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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Impacts of climate change on groundwater flooding and ecohydrology in lowland karst" *by* Patrick Morrissey et al.

Patrick Morrissey et al.

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Thank you for taking the time to review our paper and for you valuable comments. We have prepared a detailed response - it is better viewed through the supplemental pdf attached as the plain text below removes complicated equations and colours etc.

In the submitted manuscript, Morrissey et al use a semi-distributed karst model to estimate the possible impacts of climate change on a lowland karst system in Ireland both in terms of groundwater flooding and ecohydrology. Their model predicts that groundwater events that are currently considered extreme will increase in the future. In addition, a future shift of flood seasonality is simulated by the model, which the authors

suggest will likely affect ecological systems. Generally, the study is well-written and concise. Using a well-established karst model to estimate future groundwater flood frequency and ecohydrological implications is novel and of high interest for the readers of Hydrology and Earth System Sciences. As elaborated in the technical/specific remarks below, (1) comparing the RCMs' control periods simulations with meteorological observations may help to assess their trustworthiness. This comment is addressed fully below under the comment response "Methodology".

(2) estimating the uncertainty of the hydrological predictions may help avoiding wrong conclusions about moderate changes that are smaller than the prediction uncertainty This comment is addressed below under the comment "Karst Groundwater Model:" (3) A comparison with projected changes of karst processes of other karst model applications to assess future changes may permit some evaluation of the predicted changes of this study. This comment is addressed below under the comment "Results and Discussion" Overall, I am confident that the authors will be able addressing these point within the frame of minor revisions. Abstract: Some more information about the methods (model setup, climate scenarios) is necessary. The Abstract has been edited to include more detail about the methods, as well as an extra line to describe the issues of concern with flooding relating to infrastructure as well as ecology (point raised by Reviewer 2). Here is the revised text:

Lowland karst aquifers can generate unique wetland ecosystems which are caused by groundwater fluctuations that result in extensive groundwater-surface water interactions (i.e. flooding). However, the complex hydrogeological attributes of these systems linked to extremely fast aquifer recharge processes and flow through well-connected conduit networks often present difficulty in predicting how they will respond to changing climatological conditions. This study investigates the predicted impacts of climate change on a lowland karst catchment by using a semi-distributed pipe-network model of the karst aquifer populated with output from the high spatial resolution (4 km) COSMO-CLM regional climate model simulations for Ireland. An ensemble of projections for the future Irish climate were generated by downscaling from five different global climate models (GCMs), each based on four Representative Concentration Pathways (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) to account for the uncertainty in the estimation of future global emissions of greenhouse gases. The one dimensional hydraulic / hydrologic karst model incorporates urban drainage software to simulate open channel and pressurised flow within the conduits with flooding on the land surface represented by storage nodes with the same stage-volume properties of the physical turlough basins. The lowland karst limestone catchment is located on the west coast of Ireland and is characterised by a well-developed conduit dominated karst aquifer which discharges to the sea via intertidal and submarine springs. Annual above ground flooding associated with this complex karst system has led to the development of unique wetland ecosystems in the form of ephemeral lakes known as turloughs, however extreme flooding of these features causes widespread damage and disruption in the catchment. This analysis has shown that mean, 95th and 99th percentile flood levels are expected to increase by significant proportions for all future emission scenarios. The frequency of events currently considered to be extreme is predicted to increase, indicating that more significant groundwater flooding events seem likely to become far more common. The depth and duration of flooding is of extreme importance, both from an ecological perspective in terms of wetland species distribution and for extreme flooding in terms of the disruption to homes, transport links and agricultural land inundated by flood waters. The seasonality of annual flooding is also predicted to shift later in the flooding season which could have consequences in terms of ecology and land use in the catchment. The investigation of increasing mean sea levels, however showed that anticipated rises would have very little impact on groundwater flooding due to the marginal impact on ebb tide outflow volumes. Overall, this study highlights the relative vulnerability of lowland karst systems to future changing climate conditions mainly due to the extremely fast recharge which can occur in such systems. The study presents a novel and highly effective methodology for studying the impact of climate change in lowland karst systems by coupling karst hydrogeological models

with the output from high resolution climate simulations.

Introduction: Line 51: Typo “changeon” This typo has been corrected.

There is some work on groundwater level frequencies and climate change by Bloomfield & colleagues and some semi-distributed modeling of GW levels and climate change by Brenner et al (2018, NHESS), which may be useful for the state-of-the-art Thank you for this suggestion and we agree these studies are very relevant in describing the existing state-of-the-art. These references have now been added to the Introduction section – see amended extract from the Introduction below (amended reference list at end of this response).

