Revista Brasileira de Recursos Hídricos
Brazilian Journal of Water Resources
Versão On-line ISSN 2318-0331
RBRH, Porto Alegre, v. 28, e11, 2023
Scientific/Technical Article

https://doi.org/10.1590/2318-0331.282320220113

Uncertainty in groundwater recharge estimation using groundwater level fluctuation and aquifer test

Incerteza na estimativa de recarga de águas subterrâneas usando variação do nível das águas subterrâneas e teste de aquífero

Giovanni Chaves Penner[1], Rubens Takeji Aoki Araujo Martins[2], Salim Rodrigues[1] & Edson Wendland[2]

[1]Universidade Federal do Pará, Belém, PA, Brasil
[2]Universidade de São Paulo, São Carlos, SP, Brasil
E-mails: penner@ufpa.br (GCP), rubensaoki@usp.br (RTAAM), salim@ufpa.br (SR), ew@sc.usp.br (EW)

Received: November 23, 2022 - Revised: March 31, 2023 - Accepted: April 08, 2023

ABSTRACT

For sustainable groundwater management the rate of groundwater recharge and specific yield are both of the most important elements in the analysis and management of groundwater resources, and, sometimes, estimation of these parameters remains a challenge. This research presents a combining approach of the water-table fluctuation method (WTF) with an aquifer test to estimate both and quantify their uncertainty. The methodology requires at least three wells: two instrumented observation wells with a level sensor for long-term monitoring and a pump well located nearby for aquifer testing. The test interpretation was supported by the Aqtsolv Demo software obtaining the best fit with the method proposed by Tartakovsky-Neuman, with a specific yield varying, in 2σ, between 9.4% and 10.6%. Recharge was estimated with WTF, and the uncertainty in recharge is obtained by propagating the uncertainties about the specific yield (Bayesian inference) and the groundwater recession dynamics to the WTF. The uncertainty about recharge stems from uncertainty about the specific yield. The approach was applied on the campus of the Federal University of Pará, Belém, Brazil. Recharge was estimated at 1078.9 mm, from 03/sep/2020 to 30/sep/2021, with an associated uncertainty of 129.5 mm in 2σ, which equates to a range between 33.9 and 39.8% in terms of precipitation. Through the use of cost-effective instrumentation and interpretation methodology, replication of that approach can be encouraged to provide reliable estimates of recharge and specific yield in a site specific. Such condition can be useful to reduce the predictive uncertainty of groundwater management.

Keywords: Groundwater fluctuation; Aquifer properties; Specific yield; Uncertainty analysis.

RESUMO

Para a gestão sustentável das águas subterrâneas, a recarga das águas subterrâneas e o rendimento específico são parâmetros importantes na análise e gestão dos recursos hídricos subterrâneos, e, por vezes, a estimativa destes parâmetros continua a ser um desafio. No presente trabalho, apresenta-se uma combinação de um teste de aquífero com a aplicação do método da variação dos níveis da água (da sigla em inglês WTF) para estimar esses parâmetros e quantificar sua incerteza. A abordagem requer, ao menos, três poços: dois poços de observação instrumentados com sensor de nível para monitoramento de longo prazo e um poço de bombeamento, localizado nas proximidades, para o teste do aquífero. A interpretação do teste foi apoiada pelo *software* Aqtsolv Demo, obtendo o melhor ajuste com o método proposto por Tartakovsky-Neuman, com um rendimento específico variando em 2σ, entre 9,4 e 10,6%. A recarga da água subterrânea foi estimada pelo método WTF. A incerteza na recarga das águas subterrâneas é obtida pela propagação das incertezas sobre o rendimento específico (inferência bayesiana) e a dinâmica de recessão das águas subterrâneas para o WTF. A maior parte da incerteza sobre a recarga das águas subterrâneas está associada ao rendimento específico. A abordagem foi aplicada no campus da Universidade Federal do Pará, Belém-PA, Brasil. A recarga da água subterrânea foi estimada em 1.078,9 mm, entre 03/set/2020 e 30/set/2021, com uma incerteza associada de 129,5 mm em 2σ, o que equivale a faixa entre 33,9 e 39,8% em relação a precipitação. Pelo uso de instrumentação de custo reduzido e métodos consagrados de interpretação, a replicação de tal abordagem conjunta pode ser encorajada para fornecer estimativas confiáveis de rendimento específico e recarga de água subterrânea em uma região de interesse. Tal condição pode ser útil para reduzir a incerteza preditiva na gestão das águas subterrâneas.

Palavras-chave: Variação da água subterrânea; Propriedades do aquífero; Rendimento específico; Análise de incerteza.

