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Research paper/

Episodic and continuous recharge estimation from high-resolution well records

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Article Impact Statement: High-resolution well and rainfall data provide insight into episodic and continuous recharge processes depending on local aquifer conditions

Abstract

Water table fluctuation (WTF) methods are a primary and well-established way to determine groundwater recharge based on the direct response of the water table to precipitation input. An emerging complexity of recharge is whether it occurs as an episodic and transient process, or a continuous steady-state process, however most studies have not focused on these short-term vs long-term timescales, in part because of a lack of data resolution. Here, high-resolution (subhourly) precipitation and water level data are analyzed for wells in the suburbs of New York City using two contrasting WTF approaches, with a common mathematical basis, that are suited to episodic and continuous processes. The resulting hourly recharge results, like the individual water level records from comparable wells, are sensitive indicators of subtle differences in

aquifer conditions such as thickness of the unsaturated zone, position in the flow system and localized preferential flow. While the episodic, transient approach excludes diffuse recharge by design, the continuous, steady-state approach is influenced by short term precipitation events, and therefore integrates transient processes to some extent. However, the continuous, steady-state approach is subject to its own limitations relating to position in the aquifer system, and may overestimate recharge if aquifer conditions are not well understood. More widespread use of higher resolution data as well as understanding aquifer conditions and refining aquifer parameters would improve WTF recharge estimation.

Introduction

Recharge is of vital importance for groundwater resources worldwide due to water supply dependence on aquifers and their depletion around the globe (e.g., Chao et al. 2017; Famiglietti et al. 2011). Furthermore, as climate change modifies precipitation patterns (Asadieh and Krakauer 2015; Zhu 2013), fluxes of recharge to aquifers are likely to change in space and time (Herrmann et al. 2017), potentially affecting baseflow to streams and wetlands, thus making analysis of recharge more urgent. Independent estimates of recharge are useful for understanding and protecting hydrologic systems. They are essential for well-parameterized groundwater flow models used in studies to mitigate groundwater depletion, manage water supply and predict contaminant transport (Anderson et al. 2015). Use of flow models themselves to estimate groundwater recharge is problematic due to non-uniqueness (Knowling and Werner 2017; Knowling and Werner 2016). Quantifying groundwater recharge is a “wicked” problem because of uncertainties in spatial and temporal variation (Delin et al. 2007; deVries and Simmers, 2002). Considerable uncertainty remains depending on data availability, assumptions involved in estimation, and the nature and timing of recharge processes. This study uses

variations on the water table fluctuation (WTF) method at unusually high temporal resolution (subhourly) to assess influences on and relative importance of episodic and continuous recharge, which to date, have rarely been considered together.

Many methods exist for estimating recharge (Walker et al. 2019; Huet et al. 2016; Park 2012; Healy and Scanlon 2010; Scanlon et al. 2002), depending on available data. Following Scanlon et al. (2002), they may be broadly characterized into several categories. Water budget residual methods, including various modeling methods, are limited by the difficulty quantifying other, often larger terms in the water budget. Surface-water-based methods, such as hydrograph separation and baseflow discharge methods are hindered by uncertainty in surface water gaging techniques (Halford and Mayer 2000) and streams may not be available. Tracer methods focus on longer term recharge processes (e.g., Muller et al. 2016) and require ready access for sampling. Unsaturated zone processes can be important for recharge estimation, especially in very shallow water table conditions (Goncalves et al. 2019; Crosbie et al. 2005) but estimating unsaturated zone parameters is challenging. Some researchers (Chang et al. 2018; Liang et al. 2017; Park 2012; Park and Parker 2008; Sophocleous 1991) have investigated both saturated zone and unsaturated zone processes, and a new recharge estimation approach is based on GIS analysis of seasonal water table patterns (Gilmore et al. 2019). Fundamentally, most of the above methods offer only indirect insight into recharge processes whereas saturated zone methods involve hydraulic head response to direct forcing. For this reason, a saturated-zone approach is taken here, based on well water-level variations in response to precipitation events.

Climatic variation, lithology and aquifer conditions determine whether transient episodic recharge or steady-state continuous recharge fluxes are most important in a given situation.

