. During the study period, PWP staff was actively and vigorously trying to keep monochloramine concentrations high and nitrite concentrations low. According to the NMAP PWP must flush water from locations when nitrite concentrations exceed 25 µg/L and / or add chlorine. Additionally for compliance with the Total Coliform Rule (TCR) and Surface Water Treatment Rule (SWTR) a positive chlorine residual is equired. As a result, many parts of the distribution system may be flushed when chlorine residuals are low and / or chlorine may be added. These operational requirements and regulatory mandates influence the nature of he results seen in his study.

4. Study Locations

To test the above hypothesis, five sample locations were selected. Four sample locations in PWP's distribution system and one from MWDSC's distribution system. All four of PWP's locations were routinely tested for water temperature and were fed from one of the three reservoirs mentioned above during the study period. Two of the locations are close to the reservoir influent and will be referred to as the proximal locations and two locations were farther away from the reservoir influents and will be referred to as the distal locations. The sample locations are described as follows:

4.1 Arroyo Terrace (272 m (897 ft) above mean sea level (AMSL)), which is fed from the Sunset Reservoir (383 m (1,264 ft) AMSL), and has a 4:1 blend of WTP water and local well water (which has no chlorine added) and is located in the western edge of the Sheldon Zone. The sample location is 2.3 km (1.4 miles) from the outlet of the Sunset Reservoir through several different mains ranging from 20 to 30 cm (8 to 12 inches). Most of these mains are cast iron installed in or around 1930, although some of the older segments of main are ductile steel. The final segment of main where the sample point is located is 340 m (1200 ft) of 15 cm (6 inch) ductile iron with only seven service connections, all 5 cm (2 inch) in diameter or smaller. The Arroyo Terrace main is a low demand area on a dead-end loop. This is a proximal sample location.

4.2 Avenue 64 is in the Eagle Rock pressure zone, which is fed exclusively from the Eagle Rock Reservoir and uses only WTP water. The Eagle Rock Reservoir is 346 m (1,141 ft) AMSL and gravity feeds the entire Eagle Rock pressure zone. The distance from the outlet of the reservoir to the sample point at Avenue 64 (253 m (835 ft) AMSL) is 1.85 km (1.2 miles) through a 30 cm (12 inch) cast iron main that was installed in 1965. The sample location on Avenue 64 is at a point with significant flow and it is not a dead-end. The final segment of main where the sample point is located is 143 m (470 ft) of 15 cm (6 inch) cast iron with 10 service connections, all 2.5 cm (1 inch) in diameter or larger. This is a proximal sample location.

4.3 Hill Avenue has an elevation of 227 m (749 ft) AMSL), which is also fed from Sunset Reservoir. The sample location is 5.8 km (3.6 miles) from the Sunset Reservoir and the last few kilometers are made of 15 cm (6 inch) cast iron that was installed in 1917. This is a high demand area and is not a dead-end. The final segment of main where the sample point is located is 162 m (532 ft) of 15 cm (6 inch) cast iron with 11 service connections, all 2.5 cm (1 inch) in diameter but it is

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also only 178 meters from a large 20 cm (8 inch) commercial service connection. This is a distal sample location.

4.4 Tropical Avenue, which like Avenue 64, received 100% WTP water but it comes out of Jones Reservoir (280 m (924 ft) AMSL)) which was then pumped up to a second reservoir, Thomas Reservoir (5.3 ML (1.4 MG)), at a higher elevation (367 m (1,211 ft) AMSL), and then gravity fed into the Don Benito Reduced Pressure Zone. Tropical Avenue (326 m (1076 ft) AMSL) is a moderate demand area and has a 10 cm (4 inch) dead end cast iron main that was installed in 1951. The final segment of main where the sample point is located is 176 m (576 ft) of 10 cm (4 inch) cast iron with 20 service connections, all 1.9 cm (0.75 inch) in diameter. Therefore, while the linear distance from the outlet of Jones Reservoir to the Tropical Avenue sample point is only 2.1 km (1.3 miles), the detention time is significantly longer than any of the other samples points, particularly in the two reservoirs with a combined volume of 190 mL (55 MG). . This is a distal sample location. Figure 1 presents a schematic diagram of the WTP, the four reservoirs, and the four sample locations.

4.5 Additionally, water temperatures, pH, and chlorine residual of the plant effluent of MWDSC's WTP (330 m (1,089 ft) AMSL) were also obtained for the study period. For nitrite, results were obtained from a service location nearest Pasadena designated FM-1 that delivers water from the WTP.

In summary, there are two pairs of sample locations, one pair that received 100% WTP water and one pair that received an 80% blend. Each pair has a proximal sampling location and a distal.

5. Analytical Methods for Water

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5.1 Water Temperature – The water temperature was measured using an electronic thermometer using Standard Methods 2550 B [6].

5.2 Monochloramines – The concentration of total chlorine was determined by using a Hach field colorimeter using Method 4500-CI G N,N Diethyl-1,4 Phenylenediamine Sulfate (DPD) Colorimetric Method [6].

5.3 Nitrite (NO_2) - The concentration of nitrite was determined by using a Hach field colorimeter using Standard Method 4500-NO2 B Diazotization Method Colorimetric Method [6]. This test was not performed in the field but in PWP's laboratory. A Hach 850 was used in the beginning of the study a Hach 890 in the latter part.