Studies into the impacts of climate change have been carried out for the chalk aquifers of south-western England which have high porosity and are prone to karstification. Jackson et al. (2015) utilised a distributed ZOOMQ3D groundwater model of the Chalk aquifer with various emission scenario input data to investigate the predicted changes in groundwater levels. Brenner et al. (2018) conducted a further study of this chalk catchment and showed that projected climate changes may lead to generally lower groundwater levels and a reduction of exceedances of high groundwater level percentiles in the future. Chen et al. (2018) conducted a study into the effects of climate change on alpine karst using GCM data. However, the results of these studies are not directly relevant to lowland karst with significant groundwater-surface water interactions and associated eco-hydrological habitats (groundwater fed wetlands).

Regional Climate Modelling. This section is a short of a general review. Please either add study site specific information (which RCMs are available? how have they been established?) or move to Introduction. Comment is agreed - this section will now be moved to the Introduction in which it will fit better to help the flow of the paper.

Methodology Is it possible to compare the model ensembles of the historic/control time period with observed climate data? The authors will update the paper to include the following references in which this issue has been fully addressed: Nolan et al., (2017,

2020) and Flanagan et al. (2019, 2020) – see additional references list at the end of this document. The following text addresses this point and can either be incorporated into the main text or added as supplemental information: The RCMs were validated by downscaling ECMWF ERA-Interim reanalyses and the GCM datasets for multi-decadal time periods and comparing the output with observational data. Extensive validations were carried out to test the ability of the RCMs to accurately model the climate of Ireland. Figure XX(a) presents the annual observed precipitation averaged over the period 1981–2000. Figure XX(b) presents the downscaled ERA-Interim data as simulated by the COSMO5-CLM model with 4-km grid spacings. It is noted that the RCM accurately captures the magnitude and spatial characteristics of the historical precipitation climate, e.g. higher rainfall amounts in the west and over mountains. Figure XX(c) shows that the percentage errors range from approximately –30% to approximately +15% for COSMO5-CLM downscaled ERA-Interim data. The percentage error at each grid point (i, j) is given by: ãĂŰper_biasãĂŮ_((i,j))=100×(ãĂŰbiasãĂŮ_((i,j))/(OBS) ÌĚ_((i,j))) (?.?) where ãĂŰbiasãĂŮ_((i,j))=(RCM) ÌĚ_((i,j))-(OBS) ÌĚ_((i,j)) (?.?)

and the (RCM) ÌĚ_((i,j)) and (OBS) ÌĚ_((i,j)) terms represent the RCM and observed values, respectively, at grid point (i, j), averaged over the period 1981–2000. Figure XX(c) highlights a clear underestimation of precipitation over the mountainous regions. This is probably because the RCMs underestimate heavy precipitation; previous validations studies (e.g. Nolan et al., 2017) have demonstrated a decrease in RCM skill with increasing magnitude of heavy precipitation events. To assess the added value of high-resolution RCM data, and to quantify the improved skill of RCMs over the GCMs, precipitation data were compared with both RCM and GCM data for the period 1976–2005. Results, presented in Table YY, demonstrate improved skill of the RCMs over the GCMs. Moreover, an increase in grid resolution of the RCMs (from 18- to 4-km grid spacings) results in a general increase in skill. For an in-depth validation of the RCMs, please refer to Nolan et al. (2015, 2017, 2020), Flanagan et al. (2019, 2020) and Werner et al. (2019), the results of which confirm that the output of the RCMs exhibit reasonable and realistic features as documented in the historical data record and consistently demonstrate improved skill over the GCMs. The results of these validation analyses confirm that the RCM configurations and domain size of the current study are capable of accurately simulating the climate of Ireland. (a) (b) (c) Figure XX. Mean annual precipitation for 1981–2000. (a) Observations, (b) COSMO5-CLM-ERA-Interim 4-km data and (c) COSMO5-CLM-ERA-Interim error (%).

30-year average annual rainfall MAE % error GCM GCM Data COSMO5-CLM-GCM 18 km COSMO5-CLM-GCM 4 km CNRM-CM5 16.5 14.1 11.8 EC-Earth (r12i1p1) 17.3 14.0 10.0 HadGEM2-ES 20.8 14.6 15.1 MIROC5 26.0 18.2 15.6 MPI-ESM-LR 25.1 24.8 21.6

Table YY. GCM and COSMO5-CLM Mean Absolute Error (%) uncertainty estimates through comparison with gridded observations for the period 1976–2005. For each metric, the best- and worst-performing scores are highlighted in green and red, respectively.

Lines 192-193: “GCM to 18 km to 4 km” Please rephrase into full sentence. This sentence has been rephrased.

The RCMs were driven by GCM boundary conditions with the following nesting strategy; GCM to 18 km and GCM to 4 km. For the current study, only 4 km grid spacing RCM data are considered. The higher resolution data allows sharper estimates of the regional variations of climate projections. The climate fields of the RCM simulations were archived at 3-h intervals.