When water table information is available, the shape of the water level hydrograph with

sufficient resolution can be used to distinguish between them, but coarse-resolution well records can obscure episodic fluctuations. Many analyses do not distinguish between episodic and continuous recharge but yield only annual estimates. This work shows how a widely used method, the water table fluctuation (WTF) method (Delottier et al. 2018; Healy and Cook 2002), may be applied to either episodic or continuous recharge estimation, depending on the dynamics of the water table and aquifer configuration. Park (2012) introduced a hybrid WTF approach for estimating recharge that explicitly requires estimation of fillable porosity, however such data were not available here, and his work excludes diffusive continuous recharge. Recent availability of hourly and higher resolution water level and rainfall data allows more in-depth investigation of recharge processes. Here, detailed well and precipitation records are used to infer the relative importance of episodic and continuous recharge on an hourly timescale at several locations in suburban Long Island, NY, using two contrasting approaches to the WTF method. The objectives of this paper are:

- 1) To show how high-resolution well data in combination with appropriate analysis techniques allow increased insight into episodic vs continuous recharge processes and variations in recharge over time
- 2) To illustrate how subtle differences in site conditions, location in groundwater flow systems and depth to the water table over an 800 km² area affect recharge estimation results
- 3) To demonstrate, using a common theoretical framework, how both episodic and continuous WTF recharge processes occur on a continuum depending on well location and site-specific factors

Study Area

This study is focused on a suburban area of New York City in parts of the eastern borough of Queens and Nassau County on Long Island (Figure 1). Land use is moderate-density, vegetated residential development (attached and single family dwellings, 0.1-0.5 ha lots), with scattered parkland and a dense network of roads and limited-access highways. The topography is gently rolling, with a maximum elevation close to 100 masl along the west-east morainal ridge in the north central part of the map, sloping down to Long Island Sound in the north, and more gradually towards the southern coastal bays and islets sheltered behind a barrier island system from the Atlantic Ocean. The climate is temperate, with precipitation averaging about 1050 mm/yr.

Hydrogeology, monitoring wells, and weather stations

The Long Island groundwater system (Misut and Busciolano 2009; Misut and Monti 1999; Buxton and Smolensky 1999) includes a Pleistocene and two Cretaceous aquifers composed of till with outwash, and fine sands, respectively, of over 300 m total thickness. The lowermost two (Magothy and the confined Lloyd) aquifers are used for water supply in the eastern part of the study area. A rough conceptual model based on previous studies (Misut 2018, Monti et al. 2009) consists of partially saturated sand and gravel, silty sand and clay lenses in the uppermost aquifer unconformably overlying the deeper Magothy sandy aquifer which increases in thickness from north to south. Lithological details at the water-table (Figure 1) in the Upper Glacial aquifer, which likely vary across the region, are not generally known due to the lack of information from drillers' records. The water table aquifer, the focus of this study, is not routinely pumped, but is itself a source of recharge to the underlying aquifers. The area was chosen based on the location

of available wells instrumented and monitored by the U.S. Geological Survey (USGS), one of which (Q3810) is on the campus of Queens College CUNY. This study was motivated by a comparison of data from six wells from the USGS National Water Information System (NWIS) database that have high temporal resolution (15 minute) water level measurements. On Figure 1, locations are also shown of two stations (QUEE and WANT) of the NYS Mesonet, a recently established state network of weather stations for Early Warning Severe Weather Detection. These sites have high resolution (5 minute) records of rainfall and other meteorological parameters.

Research Methods

A simple mathematical framework for analyzing the balance of recharge and drainage from a given location at the water table was given by Cuthbert (2010) as follows:

$$q = S_Y \frac{dh}{dt} + D \quad (1)$$

where changes in hydraulic head in the aquifer over time (dh/dt) are related to recharge q , specific yield S_Y , and groundwater drainage D from the location at the water table. The last term on the right (D) is usually omitted in discussions of the WTF recharge estimation method (e.g., Delottier et al. 2018; Healy and Cooke 2002), where the focus is on episodic recharge tied to a specific precipitation event. Recharge is then estimated essentially by multiplying the rise in the water table dh over a given time period dt by the specific yield S_Y . However, as pointed out by Nimmo et al. (2015), recharge consists of not just a transient, episodic component but also a continuous, steady-state component, which derives from slow, downward diffusive flux through

the unsaturated zone. This latter component does not result in short term changes to hydraulic head because it is equal to or less than the amount of drainage D away from the point where the hydraulic head is measured. Hence, many well water level records in highly transmissive aquifers, with a thick unsaturated zone that dampens the rainfall signal, may not show significant episodic recharge fluctuations.

