Response to RC1 from Jonathan Kennel

This Technical Note introduces the Ocean Response Function which is an application of regression deconvolution using tidal levels as a basis for inputs. It can be used to remove the ocean signal from the water level data. It is well written and presents the underlying study well.

Thank you for your time reviewing the manuscript as well as the constructive and helpful comments provided. Following you find our responses to your comments, which are color coded with blue for neutral, green for agreement, orange for partial agreement, and red for disagreement.

Moderate concern:

- In terms of the scientific significance could you describe the difference between the ocean response function and river response function as you see it? Perhaps you might describe how you see them different or similar. Some rivers also have strong tidal effects due to ocean levels or cyclical forcing resulting from dam operations. Does each stressor (barometric, evapotranspiration, pumping, precipitation, Earth tides, river stage, lake levels, ocean tides, anthropogenic loading/unloading, seismic, …) require a separate methods paper when the underlying method is the same but the input varies? Is the key point that for this ocean tide example that the response can be approximated as linear time invariant over the time frame of analysis.

  Since we are aware that the method is established within the research community, we decided to communicate our findings as a technical note rather than a full paper. We aim to point out how the complex stressor sea level can be approached using regression deconvolution. We were interested in how regression deconvolution would perform under this setting and which time scales would be relevant for the response function to define an adequate system memory. We believe that our findings are worthy of a technical note. The manuscript also provides a generic formulation of the method to include multiple stressors. To our knowledge, present formulations in the literature only cover two stressors (barometric pressure and Earth Tides).

  We note that the River Response function of Spane and Mackley (2011) focuses on events with periods longer than typical dominating ocean tidal constituents (> 50 h) (Spane and Mackley, 2011; p. 801). Barometric and Earth Tide response functions have a stronger focus on tidal constituents with periods of typically less than 48 h. These differences are also reflected in the system memory, which is much larger in the study of Spane and Mackley (2011) than for Barometric or Earth Tide responses.

  Spane and Mackley (2011) argue that if another stressor, like barometric pressure, is to be removed, this should be done in a sequential manner, starting with the most influential stressor. Others (e.g., Toll and Rasmussen, 2007; Rau et al., 2020) have removed two stressors simultaneously and so did we here. We acknowledge that this may have not been addressed well enough in the manuscript and we will implement changes accordingly (see responses to minor comments).

  The method of regression deconvolution is not well recognized in coastal hydrogeology, even though it may be very useful to establish system understanding of coastal aquifers. Research concerned with obtaining system understanding through the stressor sea level mainly focuses on spectral analysis (thus frequency-domain focused methods) of groundwater signals in response to ocean tides to estimate aquifer properties like hydraulic diffusivity from tidal constituents (e.g., Bye and Narayan, 2009; Rotzoll et al. 2008, 2013; many others are outlined by Spane and Mackley, 2011). This approach typically relies on an analytical solution of Ferris (1952) for tidal propagation in an aquifer and is only applicable to unconfined aquifers when certain assumptions are fulfilled (observations far from the shoreline, tidal range in observation well is only small fraction of aquifer thickness, mainly horizontal flow). For Norderney, none of these requirements are fulfilled for example. Trglavcnik et al. (2018)

additionally used storm flood signals for hydraulic aquifer characterization. In conclusion, the stressors ocean tides and storm events present in sea-level time series have mostly been analyzed separately.

The time-domain focused regression deconvolution may provide two relevant opportunities for future research in coastal hydrogeology:

1. Enable hydraulic characterization of coastal aquifers based on regression deconvolution which can use the combined information of stresses at all time scales present in the groundwater signal, instead of only one (e.g., ocean tides or storm floods), independent of the assumptions required by analytical solutions.
2. Allow the extraction of a temporally highly-resolved groundwater recharge signal which is typically obscured by the strong sea-level influences at coastal sites near the shoreline. This can be relevant as groundwater recharge information, especially at a high temporal and spatial resolution is often extremely difficult to obtain.

Therefore, there may not be the need for a technical note for every stressor, but the coastal hydrogeology community may benefit from the guidance provided in this technical note on how to apply the method at coastal groundwater observation sites and the further research opportunities this method potentially provides should it be more recognized in the community.

We agree that the motivation for the technical note should be outlined more clearly and therefore we will revise the objective in the introduction (following Line 31):

> "The objective of this work is to (i) provide a generic formulation for regression deconvolution, (ii) demonstrate […] unconsolidated sediments and (iii) illustrate how the method is useful for coastal systems."