5.4 Water pH – The pH of the WTP water was determined using Standard Methods 4500-H+ [6].

6. Air Temperatures

Air temperatures for the 1985 – 2016 study period were obtained from the National Oceanographic and Atmospheric Administration's National Climatic Data Center (NCDC). A database of the daily maximum air temperatures (all maximum temperatures occurred during the daylight hours temperature so to avoid confusion are referred to as "daytime temperatures" here), minimum air temperatures (referred to as "nighttime temperature"), were created and checked for accuracy against written records. For this study, only the nighttime air temperatures were used. Nighttime air temperatures were used because they are a more sensitive measure of climatic change than daytime temperatures. The air temperature was collected at Pasadena's City Hall located at the longitude and latitude +34.15, -118.14.

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7. Statistical Procedures

7.1 The distribution of each data set was assessed using the Shapiro-Wilk Test and the skewness and kurtosis were assessed. Data was considered non-normally distributed if the probability was less than 5% ($p \leq 0.05$). All data in this study was non-normally distributed [7] for either skewness of kurtosis.

7.2 There were 16 data sets, nighttime air temperature, the water temperature, total chlorine concentration, and nitrite concentration at the five locations covering the period of 2001 - 2016. Each database was divided in half, with approximately equal numbers of results covering the periods of 2001 – 2008 and 2009 – 2016. Each pair of sub-populations were compared using the Mann-Whitney Rank Sum Test (MWRST), the non-parametric equivalent to the Student's t-test for non-normally distributed data. Differences with a 5% or less level of significance ($\alpha \leq 0.05$) were considered significant. The two sub-groups were 2001 – 2008 and 2009 – 2016. For the air temperatures, a wider study period was used, 1985 – 2016 and there were three study periods, 1985 – 2000, 2001- 2008, and 2009 – 2016. The test period of 2009 – 2016 was compared to both the 1985 – 2000 period and the 2001 – 2008 periods by MWRST (de Muth 2014).

7.3 The three air temperature populations were also compared to each other using the Kruskal-Wallis One Way Analysis of Variance on Ranks (KW). The KW test produces the Kruskal-Wallis Statistic (H). The threshold for significance was 5% ($\alpha = 0.05$) [7].

7.4 When different data sets collected over time were compared to determine they tended to follow correlated patterns, the Spearman Rank Order Correlation (SROC) test was used, which is the non-parametric equivalent of the Pearson Product Moment Correlation. For the water data, the temperature, chlorine residual, and nitrite concentrations were compared [7].

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7.5 Nitrite results were no censored for this study but used as generated by the instrument. When the instrument generated a value of zero, a value of zero was used for statistical analysis.

8. Results

8.1 Distribution of Data

The distribution of all 16 data sets were tested for normality using the Shapiro-Wilk Test and all had a non-normal distribution ($p<0.001$).

8.2 Air Temperatures

The mean, standard deviation, 25th, 50th, and 75th percentile results for the entire study population (1985 – 2016) and each of the three sub-populations are shown in Table 1. The data on a yearly mean basis including the 99% confidence intervals are shown in Figure 2. The median air temperatures increased through the study period, both between the three sub-groups as seen in Table 1 but even on year to year basis as seen in Figure 2. The median nighttime air temperature of the 2009 – 2016 period was 1.6 ^{o}C higher than the 1985 – 2000 period and 0.5 ^{o}C higher than the 2001 – 2008 period. The mean air temperature before 2003 was never higher than 12.5 ^{o}C but after 2003, it was never lower than 12.5 ^{o}C (the same was true for the median results except for 1992). In fact, 2016 was the coolest year since 2003 but it was still warmer than all years preceding 2003. These differences in the median air temperature were of a statistically significant nature with the MWRST having a probability of <0.05.

8.3 Water Temperatures

The mean, standard deviation, 25th, 50th, and 75th percentile results for the entire study population (2001 – 2016) and each of the two sub-populations (2001 – 2008 and 2009 – 2016) for all five locations are shown in Table 2. The WTP shows no change in median water temperatures when the two sub-

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populations are compared by MWRST with the median water temperature actually 0.9^o C lower. However, all four locations in the distribution show statistically significant increases in water temperature. The median temperatures increased at Avenue 64 by 1.0^o C, Tropical Avenue by 1.4 ^{o}C, at Arroyo Terrace by 0.9^o C, and at Hill Avenue by 0.7 ^{o}C. These increases parallel the increase in nighttime air temperature, which was 0.5 ^{o}C. To better assess the relationships between air and water temperature, the monthly median water temperatures of each of the five locations was plotted on a monthly basis which is summarized in Figure 3.

8.4 Chloramine Residual

The chlorine residual is shown in Table 3 including the mean, standard deviation, 25th, 50th, and 75th percentile results for the entire study population (2001 – 2016) and each of the two sub-populations (2001 – 2008 and 2009 – 2016) for all five locations . The WTP showed a slight increase in residual when the two sub-populations are compared by MWRST by 0.05 mg/L. This was due to an operational target concentration of chlorine dosing at the WTP. However, some locations in PWP's distribution show statistically significant decreases in residual concentration. The median chlorine residuals decreased at Avenue 64 by 0.03 mg/L, Tropical Avenue by 0.27 mg/L, at Arroyo Terrace by 0.51 mg/L, but at Hill Avenue showed a slight increase in residual concentration of 0.07 mg/L but this was not statistically significant.