Continuous steady-state recharge

To investigate this case, Cuthbert (2010) analyzed a simplified aquifer configuration using a one-dimensional Boussinesq governing equation assuming sinusoidal seasonal recharge. For reasons of space, his analysis is only summarized briefly here. From a quasi-steady-state solution of head as a complex function, he showed for arbitrary aquifer parameters that aquifer drainage D can be accurately estimated when its temporal variation is low, minimizing the amplitude of the oscillatory part of the quasi-steady-state solution. Cuthbert (2010) then described criteria when this is the case, allowing recharge q to be approximated as aquifer drainage D and calculated using long-term well records. The criteria consist of conditions of aquifer diffusivity (T/S_y) and aquifer dimensions x/L where x is the distance in one dimension in the aquifer of length L . Since the method is based on a one-dimensional flow assumption, this distance is assumed to be along an approximately linear, representative flowline intersecting the well in which water level variation is measured. Essentially, the farther away the well is from the discharge outlet of the aquifer (small x/L) and the lower the aquifer diffusivity, the better the assumption that the steady-state diffusive recharge is equivalent to aquifer drainage D . By equating recharge q to aquifer drainage D , and combining part of the complex function solution with Eqn.1, Cuthbert (2010) derived a discretized expression for estimating the continuous steady-state diffusive recharge over a time increment t as follows:

$$q_t = \frac{S_Y(h_t - h_{(t-\Delta t)})}{\Delta t} + \frac{2\hat{h}T}{(L^2 - x^2)} \quad (2)$$

where $\hat{h}$ is the long-term average hydraulic head, h_t and $h_{(t-\Delta t)}$ are hydraulic heads at times t and $t-\Delta t$ respectively, and T is aquifer transmissivity.

Episodic transient recharge

On the other hand, at locations with shallow water tables, or aquifers with low storage coefficients, such as karst, precipitation events may cause significant transient, episodic variations in hydraulic head when q is much larger than D , so D can be disregarded as negligible over short time intervals and omitted from Eqn.1. Several versions of the episodic transient WTF recharge estimation method have been used, including graphical and fixed time increment approaches (Nimmo et al. 2015), but considerable uncertainty is associated with the effect of air entrapment (Goncalves et al. 2019; Crosbie et al. 2005), and overlapping of precipitation impulses that combine to cause water table rise. To compensate for these uncertainties, which cause “overshoot” of the episodic water table rise with respect to the causative precipitation impulse, a master recession curve (MRC) based on many observed WTF episodes has been used (e.g., Delottier et al. 2018). The MRC is the relationship between the rate of change in hydraulic head dh/dt as a function of hydraulic head which is obtained by curve fitting. MRC backward and forward extrapolation is the key to a new implementation of the WTF episodic recharge estimation method, called the Episodic Master Recession (EMR) approach (Nimmo and Perkins 2018, Nimmo et al. 2015).

This EMR approach to episodic transient recharge estimation using the MRC has the advantages of reducing the subjectivity involved in applying the WTF episodic recharge estimation method.

For example, it is necessary to determine what lag time is appropriate to associate a given precipitation event to a resulting change in hydraulic head, what magnitude of water table fluctuation is sufficient to be designated a response to recharge, and how far forward and backward to extend the MRC to make the determination of what value of dh/dt to be used in Eqn.1 for the recharge episode. By deciding on these parameters for many recharge episodes at once rather than episode by episode, unnecessary subjectivity is eliminated for a given water level record. Nimmo et al. (2015) have implemented the EMR approach to WTF episodic recharge estimation in a computer code written in the R language (R Core Team 2016) that uses continuous records of hydraulic head and precipitation at a relatively high time resolution.

Specific yield and hydraulic conductivity uncertainty

One major uncertainty common to both episodic transient and steady-state continuous implementations of the WTF recharge estimation methods above is the value of specific yield (S_y) which appears in both Eqns. 1 and 2. The appropriate specific yield value to use is very hard to constrain because of its dependence on the hysteresis of the soil moisture curve, the depth to the water table and the role of air entrapment causing reduction in soil moisture (Healy and Cook 2002). Sophocleous (1991) was one of the first to address this issue in conjunction with the WTF method, and more recent workers (Park 2012; Park and Parker 2008) have investigated this problem in more detail. In very shallow water table conditions (Crosbie et al. 2005), specific yield is not constant and the variation can have significant effects on recharge estimates.

In rare cases, it may be possible to use specific yield obtained by conventional analysis of an aquifer test (Delottier et al. 2018), however no such aquifer tests were available for this study. Even this may not always be appropriate since the volume available to fill for the rising water table (the “fillable porosity” θ_f) is considerably reduced by trapped air (Goncalves et al. 2019),

and using a conventional S_Y value from the literature may overestimate resulting recharge because fillable porosity can be much less than S_Y . Park (2012) developed a complex method that incorporates a more realistic fillable porosity parameter, but most WTF analyses simply assign an estimated S_Y value, and that was the approach used for this study. To minimize the variation in results that could result from unknowable spatial variation in S_Y , a value of 0.1 was used for all analyses, at the lower end of the range of values found in USGS regional Long Island aquifer modeling analyses (Misut 2018; Buxton and Smolensky 1999).

