Wavelet Analysis of Groundwater Level Fluctuations in Long Island and The Metropolitan Area, NY

Parag, A. S.[1], Jones, W.[1], Bradley, C.[2], Cann, I.[1], Marsellos, A.E.[1] , Tsakiri, K.G.[3]
[1]Dept. Geology, Environment and Sustainability, Hofstra University, NY, USA.
[2]Dept. Engineering and Applied Sciences, Hofstra University, NY, USA.
[3]Dept. Information Systems, Analytics, and Supply Chain Management, Rider University, NJ, USA.
aparag1@pride.hofstra.edu

Abstract

Long Island's groundwater levels fluctuate annually over time due to precipitation, human activities, the aquifer's ability to replenish, and other possible geological and atmospheric factors. This research investigates the relationship between groundwater periodicity and human interference to visualize the probable effects on the water supply throughout Long Island between the years 2002 to 2024. This study includes the possible impacts of human interference across Long Island's groundwater system using wavelet analysis to compare the effects caused before, during, and after the COVID-19 pandemic in 2020. The methods within this research incorporate coding of groundwater data in active groundwater stations reported by the monitoring wells of the USGS (United States Geological Survey) database using R programming language in RStudio. Stations are located within large industries like shopping areas, laboratories, universities, and even in parks throughout NYC, White Plains, Nassau, and Suffolk County. Wavelet analysis figures were constructed containing the groundwater data that was utilized to visually determine the quantity of groundwater before, during, and after the pandemic period based on the patterns of strong and weak fluctuations within the groundwater system. The separation of long-term and short-term data from the raw wavelet figures aided in uncovering oscillating patterns. This oscillation frequency indicates a recharging or discharging component in the aquifer. The raw and long-term wavelets of groundwater levels reveal stronger frequencies sometime before the pandemic, weak to no frequencies during the pandemic, and some indications of stronger frequencies returning after the pandemic. However, short-term wavelets of groundwater levels appeared to show random patterns that weren't as abundant as the raw and long-term wavelets. Precipitation data patterns seem relatively consistent except for a slight decrease in the overall precipitation pattern shortly after 2015, indicating another factor, other than human interference during COVID-19, potentially causing this phenomenon. Therefore, the weaker fluctuations in groundwater levels during the year 2020 are possibly due to the COVID-19 pandemic, when large industries went out of business and stopped using groundwater for their large productions. The use of wavelet analysis allows for a more visual perceptive to display how the frequencies change over time. This technique can be used to monitor and ensure the stability of freshwater accessible to Long Island.

Introduction

This research aims to collect groundwater level and precipitation data throughout Long Island and the metropolitan area over several years before, after, and during the COVID-19 period to analyze the changes throughout the pandemic of 2020 using a wavelet analysis approach. During March of 2020, everyone was asked to stay home due to the effects of COVID-19. People were spending more time at home due to the pandemic period, which lasted throughout the following year. With a decreasing number of people within business areas, comes an increase in groundwater levels within those areas, depending on the recharge ability of the aquifer and the amount of precipitation. Similarly, water use is lowest within industries such as universities during the holidays in the winter quarter because faculty and students are not present within the university for weeks (Yale University, 2010).

The aquifers in Long Island are mainly replenished by precipitation, therefore freshwater from the aquifers can become limited after long periods of overuse. The water extracted in highly dense and populated areas within Long Island was observed to lower the groundwater levels (Hart et. al, 2023). Large industries require a high demand for groundwater to provide cleaning, cooling, and steam generating which tends to reduce groundwater levels. Overuse of the groundwater affects the aquifer system by not allowing enough time for replenishment since Long Island gets its freshwater only from precipitation. However, there has not been research done involving wavelet analysis of groundwater levels on Long Island, so we approached this study using this method to get efficient and available data into one area that can be viewed in a practical way.

Wavelet analysis is a mathematical technique that decomposes a time series into time-frequency components, enabling the detection of localized variations and transient periodic patterns in the data. It can be used to better understand groundwater and surface-water interactions under non-stationary assumptions which can be used to study long-term hydrological inter-annual times series (Treviño, 2023). A wavelet is a graph that displays a wave pattern demonstrating how the periodicity changes over time depending on the variables. This analysis helps to detect the natural phenological cycles in groundwater levels driven by inputs like rain or snow. Therefore, wavelet analysis can highlight patterns at different time scales and frequencies whereas the periodograms show the frequencies.

Long Island is expected to face increasing challenges with maintaining the quantity and quality of groundwater resources. Groundwater is the main source of freshwater for public supply, industrial uses, and agriculture on Long Island (Bouhton et. al, 2021). If there were lower amounts of groundwater available on Long Island, then people wouldn't have the freshwater they need for drinking, agriculture, and industrial processes. Recent research on groundwater impacts has shown that the COVID-19 pandemic in 2020 resulted in a decline in groundwater supply because everyone had to stay at home and use more groundwater, rather than draw from New York City's water supply (Hart et. al, 2023). However, when everyone had to stay indoors the groundwater level fluctuations were weak in areas like White Plains, Nassau, and Suffolk County, indicating that there was less groundwater being used up. Therefore, before COVID-19 when everyone was out and about or working, more groundwater was being used up because these large businesses would require larger amounts of groundwater intake to satisfy their productions and public needs.

Based on the comparison of the groundwater and precipitation wavelets, if we see annual or short-term patterns that are absent or disrupted, then this can indicate that human activities could be affecting the aquifer's natural recharge process. Precipitation data is included to reveal the expected seasonal signals, which will further support the idea that any disruption in groundwater periodicity is due to human factors. Therefore, if the precipitation data displays the usual seasonal patterns, but the expected periodicities in groundwater levels are absent or disrupted, then the results are that an additional factor may be altering aquifer recharge throughout Long Island. We are investigating this spectral analysis of the groundwater data oscillations within a long-term period, including before and after the pandemic, to predict the future of groundwater supply for Long Island.