8.5 Nitrite Concentration

The nitrite measured in µg/L is shown in Table 4 including the mean, standard deviation, 25th, 50th, and 75th percentile results for the entire study population (2001 – 2016) and each of the two sub-populations (2001 – 2008 and 2009 – 2016) for all five locations. Three of the distribution system

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samples showed significant increases in the median concentration of nitrite. At Avenue 64 the median concentration of nitrite doubled from 5.0 to 10.0 µg/L and the mean concentrations showed a parallel increase. At the Tropical Avenue location, the median concentration increased from zero to 3.0 µg/L while the mean concentration more than doubled from 2.3 to 5.9 µg/L. The Hill Avenue location the median concentration increased from zero to 3.0 µg/L while the mean concentration almost tripled from 1.6 to 4.3 µg/L. The Arroyo Terrace data are more complicated. The median concentration of nitrite decreased slightly, from 14.5 to 14.0 µg/L while the 25th percentile remained constant. However, the mean increased from 22.1 µg/L to 28.4 µg/L and the 75th percentile increased from 29.0 µg/L to 42.0 µg/L. So the concentration increased overall but the alpha value was only 0.028, which is statistically significant but much less so as compared to the other locations. Arroyo Terrace also had a considerably higher median and mean concentration of nitrite as compared to the other sites. No nitrite was ever detected at the WTP effluent but at the FM-1 distribution location there were 798 samples collected but only 21 had nitrite at a concentration of greater than 5 µg/L and only seven of those were 6 µg/L or greater and the highest value was 9 µg/L. With so few quantifiable results, which are all quite low, there is no evidence that the rate of nitrification increased between the two study periods (although 13 of the measurable nitrite results occurred in 2016). A number of the nitrite results were reported at the lower end of the linear dynamic range for this method, which might increase the uncertainty in the data. However, over 700 data points were collected over a 15-year period, which significantly increased the robustness of the statistical analysis.

8.6 pH

The pH of WTP water during this study ranged 8.0 to 8.1. The pH was controlled through the addition of sodium hydroxide.

8.7 Correlation

If the hypothesis is correct, as air temperatures increase, water temperatures should also increase which should cause the concentration of chlorine residuals to decrease and nitrite concentrations to increase. In other words there ought to be a negative or inverse correlation between water temperature and chlorine concentration and a positive correlation with nitrite. Additionally there ought to be an inverse relationship between chlorine concentration and nitrite concentration. To test this, the data from the five water locations were analyzed using the SROC. The correlation coefficient and probability for each paired set of data are shown on Table 5. No correlation was observed in the data from the WTP, which is not surprising since the concentrations of chlorine residual are high and there is little opportunity for the chlorine to decay. Given the fact that there was very little evidence of nitrification, no attempt to correlate nitrite concentrations with either water temperature or chlorine residual. At Avenue 64, Tropical Avenue, and Arroyo Terrace, there was similarly no correlation between water temperature and chlorine residual. Hill Avenue however showed a weak but statistically significant negative correlation between water temperature and chlorine residual concentration. In contrast, Avenue 64, Tropical Avenue, and Arroyo Terrace, there was a correlation between water temperature and nitrite concentration, which ranged from weak to moderate but all of it was significant. The Hill Avenue sample location showed no pattern with no measurable correlation between water temperature and nitrite concentration. The relationship between chlorine residual concentration and nitrite concentration is more complex. The sample location on Avenue 64 did indeed produce the expected negative correlation, which, while not strong at -0.20 was statistically significant. Tropical Avenue had similar results but with a slightly weaker correlation coefficient. On the other hand, the Arroyo Terrace sample location did not show a statically significant correlation between chlorine residual and nitrite

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concentration while the Hill Avenue location showed a weak but positive and statistically significant correlation.

9. Discussion

The air in Pasadena have been warming significantly since 1985 as can be seen in Figure 2 and Table 1. In parallel with the increasing air temperature, water temperatures in PWP's distribution system have increased as well. While the median air temperature in Pasadena increased by 0.5 °C in the period of 2009 – 2016 as compared to 2001 – 2008, when comparing the two periods, the median water temperature at the WTP changed by -1.1 °C, although this was not statistically significant. This is also a bit misleading as the 75th percentile of the water temperature was actually higher in the second period than that in the first period by 0.6 °C and the 25th percentile only decreased by 0.1 °C while the mean is 0.5 °C lower. Obviously, the water temperatures are distributed in a complex fashion that is not easily captured in a single measure of the central tendency. Suffice it to say, there is no evidence that the water temperate of the effluent of the WTP has increased between the two study periods.

In contrast, the median water temperature at Arroyo Terrace increased by 0.9 °C, Avenue 64 by 1.0 °C, Hill Avenue by 0.8 °C, and at Tropical Avenue by 1.4 °C. These were all statistically significant increases. That the water temperature should increase more than the air temperature is not necessarily surprising, as the heat capacity of water is five times higher from that of air and can thus retain more heat much longer than air. It is also not surprising is the fact that the water at Tropical Avenue showed a larger median increase in water temperature as compared to the other three sites. This is because as the water first enters PWP's distribution system through Jones Reservoir (by far the largest of PWP's reservoirs) from which it is pumped up to Thomas Reservoir before reaching the sample tap. As a result, the detention time is considerably longer and much of that detention time is in above grade

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reservoirs as opposed to the other three distribution system sample locations where the water, once it leaves the smaller reservoirs, travels through mains so detention times are considerable shorter.

