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The impact of sampling intervals on the evaluation of coastal ground water data for a proper design of engineering structures

Les effets des intervalles de prises d'échantillons sur l'évaluation des données d'eaux souterraines côtières pour une conception adéquate d'ouvrages de génie civil

Thomas Nuber, Wolf Pfeiffer & Martin Pohl
Federal Waterways Engineering and Research Institute, Hamburg, Germany, thomas.nuber@baw.de

ABSTRACT: Aquifers in coastal areas are influenced by the sea, where groundwater heads follow the tidal movement more or less damped and time-delayed depending on the geometry of the aquifer and its hydraulic properties. In coastal engineering projects, knowledge of the hydraulic properties of the subsurface and the groundwater heads at certain hydrological situations is crucial for a reliable and economical design. Since the 1950s analytical formulations describing the tidal propagation have been developed, allowing the estimation of hydraulic properties using measured ground water heads. For this an accurate recording of the ground water heads with a high temporal resolution is deemed necessary. Thus, groundwater measuring intervals are typically and arbitrarily set to 5 to 10 minutes. Considering the accuracy of the analytical evaluation approaches, much longer recording intervals may be reasonable under certain conditions. Based on several case studies in northern Germany, the impact of different recording intervals on the prediction accuracy of hydraulic properties for the construction design of locks and walls is evaluated. The results show that different evaluation objectives require individual measuring intervals to fulfill a given prediction accuracy. Despite differences in the geometry of the sea-aquifer connection, a maximum measuring interval of 15 minutes is small enough to achieve an accuracy of 99% for the common evaluation objectives, while increasing the measuring intervals to up to 60 minutes still results in accuracies higher than 95%.

RÉSUMÉ : Les aquifères dans les zones côtières sont soumis à l'influence de la mer. Dans les zones côtières, la charge hydraulique suit les mouvements des marées de manière plus ou moins affaiblie et avec un certain délai – dépendant de la géométrie de l'aquifère et de ses caractéristiques hydrauliques. Dans des projets de génie côtier, il est essentiel de bien connaître les caractéristiques hydrauliques des sous-sols et de la charge hydraulique relatives aux situations hydrologiques spécifiques pour une conception fiable et économique. Des formulations analytiques décrivant la progression des marées, développées depuis les années 50, ont permis d'estimer les propriétés hydrauliques sur la base de mesures de charges hydrauliques. Pour cela on pense qu'il est nécessaire d'enregistrer précisément les charges hydrauliques avec une résolution temporelle élevée. Les intervalles types de mesure des eaux souterraines ont donc été fixés, de manière arbitraire, à 5-10 minutes. Par-contre, en tenant compte de la précision des approches d'évaluation analytiques, des intervalles d'enregistrement beaucoup plus longs pourraient être plus appropriés sous certaines conditions. Les effets de différents intervalles d'enregistrement sur la précision de prévision des propriétés hydrauliques sont évalués sur la base de plusieurs études modèles en Allemagne du Nord, dans le but de construire et concevoir des écluses et des murs. Les résultats démontrent que différents objectifs d'évaluation exigent des intervalles de mesurage individuels pour obtenir une précision de prédiction donnée. En dépit de différences dans la géométrie de la jonction entre mer et aquifère, un intervalle de mesurage maximum de 15 minutes est suffisamment petit pour obtenir une précision de 99 % pour les objectifs d'évaluation habituels ; et une augmentation des intervalles de mesurage jusqu'à 60 minutes mène encore à des précisions supérieures à 95 %.

KEYWORDS: coastal aquifers; tidal propagation, ground water monitoring; sampling intervals, reliable design

1 INTRODUCTION

Ground water heads of coastal aquifers follow the movement of the tidal influenced surface water level damped and time-delayed depending on the geometry of the aquifer and its hydraulic properties. For the design of coastal structures, the determination of ground water heads during different design situations is required. Here, the consideration of the tidal propagation of the surface water level into an adjacent aquifer plays an important role. In this context the knowledge of the geohydraulic properties of the aquifer is necessary, especially when ground water heads for certain design situations have to be predicted. Since the 1950s analytical formulations of the tidal propagation for different hydrogeological conditions exist. Applying these approaches, the geohydraulic properties and the characteristic ground water heads can be calculated for different design situations if adequate data is available. In order to reproduce the tidal movement in the aquifer and to capture the required ground water heads as accurate as possible, a certain temporal resolution of the ground water data is necessary. Today, continuous measurements of ground water heads with data logger systems are state of the art. In order to record the tidal dynamics with a high temporal resolution usually measurement intervals of 5 to 15 minutes are selected. However, existing datasets with far lower measuring intervals may have to be evaluated in retrospect. In this context it is useful to assess the possible error resulting from the sampling interval.