INTRODUCTION

According to Nlend et al. (2021), there is still little knowledge about the functioning of groundwater in humid tropical regions and papers on the hydrogeology of the humid tropics are less frequently reported in the literature; for such regions, the main focus is generally on water quality and the economic and environmental importance of this resource. Fosberg et al. (1961) physically identify these regions by: (i) monthly temperature equal to or greater than 20°C during at least eight months of the year; (ii) vapor pressure and relative humidity average of ~20 millibars and 65%, respectively, for at least 6 months of the year; (iii) annual precipitation greater than 1500 mm; (iv) rain falling all year with at least six months with rainfall ≥75 mm/month. They represent approximately 22% of the Earth's surface (Nlend et al., 2021) and are home to many developing countries, which have the highest population growth rates, and whose population is expected to represent 50% of humanity by 2050. In this context, there is an urgent need to increase knowledge on aquifers functioning in humid tropical regions and particularly in areas of Latin America representing 45% of the humid tropics (30% in Sub-Saharan Africa and 25% in Asia) (Nlend et al., 2021).

Thus, reliable estimates of aquifer parameters such as: hydraulic conductivity, storage and recharge become more important for management of groundwater resources (Delottier et al., 2018). Collect reliable information on aquifer parameters and inclusion in models and in management plans is extremely important to be used before the calibration of the aquifer model or uncertainty analysis (Delottier et al., 2018).

The literature mentions the numerous methods used to estimate groundwater recharge classified by the source of data (surface water, unsaturated and saturated zones), the governing hypotheses, and the range of applicability (Healy & Cook, 2002; Delin et al., 2007; Healy & Scanlon, 2010; Lucas et al., 2015). The water-table fluctuation method (WTF) is a very simple method to estimate groundwater recharge based on the general knowledge of groundwater levels and the simplicity of its application (Scanlon et al., 2002; Simon et al., 2017; Delottier et al., 2018; Mattos et al., 2019). The WTF method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water-table caused by precipitation events. Recharge comes from the product of the specific yield (S_y) with the water-table rise (Δh), with attention to corrects, if necessary, to the presence of entrapped air, changes in barometric pressure, evapotranspiration, or other phenomena (Healy & Cook, 2002; Crosbie et al., 2005; Cuthbert, 2010; Crosbie et al., 2019).

As can be seen the estimation of recharge with WTF requires an accurate value of specific yield (S_y). The specific yield of an unconfined aquifer corresponds to the ratio of the pore volume of water that is drained by gravity when the water table drops (Healy & Scanlon, 2010; Rama et al., 2018). Specific yield values can be obtained from three different ways: theoretical (literature), laboratory (core sample analysis), and field methods (aquifer test). Sometimes, the literature value is unavailable for a site, and extraction and analysis of core samples is costly and may be poorly representative (Delottier et al., 2018), the field alternative then become more appropriate, applying a careful aquifer test, even though associate costs. According to Pendiuk et al. (2020), estimating specific yield is still a challenge due to theoretical and methodological limitations, and a novel methodology based on superconducting gravimeter data was proposed to estimate the specific yield.

Maybe the main limitation of the WTF is the overall uncertainty in estimating specific yield, which has a strong impact on recharge estimates, and is difficult to evaluate precisely (Healy & Cook, 2002; Cuthbert, 2010; Healy & Scanlon, 2010), because specific yield could be a variable value. However, the specific yield is most often obtained from the literature (Crosbie et al., 2019; Tesfaldet et al., 2020), and it is rarely associated with an aquifer test. With this point of view, a meticulous determinate of the specific yield joint with the WTF may become more powerful recharge estimation (Delottier et al., 2018). In this context, the main goal of this article is to apply an aquifer test to estimate the specific yield. And, therefore, its impacts on recharge estimation, through an uncertainty propagation.

The transient movement of water to unsaturated-zone during the aquifer test interpretation can give more realistic result about the specific yield taking in account the drainable porosity. It's important to take attention to delayed drainage of the unsaturated zone in association with falling water levels (Nachabe, 2002). The WTF can give better results applied with the drainable porosity idea. Thus, the interest in a joint application of the WTF with an aquifer test is to look for consistency in the specific yield value (Delottier et al., 2018).

Based on the above information, the article is structured as: the characteristics of the site and general guidelines for appropriate monitoring; then, the aquifer test implementation and solution; the WTF method application; uncertainty analysis. Finally, following the idea of a monitoring station proposed by Delottier et al. (2018), it is applied at a site in the Federal University of Pará, Belém, Brazil. To conclude, the replicability of the approach is commented.

MATERIAL AND METHODS

Study area

The study area is located in the Federal University of Pará (UFPA), which has 8 monitoring wells (MW) and 3 reference points (RP). UFPA is located in an urban area, south of Belém city, the capital of the state of Pará, inside the Brazilian Amazon. In general, the monitoring wells were distributed in the professional and health sectors of UFPA, as see in Figure 1.