The vast majority of the warming is occurring in the distribution system itself. The influent water from the WTP showed no increase in water temperature during the study period and no loss of chlorine residual (although 2014 and 2016 were the two warmest years in the study period). However, what is clear is that as the water moves further from the reservoirs where the water is taken from WTP, the water temperatures changes. In winter, the WTP water comes in cold and is warmed as it passes through the distribution system. In the summer, the exact opposite is observed at most locations; the WTP enters the system and is slightly cooled, except for Tropical Avenue where it warms very slightly. The two distal locations showed this pattern more than the two proximal locations as can be seen in Figure 3.

In examining the monthly data pattern emerges. The month of December had the lowest mean air temperature, 8.3 °C, while August had the highest, 18.3 °C, a range of 10 °C. The mean temperature of the effluent of the WTP ranged from a low in January of 13.1 °C to 26.2 °C. a 13.0 °C difference. Arroyo Terrace showed a range of monthly averages of 10.9 °C, 14.4°C in January and 25.3 °C in August. Avenue 64 presesnted a range of monthly averages of 11.3 °C, 14.4oC in January and 25.7 °C in August. Hill Avenue had a range of monthly averages of only 7.7 °C, 17.8 °C in February and 25.5 °C in August. Tropical Avenue had a range of monthly averages of only 8.8 °C, 18.6 °C in December and 27.4 °C in August. The two distal sample locations showed a range of mean temperatures that were very similar to the changes in local air temperature. The WTP and the two proximal sample locations showed a wider range of mean monthly temperatures. The two proximal locations were more influenced by changes in water temperature from the WTP while the two distal locations were more influenced by changes in local air temperature. There is only small differences between the maximum mean water

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temperature, the differences in the range of monthly averages is almost entirely due to differences in the minimum monthly temperatures.

Changes in concentration of chlorine residuals were largely parallel to that seen in water temperatures. There was no decrease in median concentration of chlorine in the effluent of WTP during the study period. Avenue 64 showed a small decrease while Arroyo Terrace and Hill Avenue both showed larger decreases. Arroyo Terrace and Hill Avenue have longer detention times than Avenue 64 so this is not unexpected. In addition, the Arroyo Terrace sample tap is on a dead end loop and has tuberculation so this site could be expected to show the greatest median chlorine loss. The Tropical Avenue sample location however showed the least chlorine loss, which would seem counterintuitive given the fact that that location showed the greatest water temperature increase. However, at both Jones and Thomas Reservoirs, chlorine gas is routinely fed during the warmer months of the year. At no point was enough chlorine gas added to break over the water to free chlorine. As seen in Figure 4, the median chlorine concentrations at each of the five locations arranged by month. As can be seen the chlorine concentration increases significantly at Tropical Avenue in the summer months while the pattern does not hold at any other location.

The nitrite results are also informative. The FM-1 water no significant increase in nitrite concentration while all four PWP distribution system sample locations showed significant increases in the median concentration of nitrite. Both Hill Avenue and Tropical Avenue had almost no nitrification prior to 2009 but afterwards showed a very noticeable and statistically significant increase. Both showed an increase of ~3 µg/L in both the mean and median concentrations. This is not a large increase in absolute value but it does represent a dramatic shift the water quality of these two locations. What this means is that nitrification had not been occurring before but was later. Avenue 64 likewise showed a definite increase in median nitrite concentration. The mean and median concentrations both double in value, from 5.0 to 10.0 µg/L and 6.3 to 13.9 µg/L respectively. Arroyo Terrace actually showed a slight decrease in the median concentration of nitrite from 14.5 mg/L to 14.0 µg/L but the mean increased by 6.3 µg/L and a 13 µg/L increase in the 75th percentile concentration. The absolute difference in the means and medians was generally 3 to 6 µg/L.

The hypothesis is that as water temperatures rise, the concentration of chlorine should fall and if this is the case, there ought to be a negative correlation between these two variables. However, no such correlation is observed for four of the locations. At Hill Avenue though the correlation, while significant, is not strong (R = -0.22). For WTP this is not surprising since there has been no increase in water temperature or loss of chlorine residual. Similarly, Tropical Avenue is feed by two reservoirs in tandem where chlorine is added so the lack of correlation is not surprising. Avenue 64 showed only a minor loss of chlorine so like the WTP, a lack of correlation might be expected. Nonetheless, Arroyo Terrace showed considerable chlorine so a lack of correlations is unexpected.

On the other hand, Arroyo Terrace, Avenue 64, and Tropical Avenue all showed significant positive correlations between water temperature and nitrite concentration. Generally, as water temperatures rose nitrite concentrations rose at these three locations. Why Hill Avenue should show no correlation between nitrite concentrations and water temperature but show the expected negative correlation between chlorine residual and water temperature is not clear.

Finally, both Avenue 64 and Tropical Avenue showed the expected negative correlation between chlorine residual concentration and nitrite concentration while Arroyo Terrace showed no correlation and Hill Avenue actually showed a weak but significant positive correlation, the opposite of what would be expected. Of 13 possible correlations among the variables in the water samples, seven were statistically significant and six were of the expected direction. So the data generally supports the hypothesis, increasing air and water temperatures are impacting the quality of water in the form of

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decreasing monochloramine concentrations and increasing nitrite concentrations. The pattern is not entirely consistent with the hypothesis but as was noted above, operational practices may have influenced the association between water temperature and distribution water quality. The data was gathered from two working distribution systems (WTP and PWP) where staff were working diligently and vigorously to prevent the loss of monochloramine residual and the increase in nitrite concentrations. Without the addition of chlorine gas at Jones and Thomas Reservoirs and a very active program of flushing numerous parts of the distributions system, a much greater impact and clearer correlations would no doubt have been observed.