Methods

To gather the groundwater and precipitation data needed to conduct the wavelet analysis, R-programming language was used in RStudio. Multiple packages were used in RStudio such as data.table, dplyr, glue, lubridate, curl, shape, purrr, zoo, celestial, leaflet, htmltools, and WaveletComp. Data.table package used for fast and memory-efficient data manipulation for large datasets. Dplyr is used for easier data manipulation. Glue is used for creating an interpreted string of data. Lubridate is used to format dates. Curl is used to bind to the libcurl C library. Shape used for statistical analysis of shapes. Purrr is used for more efficient tools. Zoo used for time-series analysis. Celestial is used to match datasets quickly. Leaflet are used to create dynamic online maps. Htmltools is used to customize the user interface. WaveletComp is used for continuous wavelet-based analysis of univariate and bivariate time series.

Previous studies have been made using spatial time series analysis (Hart et. al, 2023), therefore this methodology views the data from a different perspective to develop new strategies that can view similar datasets from various angles, possibly even enhancing the outlook and efficiency of the data as a whole. The groundwater level data was collected and downloaded into RStudio from 58 stations in Long Island through the USGS online resources. Station identifiers were defined manually in a for-loop sequence, and URLs were constructed for various measurement codes (e.g., 62610, 62611 depending on the reference plane of measurement) to download daily or 15-minute data spanning February 1, 2000, to February 10, 2025. The data was then cleaned in R to get rid of inconsistencies, duplications, missing values, and formatting issues. Gaps in the groundwater time series were handled with interpolation using the na.approx() function from the zoo, filling gaps of up to 14 days, and trailing NAs (data at the edges) were addressed with na.locf() to ensure complete series.

The groundwater and precipitation data was plotted in a time series analysis after cleaning to identify any stations with dates that may be out of our time frame of COVID-19. The graph displaying all the stations and their depths was reshaped from wide to long to view the dataset from a different format of the columns. This process involved breaking up the multiple columns representing different measurements or time points into just two columns: time and individual stations. This new graph gave us a range of each station's data and we could finalize which stations to use. After the cleaning and interpretation of data, 10 stations were studied due to the other 48 stations missing dates, outliers, or not displaying data within our time frame (during COVID-19).

Next, the coordinates of each station were identified by locating each station on the USGS online resource, and then using those coordinates to construct an interactive map of Long Island displaying the 10 stations in RStudio. For spatial analysis, station coordinates were extracted from their USGS site names and converted from degrees, minutes, and seconds to decimal degrees with the celestial package. These spatial data were visualized using both static maps (via ggplot2 and ggspatial) and interactive maps (using a leaflet).

In the 10 wells containing the data that remained within our time frame, the wavelet transformation was applied using analyze.wavelet() function from WaveletComp so that we can analyze the frequency variations of groundwater levels before, during, and after COVID-19 and with this we were able to zoom into the raw data by separating the short-term or long-term oscillation periods using the kz() function from kza. Wavelet analysis was applied using the WaveletComp package to explore periodicities over scales ranging from 20 to 730 days. For each station, the groundwater time series was analyzed and visualized via power spectra plots that include annotations (e.g., a vertical line marking the onset and end of the COVID-19 period).

Next, a moving average was created also using the kz() function in kza to remove the noise, and smooth out the raw, short-term, and long-term oscillations. The moving average (natural oscillations over time) was subtracted from the raw data to highlight any disruptions in the groundwater oscillations revealed throughout the short-term frequencies. We then averaged the raw data over 29 days, 3 times to obtain the long-term frequencies to analyze separately, before comparing.

Further analysis was made by determining the station locations displayed on the interactive map and the industries that lay within each station to compare it to its matching wavelet. After constructing and analyzing the groundwater data, the precipitation data was gathered and analyzed from NOAA (National Oceanic and Atmospheric Administration). An API (Application Programming Interface) code was plugged into RStudio to retrieve daily precipitation data from the Islip-Macarthur Airport station between 2002-2025. The data was cleaned and interpolated to form a moving average and run a wavelet analysis. A moving average was again developed to run a wavelet analysis the same way the groundwater data was established. The precipitation wavelet was also broken down into raw, short-term, and long-term data and compared to the groundwater wavelets to identify any disruptions within its pattern and to create further interpretation to determine if human interference caused a major impact on the aquifers of Long Island.

Results

The wavelet analysis results for groundwater oscillations were taken from data from ten monitoring stations on Long Island and the metropolitan area. One station is located in White

Plains, two stations are located in Queens, three stations are located in Nassau County, and four are located in Suffolk County (Figure 1). The wavelet analysis results for precipitation oscillations were taken from the data of the Islip-Macarthur Airport monitoring station. The findings highlight periodicities in groundwater levels and precipitation variations over different time scales.

The precipitation wavelet containing raw, short-term, and long-term effects (Figures 6, 7, and 8) reveals no major disruptions to the fluctuations during the 2020 pandemic. However, there appears to be a slight decrease in the precipitation fluctuations after 2015. When the short-term and long-term data are separated from each other they reveal a sharper divide between the stronger fluctuations that were harder to visualize when together. The raw and long-term groundwater wavelets of all the stations except two appear to reveal a similar pattern of somewhat consistent strong fluctuations before 2020, weak to no fluctuations during 2020, and in some stations weak fluctuations occurring again after 2020 (Figures 3 and 5). The two stations that reveal strong fluctuations throughout, even during and after 2020, were located within parks (Figure 2). One of the stations was located on Fire Island Beach and the rest of the stations were located within or near large industries (Figure 2). However, the short-term groundwater data was random and does not appear to be consistent with the raw and long-term data (Figure 4).