In this paper the effects of the sampling frequency on the accuracy of evaluation results of ground water heads in tidal influenced confined aquifers is examined. Here, a theoretical approach is compared with observations from two case studies, which are representative for conditions of tidally influenced areas in Northern Germany. The objective of this assessment is the derivation of sampling intervals, which provide appropriate accuracy for the common evaluation approaches.

2 EVALUATING COASTAL GROUND WATER DATA

Tidal induced sea water level changes are caused by direct or indirect mass attraction of the moon and the sun in connection with the Earth's rotation. One of the first observations regarding the tidal influence on the ground water heads in Northern Germany is reported by Prinz (1923), showing through ground water observations in the Hamburg area that the changes in water level of an estuary propagated damped and time-delayed into an adjacent aquifer. Here, the tidal fluctuation in the aquifers showed a sine wave-form (Figure 1), where the damping and the time lag depend on the shore-distance of the observation well.

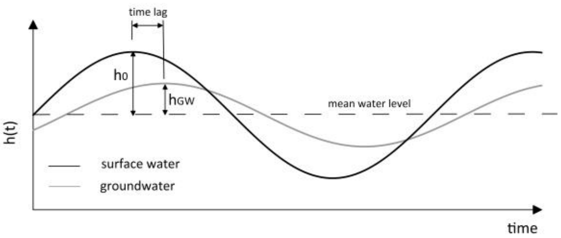

Figure 1. Water levels within a tidal cycle.

Since the 1950s numerous analytical approaches formulating the tidal propagation into an adjacent aquifer were developed and are still under development for the most diverse hydrogeological conditions. By now, there are 1d vertical-plane approaches (Dong et al. 2012, Ferris 1951, Guomin and Chongxi 1991, Hailong et al. 2007, Song et al. 2007), 2d vertical-plane approaches (Ataie-Ashtiani et al. 2001) as well as 2d horizontal-plane approaches (Huang et al. 2015, Li and Jiao 2002, Sun 1997). A recent comprehensive summary of these approaches is given in Jiao and Post (2019).

For the idealized case of an undisturbed hydraulic connection between the tidal influenced surface water body and the adjacent aquifer Ferris (1951) derived an approach for the propagation of a sine-waved tide into a confined aquifer for isotropic, homogeneous and confined groundwater conditions (Figure 2).

Based upon this simplified approach Ferris (1951) determined the hydraulic diffusivity T/S by introducing the so-called amplitude-ratio method and time-lag method. For this the amplitude-ratio and the time lag of the groundwater data is calculated for each tidal cycle. In theory the data for observation wells located in the groundwater flow direction should represent as straight lines when either plotting the amplitude-ratio versus distance in a semi-log graph or the time lag versus distance in a linear graph. According to the analytical formulations the slopes of the lines reflect the hydraulic diffusivity of the aquifer. Both of those methods are well established, with their applicability being proven in numerous case studies (Smith 1999, Fakir & Razack 2003, Merrit, 2004).

Applying the two evaluation methods to an identical dataset often lead to different results (Fakir & Razack 2003, Erskine, 1991, Trefry & Johnston 1998). Various explanations for that discrepancy exist, e.g. effects of the anisotropy or spatial heterogeneity of an aquifer (Trefry 1999, Jha et al. 2008, Trefry & Bekele 2004). Nevertheless, Jha et al. (2008) recommend the application of the amplitude-ratio method rather than the time-lag method and Trefry and Johnston (1998) proved that results of pumping tests are in good accordance with results of the amplitude-ratio method, whereas the results of the time-lag method showed significant deviations.