The assumption of linearity and time invariance of the response is important but probably hardly ever fulfilled by field data. As outlined in our responses below (minor comments), the response characteristics may differ if storm events are present. However, if two time series contain similar sea-level stresses, the response is comparable in our data set. Regarding linearity, Spane and Mackley (2011) point out (citing Smith, 2008; Reilly et al., 1987) that the linear approximation can hold true for a nonlinear system under certain conditions (changes in saturated aquifer thickness due to the periodic flow are comparably small). As a coastal aquifer is a nonlinear system regarding sea-level propagation, we will add information regarding this. For Norderney, we assume the linear approximation to be adequate as the saturated aquifer thickness is likely at around 400-450 m (Haehnel et al., 2023).

Minor concerns:

- Lines 85:88 "It is recommended to perform the deconvolution using the first differences of the measurements, leading to Eq. 5 becoming $\Delta y = \beta \, \Delta X$. This removes the effect of persistent trends in the data and therefore avoids a bias in the regression (Rasmussen and Crawford, 1997; Butler Jr. et al., 2011). " It is also possible to prefilter data or include a background trend term(s) in the regression equation. I would probably not include the difference formulation as a recommendation, but can mention why you did it. In general if appropriate data is available the analysis can be done on non-differenced data. It also avoids the correction required in line 89.

  Thank you for pointing this out. We will change the paragraph's phrasing accordingly. The reason for using first differences is outlined in Line 87 (trend removal).

- The term "corrected" is used throughout. While this is commonly used and has been defined before, it suggests that the raw water level is in error. I prefer, the water level with the ___ component(s) removed.

While we agree with the possible perception of “corrected” as stating the original time series was erroneous, the alternative formulations using “removed” are often cumbersome and prevent concise formulations. We will address this by clarifying the use of the term “corrected” with a short statement in the manuscript.

- With different length maximum lags you are comparing response functions based on different time periods, you may want to say this or highlight the applicable analysis length. It might not be important with long datasets and relatively short lags, but in shorter length datasets it may be important. Also if the relationship isn’t strictly LTI it can be an issue.

Please refer to our response to the comment below regarding the reproducibility of the ORF for smaller portions of the time series.

- Perhaps mention how ocean tides and barometric pressure are spatially variable. What is the influence of the tide monitoring location and weather monitoring location. Is it important for this study?

The spatial variability should not be a concern for this study, but we agree that this should be mentioned.

Barometric pressure observed at Norderney is very similar to such observed at other meteorological stations nearby in absolute values and dynamics. We therefore compared the data from Norderney with the data from the two closest meteorological stations “Wittmund” (located on the main land, ca. 39 km south of Norderney) and “Leuchtturm Alte Weser” (located in the German Wadden Sea, ca. 66 km west of Norderney). Cross-correlation analysis of these datasets show little temporal offsets to Norderney (maximum correlation at time lags $\leq 2\ \mathrm{h}$). Linear regression analysis showed barometric pressure has no discernable offset from Norderney at station “Wittmund” and ca. 6 cm H2O at station “Leuchtturm Alte Weser”. Given that these differences occur at a scale of tens of kilometers, the spatial difference of ca. 1.5 km between the meteorological station and the observation wells should not be relevant.

For the sea-level data, we compared the data from tide gauge “Norderney Riffgat” with tide gauge “Spiekeroog” located ca. 35 km east of Norderney. Cross-correlation shows that the maximum correlation is found at a time lag of 33 min so that the time difference between the shore segments closest to the observation wells and the tide gauge should be in the order of minutes (well below the measurement time interval).

We will add a short statement regarding the spatial variability of the barometric pressure and sea level data, update Figure 2 to display the locations of the additional measurement sites, and add additional information on the analysis of these datasets as Supplementary Material.

- 162:163 “Tidal data were downsampled to hourly intervals for subsequent analysis.” Readers may be interested in how - dropping non-matching values or other decimation procedure.

The sentence in Lines 162-163 will be rephrased to make the procedure clearer:

> “Tidal data were downsampled to hourly intervals for subsequent analysis by discarding observation time points that did not match the sampling times of groundwater and barometric pressure data, which were collected at each full hour.”

- 183:184 “The precipitation response of BS3 and NY-10 is discernible in mid-August 2019, where groundwater levels increase despite a lack of change in sea levels.” Did you calculate a response function for these? If not why not?

We opted not to include a precipitation response function in our study due to the complexities involved in quantifying the additional impact of precipitation on groundwater recharge and evapotranspiration. Discussing this aspect in depth would have significantly extended the manuscript, as it would entail delving into the intricate mechanisms by which precipitation translates into recharge, especially in unconfined aquifers with shallow groundwater tables. In such scenarios, both evapotranspiration from the unsaturated zone and the saturated zone are pertinent considerations.

Our primary focus in this manuscript centers on the removal of sea-level influences from groundwater-level time series. As outlined in the manuscript, this approach allows us to isolate the groundwater recharge signal within the time series, effectively eliminating other external factors. This successful isolation was demonstrated in our study with observation wells BS3 and NY-10.