Hydraulic conductivity in the Upper Glacial Aquifer is known to be high, although the spatial variation in this parameter is also unknown. Values of hydraulic conductivity used for regional modeling analyses average 82 m/day (Misut 2018; Monti et al. 2009; Buxton and Smolensky 1999), which is exceeded by local slug testing analyses at the well (Q3810) at Queens College, suggesting that this value may be low and values at the water table may be higher. The analyses for this study correspond to the uppermost part of the Upper Glacial Aquifer at the water table, and this aquifer has an approximate thickness of 33 m (Misut 2018; Buxton and Smolensky 1999). Therefore, as a conservative estimate, the transmissivity value selected for use in the analyses for this study was 150 m²/hr, making the diffusivity value T/S_Y equal to 1500 m²/hr or 36000 m²/d for this study. According to Cuthbert (2010, his Table 1), for aquifer flowline length $L \sim 10,000$ m and a diffusivity value 10,000 m²/d, values of x/L less than 0.677 indicate suitable conditions for application of the continuous steady-state recharge estimation method.

Data compilation

Precipitation and well water level data were compiled from the New York State Mesonet and the USGS NWIS database, respectively, for the period from April 2017 through April 2018.

Although the new QUEE precipitation station was originally intended to be used for this study due to its proximity to well Q3810 on Queens College campus, errors in data recording were found to make long stretches of winter precipitation unusable, leaving gaps in the record. The next closest station WANT was found to have very similar precipitation patterns, was assumed to represent the precipitation across the region, and used for the analyses here. Continuous data at a five minute interval was cumulated to 15 minute intervals to correspond to the resolution of USGS well water level records for EMR analysis, and further simplified to hourly intervals for comparison with continuous, steady-state recharge estimates.

Most wells in the USGS NWIS database do not have autonomous instrumentation with high resolution (15 minute, “real-time”) water level data, but are sampled periodically at different intervals from weekly to every few years or not at all. Furthermore, only a subset are finished in the shallow Upper Glacial Aquifer. Wells (Figure 1) were chosen for this study because they were suitably instrumented and shallow (<30 m depth) for monitoring the water table, and had mostly continuous records. Precipitation data were combined with groundwater level data for EMR analysis for well N1129 using the 15 min data intervals for each due to the dominant episodic variability of the water level data. A master recession curve (MRC) was calculated using the method of Nimmo et al. (2015), from which parameters were determined for EMR analysis, which was then performed on the precipitation and groundwater level data. The resulting total amounts of recharge for each episode delineated by EMR analysis are not associated with constant time periods, however for comparison purposes to continuous, steady-

state analyses of other well records, resulting recharge values were assumed to be distributed evenly over each hour of each episode, and plotted accordingly.

For the other wells, water level data were simplified to hourly averages and compiled in a spreadsheet for analysis described by Cuthbert (2010) using Eqn.2. Resulting recharge estimates per hour were negative if the water level decreased during that interval, so those negative values were assumed to be zero for purposes of recharge. Location characteristics and hydrologic data for the different wells are presented in Table 1.

Table 1. Characteristics for wells considered for recharge analysis: estimated parameters L and x are based on analysis of water table contours (Figure 1)

USGS Well designation	Land surface elevation (masl)	Water table elevation (masl)	Unsaturated zone thickness (m)	Associated flowline length L (m)	Estimated pos'n along flowline x (m)	x/L criterion (Cuthbert, 2010)
N1129	15.5	9.2	6.3	23000	16000	0.70
N1615	18.6	12.7	5.9	16000	10000	0.625
N9099	18.3	8.6	9.7	N/A	N/A	N/A
N1616	36.9	22.0	14.9	21000	5000	0.24
N8269	34.0	20.2	13.8	N/A	N/A	N/A
Q3810	23.3	6.0	17.3	>10000	>8500	0.85?

Overall, the general similarities in well records (Figure 2) supports the assumption that observed variations are not primarily due to differences in precipitation inputs. While records for wells N1616 and Q3810 had small gaps of less than 5 days that could be reasonably filled by interpolation, wells N8269 and wells N9099 were discarded from recharge analysis due to larger gaps (Figure 2), because of the need for continuous data. The annual variation in hydraulic head in each of the four retained wells: Q3810, N1616, N1615 and N1129 was less than or equal to

one meter so these records were plotted at the same vertical scale for comparison (Figures 3b-6b).