It is important to note that during part of the study period California suffered a period of intense drought (Kimbrough 2017, Kimbrough 2018). This resulted in unprecedented reductions in water demand and water age. This may well have exaggerated the impact of increasing air temperatures on water temperatures.

10. Summary and Conclusions

Local climatic change has resulted in significant and measurable increases in the temperature of the nighttime air in Pasadena, which in turn has increased the water temperature in the distribution system of PWP. This has caused increased rates of chlorine decay and increased rates of nitrification.

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Figure 1
Schematic of the Studied Distribution System

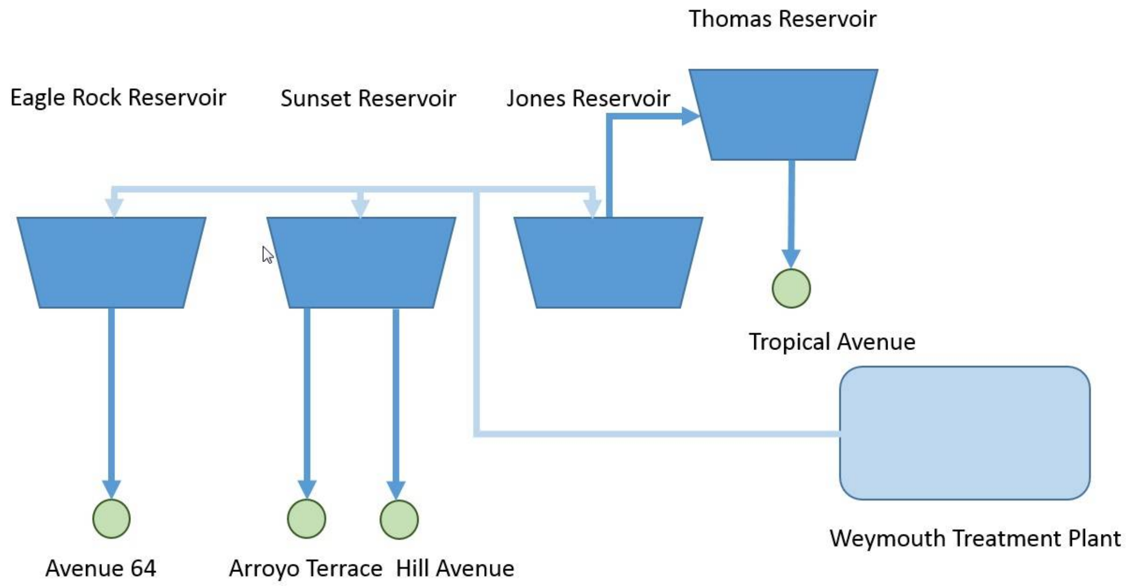

Figure 2

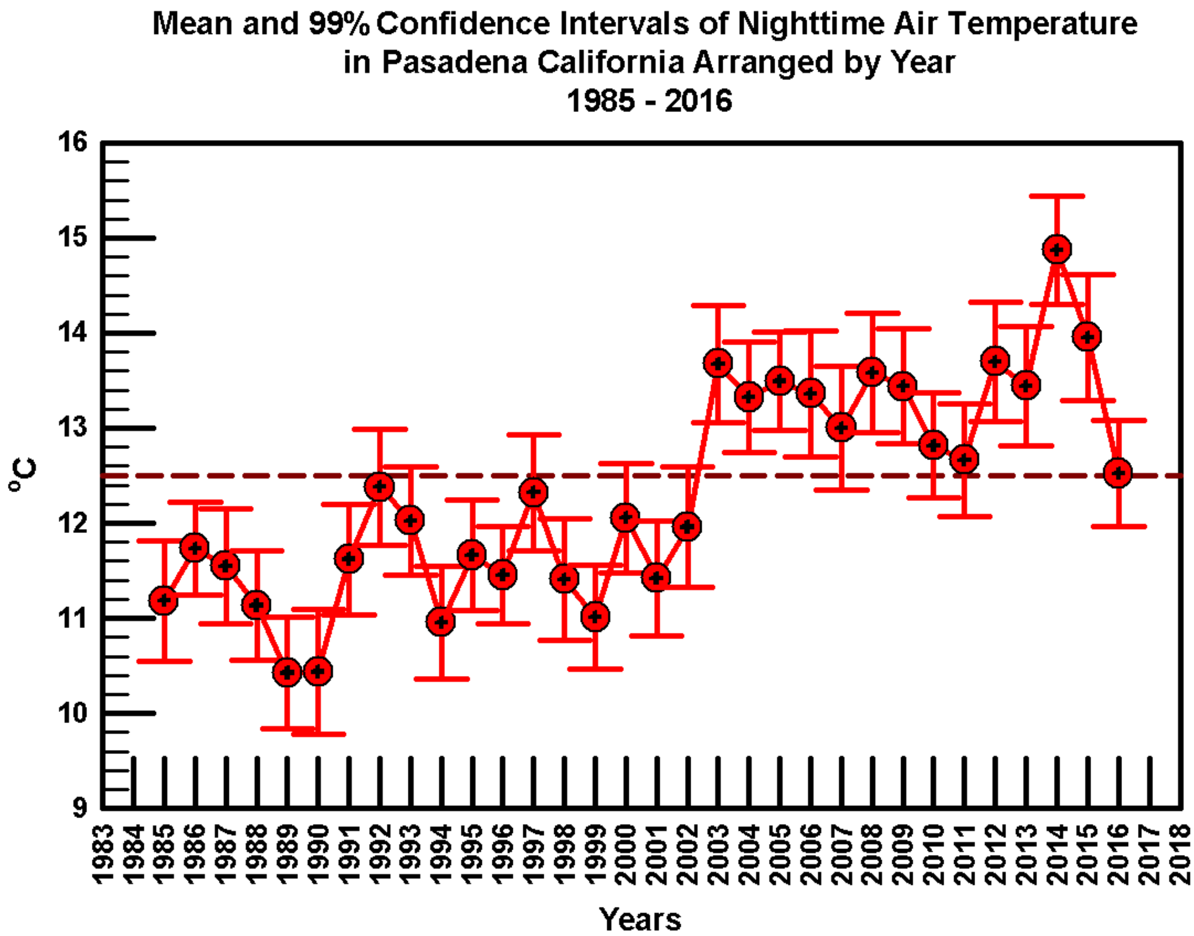
Mean and 99% Confidence Intervals of Nighttime Air Temperature
in Pasadena California Arranged by Year
1985 - 2016
°C
16
15
14
13
12
11
10
9
1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
Years