Belém city has a partially peninsular terrain of recent fluvial geomorphological formation, very flat surface, composed of lakes, rivers and streams that intersect the urban and natural environments, almost all rectified by channels, forming areas of mainland and floodable areas subject to flooding under the influence of tides or rainfall (Agência Nacional de Águas e Saneamento Básico, 2018).

From a meteorological point of view, according to the global classification system of climate types, proposed by Köppen-Geiger, Belém is included in the equatorial category, hot and humid with high temperatures, strong convection, unstable air and high air humidity favoring the formation of convective clouds (Bastos et al., 2002; Agência Nacional de Águas e Saneamento Básico, 2018).

In Belém, the Intertropical Convergence Zone influences the most rainfall season (December to May). At the end of the previous season (June to August) southwest trade winds, that form in the tropical belt of the globe, affect the region and in the less rainfall season (September to November) precipitation is caused by mesoscale phenomena (Bastos et al., 2002).

The aquifer systems identified in the metropolitan region of Belém are formed by tertiary-quaternary sedimentary rocks that lie on substrate of, probably, Cretaceous age. These systems are individualized in aquifers that comprise recent covers (alluvium, colluvium and eluvium), unconsolidated deposits identified as post-Barreiras and sedimentary rocks of the Barreiras and Pirabas formations, and are recognized by the same names assigned to the lithostratigraphic units that enclose them (Agência Nacional de Águas e Saneamento Básico, 2018).

The unconfined aquifer considered in this research underlying the UFPA Campus. The geological units consist, from top to bottom, up to 1.5 m, unsaturated zone, composed mainly of embankment sandy, whereas the saturated zone, observed from this depth, is composed of sandy clay up to a depth of 5.5 m, which is the maximum depth considered in this research. The natural dynamics of the unconfined aquifer is mainly controlled by precipitation, evapotranspiration and surface water. There is a pumping well just over 400 m away from the monitoring wells, used to supply water to the Campus that exploits the Pirabas aquifer at a depth of 250 m.

The unconfined aquifer levels are monitored in 8 monitoring wells. Specifically for this study, between 09/jul/2021 and 10/jul/2021, PM-02 was used as a pumping well and PM-01 and PM-03 were considered as observation wells. The three wells have similar characteristics with a casing of 3 m below the ground surface and 2 m of filtering section, with the base of the monitoring wells 5 m below the ground surface. The average thickness of the free aquifer is considered a known parameter, equal to 20 m (Agência Nacional de Águas e Saneamento Básico, 2018).

The observation period, for this research, was from 03/sep/2020 to 30/sep/2021 (392 days). Precipitation and classic climatic variables are recorded in a meteorological station, located next to the wells, and records are stored hourly. During this period, a total of 3,239 mm of precipitation was recorded. Transducers were used to record water level, in each monitoring well, with an interval of 15 min, and manually checked once a week. However, PM-06 was elected to recharge calculate based on the longer data series.

Figure 1. Study area within the campus of the Federal University of Pará, Belém, Brazil.

Unconfined aquifer test

In this research, the aquifer test main goal was to estimate the specific yield of the unconfined aquifer. For this purpose, the pumping drawdown and recovery curves are interpretated. The aquifer test principle is to pump at a known constant discharge rate (Q) from a pump well and record observed drawdown(s) and recovery in one or more observation wells at a known distance (r) from the pumped well (Kruseman & De Ridder, 2000).

An aquifer test was carried out over 24 h, during the first 8 h was conducted a constant pumping of 6.45 L/min, and in the final 16 h the recovery of levels was monitored. The values of drawdown and recovery of water levels were recorded at fixed intervals of 1 min. PM-02 was used as pumping well, while both PM-01 and PM-03 were used as observation wells. The three wells are supplied with a vented pressure transducer of a range of 5 m and an accuracy of ± 0.1% F.S.; therefore, the transducers automatically correct measurements by pressure, to be vented, and by temperature deviation, with a linearizing algorithm of two known points; the resulting total error is in the order of ± 2 mm.

The Theis solution presented in 1935, and its approximation presented by Cooper and Jacob in 1946, both initially developed for confined aquifers, are the basis of aquifer test interpretation used in this paper. For specific yield estimation is acceptable these solutions to unconfined aquifers, but the drainable porosity from the unsaturated zone is disregarded.

The Neuman solution from 1972 gives time-drawdown curves on log-log axis and shows the three parts of the theoretical S-shape observed for unconfined aquifers. That solution again assumes instantaneous drainage of the unsaturated zone, in reality, the release of drainable porosity is not instantaneous.

Nevertheless, in a real aquifer test, only a small amount of water from the unsaturated zone is drained at the beginning of the test (Moench, 2004). Consequently, the aquifer test interpretation underestimates the specific yield, because of not instantaneous drainable porosity of the unsaturated zone (Delottier et al., 2018).