It is important to note that the time series, once cleaned of all influences except recharge, can potentially be used to calculate recharge values. However, delving into this aspect would open up an entirely new avenue of investigation beyond the scope of our intended objective. Such an exploration would have extended the manuscript beyond the confines of what is typically expected in a Technical Note published in HESS, which is designed to be concise and focused.

- 187 “Periodic and aperiodic sea-level fluctuations” consider simplifying to “Sea-level fluctuations”

We would like to keep the formulation because it highlights that both ocean tide influences as well as meteorological/storm related influences can be removed simultaneously.

- How reproducible are the response functions when calculated for different portions of the dataset?

When using less than a year of the dataset, the response functions are not necessarily reproducible. Since different time scales of the stressor are relevant for the ORF (here ocean tides and storm floods), the dataset should be long enough to contain all these time scales if a time-invariant response is desired. For Norderney, the storm events occur almost exclusively during the winter season. Should the dataset not cover such a period, the ORF might look different and the maximum time lag required to remove the influence of sea levels may be shorter as mostly ocean tides are relevant then. We found that time series portions without storm floods present yield smaller maximum ORF values. This is not a shortcoming of the method, but actually highlights that the ORF responds to the stresses present in the sea-level time series.

We will add an additional figure showing ocean response functions for shorter portions of the time series and discuss the results and implications of this in accordance to Brookfield et al. (2017).

- The ocean tide data also includes a barometric related component which may be worth mentioning more directly. This could influence the analysis when barometric pressure and ocean tides were used as it now ends up having correlated data.

Agreed. This cross-correlation existing between the sea-level signal and the barometric pressure signal violates the assumption that inputs are independent of each other (Line 65). The barometric pressure influence is present in the groundwater time series 1) by direct vertical influence, with possibly smaller time lags, and 2) by indirect horizontal influence via the sea levels, with possibly larger time lags. One option would be to perform a regression deconvolution on the sea-level data first using the barometric pressure time series. However, the barometric pressure influence carried by the sea level signal would still be present in the groundwater-level time series and may be erroneously mapped to the barometric response function then.

The barometric response functions at the observation wells have rather small values, so that we expect the vertical influence of the barometric pressure to be much smaller than the indirect horizontal influence through the sea-level signal.

We will add a paragraph to outline this in Section 2.1 and update Figure 1 to show that also sea levels are influenced by barometric-pressure changes. To state the barometric influence clearer in general, we will add a Figure showing the barometric response functions, instead of only stating that direct barometric influence on the groundwater levels was very small.

- In the ocean response functions, did you compensate for salt water density? Might be worth mentioning if you did or didn't and how it might affect the response function numbers.

No, we did not compensate for salt water density. The variable-density effects are commonly considered negligible when concerned with propagation of ocean tide signals in coastal aquifers (Ataie-Ashtiani et al. 2001; Slooten et al., 2010) and most studies presenting analytical solutions for ocean tide propagation do not consider density effects (e.g., Nielsen 1990; Li et al., 2000; Rotzoll et al., 2008).

Regarding sea levels:

Calculating freshwater heads for the sea-level time series would change the magnitude of the signal but not the timing. The associated error would be in the order of a few percent of the tidal amplitude, likely substantially less than other uncertainties. Further, the entry point of the seawater into the aquifer is not a discrete point but spread over the sub- and intertidal zone most of the time. Thus, in the current approach, some kind of average elevation for the aquifer-ocean connection would have to be defined. This would offset the absolute values of sea level by a constant factor and would thus be eliminated again when long-running trends are removed by first differencing or another kind of trend removal prior to the analysis.

Regarding groundwater hydraulic heads:
All observation wells presented in this study are located within the freshwater lens of Norderney and thus measured heads are freshwater heads.

Overall, we do not see any potential effect of salt water density on the response function but agree that the arguments presented above should be briefly mentioned in the manuscript.

- A key aspect of this is the linear time invariant assumption. I think you should mention this in the applicability portion of the conclusions.

Regarding the time-invariant assumption, we will add the following text to the conclusions:

> "The ORF shape depends on the stresses being present in the sea-level time series and are only similar for different time frames, i.e., time invariant, when the stresses of the time frames are comparable. A time frame containing storm events may yield a different ORF than a time frame were ocean tides are the most prominent sea-level influence."

Regarding the linearity assumption, we will add the following**:**

> "In the case of Norderney, the assumption of a linear response of groundwater levels to sea-level influences will likely be valid approximately resulting from the small changes in saturated aquifer thickness introduced by the sea-level fluctuations."