Figure 1: Map of Groundwater Stations in Long Island

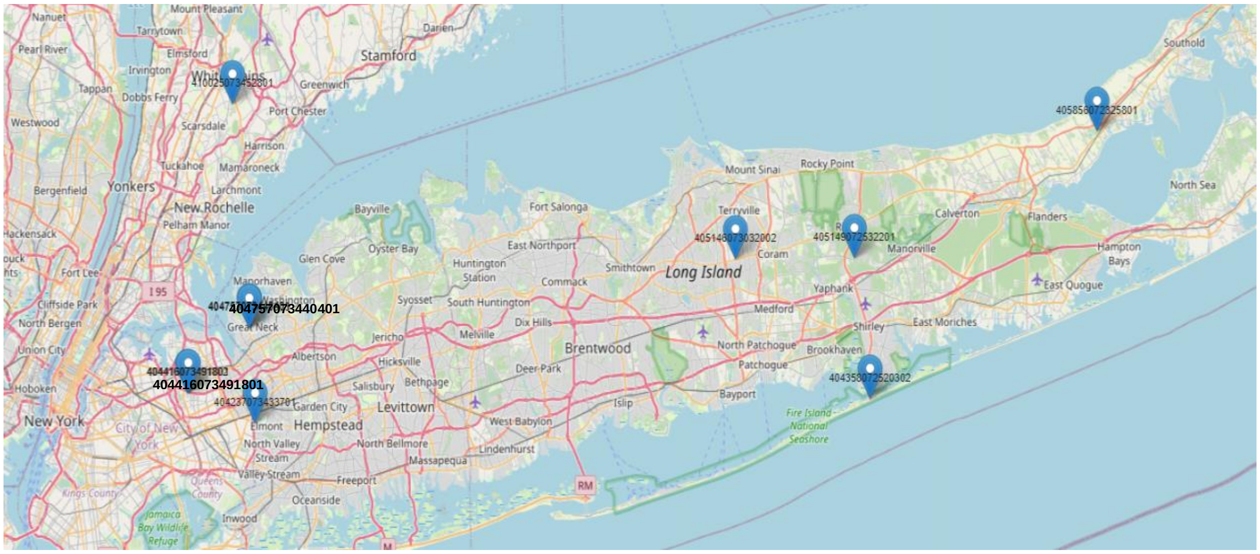

Figure 1: Map displays the 10 stations, located at the east and the west of Long Island, studied in this research. Interactive map created in RStudio.

Figure 2: Images of Stations Locations

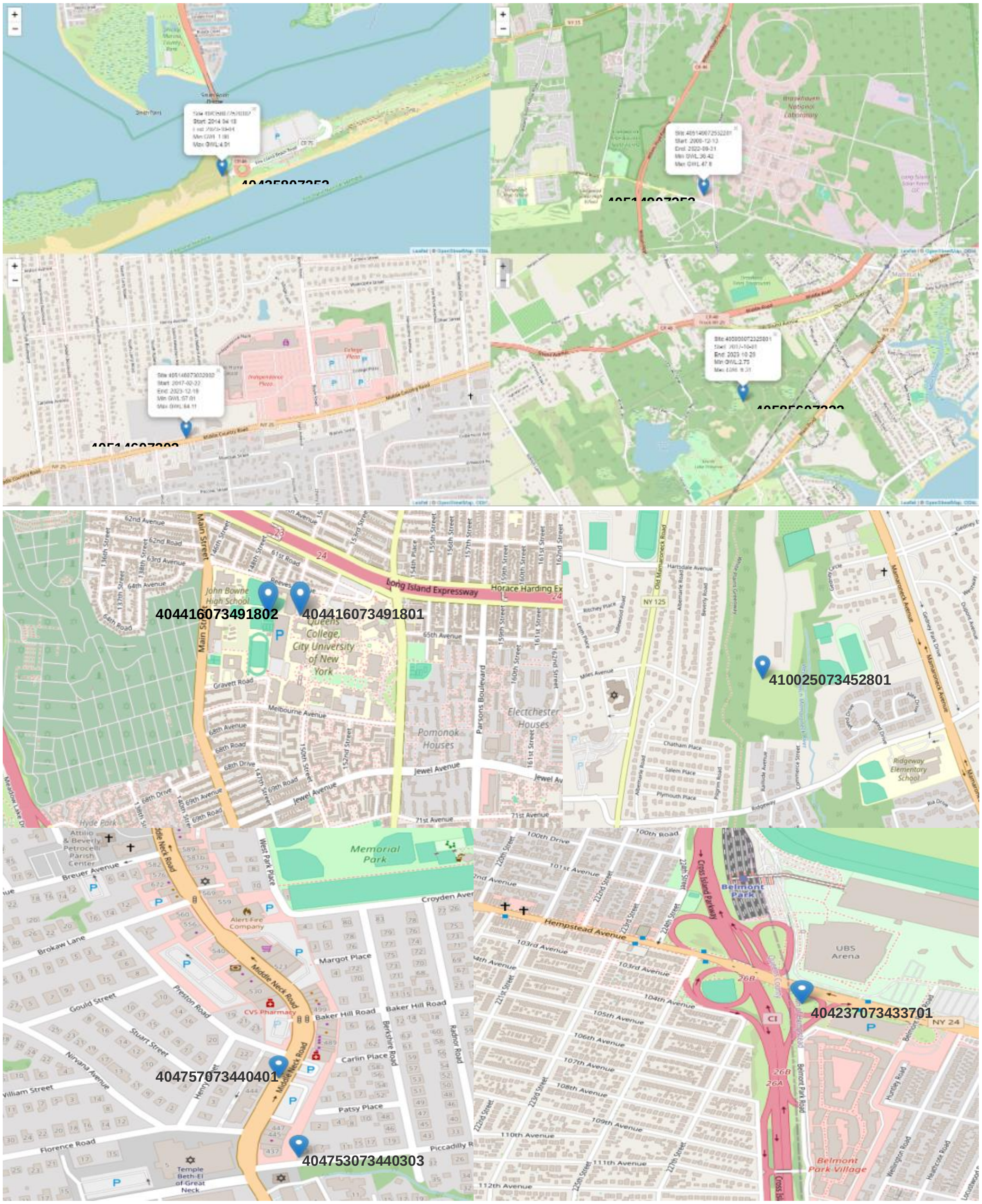

Figure 2: These images display the industries located within or near the stations studied. Each station is labeled with their station name and pinpointed by the blue markers. Interactive map created in RStudio.