Delottier et al. (2018) suggest as a solution to conduct a long-term aquifer test to solve time-dependence of drainage in the unsaturated zone. However, this idea has limitations. First, in a long-term test, the assumption of infinite aquifer could not be valid, caused by reach the boundaries. Second, during the aquifer test, a precipitation event could occur, and spoil the interpretation. Third, the cost associated with the test. For those reasons is easier interpreted the aquifer test with not instantaneous drainable porosity idea.

Boulton's solution, 1954, assumes gradually drainage of the unsaturated zone. Moench's and Tartakovsky-Neuman's solutions, Moench (2004), Tartakovsky & Neuman (2007), combines both approaches, Boulton's and Neuman's. Conceptually, the use of Moench's and Tartakovsky-Neuman's solutions are better options for specific yield estimation. However, Tartakovsky-Neuman's solution enlarge the condition of slow drainage in the unsaturated zone.

Aquifer test interpretation

AQTESOLV is major universal software for the analysis and design of the aquifer tests such as: slug test, pumping test, and constant head test. The AQTESOLV was created by Glenn M. Duffield, HydroSOLVE, Inc. being versatile in different types of applications of aquifers: from semi-confined, free, confined and fractured (Jasim & Jalut, 2020). In this study, the aquifer test data were interpreted using the AQTESOLV Demo version 4.0, free use, with the limitation of not saving the projects and only viewing the final report.

Water-Table Fluctuation method (WTF)

As described, the WTF method was applied to estimate the annual recharge rates. The WTF method assumes that any single rise in groundwater (unconfined aquifer) levels is entirely attributable to the recharge of water reaching the aquifer (Healy & Cook, 2002). Thus, based on a sufficiently small-time interval (minutes or hours) for this premise to be valid, the recharge is expressed in Equation 1.

$$R = S_y \bullet \frac{\Delta h}{\Delta t} \tag{1}$$

where R (mm) is the recharge between an interval of time, Dt (days or another time interval), Sy (-) is the specific yield of the aquifer, and Dh (mm) is the difference between the peak of the rising curve and the lowest point of the previous recession curve extrapolated to the time of the peak. To reduce recession curve extrapolation subjectivity is followed the method presented by Mattos et al. (2019).

The PM-06 was selected for continuous monitoring of groundwater levels, with 15 min intervals, and, therefore, chosen to apply the WTF method. Additionally, the pumping well used to supply the campus exploits the Pirabas aquifer, at a depth of 250 m, therefore not interfering with the observations made.

Uncertainty analysis

The inherent error of the WTF is associated to the uncertainty on specific yield and effective water-table rise. Based on Delottier et al. (2018), the rule for the propagation of errors for the WTF method (Equation 1) can be written as in Equation 2.

$$\sigma_R = R \bullet \left[\sqrt{\left(\frac{\sigma_{S_y}}{S_y} \right)^2} + \sqrt{\left(\frac{\sigma_{\Delta h}}{\Delta h} \right)^2} \right] \tag{2}$$

where σ_{Sy} and $\sigma_{\Delta h}$ are the uncertainties related to the estimation of the specific yield (-) and to the effective water-table rise (mm) for the whole period. σ_R is the error for the WTF method (mm).

RESULTS AND DISCUSSION

Aquifer test interpretation and specific yield determination

The aquifer test results, i.e., the observed drawdown levels were presented with their respective adjustments to the theoretical analytical solutions, Theis, Neuman, Moench and Tartakovsky-Neuman, respectively, see Figure 2.

At first, in visual terms, a better fit to the solution proposed by Tartakovsky-Neuman is noticeable, but not indicating a perfectly adhered to fit. Such behavior of the non-adherence of the analytical solutions can be explained by the influence of the slow drainage and recovery of the overlying unsaturated zone during the aquifer test.