Analysis and Results

An initial comparison of water level data for each well showed that some had smoothly varying water levels (Q3810, N9099, N1616) with differences mainly in timing of the seasonal peak and trough (Figure 2). Well N1129 showed the most episodic variations, with distinctive rises and recessions corresponding to major precipitation events, especially in May-August, 2017. Wells N8269 and N1615 showed intermediate responses, with a distinctive episodic response to precipitation at N8269 just prior to November 1, like N1129. The N1615 record was smoother but still responded more rapidly to precipitation, particularly around November 1 and later in February and March, like N1129. Although these distinctions are subtle due to the range in vertical scale (Figure 2), they are more apparent in the individual plots (Figures 3b-6b).

Well records (Figures 3b-6b) differ in appearance both according to the thickness of the saturated zone at each site (Table 1) and their location in the regional flow system (Figure 1). In contrast to the example application in Shropshire, UK, discussed by Cuthbert (2010), the flow system of the shallow aquifer on Long Island (Figure 1) is not readily subdivided into subwatersheds due to the coarse scale of the regional water table map (New York Water Science Center, 2017), making determination of x/L values difficult. However, it is clear that some wells are located closer to the highest elevation area in the northeast (Figure 1) which serves as the water table divide, and others are located downgradient along possible flowlines closer to the regional aquifer discharge boundary to Long Island Sound or the Atlantic Ocean, or local discharge points such as the lakes just west of Q3810.

Well by well analysis of water level variation

The well records in this study can generally be classified into three categories, with N1616, N8269 and Q3810 having relatively thick unsaturated zones, N9099 having an intermediate thickness unsaturated zone, and N1129 and N1615 having relatively thin unsaturated zones (Table 1). Comparing Figure 2 with selected individual records in Figures 3b-6b, Q3810 and N8269 have relatively similar smoothly varying records, with the major difference being a later peak water level for Q3810 (Sept 1) compared to N8269 (approximately June 1). The smoothness and the lag time are undoubtedly due to the greater signal dampening by the thick unsaturated zone (Table 1), and perhaps the longer flowpaths leading to Q3810. Well N1616 (Figure 4b) also has a smooth water level record, but with a slightly greater responsiveness to specific rainfall events (Nov 1) and a more rapid rise from March 1. This pattern and an earlier peak water level around June 1, likely are due to the proximity of the well to the water table divide, hence short upgradient flowlines. Well N9099 has a later peak water level around Sept 1, similar to Q3810, and is also close to its aquifer discharge outlet at the end of long flowlines.

The records from wells N1615 (Figure 5b) and N1129 (Figure 6b) are in a category of their own due to their overall greater responsiveness to rainfall and thin unsaturated zones, which do not dampen the recharge signal very much. N1129 has a much more jagged pattern, with many more noticeable rapid rises and small recessions that are easily linked to specific high-intensity rainfall events (Figure 6a). The major reason for this is apparently the well's proximity to a shallow, vegetated $\sim 1000 \text{ m}^2$ recharge basin approximately 50 m to the north, which causes preferential flow to the water table compared to the surrounding residential land use. Few studies have investigated the role of recharge basins in focusing groundwater recharge (Bhaskar et al. 2018). The similar locations (Figure 1) of wells N1129 and N1615 midway along flow lines (similar x/L

criteria, Table 1) make them comparable, but the water level record at N1615 is much smoother. Major similarities in water level patterns (Figures 5b, 6b) include a dip of 0.1 m in June, a significant recession until late October/early November, when there is a >0.2 m rise, followed by further recession then a very rapid and large (>0.6 m) rise in response to rainfall in February and March.

Recharge estimation

Based on the assessment of primarily non-episodic well water level patterns above, the Cuthbert (2010) method was applied to water level records from wells Q3810, N1616, and N1615 using Eqn. 2 and the parameters in Table 1, with the aquifer data previously described. Recharge estimation results on an hourly basis (Figures 3c, 4c and 5c, Table 2), show that in response to essentially the same precipitation input, recharge corresponding to each of the locations has small but important differences. With no hourly recharge value exceeding 0.4 mm, and a relatively low mean and standard deviation (Table 2), the record at well N1616 (Figure 4c) presents a very uniform recharge pattern in part due to the thick unsaturated zone. The very low value of the x/L criterion (0.24, Table 1) indicates that the Cuthbert (2010) method is well suited because $q \approx D$ (Eqn.1) and recharge is dominated by steady-state continuous processes.