Besides the evaluation approaches concerning the hydraulic characteristics of an aquifer, ground water data can be also evaluated in the context of structural analyses of engineering structures. Generally, the pressure and flow forces resulting from the ground and surface waters must be considered as impacts for the individual design situations.

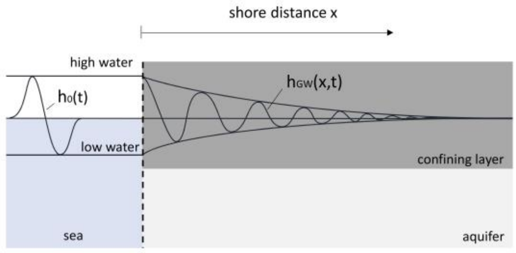

Figure 2. Tidal propagation according to Ferris (1951).

In this context, characteristic water levels and maximum ground water heads are required for the persistent, temporal and accidental design situations. For bank walls in tidal areas recommendations of the working committee "Bank Embankments, Ports and Waterways" (EAU 2012) contain approximation approaches for each individual design situation. Due to the required general validity of the approximation approaches, they might be too far on the safe side. Thus, site-specific evaluation of ground water data might result in a more economical dimensioning. Further descriptions how to evaluate ground water data in this context and how to assign them to different design situations are given in Nuber & Pohl (2020).

Thus, the impact of the sampling interval on the calculation of the amplitude-ratio and on the determination of the maximum ground water heads corresponding to the high-water levels of the surface water body are the main objectives of this paper. For this the amplitude-ratio for one tidal cycle should be calculated by the ratio of the standard deviations of the measured ground water heads and of the measured surface water level (Erskine 1991). The advantage of this approach is that every measured value is taken into account and that the influence of measurement errors can be minimized.

Alternatively, the amplitude-ratio can be determined from the ratio of the differences at high and low tide measured for ground and surface water. However, this method shows higher inaccuracies, so that the determination of the ratios of the standard deviations should be preferred (Smith 1994).

3 THEORETICAL ASSESSMENT APPROACH

3.1 *Nyquist-Frequency*

For the evaluation of tidal influenced ground water data, the tidal dynamic of the surface water level is assumed as a sine function using

$$h(t) = h_0 \cdot \sin(\omega t) \quad (1)$$

where h_0 is the amplitude and ω the frequency of the signal.

In order to reconstruct a sine signal with the correct frequency from point observations it is required to measure with a frequency at least twice as high than the frequency of the original signal – the so-called Nyquist-Frequency (Nyquist 1928). Measuring tidally influenced ground water heads with a lower frequency than the Nyquist frequency results in a hydrograph with a lower frequency - the so-called “alias-effect” (Figure 3).

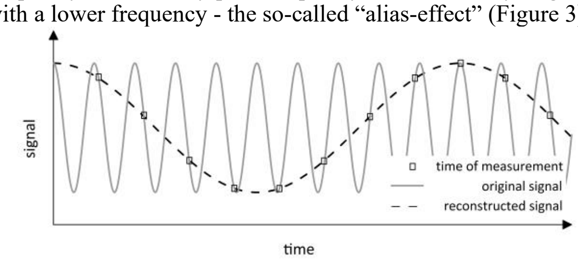

Figure 3. Alias effect for sinusoidal input signal.

Furthermore, an exact reproduction of the tidal cycle is not possible using the Nyquist-Frequency. For that, a frequency far higher than the Nyquist frequency is required. Here, it is obvious that the accuracy increases with the number of sampling points within a tidal cycle (Figure 4).

Nevertheless, the determination of the amplitude-ratio according to Erskine (1991) requires just enough values to calculate the standard deviation of the measured values for each tidal cycle rather than a perfect reconstruction of the hydrograph. Also, capturing of the maximum ground water levels with the precision required does not demand a perfect reconstruction of the hydrograph for the task at hand since the maximum ground water heads occur at times when the gradient of the sine function is at its lowest and small deviations from the maximum levels are acceptable.