Figure 3: Raw Groundwater Wavelet Analysis

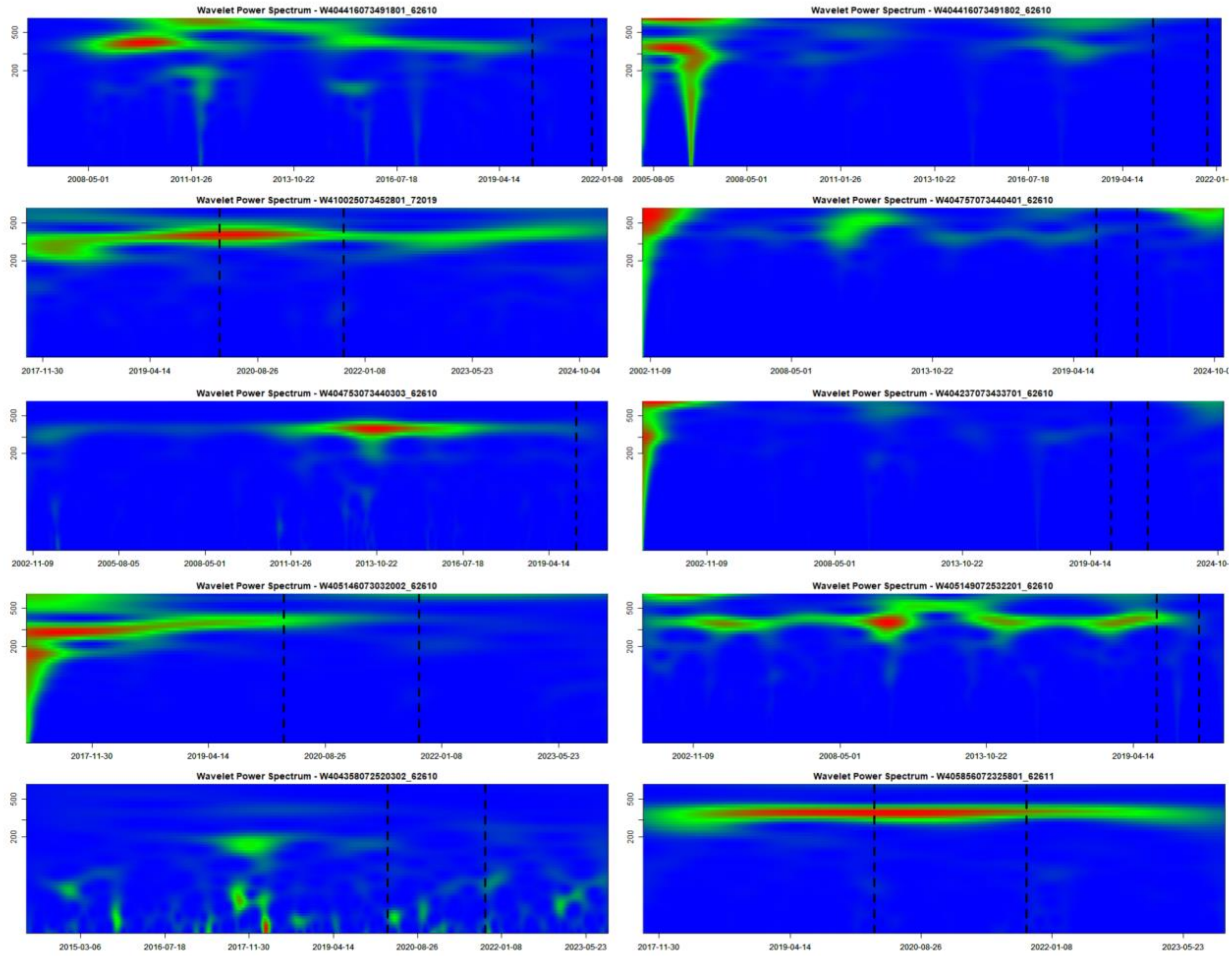

Figure 3: These graphs display the raw data of groundwater levels in a wavelet analysis for our 10 stations studied. The red areas reveal stronger oscillations while the green and blue areas reveal weaker oscillations in the groundwater. The COVID-19 period is outlined for each station. Includes long-term periods (one year and over) and short-term periods (one year and under). Labeled if station within an industry like shopping areas or universities and labeled is within park or vegetated beach (barrier island). The y-axis represents periods (in days).