The record of recharge at well N1615 (Figure 5c) is slightly more variable, with similar mean and standard deviation (Table 2). However, the N1615 record includes several spikes approaching or exceeding 1 mm/hr (Figure 5c), and a more clustered pattern of higher recharge intensity over successive hours at important fluctuations in the water level, particularly in late June, early November and late Feb/early March. While this well is situated midway along the flowline (x/L value 0.625), it has a thin unsaturated zone (Table 1), which suggests that some of the magnitude of these fluctuations is due to episodic recharge mechanisms, even though there

are no obvious characteristic short jagged water-level rises and recessions like for well N1129 (Figure 6c). According to the x/L and diffusivity criteria of Cuthbert (2010), this record also appears well suited to the continuous steady-state recharge analysis when $q \sim D$ and the variation in D is likely to be relatively small.

The water level record of Q3810, as noted previously, is very smooth and gradual but does show some very minor fluctuations (Figure 3b), which can be associated in some cases with high intensity precipitation (e.g., late Oct, early Nov). However, the calculated hourly recharge (Figure 3c) is quite variable, with a mean and standard deviation that is approximately double that for records of wells N1616 and N1615 (Table 2). Due to the position of well Q3810 at the end of long flowlines near the aquifer discharge point, and the multi-dimensional divergent flow nearby inconsistent with the derivation of Eqn.2, this record is not ideally suited to the Cuthbert (2010) analysis method. Despite the fact that steady-state diffusive recharge clearly dominates here because of the thick unsaturated zone (Table 1), the well's close proximity to the discharge point (high x/L value) causes the assumptions that $q \sim D$ and D is relatively constant to be violated. Hence Eqn.2 will not result in a valid estimate of recharge, which explains the unusually high and variable recharge pattern calculated (Figure 3c).

Table 2. Summary results of recharge calculations

USGS Well designation	Mean hourly recharge (mm)	Standard deviation hrly recharge (mm)	Mean daily recharge (mm)	Standard deviation daily recharge (mm)	Equivalent annual recharge (mm)	RPR*
N1129†	--	--	--	--	172	0.14
N1615	0.050	0.069	1.21	0.802	442	0.35
N1616	0.042	0.059	1.01	0.353	369	0.29
Q3810	0.102	0.126	2.46	0.693	898	0.72

*RPR: annual recharge to precipitation ratio based on study period precipitation of 1252 mm

†N1129 estimate based on episodic precipitation only, does not include steady-state continuous recharge, so hourly and daily means were not calculated, for details see Table 3

The classically episodic pattern of water level variation for well N1129 (Figure 6b) clearly indicates that due to the thin unsaturated zone (Table 1) and the likely preferential flow caused by the proximity of the recharge basin, recharge $q \gg$ drainage D , so Eqn.2 is not appropriate for calculating recharge using the Cuthbert (2010) method. Instead the EMR method (Nimmo and Perkins 2018, Nimmo et al. 2015) was employed. The resulting output is presented in the form of total recharge per transient recharge episode (Table 3) and a water level hydrograph combined with a cumulative precipitation record (Figure 7) which enables delineation of time-periods of episodic recharge and intermediate continuous recharge, which is not quantified by this method.

Table 3. Output from EMR analysis of episodic recharge from N1129 well record

Transient recharge episode	Start time (hrs)	Duration (hrs)	Change in water level (m)	Causal precipitation (mm)	Transient recharge (mm)	Equiv. hrly recharge (mm/hr)	RPR*
1	49.1	58.1	0.088	24.13	8.82	0.152	0.37
2	108.1	50.3	0.063	8.89	6.34	0.126	0.71
3	570.2	59.8	0.063	26.67	6.27	0.105	0.24
4	813.7	50.9	0.092	40.13	9.19	0.181	0.23
5	1002.9	58.6	0.073	45.21	7.28	0.124	0.16
6	1219.7	63.2	0.075	22.35	7.52	0.119	0.34
7	1298.7	54.5	0.030	23.37	3.05	0.056	0.13
8	1776.0	38.1	0.050	12.45	4.98	0.131	0.40
9	1905.1	43.4	0.086	25.40	8.62	0.199	0.34
10	2017.2	39.2	0.057	45.97	5.74	0.146	0.12
11	2333.5	41.2	0.077	42.93	7.74	0.188	0.18
12	2707.3	32.1	0.055	30.99	5.48	0.171	0.18
13	2739.3	38.2	0.022	22.10	2.23	0.058	0.10
14	3335.1	43.5	0.087	3.81	8.66	0.199	2.27
15	3702.8	49.4	0.062	24.38	6.16	0.125	0.25