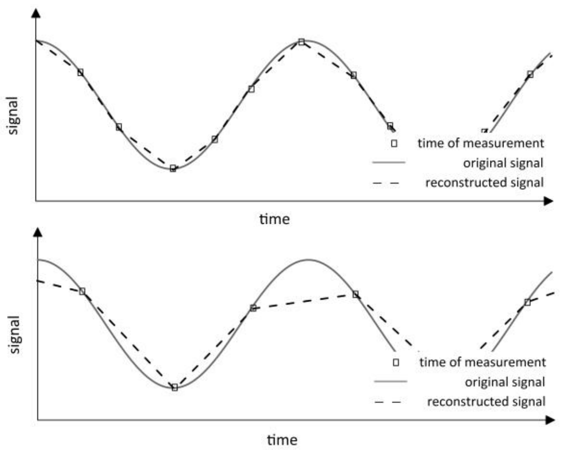

Figure 4. Reconstruction of a sine function based on measurements with different intervals.

3.2 *Accuracy in determining the amplitude-ratio*

In general, the accuracy can be described by the relative error ε that is calculated by the following equation.

$$\varepsilon = \frac{|v_a - v_e|}{v_e} \quad (2)$$

where v_a is the value resulting out of the measurements and v_e is the exact value.

As mentioned in section 2, the amplitude-ratio should be calculated by the ratio of the standard deviations of the measured values of ground water heads σ_{Gw} and the surface water heads σ_{Sw}. The exact value is defined as the amplitude ratio h/h_0, so equation 2 can be written as

$$\varepsilon = \frac{\left|\frac{\sigma_{Gw}}{\sigma_{Sw}} - \frac{h}{h_0}\right|}{\frac{h}{h_0}} = \left|\frac{\sigma_{Gw}}{\sigma_{Sw}} - \frac{h}{h_0}\right| \cdot \frac{h_0}{h} \quad (3)$$

The standard deviation of the ground water data σ_{Gw} is calculated out of n-values of h_i assuming an equidistant sampling interval. According to equation 1, the mean value is $\bar{x} = 0$ for a non-shifted sine function, so that the standard deviation for the ground water functional values h_i can be described as:

$$\sigma_{Gw} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_i)^2} \quad (4)$$

In order to asses only the influence of the ground water sampling interval, the standard deviation of the surface water can be calculated by the exact standard deviation defined for one period of sine function as:

$$\sigma_{Sw} = h_0 \frac{\sqrt{2}}{2} \quad (5)$$

Considering equations (3), (4) and (5), for each ground water amplitude h the functional correlation between the percentage error PE on the number of sampling points n can be approximated:

$$\varepsilon(n) = \left|\frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_i)^2}}{h\frac{\sqrt{2}}{2}} - 1\right| \quad (6)$$

3.3 *Accuracy in capturing maximum ground water levels*

Assessing the accuracy in capturing the maximum ground water levels during a tidal cycle, at first the maximum functional values for a sine half arc ranging from 0 to π were determined assuming different sampling frequencies. Assuming that the peak value occurs in the middle of the considered sampling interval, the maximum possible difference dh_{max} between the exact and the measured values is captured (Figure 5).

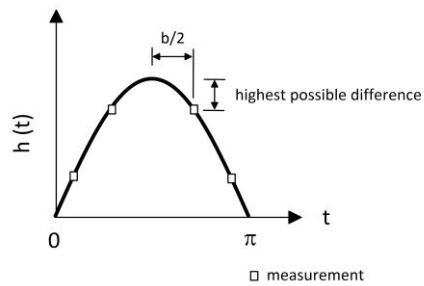

Figure 5. Determination of the maximum difference in a sine half-arc.

With this assumption, the measured maximum value h_m for a given sampling interval b can be calculated with:

$$h_m = h_i \sin\left(\frac{\pi}{2} + \frac{b}{2}\right) \quad (7)$$

The relation of the length of a sampling interval b and the number of sampling points n within one tidal cycle is

$$b = \frac{2\pi}{n-1} \quad (8)$$

Thus, the functional relation between the maximum value h_m and the number of sampling points n can be written as

$$h_m(n) = h_i \sin\left(\frac{\pi}{2} + \frac{\pi}{n-1}\right) \quad (9)$$

Since the exact maximum value for the maximum water level equals the amplitude h, the error related to the number of sampling points n can be calculated by

$$\varepsilon(n) = \frac{\left|h \sin\left(\frac{\pi}{2} + \frac{\pi}{n-1}\right) - h\right|}{h} = \left|\sin\left(\frac{\pi}{2} + \frac{\pi}{n-1}\right) - 1\right| \quad (10)$$

The derived relationships between the errors and the number of sampling points regarding the capturing of the maximum ground water heads and the calculated amplitude-ratios according to equations 6 and 10 are illustrated in Figure 6.