Figure 4: Short-term Groundwater Wavelet Analysis

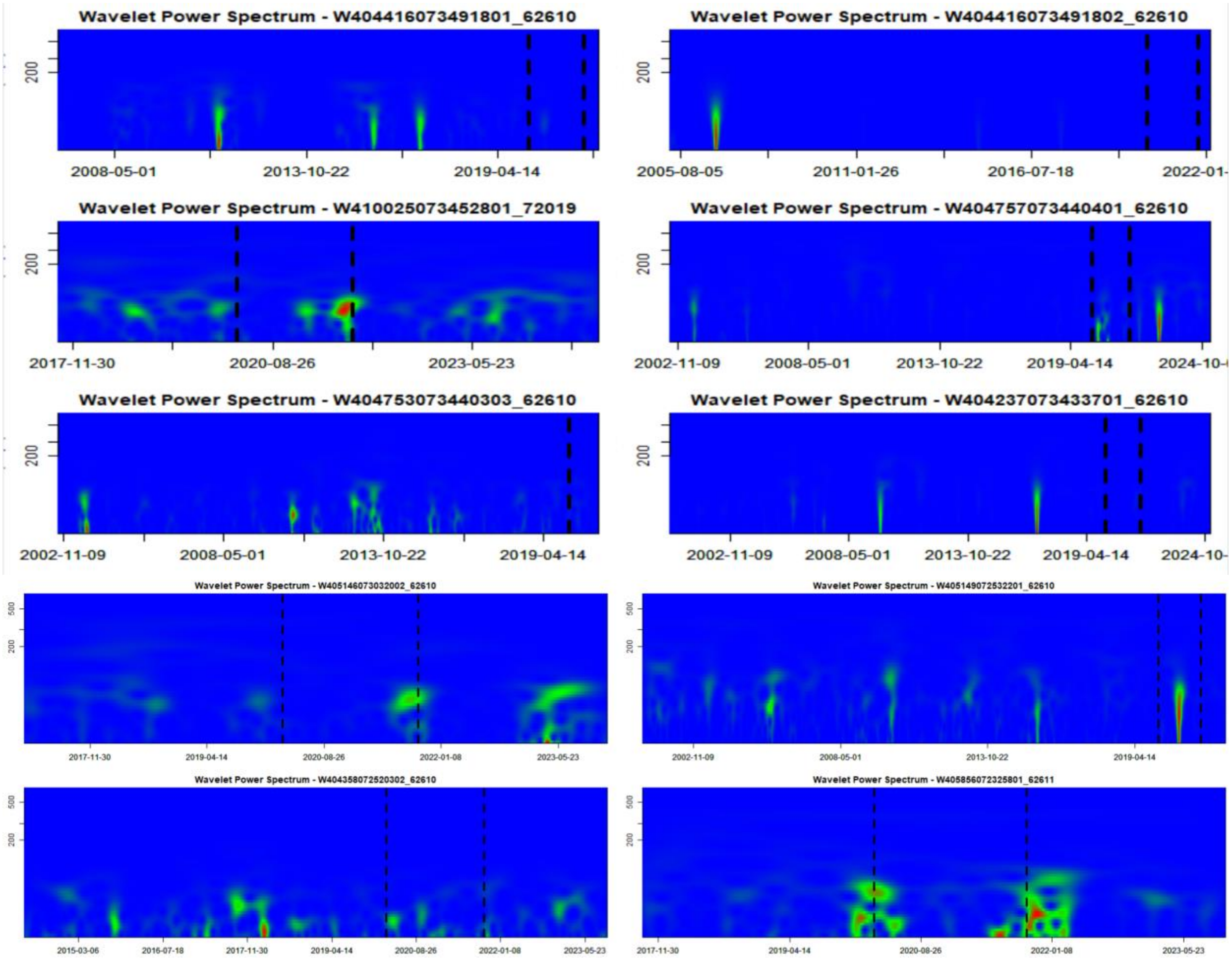

Figure 4: These graphs display the zoom in of the short-term data of groundwater levels in a wavelet analysis for our 10 stations studied. The red areas reveal stronger oscillations while the green and blue areas reveal weaker oscillations in the groundwater. The COVID-19 period is outlined for each station. Includes short-term periods (one year and under). Labeled if station within an industry like shopping areas or universities and labeled is within park or vegetated beach (barrier island). The y-axis represents periods (in days).