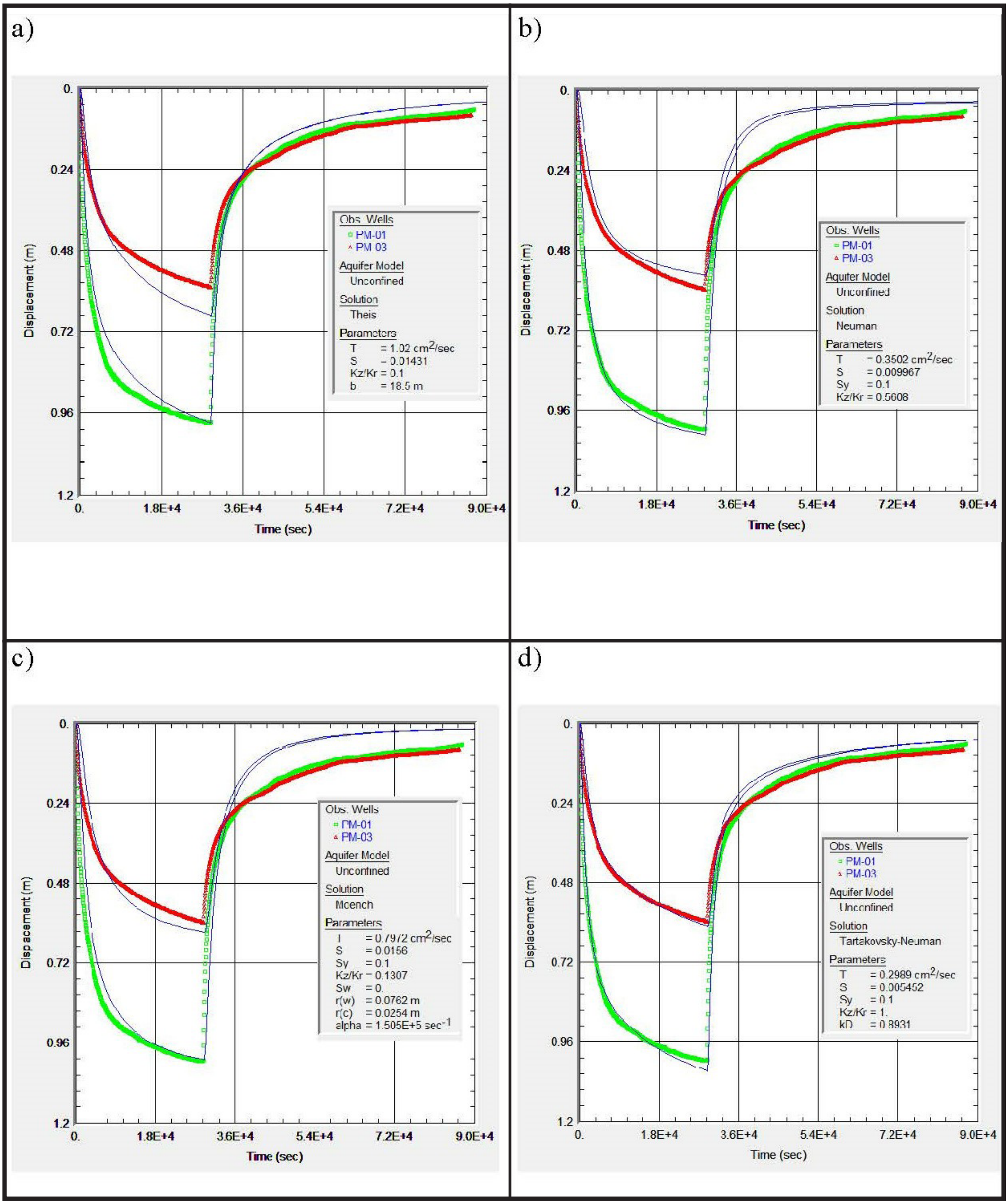

Figure 2. Drawdown and recovery curves observed along with analytical solutions: Theis (a), Neuman (b), Moench (c) and Tartakovsky-Neuman (d).

The solution proposed by Tartakovsky-Neuman presented the lowest value of RSS (i.e., the Sum of Squares of Residuals, with a value of 3.16), followed by the solutions proposed by Theis (6.41), Neuman (13.4), and Moench (16.3). Consequently, the Tartakovsky-Neuman model was chosen to estimate the specific yield.

Groundwater recharge estimation

The records of groundwater level height were first plotted in a graph to facilitate the delineation of the level variation events. Based on an autocorrelation analysis applied for the entire monitoring period, it was found that the aquifer does not respond to precipitation events of less than 7.87 mm. In addition, a partial cross-correlation between the rainfall records and groundwater level fluctuation data showed that the rainfall delay, which accounts transit through the unsaturated zone, can be fixed between 42 min. The recession curve was determined from the identified recession periods based on a precipitation absorption time between 20 and 24 h.

The fluctuation tolerance (δ_T) of the pressure probe accuracy is fixed to 0.001 m. Table 1 presents monthly rainfall and calculated recharge based on PM-06 variation recording. 56 individual recharge events were identified during the research time, as an example, in Figure 3 shows the procedure performed for the records for the month of February 2021. The water-table rise is estimated for each of them and summed up to obtain a total. For the entirely period of this research there was an accumulated elevation of 10.789 m, with a standard deviation of 0.694 m (1σ). The uncertainty in determining the total water-table rise is related to the regression parameters associated with each recharge event.

The total recharge estimated with Equation 1 for the whole period was 1078.9 mm, with an associated uncertainty of 129.5 mm at 2σ. In terms of the recharge-to-precipitation ratio (RPR), the mean groundwater recharge corresponds to 33.9 and 39.8% of the precipitation recorded at 2σ.