Both relations show a clear dependency of the error on the number of sampling points, whereas obvious difference between the two relations are recognizable. Here, the determination of the maximum ground water heads with errors of 1% requires around 25 measurements per tidal cycle, the calculation of the amplitude ratio approx. 50 measurements.

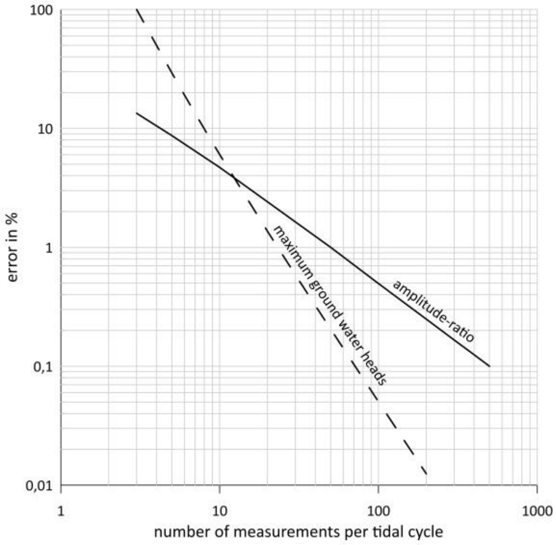

Figure 6. Percentage errors as a function of the number of measurements.

4 CASE STUDIES

4.1 *Site description*

Since the assumptions for the theoretical assessment (e.g. groundwater heads as a continuous sine function, no variations of the tidal amplitudes, no variation of the mean water level) cannot be found in the real-world, a verification of this theoretical approach is done by analyzing two real-world case studies located in the tidal influenced area of Northern Germany (Figure 7).

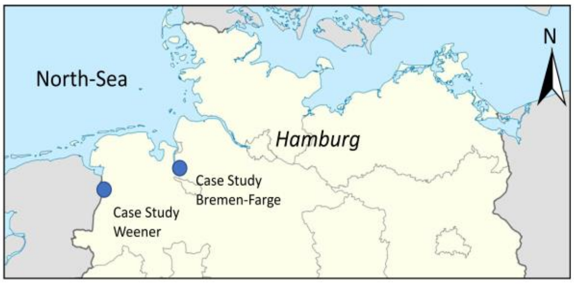

Figure 7. Location of the case studies.

Both study sites are characterized by representative geological and hydrogeological conditions for Northern Germany. The geological setting is similar at both sites, with an upper impermeable layer of several meters thickness confining sandy aquifer, which is hydraulically connected to a tidally influenced surface water body. The hydrogeological conditions are schematically illustrated in Figure 8.

The study area in Farge is located at a small port bordered by a sheet pile wall. Here, three observation wells form a transect in the direction of the ground water flow. Measured ground water data is available for a period from October, 17th 2014 until April, 13th 2015 with a sampling interval of 10 minutes.

The case study "Weener" is located at the River Ems. Here, two groundwater observation wells are oriented as a transect perpendicular to the River Ems in the groundwater flow direction. For the case study Weener ground water data is available from June, 6th 2019 to September, 24th 2019 at an interval of 5 minutes.