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Figure 3

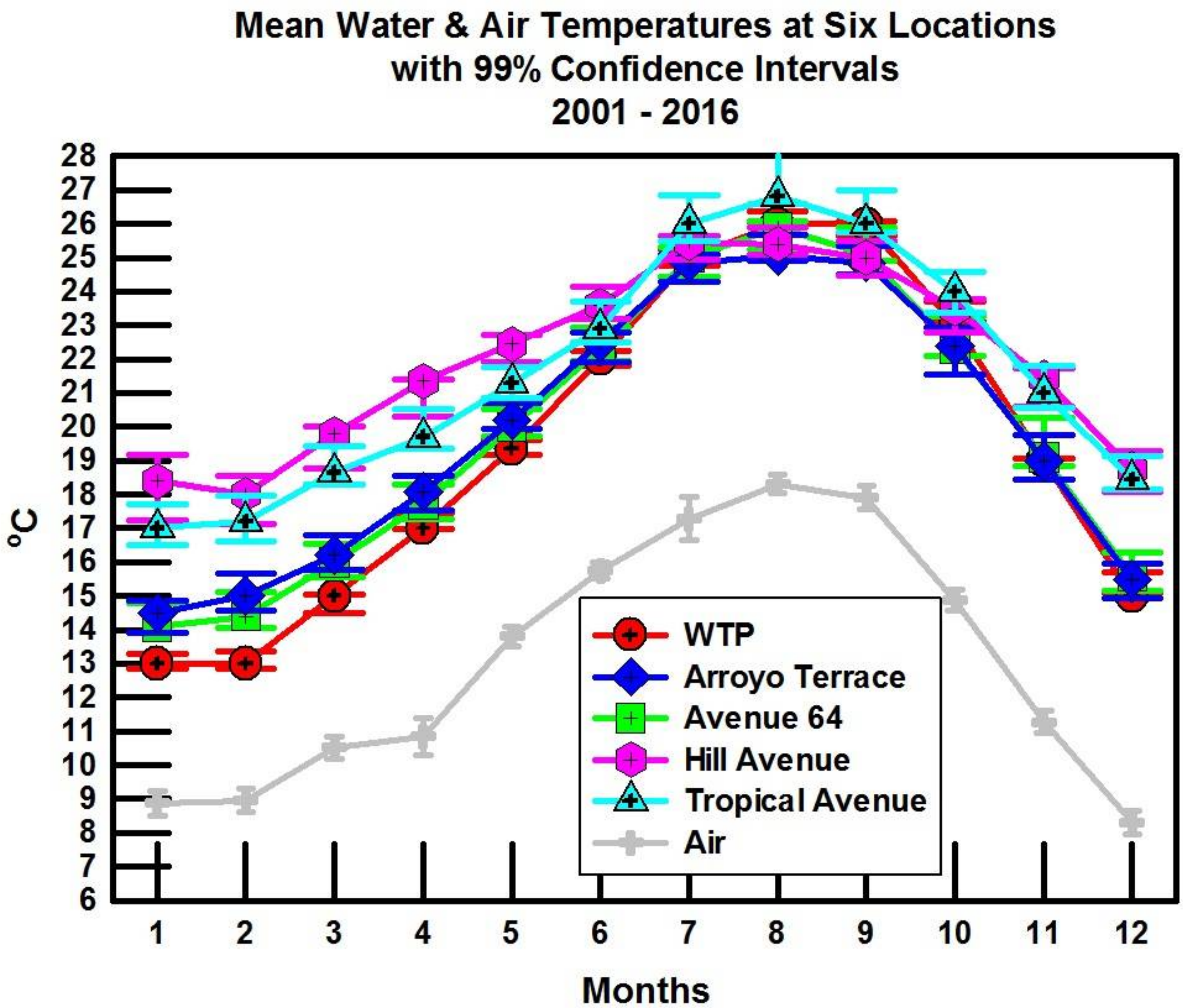

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Figure 4

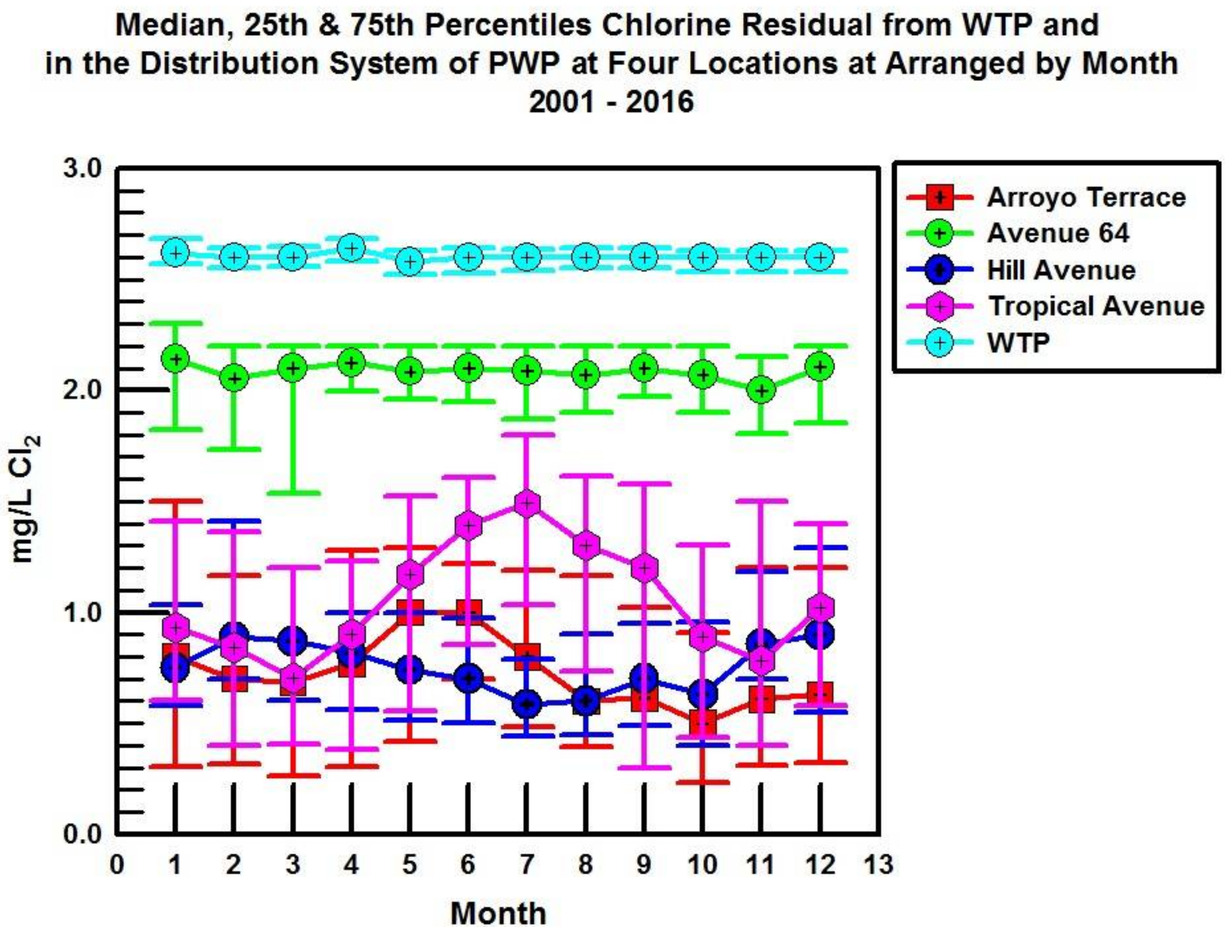

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Table 1

Nighttime Air Temperatures in Pasadena between 1985 – 2016

All Results in °C

Period	n	Mean	SD	25^{th}	50^{th}	75^{th}	Skewness	Kurtosis	p
1985 - 2016	11,531	12.3	4.5	8.9	12.2	15.6	0.008	-0.34	<0.001
1985 - 2000	5,832	11.5	4.4	8.3	11.7	14.4	-0.04	-0.42	<0.001
2001 - 2008	2,810	13.0	4.5	10.0	12.8	16.1	0.007	-0.48	<0.001
2009 - 2016	2,889	13.4	4.5	10.6	13.3	16.7	0.04	-0.28	<0.001