Figure 5: Long-term Groundwater Wavelet Analysis

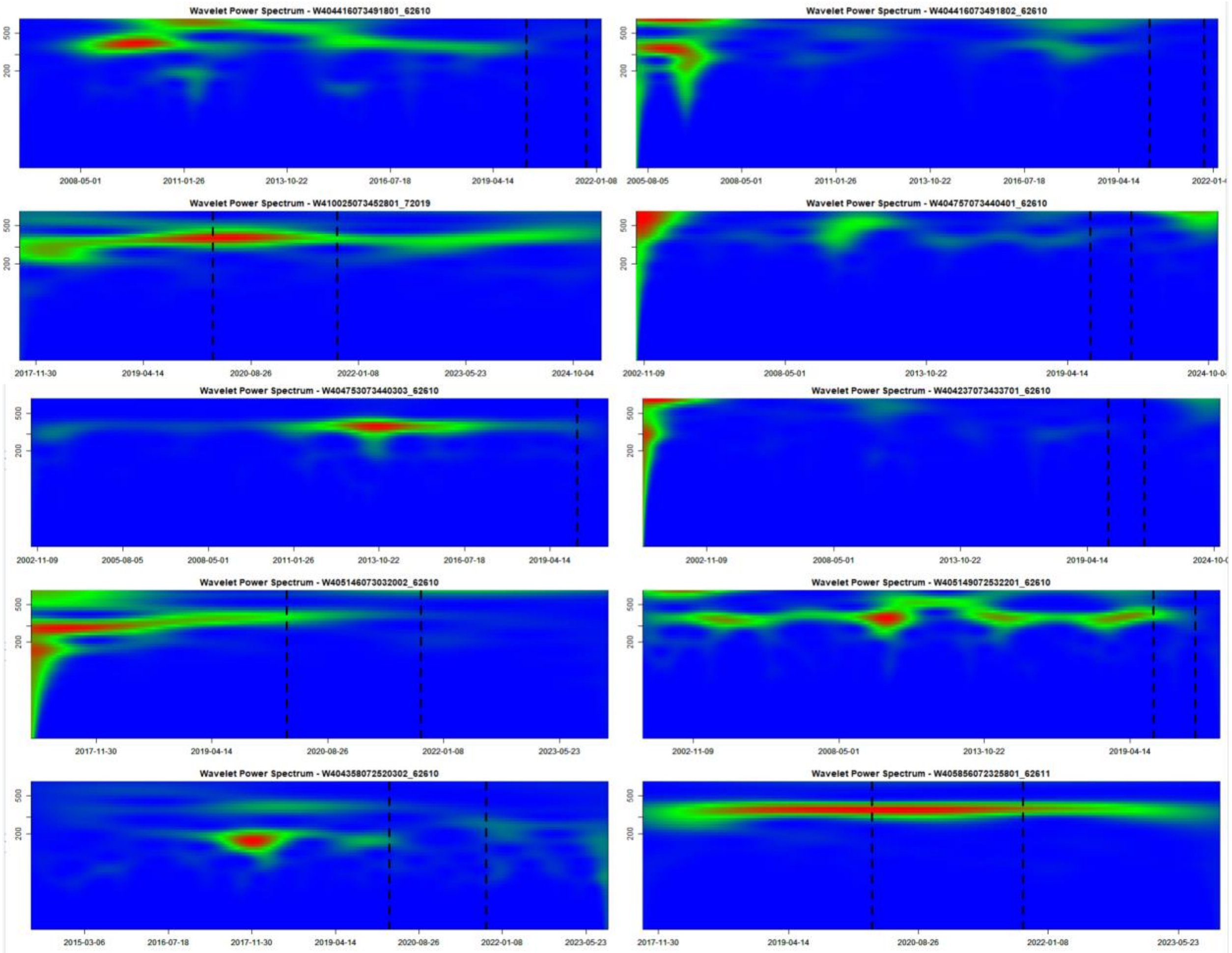

Figure 5: These graphs display the zoom in of the long-term data of groundwater levels in a wavelet analysis for our 10 stations studied. The red areas reveal stronger oscillations while the green and blue areas reveal weaker oscillations in the groundwater. The COVID-19 period is outlined for each station. Includes long-term periods (one year and over). Labeled if station within an industry like shopping areas or universities and labeled is within park or vegetated beach (barrier island). The y-axis represents periods (in days).

Figure 6: Raw Precipitation Wavelet Analysis

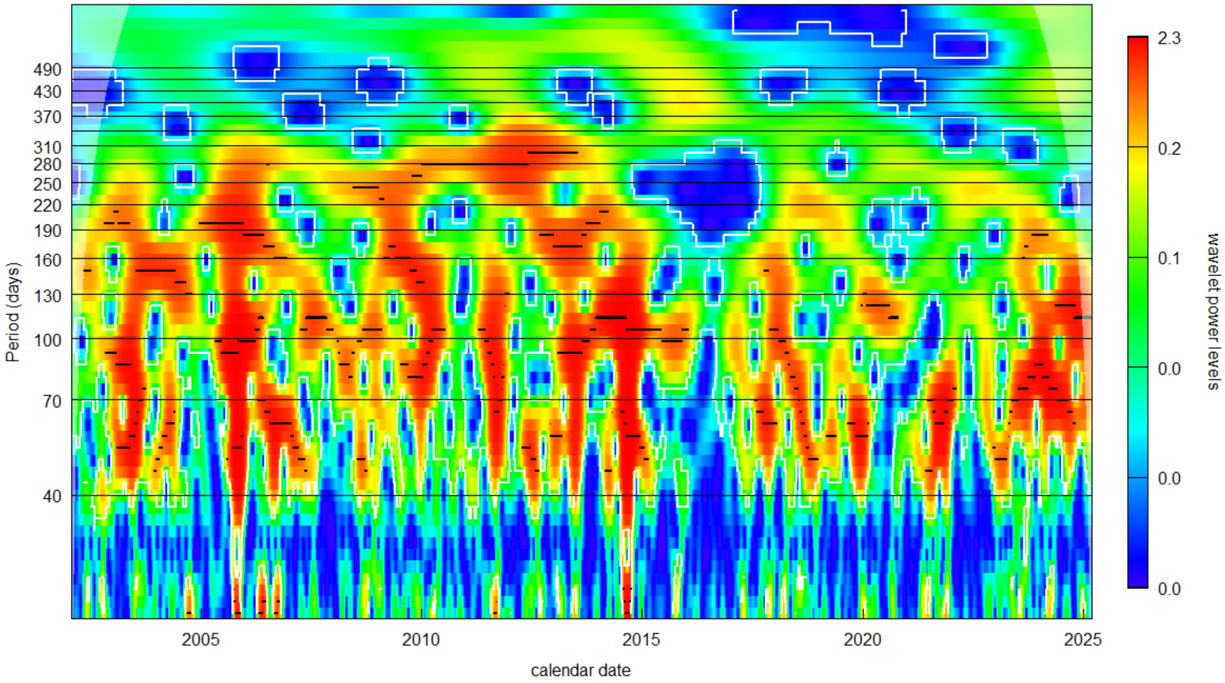

Figure 6: This graph displays the raw data of the precipitation oscillations in a wavelet analysis for one station: Islip-Macarthur Airport. The red areas reveal stronger oscillations while the green and blue areas reveal semi-annual weaker oscillations in the precipitation. The COVID-19 period is outlined for each station.