16	3806.1	34.2	0.038	33.07	3.81	0.111	0.12
17	4955.5	32.0	0.048	11.58	4.85	0.152	0.42
18	5063.3	62.4	0.207	62.23	20.67	0.331	0.33
19	5287.1	32.1	0.034	0.25	3.40	0.106	13.6
20	6854.4	60.9	0.056	7.48	5.61	0.092	0.75
21	7412.0	59.3	0.059	26.16	5.85	0.099	0.22
22	7485.0	51.6	0.053	20.57	5.27	0.102	0.26
23	7567.3	62.0	0.059	38.09	5.91	0.095	0.16
24	7903.8	60.9	0.055	32.51	5.47	0.090	0.17
25	8015.5	57.5	0.160	54.80	16.04	0.279	0.29
26	9104.8	58.9	0.104	42.67	10.36	0.176	0.24

*RPR: recharge to precipitation ratio, calculated for entire episode

Output from the EMR analysis is shown graphically in Figure 7. Due to the high resolution timescale (hours), extrapolations of the master recession curve for each episode are shown as very short red segments between which the water level rises are calculated. At the hourly timescale, these extrapolations are very limited in length to avoid overlapping successive recharge episodes that are defined by the jagged water level record. In many cases, there is obviously overshoot, as the peak in the water levels clearly rises well above the top red extrapolation segment for each episode. The dark blue bands identify isolated recharge episodes that result from step increases in the cumulative precipitation record. Corresponding data on the individual recharge episodes is shown in Table 3.

The number of transient recharge episodes identified from the EMR analysis (Table 3) depends on the parameters selected for the MRC determination and EMR input, as described earlier, however the analysis here was judged to be acceptable because all major fluctuations in water level were identified as recharge episodes. Some minor fluctuations (~4100 hrs, 5500-6700 hrs, 8500-9000 hrs, Figure 7) were not identified for recharge estimation because they didn't meet thresholds for lag time, sufficient water level fluctuation or associated rainfall. Values of

recharge to precipitation ratio (RPR) calculated for each episode (Table 3) generally seem reasonable, ranging from 0.10 to 0.75, with some erroneous values exceeding 1 as found by others (Nimmo and Perkins 2018; Nimmo et al. 2015), corresponding to low causal precipitation often immediately following a previous recharge episode. These excessive RPR values illustrate the difficulty of isolating individual recharge events even at the high temporal resolution of data used in this study. Higher values of RPR are generally associated with greater precipitation intensity (> 5 mm/hr, Figure 6a). Transient recharge for each episode distributed equally over the length of the episode, expressed as equivalent hourly recharge (Table 3) is plotted in Figure 6c.

Compared to recharge estimates at other wells using the continuous steady-state method (Cuthbert 2010), well N1129 shows comparable magnitudes in estimated hourly recharge (Figures 3c,4c,5c,6c), however there are gaps in the N1129 record when unquantified continuous steady-state recharge is occurring. This explains the much lower equivalent annual recharge for N1129 and RPR (Table 2) compared to the other wells. The implication of the comparison between the N1129 and N1615 results is that the episodic transient EMR method significantly underestimates total recharge in this case whereas the continuous, steady-state method likely presents a more comprehensive quantification of recharge that includes transient processes, when water levels are very responsive like at N1615 (Figure 5b), and to a lesser extent at N1616 (Figure 4b). On the other hand, when it is not clear that the criteria established by Cuthbert (2010) are met, such as at well Q3810 (Table 1, Figure 3), the continuous steady-state method does not always provide reliable results, and may (as in this case) overestimate recharge. This explains why the equivalent annual recharge and RPR for Q3810 (Table 2) are so high.

Spatial variation in recharge is high and difficult to quantify, especially in suburban areas due to impervious surface cover. While this study focused on analysis of episodic and continuous recharge estimation at specific well locations where high-resolution water-level data was available, summary results (Table 2) are comparable to existing estimates used for regional flow modeling of the Upper Glacial aquifer. In the borough of Queens, Misut and Monti (1999) estimated annual recharge based on land use and impervious area analysis to range between 406 and 711 mm/yr in the vicinity of well Q3810. In Nassau County where the other wells are located, values ranged between 711 and 1168 mm/yr. A more recent investigation (Misut 2018) used an areally averaged recharge rate of 635 mm/yr to analyze contaminant transport in the Long Island aquifer system even further east in Nassau County beyond the current study area. The concurrence of these estimates with the results of this study, and reasonable recharge to precipitation ratios (RPRs), provides confidence in the approach used here despite uncertainties involving local conditions such as recharge basins and the applicability of the continuous, steady-state method due to location in the groundwater system.