Kruskal-Wallis One Way Analysis of Variance on Ranks H = 389, $p < 0.001$

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Table 2

Water Temperatures in Pasadena at Five Locations between 2001 – 2016

All Results in °C

Location	Period	n	Mean	SD	25th	50th	75th	S	K	p
Arroyo Terrace	2001 - 2016	830	19.9	4.2	16.2	20.0	23.7			
Arroyo Terrace	2001 - 2008	417	19.4	4.1	15.8	19.5	23.3	-0.03	-1.2	<0.001
Arroyo Terrace	2009 - 2016	413	20.4	4.2	16.7	20.4	24.2	-0.03	-1.1	<0.001
Mann-Whitney U Statistic= 74,811 p=0.001										
Avenue 64	2001 - 2016	832	19.9	4.3	16.0	20.0	24.0			
Avenue 64	2001 - 2008	414	19.3	4.3	15.2	19.3	23.4	0.04	-1.3	<0.001
Avenue 64	2009 - 2016	418	20.6	4.3	16.9	20.3	24.4	0.04	-1.2	<0.001
Mann-Whitney U Statistic= 71,496 p<0.001										
Hill Ave.	2001 - 2016	832	21.8	3.3	19.6	22.0	24.3			
Hill Ave.	2001 - 2008	418	21.1	3.2	19.0	21.7	23.8	-0.54	-0.4	<0.001
Hill Ave.	2009 - 2016	414	22.4	3.2	20.0	22.5	25.2	0.08	0.2	<0.001
Mann-Whitney U Statistic= 69,260 p<0.001										
Tropical Ave.	2001 - 2016	832	21.8	3.9	18.8	21.4	24.8			
Tropical Ave.	2001 - 2008	419	21.0	3.6	18.1	20.8	24.0	0.01	-0.7	<0.001
Tropical Ave.	2009 - 2016	413	22.6	4.1	19.6	22.2	25.0	0.40	-0.4	<0.001
Mann-Whitney U Statistic= 67,706 p<0.001										
WTP	2001 - 2016	2,548	20.1	4.8	15.8	20.1	24.6			
WTP	2001 - 2008	1,206	19.9	4.9	15.4	20.6	24.4	-0.19	-1.25	<0.001
WTP	2009 - 2016	1,342	19.4	5.9	15.3	19.5	25.0	-0.76	0.67	<0.001
Mann-Whitney U Statistic= 782,378 p=0.15										

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Table 3

Total Chlorine Residuals in Pasadena at Five Locations between 2001 – 2016

All Results in mg/L

Location	Period	n	Mean	SD	25^{th}	50^{th}	75^{th}	S	K	p
Arroyo Terrace	2001 - 2016	830	0.82	0.57	0.35	0.73	1.20			
Arroyo Terrace	2001 - 2008	417	1.06	0.57	0.60	1.00	1.40	0.5	-0.3	<0.001
Arroyo Terrace	2009 - 2016	413	0.58	0.46	0.20	0.49	0.85	1.0	0.6	<0.001
Mann-Whitney U Statistic= 74,811 p=0.001										
Avenue 64	2001 - 2016	832	2.03	0.38	1.90	2.09	2.20			
Avenue 64	2001 - 2008	414	2.09	0.40	1.82	2.10	2.30	-0.5	1.2	<0.001
Avenue 64	2009 - 2016	418	1.97	0.35	1.92	2.07	2.19	-2.9	9.9	<0.001
Mann-Whitney U Statistic= 72,211 p<0.001										
Hill Ave.	2001 - 2016	832	0.86	0.5	0.50	0.74	1.02			
Hill Ave.	2001 - 2008	418	0.83	0.48	0.50	0.70	1.00	2.0	5.2	<0.001
Hill Ave.	2009 - 2016	414	0.90	0.53	0.50	0.77	1.20	0.7	-0.4	<0.001
Mann-Whitney U Statistic= 81,953 p=0.19										
Tropical Ave.	2001 - 2016	832	1.07	0.62	0.52	1.04	1.50			
Tropical Ave.	2001 - 2008	419	1.22	0.63	0.70	1.20	1.70	0.2	-0.8	<0.001
Tropical Ave.	2009 - 2016	413	0.92	0.58	0.40	0.93	1.38	0.2	-0.7	<0.001
Mann-Whitney U Statistic= 63,310 p<0.001										
WTP	2001 - 2016	2,548	2.60	0.09	2.55	2.60	2.65			
WTP	2001 - 2008	1,206	2.58	0.09	2.51	2.57	2.62	1.7	8.9	<0.001
WTP	2009 - 2016	1,342	2.63	0.07	2.60	2.62	2.67	4.7	21	<0.001
Mann-Whitney U Statistic= 474,479 p<0.001										

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Table 4

Nitrite Concentrations in Pasadena at Four Locations between 2001 – 2016

All Results in µg/L

Location	Period	n	Mean	SD	25th	50th	75th	S	K	p
Arroyo Terrace	2001 - 2016	825	25.3	29.3	5.0	14.0	35.0			
Arroyo Terrace	2001 - 2008	416	22.1	26.8	5.0	14.5	29.0	2.6	10.4	<0.001
Arroyo Terrace	2009 - 2016	409	28.4	31.9	5.0	14.0	42.0	1.6	2.0	<0.001
Mann-Whitney U Statistic= 77,576 p=0.028										
Avenue 64	2001 - 2016	750	9.7	11.7	3.0	6.0	12.0			
Avenue 64	2001 - 2008	414	6.3	8.4	0.0	5.0	8.0	4.4	31.4	<0.001
Avenue 64	2009 - 2016	336	13.9	13.7	5.0	10.0	19.0	3.4	21.7	<0.001
Mann-Whitney U Statistic= 38,075 p<0.001										
Hill Ave.	2001 - 2016	705	2.7	3.3	0.0	2.0	5.0			
Hill Ave.	2001 - 2008	418	1.6	2.4	0.0	0.0	3.0	1.3	0.33	<0.001
Hill Ave.	2009 - 2016	287	4.3	3.7	2.0	3.0	5.0	2.1	6.6	<0.001
Mann-Whitney U Statistic= 28,484 p<0.001										
Tropical Ave.	2001 - 2016	705	3.7	10.7	0.0	1.0	4.0			
Tropical Ave.	2001 - 2008	419	2.3	5.2	0.0	0.0	3.0	4.3	23.4	<0.001
Tropical Ave.	2009 - 2016	286	5.9	15.3	1.0	3.0	5.3	8.8	90.1	<0.001
Mann-Whitney U Statistic= 31,410 p<0.001										

K = Kurtosis S = Skewness p = Probability