Uncertainty estimation

This approach was used to estimate recharge and uncertainty from the joint application of an aquifer test with the WTF (Delottier et al., 2018). In this case, the storage parameter (specific yield) ranges between 0.094 and 0.106 at 2σ. The effective elevation water-table rise (Δh) is estimated to be 10.789 m with negligible uncertainty (4 mm in 2σ). These values were used, for example, to obtain the estimate of recharge, i.e., 1078.9 mm with an associated uncertainty of 138.7 mm at 2σ.

Table 1. Monthly rainfall and calculated recharge.

Month/year	Δh (m)	S_y	Recharge (mm/month)	Precipitation (mm/month)	Recharge/ Precipitation (%)
Sep/20	0.77		76.80	190.00	40.42
Oct/20	0.40		40.00	118.00	33.90
Nov/20	0.86		86.00	371.60	23.14
Dec/20	0.88		87.90	185.20	47.46
Jan/21	1.26		126.10	375.20	33.61
Feb/21	2.16	0.10	215.50	524.40	41.09
Mar/21	2.19		218.80	307.20	71.22
Apr/21	0.19		19.30	77.20	25.00
Jul/21	0.22		21.60	143.20	15.08
Aug/21	0.56		56.00	208.80	26.82
Sep/21	1.31		130.90	275.40	47.53

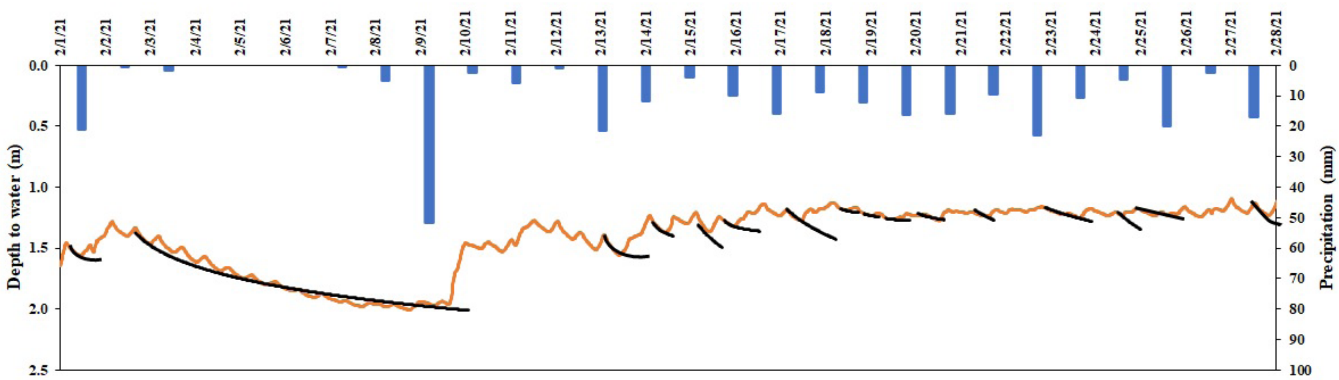

Figure 3. Combined plot showing water level fluctuations in the February/21. Orange line represent continuously monitored PM-06 levels, black lines represent recession curves, and the bar plot shows recorded precipitation.

It is evident that the uncertainty associated with the storage parameter is responsible for most of the uncertainty about recharge. Therefore, particular care must be taken in interpreting the aquifer test to obtain a reliable estimate of the specific yield. To reduce the recharge uncertainty, the parameterization of the analytical models used to interpret the aquifer test must be linked to the degree of complexity of the observed drawdown and recovery curve. A parsimonious model should be fitted when compatible with observed data (Delottier et al., 2018).

Despite the associated costs, the use of an aquifer test to obtain an estimate of the specific yield emerges as the most appropriate method when compared with a value taken from the literature, based on the observed lithology, a method used in several cases. If compared with core sample analysis, an aquifer test result has greater spatial representation; however, interpretations of aquifer tests are based on the assumption of a homogeneous medium. As observed by Pendiuk et al. (2020), an effective estimate of the specific yield is a challenge due to theoretical and methodological limitations, as assumption of an aquifer as a homogeneous medium.

For this purpose, two observation wells were used, as suggested by Delottier et al. (2018) to use data from multiple observation wells around the pumping well, a condition that could solve this problem. However, when there is marked vertical heterogeneity of the geological environment in the range of groundwater level fluctuation (which is not in the case of the present study), Crosbie et al. (2005) recommend using a specific depth-dependent yield value for the application of the WTF method.

While the aquifer test, considering the solution of Tartakovsky & Neuman (2007), which accounts for a delay in pore drainage in the unsaturated zone, the drainable porosity is estimated, which is of fundamental importance for the WTF method (Crosbie et al., 2005, 2013). Both parameters theoretically converge to the same value, that is, the specific yield (Sy), with increasing time after a disturbance (Nachabe, 2002). It should therefore be noted that the approach presented is applicable only to relatively shallow water tables and permeable (Delottier et al., 2018).

Following the idea proposed by Delottier et al. (2018), the instrumentation necessary for the approach now applied consists, at least, for the best cost-benefit, in two wells: a pumping well used for the test of the aquifer and a well of observation.