Discussion

Various uncertainties remain due to the complexity of the recharge process and the limitations inherent to the two WTF approaches employed in this study. It is possible that some of the variation in water level responsivity and hence recharge is due to spatial variations in aquifer properties (hydraulic conductivity, specific yield), and further work would be needed to obtain data necessary to evaluate this limitation. While evaluating uncertainty in spatial hydraulic properties is beyond the scope of this study, a calculation of error propagation in Eqn. 2 using

different values of S_y (assumed to be 0.1 in this study) showed that resulting variation in hourly calculated values of recharge q_t was less than the standard deviations presented in Table 2.

Resulting recharge estimates are consistent with the identified limitations and applicability of the two approaches, as well as existing estimates of recharge used in regional flow models of the Long Island aquifer system. If high temporal resolution water level records become more widely available, the continuous, steady-state WTF approach could be useful to identify preliminary spatial variations in recharge and refine our understanding of this complex hydrological process.

Each of the approaches to the WTF recharge estimation method used here has limitations, as with any attempt to quantify complex hydrologic processes occurring in heterogeneous unsaturated and saturated media. Both approaches require correction for the approximation in using specific yield in lieu of a more physically realistic incorporation of air entrapment and fillable porosity (Goncalves et al. 2019). Some of this limitation is addressed by the “overshoot” correction of the EMR approach (Nimmo et al. 2015). However, EMR is only able to quantify recharge intermittently resulting from episodic transient water level fluctuations, and in some cases produces errors when precipitation pulses are superposed. The continuous steady-state approach (Cuthbert 2010) requires care in application to make sure the specified criteria (x/L and diffusivity T/S_y) are met to avoid errors in recharge estimation due to position in the flow system.

An important aspect of this study is the combined application of both of these approaches, and use of very high-resolution temporal datasets, neither of which are common in recharge investigations. The fine-scale temporal variability found in the hourly recharge estimates, corresponding to similarly high-resolution precipitation variations, indicates that the continuous steady-state approach (Cuthbert 2010) incorporates some elements of transient recharge where

water levels are most responsive, even if they do not exhibit the classic WTF rises and recessions. This follows logically from the common theoretical framework introduced in this study, when aquifer drainage D is the dominant term on the right side of Eqn.1, and is therefore equivalent to the second term on the right side of Eqn.2. Episodic and continuous recharge processes, especially in such temperate climates, occur simultaneously on a continuum as transient recharge pulses are superposed on longer-term seasonal and more gradual changes in well water levels.

Conclusion

In this study, hourly water level records at multiple wells have been analyzed using both episodic transient (EMR, Nimmo et al. 2015) and continuous steady-state (Cuthbert 2010) approaches to the WTF method to estimate groundwater recharge. With the high temporal resolution of the well records and associated precipitation data, differences in water level responsivity were interpreted in light of local aquifer conditions (thickness of the unsaturated zone, location of well in flow system) and site-specific conditions (presence of recharge basin).

The availability of high resolution data enabled recharge to be estimated on an hourly timeframe, which allowed analysis of transient vs. continuous processes for comparable wells based on their hydrogeologic context. In settings where both processes are important, the continuous, steady-state approach is somewhat sensitive to transient inputs even where classic rise and recession patterns in the water table fluctuation are not apparent. Conversely, the episodic, transient EMR approach would underestimate total recharge by definition, because it explicitly excludes continuous diffusive processes. On the other hand, if uncertainties in well position within the

aquifer flow system, and proximity to groundwater divides and discharge areas are not understood, the continuous, steady-state approach could overestimate total recharge values. This application of two approaches to the well-known WTF method, based on a similar mathematical framework, therefore shows how high-resolution water level and precipitation data are important for a nuanced understanding of recharge processes over time.

As humans continue to modify their environment, quantifying the spatial and temporal resolution of groundwater recharge processes will remain a long-term challenge, as land uses change and precipitation becomes more variable. Recharge estimates are needed on a finer-scale timeframe to understand transient changes that have an impact on aquifer conditions, for example: climate change, urbanization, focused infiltration, vegetation clearing, or even agricultural crop changes. Without high-resolution data on well water levels and corresponding precipitation data, evidence for episodic recharge in short-term water level changes, and important locations for preferential flow like recharge basins, may be overlooked. On the other hand, detailed water table maps are necessary to understand aquifer conditions for assessing continuous, steady-state recharge, and both processes are important in many areas.

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Figure 1. Map of study area showing water table elevations (m above sea level) in western Long Island (LI) in the suburban area of New York City. Contours (3 m interval) are redrawn from New York Science Center (2017). Circle symbols indicate well locations used in this study. Stars indicate meteorological stations of the NYS Mesonet.

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