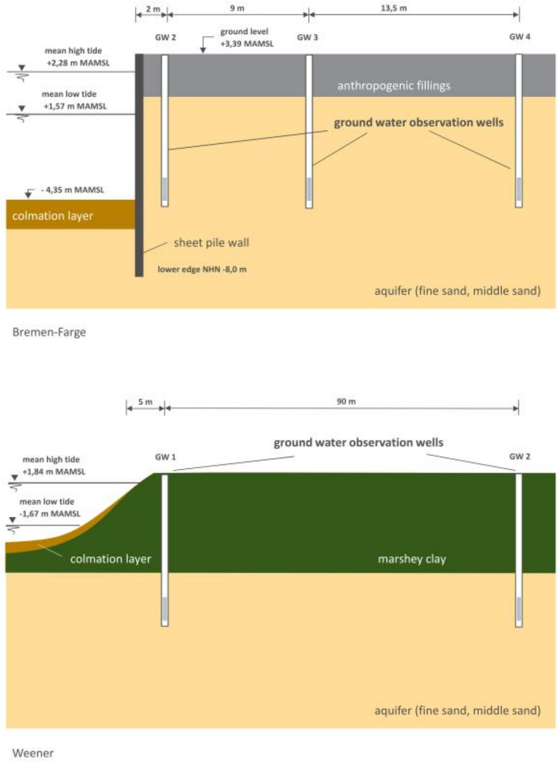

Figure 8. Schematic cross-section for the case studies "Farge" (upper figure) and "Weener" (lower figure).

4.2 *Approach and results*

The original data sets of both case studies were resampled at intervals of 10 or 20, 30, 60, 90, 120 and 180 minutes (equidistant). Using a python-based script the tidal cycles were identified and subsequently the maximum ground water heads and amplitude ratios for each cycle were determined.

For the case study Bremen-Farge, this yielded a total of 342 tidal cycles, whereas 223 tidal cycles were detected for the case study Weener.

The mean values and the standard deviations of the detected maximum ground water heads and of the amplitude-ratios for the original data set as well as for the generated data assuming sampling intervals of 30, 60, and 90 minutes are summarized in Table 1 and Table 2. Conducting t-tests it can be shown that none of the distributions of the generated data sets show statistically significant differences to the distributions of the original data sets.

Table 1. Mean values and standard deviation of the peak values for different measuring intervals.

$\bar{x}$ s	*10 min*	*30 min*	*60 min*	*90 min*
GW2-Farge	1.10 0.250	1.10 0.250	1.09 0.248	1.01 0.200
GW3-Farge	1.04 0.24	1.04 0.24	1.03 0.24	1.03 0.24
GW4-Farge	1.00 0.21	1.00 0.21	1.00 0.21	0.79 0.21
GW1-Weener	-1.23 0.156	-1.23 0.155	-1.24 0.155	-1.24 0.154
GW2-Weener	-1.44 0.152	-1.44 0.152	-1.44 0.152	-1.44 0.151

Table 2. Mean values and standard deviations of amplitude ratios for different measuring intervals.

$\bar{x}$ / s	*10 min*	*30 min*	*60 min*	*90 min*
GW2-Farge	0.314 0.021	0.314 0.021	0.314 0.021	0.315 0.022
GW3-Farge	0.248 0.014	0.246 0.013	0.246 0.015	0.249 0.015
GW4-Farge	0.179 0.008	0.179 0.008	0.179 0.010	0.180 0.010
GW1-Weener	0.273 0.021	0.274 0.023	0.269 0.024	0.261 0.025
GW2-Weener	0.154 0.012	0.155 0.013	0.151 0.014	0.146 0.015

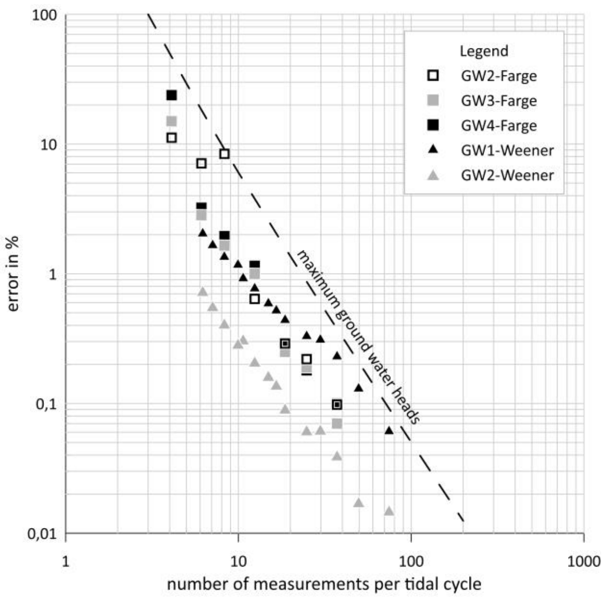

Figure 9. Errors of the captured maximum ground water heads.