Although what was observed in the present research, the ideal is that there are at least two observation wells to better address the heterogeneity of the medium, both equipped with a pressure probe for continuous water table monitoring. The availability of a weather station is recommended, but not obligation (Delottier et al., 2018). Such a suggestion of a minimum monitoring structure becomes more affordable, facilitating the monitoring and interpretation of results through relatively simple analytical solutions, making the approach practical from an operational point of view and potentially replicable for different areas of interest.

Delottier et al. (2018) also mention that when dealing with groundwater management of large aquifer systems, it would be of interest to replicate this approach over the major units of land cover and geological formations, making it possible to investigate the spatial variability of recharge in more detail.

Such a proposal, for an experimental area, for estimating recharge can be directly related to studies of groundwater management, such as the one carried out in the Belém Metropolitan Region, in Pará estate, Brazil, described in Agência Nacional de Águas e Saneamento Básico (2018). Nevertheless, in the case cited, the recharge was estimated as 6% of the annual precipitation, and not based on wells and measurements carried out within the study area.

CONCLUSIONS

This research estimates groundwater recharge and its uncertainty using groundwater level fluctuation and aquifer test on the Federal University of Pará, Belém city, Brazil.

In the experimental area, a pumping and recovery test was done using a monitoring well adapted for pumping, and two observation wells, all equipped with a pressure transducer for groundwater levels monitoring. The specific yield was estimated by interpreting the pumping and recovery test with a better fit of the Tartakovsky-Neuman model. This value, between 9.4% and 10.6%, in 2σ, was then applied to the WTF method, with an estimated recharge of 1078.9 mm and an associated uncertainty of 129.5 mm in 2σ, to a range between 33.9% and 39.8% in relation to precipitation.

The ideal conditions for application of the joint method are: shallow unconfined aquifers with relatively permeable formations. In those cases, uncertainty about groundwater recharge is mainly associated with uncertainty related to specific yield.

The described and applied joint approach combining an aquifer test with application of the water-table fluctuation (WTF) method can be replicated on different sites or catchments, being useful to provide prior information and improve the predictive abilities of groundwater management.

REFERENCES

Agência Nacional de Águas e Saneamento Básico – ANA. (2018). *Estudos hidrogeológicos para gestão das águas subterrâneas da região de Belém/PA*. Brasília: ANA.

Bastos, T. X., Pacheco, N. P., Nechet, D., & Sá, T. D. A. (2002). *Aspectos climáticos de Belém nos últimos cem anos*. Retrieved in 2022, November 23, from https://www.embrapa.br/busca-de-publicacoes/-/publicacao/389773/aspectos-climaticos-de-belem-nos-ultimos-cem-anos.

Crosbie, R. S., Binning, P., & Kalma, J. D. (2005). A time series approach to inferring groudwater recharge using the water table fluctuation method. *Water Resources Research*, *41*(W01008), 1-9. http://dx.doi.org/10.1029/2004WR003077.

Crosbie, R. S., Doble, R. C., Turnadge, C., & Taylor, A. R. (2019). Constraining the magnitude and uncertainty of specific yield for use in the water table fluctuation method of estimating recharge. *Water Resources Research*, *55*(8), 7343-7361. http://dx.doi.org/10.1029/2019WR025285.

Crosbie, R. S., Scanlon, B. R., Mpelasoka, F. S., Reedy, R. C., Gates, J. B., & Zhang, L. (2013). Potential climate change effects on groundwater recharge in the High Plains Aquifer, USA. *Water Resources Research*, *49*(7), 3936-3951. http://dx.doi.org/10.1002/wrcr.20292.

Cuthbert, M. O. (2010). An improved time series approach for estimating groundwater recharge from groundwater level fluctuations. *Water Resources Research*, *46*(9), 1-11. http://dx.doi.org/10.1029/2009WR008572.

Delin, G. N., Healy, R. W., Lorenz, D. L., & Nimmo, J. R. (2007). Comparison of local- to regional-scale estimates of ground-water recharge in Minnesota, USA. *Journal of Hydrology (Amsterdam)*, *334*(1–2), 231-249. http://dx.doi.org/10.1016/j.jhydrol.2006.10.010.

Delottier, H., Pryet, A., Lemieux, J. M., & Dupuy, A. (2018). Estimating groundwater recharge uncertainty from joint application of an aquifer test and the water-table fluctuation method. *Hydrogeology Journal*, *26*(7), 2495-2505. http://dx.doi.org/10.1007/s10040-018-1790-6.

Fosberg, F. R., Garnier, B. J., & Küchler, A. W. (1961). Delimitation of the humid tropics. *Geographical Review*, *51*(3), 333-347. Retrieved in 2022, November 23, from https://www.jstor.org/stable/212781

Healy, R. W., & Cook, P. G. (2002). Using groundwater levels to estimate recharge. *Hydrogeology Journal*, *10*(1), 91-109. http://dx.doi.org/10.1007/s10040-001-0178-0.