Figure 7: Short-term Precipitation Wavelet Analysis

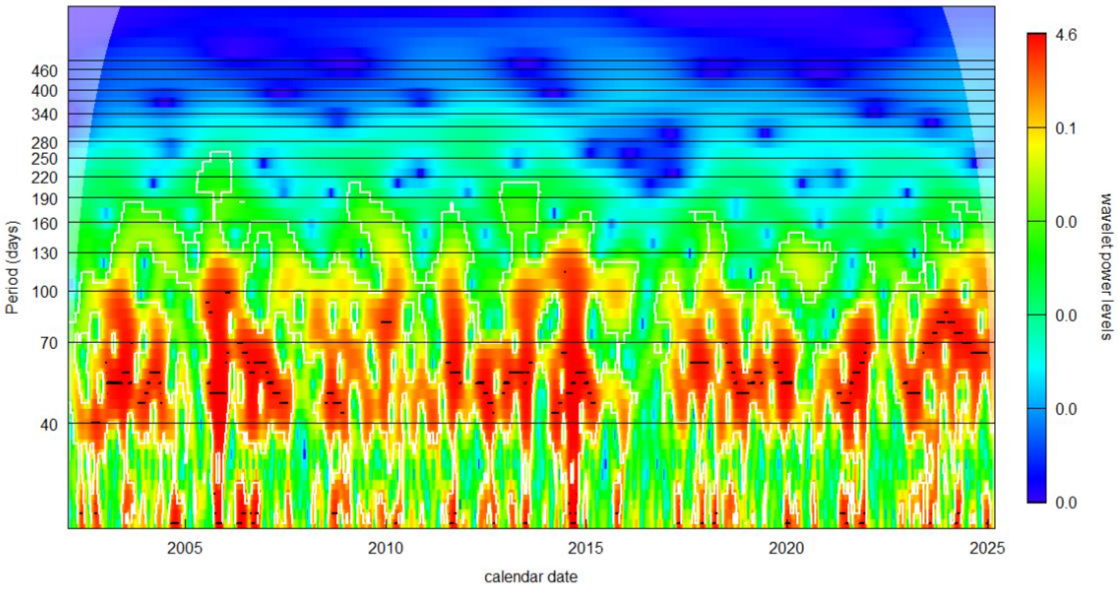

Figure 7: This graph displays the zoom in of the short-term data of precipitation oscillations in a wavelet analysis for one station: Islip-Macarthur Airport. The red areas reveal stronger oscillations while the green and blue areas reveal weaker oscillations in the groundwater. The COVID-19 period is outlined for each station.

Figure 8: Long-term Precipitation Wavelet Analysis

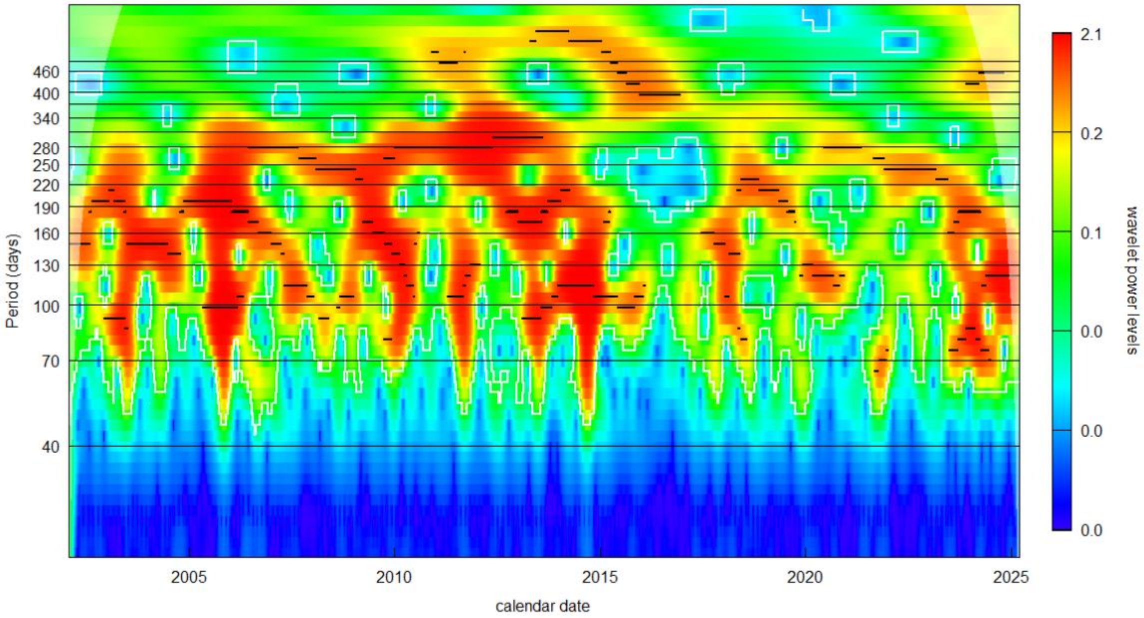

Figure 8: This graph displays the zoom in of the long-term data of precipitation oscillations in a wavelet analysis for one station: Islip-Macarthur Airport. The red areas reveal stronger oscillations while the green and blue areas reveal semi-annual weaker oscillations in the groundwater. The COVID-19 period is outlined for each station.

Discussion

This study examined how Long Island's sole freshwater source - its groundwater aquifer system - responded to varying precipitation patterns and human activities before, during, and after the COVID-19 pandemic. By applying wavelet analysis, we evaluated changes in groundwater level oscillations at stations in industrial/commercial zones, parks, and barrier island settings. Seeing that Long Island gets all of its freshwater from groundwater aquifers, that means that anything that affects the groundwater supply, affects all of Long Island's drinking water. Many things can affect the groundwater levels on Long Island, specifically how it would leave the aquifers. However, due to Long Island's geography being completely surrounded by saltwater, precipitation is essentially the only way for its aquifers to replenish, either directly or indirectly by runoff captured in recharge basins (New York Water Science Center 2017B). Precipitation gets broken up into two different forms: rainwater and snow. Our wavelet analysis of rainwater precipitation data from the Islip-MacArthur Airport station showed relatively stable annual and sub-annual patterns, with no abrupt changes during 2020. The only change in pattern came a little bit after 2015 (Fig. 6, 7, and 8), which predates the pandemic and was likely due to a broader climatic variability, such as the ENSO phenomena (Chen et. al, 2024). Therefore, natural recharge from rainfall alone does not seem to explain the marked shifts in groundwater fluctuations we observed during the pandemic. However, this precipitation data came solely from one station and, therefore there is the potential for spatial variability across Long Island. Also, snow data is something that was not taken into account but would like to be included in this research in the future.