- There is no interpretation of the responses. Given that the ocean tides can be considered similar to other surface water bodies - it is likely very similar to a river response function analysis (Brookfield et al, 2017). Interpreting temporal variations in river response functions: an example from the Arkansas River, Kansas, USA

Thank you for the literature suggestion. In the manuscript, we state the reasons for the different responses to sea levels at the different monitoring wells in Lines 208-214. Further interpretations will be added according to our response to the comment about reproducibility of the ORF for shorter portions of the time series.

Considering Brookfield et al. (2017), we will also add the information that the oceanic response function can change with time as a result of the variable characteristics of the sea-level influence.

Figure suggestions:

Figure 4: Were ocean levels converted to freshwater head for the comparison? If the goal of this figure is to highlight the signal with the ocean response removed, you may want to make this the focus by using a smaller vertical range for these. Right now they are somewhat obscured by the large y-axis range. I'm not sure it is necessary to repeat the ocean levels and precipitation on each facet and I would probably just have them in separate facets. This also improves readability by not having dual axes. A subset of the total time can also be helpful.

No, the sea levels were not converted to freshwater heads (cf. to our response above).

We agree that the outline of Figure 4 is not optimal as is. We will therefore merge Figures 3 and 4 into a single Figure showing the stressors as in Figure 3ab and all groundwater-level time series shown in Figure 3c and Figure 4 in a separate panel for each monitoring well. We will not show additional subsets of the time series as we believe the major arguments can be followed from the updated figure and this technical note already has many figures.

Figure 5: Perhaps you want to comment on the oscillations in the response function – what frequency and the potential causes – method related, noise related.

The oscillations visible are at a frequency of approx. 4 cpd for BS3 and NY-10 and at variable between roughly 2.67 and 2 cpd for SN12/1. A spectral analysis (FFT and HALS) was performed on the groundwater-level time series with sea-level and barometric pressure influences removed. This analysis shows that the main frequencies that remain in the groundwater-level signal match the S1 and M4 tidal constituents. Further, frequencies around 2 cpd are present as well.

The S1 constituent originates from the pumping pattern of the production wells as shown in the manuscript for SN12/1, where it is very prominent. Since the island is small the pumping pattern is present in the groundwater-level time series throughout the island but at a much smaller amplitude at BS3 and NY-10.

The shallow water tidal constituent M4 likely originates from the generation of higher harmonics of the major tidal constituents in the sediment of the aquifer (Bye and Narayan, 2009). The amplitude of the generated constituent depends on the amplitude of its base frequency and the phase shift likewise on the phase shift of its base frequency (Bye and Narayan, 2009). Since M2 is the dominating tidal constituent at the study site, its first higher harmonic M4 is very likely to be generated in the aquifer and thus present in the time series analyzed here. Since this generated M4 is not present in the sea-level time series it will not be removed by the regression deconvolution, just like the influence of pumping.

Comparing FFT and HALS results shows that the frequencies around 2 cpd do not exactly match the major semi-diurnal tidal constituents. Thus, we assume this to be noise.

This additional information is potentially interesting to readers, therefore we will change the heading of section 3.5 to "Revealing groundwater extraction and aquifer-generated tidal constituents" and add the above mentioned information to this section. We will include an additional figure showing results of the spectral analysis (FFT and HALS) of the corrected groundwater-level time series (amplitude over frequency) to outline the presence of S1 and M4 in these time series.

Figure 6: I don't think I would highlight the pumping times with the grey boxes in A. It makes it seem like this is actual data. If you include it, I would clearly annotate on the figure to say inferred.

The grey boxes will be deleted from Figure 6 and the figure caption will be updated accordingly.

HESS questions

- Does the paper address relevant scientific questions within the scope of HESS? Yes
- Does the paper present novel concepts, ideas, tools, or data? The tools, concepts, and ideas are well developed previously, data and the relationships are new for this site.
- Are substantial conclusions reached? Yes/No
- Are the scientific methods and assumptions valid and clearly outlined? Yes
- Are the results sufficient to support the interpretations and conclusions? Yes
- Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)? Yes
- Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Yes
- Does the title clearly reflect the contents of the paper? Yes
- Does the abstract provide a concise and complete summary? Yes
- Is the overall presentation well structured and clear? Yes
- Is the language fluent and precise? Yes
- Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Yes
- Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? See comments
- Are the number and quality of references appropriate? Yes
- Is the amount and quality of supplementary material appropriate? The supplementary data and code are good. I don't know that the appendix B is necessary.

  We would like to keep Appendix B especially when keeping in mind the community of coastal hydrogeologists. Appendix B shows in detail at which time lags ocean tides would be removed, further elaborating on the statement in Lines 210-212. This gives guidance regarding system memory when aperiodic events are less common at a study site or if the studied time frame does not include such events. While this may seem obvious when familiar with regression deconvolution, we think it may be a helpful addition to the main points of the manuscript for coastal hydrogeologists. Further, Appendix B is now even more referred to in the manuscript following the changes applied in response to the comments of this review.

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