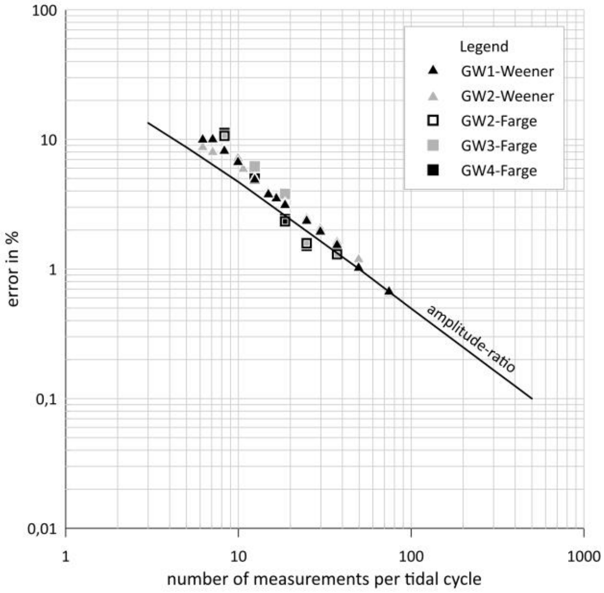

Figure 10. Errors of the calculated amplitude ratios.

The errors for the captured maximum ground water heads as well as for the amplitude-ratios, which were calculated for all data sets with different sampling intervals, are shown in Figure 9 and Figure 10. Here, the mean maximum ground water heads and respectively the mean amplitude-ratios calculated for the original data set were assumed as the exact values v_e the sampled data was compared to, given that the exact values are unknown and since a very low error can be assumed for the small sampling intervals of the original data sets.

As shown in Figure 9 the errors for the case studies are lower than the derived theoretical errors. One assumption for this derivation is that the exact maximum value occurs in the middle of a sampling interval, providing a conservative estimate. This assumption doesn't always hold in reality; thus the theoretical approach is overestimating the error associated with a specific measuring frequency. Therefore, selecting a sampling interval by the results of the theoretical approach provides results on the safe side for the task of identifying maximum ground water heads. Regarding the determination of the amplitude ratios, the errors approximated for the case studies are matching those of the theoretical relationship in a highly acceptable manner.

5 CONCLUSIONS

Regarding the results of the two case studies and the results of the theoretical approach it can be concluded that for the determination of the amplitude ratio and for the capturing of the maximum ground water heads an accuracy of 95% can be achieved by approx. 12 measurements per tidal cycle. In general, the determination of the amplitude-ratio requires smaller sampling intervals than the capturing of the maximum ground water heads at similar accuracies. Here, identifying the maximum ground water heads with an accuracy lower than 1 % requires approx. 25 measurements per tidal cycle. Assuming a tidal period of 12 h and 25 minutes, a sampling interval of approx. 30 minutes is needed. In contrast, the determination of the amplitude-ratio requires 50 measurements within a tidal cycle to obtain a similar accuracy, which means a sampling interval of approx. 15 minutes.

In this context a measuring interval of approx. 15 minutes is recommended. With this measuring interval, the error resulting from the measuring interval is also far below errors resulting from the accuracy of the measuring probe or its positioning, therefore minimizing the influence of the sampling interval on the evaluation results. In addition, measuring intervals of 15 min provide a clear tidal curve when presenting the groundwater data.

Furthermore, the results of the evaluation of the resampled groundwater data do not show statistically significant differences to those obtained for the original, i.e. not sampled, data sets. So even with longer sampling intervals than 15 minutes a reliable evaluation of the ground water data seems possible.

It should be noted, however, that the investigations were carried out for two case studies that are typical for the tidally influenced areas in Northern Germany (e.g. confined groundwater conditions, good hydraulic connection of the aquifer and the tidal influenced surface water). Whether recommendations are transferable to other hydrogeological conditions (e.g. free groundwater conditions) has to be examined in other case studies using the approach proposed in this paper.

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