Aquifers on Long Island have several outflows. These outflows consist of natural discharge to the ocean, evapotranspiration, and human consumption (New York Water Science Center 2017A). We only focused on human consumption during the pandemic because that is when it would be most influential. When analyzing a specific time, like COVID-19, we can isolate a period with exaggerated results. During COVID-19, people had to work from home, leaving Long Island industries and businesses using less water. To look at how COVID-19 affected groundwater supplies, the groundwater stations had to be analyzed based on their location and groundwater fluctuations, that is the varying groundwater levels, through wavelets. From the raw data wavelet for groundwater oscillations, we created long-term and short-term wavelets, which we used in our analysis. However, the short-term wavelets were not used as much for our analysis as we looked at the long-term effects of lockdown on groundwater oscillations, prompting us to prioritize the long-term wavelets.

The first four of the groundwater stations that we analyzed: W405146073032002, W405149072532201, W405856072325801, and W404358072520302, were located in Suffolk County (Fig. 1). Two of the four stations were located in industrial and commercial areas, with one being Brookhaven National Lab, a particle accelerator (Fig. 2). The other two stations are located on a barrier island and in the middle of a park (Fig. 2). When looking at these stations' wavelets, all, apart from the one located in the park, showed strong oscillations in groundwater levels leading up to COVID-19, indicating high human usage (Fig. 3, 4, and 5). Then, during and after COVID-19, these stations started showing weaker oscillations in groundwater levels, indicating less human usage (Fig. 3, 4, and 5). The oscillations started to dissipate at the start of COVID-19 and almost completely stopped during COVID-19. The park, however, maintained relatively strong oscillations going well into the pandemic. This is likely due to park-based wells being predominantly used for irrigation, so usage may not have dropped as dramatically as it did for large industries during the lockdown. The stations located in Nassau County (W404757073440401, W404753073440303, and W404237073433701) showed similar long-term trends to the ones in Suffolk County. These three stations, two being right next to each other, are located next to a shopping center and UBS arena (Fig. 2). All of the Stations within Nassau and Suffolk counties, apart from the station within the park, follow the same pattern of high oscillations before COVID-19 and the usage dissipates during COVID-19 shortly after it as well.

However, not all of our stations were located on Long Island, posing questions on whether groundwater levels would be affected by humans in those areas or not. These stations in question were located in Queens (W404416073491802 and W404416073491801) and White Plains (W410025073452801) (Fig. 1). While Long Island obtains its freshwater from groundwater, NYC and White Plains only use groundwater for certain instances, and instead opt for surface water from upstate New York for their drinking water. Those instances where groundwater gets used are specific golf courses and parks (New York City Department of City Planning). Two of the parks/golf courses (Corona Park and Kissena golf course) were located within a distance of two of our stations, meaning usage would include human consumption and not just natural instances (Fig. 2). The station in White Plains is also inside of a park, meaning its water use came from groundwater (Fig. 2). The wavelets for the stations in Queens both showed very similar patterns to the ones in Nassau and Suffolk county. Those patterns were high oscillations before COVID-19, diminishing to no oscillations during COVID-19, and very weak oscillations after COVID-19 (Fig. 3, 4, and 5). Therefore, all of the industrial/commercial stations have similar patterns of high human usage before lockdown, weaker to no usage during lockdown, when everyone was home and not at work, and weak human usage following the pandemic, as the world adjusted to COVID-19. However, the station in White Plains showed similar patterns to the park station in Suffolk County. Those patterns were relatively strong oscillations continuing well into COVID-19 (Fig. 3, 4, and 5). As stated before, that is likely to do with irrigation being less affected than industry by the lockdown. These two park stations highlight that groundwater level patterns are strongly linked to local land use and extraction rates.

While these findings offer insight into the temporal dynamic of groundwater use on Long Island, there are limitations. First, snowfall data, an important contributor to recharge, was not isolated in our precipitation dataset and should be explored in future studies. Second, analyzing only one precipitation station may not capture regional variability across Long Island. Finally, wavelet analysis reveals patterns but does not alone establish causation. Many factors were not taken into account, such as economic conditions, local regulation changes, or infrastructure updates (just to name a few) that could have also affected these patterns.

Conclusion

Our wavelet analysis has indicated significant patterns of activity and fluctuations within Long Island's groundwater system before, during, and after the COVID-19 pandemic. In conclusion, these wavelets reveal indications of human interferences and other prominent factors impacting groundwater levels. Through the individualized long-term wavelet data, stronger oscillations were recorded in the years prior to COVID-19, and ultimately weaker oscillations were recorded after the pandemic. For the majority of the stations, and all of the stations near industries, groundwater level fluctuations were significantly stronger before COVID-19, and much weaker after COVID-19, showing the impact of the lockdown. However, in environments where lockdown was irrelevant, like the parks, the wavelet's oscillations remained high before and during COVID-19. Long Island's precipitation data has remained, on average, consistent through the years before, during, and after COVID-19. This indicates that the rapid change in human activity and behavior as a reaction to this unique period is made evident in the sudden oscillating wavelet patterns, which began explicitly in 2020. Another significant point of reference in the wavelet analysis is how the long-term data records human interference through an average display of change across the span of multiple years, whereas the short-term data records human interference that ranges from a year to anything less than a year. The long-term data supports the conclusion of how human activity caused unexpected influxes in groundwater levels and the rapid occurrence of these influxes. Our analysis and data strongly suggest a fragile relationship between human activity and the natural processes of the environment, as precipitation is purposed to replenish the aquifers. This study can be used to conduct further research to determine what exact behavioral and habitual changes caused the shift in Long Island's water usage levels, affecting the groundwater and wavelet levels as a result.

Credit Authorship Contribution Statement

Parag, A: Literature, Editing, RStudio Coding, Writing- Abstract, Introduction, Methods, Results, Results- Figures 1-5. Jones, W: Literature, Editing, RStudio Coding, Writing- Methods, Discussion, Results- Figure 2. Cann, I: Literature, Editing, RStudio Coding, Results- Figures 6,7,8. Bradley, C: Literature, Editing, RStudio Coding, Writing- Conclusion

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