Healy, R. W., & Scanlon, B. R. (2010). *Estimating groundwater recharge.* New York: Cambridge University Press. https://doi.org/10.1017/CBO9780511780745.001.

Jasim, S. M., & Jalut, Q. H. (2020). Estimation of aquifer hydraulic parameters from pumping test data analysis: a case study of baquba shallow unconfined aquifer. *Diyala Journal of Engineering Sciences*, *13*(2), 22-33. http://dx.doi.org/10.24237/djes.2020.13204.

Kruseman, G. P., & De Ridder, N. A. (2000). *Analysis and evaluation of pumping test data.* Wageningen: International Institute for Land Reclamation and Improvement.

Lucas, M., Oliveira, P. T. S., Melo, D. C. D., & Wendland, E. (2015). Evaluation of remotely sensed data for estimating recharge to an outcrop zone of the Guarani Aquifer System (South America). *Hydrogeology Journal*, *23*(5), 961-969. http://dx.doi.org/10.1007/s10040-015-1246-1.

Mattos, T. S., De Oliveira, P. T. S., Lucas, M. C., & Wendland, E. (2019). Groundwater recharge decrease replacing pasture by Eucalyptus plantation. *Water (Switzerland)*, *11*(6), 1-13. http://dx.doi.org/10.3390/w11061213.

Moench, A. F. (2004). Importance of the vadose zone in analyses of unconfined aquifers tests. *Ground Water*, *42*(2), 223-233. https://doi.org/10.1111/j.1745-6584.2004.tb02669.x

Nachabe, M. H. (2002). Analytical expressions for transient specific yield and shallow water table drainage. *Water Resources Research*, *38*(10), 11-1-11-7. https://doi.org/10.1029/2001wr001071.

Nlend, B., Celle-Jeanton, H., Huneau, F., Garel, E., Ngo Boum-Nkot, S., & Etame, J. (2021). Shallow urban aquifers under hyper-recharge equatorial conditions and strong anthropogenic constrains. Implications in terms of groundwater resources potential and integrated water resources management strategies. *The Science of the Total Environment*, *757*, 143887. http://dx.doi.org/10.1016/j.scitotenv.2020.143887.

Pendiuk, J. E., Guarracino, L., Reich, M., Brunini, C., & Güntner, A. (2020). Estimating the specific yield of the Pampeano aquifer, Argentina, using superconducting gravimeter data. *Hydrogeology Journal*, *28*(7), 2303-2313. http://dx.doi.org/10.1007/s10040-020-02212-z.

Rama, F., Miotlinski, K., Franco, D., & Corseuil, H. X. (2018). Recharge estimation from discrete water-table datasets in a coastal shallow aquifer in a humid subtropical climate. *Hydrogeology Journal*, *26*(6), 1887-1902. http://dx.doi.org/10.1007/s10040-018-1742-1.

Scanlon, B. R., Healy, R. W., & Cook, P. G. (2002). Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal*, *10*, 18-39. http://dx.doi.org/10.1007/s10040-0010176-2.

Simon, F. W., Reginato, P. A. R., Kirchheim, R. E., & Troian, G. C. (2017). Estimativa de recarga do sistema aquífero Guarani por meio da aplicação do método da variação da superfície livre na bacia do rio Ibicuí-RS. *Águas Subterrâneas*, *31*(2), 12-29.

Tartakovsky, G. D., & Neuman, S. P. (2007). Three-dimensional saturated-unsaturated flow with axial symmetry to a partially penetrating well in a compressible unconfined aquifer. *Water Resources Research*, *43*(1), 1-17. http://dx.doi.org/10.1029/2006WR005153.

Tesfaldet, Y. T., Puttiwongrak, A., & Arpornthip, Ta. (2020). Spatial and temporal variation of groundwater recharge in shallow aquifer in the Thepkasattri of Phuket, Thailand. *Journal of Groundwater Science and Engineering*, *8*(1), 10-19. http://dx.doi.org/10.19637/j.cnki.2305-7068.2020.01.002.

Authors contributions

Giovanni Chaves Penner: First author who contributed to literature review, methodology proposal, analysis and discussion of results, as well as writing and formatting of the article.

Rubens Takeji Aoki Araujo Martins: Worked on the conceptualization, methodology, data curation, formal analysis, visualization, writing - original draft paper and writing – review and editing.

Salim Rodrigues: Worked on the conceptualization, methodology, data curation, formal analysis, visualization, writing - original draft paper and writing – review and editing.

Edson Wendland: Was responsible for the supervision, project administration, and funding acquisition.

Editor-in-Chief: Adilson Pinheiro

Associated Editor: Michael Mannich