Table 1: Not all RCPs are available for all of the models. How was this handled when working with the model ensembles? In each case, the future 30-year periods are compared with the past RCM period 1976-2005. the mean of three RCP2.6, five RCP4.5 and five RCP8.5 RCM projections were calculated. The RCP6.0 simulation comprises just one simulation so was compared directly with the past RCM period.

This methodology was summarised in the methodology section but the text above can be added to the caption of Table 1 if required.

Figure 2: numbers in grey circles within figures not elaborated in caption Explanation of these numbers now added to the Figure caption (see response to Reviewer 2).

Karst Groundwater Model: Since the model parameters are estimated via calibration, it would make sense providing some estimate about their uncertainty especially since the model is used for prediction far in the future. Moderate predicted changes in flood frequency might be still within the envelop of the simulation uncertainty.

This is a valid issue and was one which we had considered when conducting this study. A thorough calibration and validation of the model was carried out which took over two years and required a large amount of field effort coupled with tedious model calibration. The process is described in detail in Morrissey et al. (2019). Whilst the model incorporates 15 flooding nodes which were calibrated using 2 years worth of field data – more long-term data were available at 5 locations where were the subject of numerous long term research projects. This allowed the model uncertainty to be compared over two separate overlapping time horizons: 2016-2018 and 2007-2018 at these locations. The resulting model uncertainty (using Nash-Sutcliff Efficiency values - NSE) was calculated for each location over these periods allowing an envelope of uncertainty to be determined – see Table 1 below. It can be seen that for the shorter and more recent calibration period the uncertainty for the model is approximately 5.2% (3% - 11%). For the longer validation period the uncertainty increases to 7.6% (3% - 14%). Using this envelope of uncertainty and comparing it to the projected changes in mean flood levels under climate change of 3.5% - 7.9% would suggest that the potential impacts of climate change are within the bounds of model uncertainty. Similarly, potential impacts of climate change on the average change in AEP flood level ranged between 2.92% - 10.07% and comparing this to the uncertainty envelope would appear to suggest a far more modest increase even in the High emissions scenario. Similar comparisons for the other key parameters such as flood duration would also yield results which appear to dampen the outcome of this study.

Table 1 Summary statistics for model uncertainty within the calibration & validation periods (Uncertainty = [1 – NSE] * 100) Location 2016 - 2018 Calibration Period 2007 - 2018 Validation Period Model uncertainty based on Volume (m3) Blackrock 3.00% 3.00% Caherglassaun 3.00% 2.00% Coole 8.00% 13.00% Coy 11.00% 14.00% Garryland 1.00% 6.00% Mean 5.20% 7.60%

However, the approach taken in this study circumvented the apparent issues outlined above by comparing the modelled past with the modelled future scenarios and by comparing within these model bounds for anomalies. The same model with uncertainty bounds as per Table 1 was used to both simulate the past RCM period (1976 – 2005) and the future time slice 2071 – 2100. By comparing the output from the RCM past and future simulations using the same calibrated model the error or bias within the model itself is accounted for and the anomalies between both periods represents the potential changes due to climate change. Other approaches for climate change modelling with GCM's use bias correction techniques to correct the simulated outputs for the past to correct the future and then utilise the differences between the two corrected datasets. This process can introduce further error given that bias correction for such models is an evolving field. The approach taken in this study has the advantage of eliminating the need for bias correction (which is a recognised method in the literature) and accounts for the karst model uncertainty.

We feel that this approach has in effect filtered out the karst model uncertainty thus the potential effects of climate change as reported in the paper do not need to account for model uncertainty. This approach was described in the paper between lines 198 – 206. The authors will add additional text similar to the above into the amended version of the paper to better explain the issue of the karst model uncertainty.

An overview of the simulations is presented in Table 1. Data from two time-slices, 1976–2005 (the control or past) and 2071–2100, were used for analysis of projected changes in the Irish climate by the end of the 21st-century. It must be noted that the full RCM simulations in fact covered the entire period 1976 – 2100 and these time slices were simply used to make a past versus future comparison (Figure 2 shows results from the full simulation and not just the chosen time slices for this current study). The historical period was compared with the corresponding future period for all simulations within the same RCM-GCM group. This results in future anomalies for each model run; that is, the difference between future and past.

Results & Discussion: A general assessment on how much you trust the model projections is necessary. A comparison of the karst hydrological projections of this model with the hydrological projections of other karst models might be useful for that. Which processes are prediction to become more pronounced by this model and is this in agreement to the projected changes in hydrological behavior of other karst simulation models that were run with climate projections? In relation to uncertainty - see response above under Karst Groundwater Model. The following text can be added: Model uncertainty was compared to other karst models the reported uncertainty of our model (3 -14%) is comparable and within the same window when compared to other reported studies (e.g. Mudarra et. al., 2019, Sofia et. al, 2020)

The following text can be added to address comparison to other karst/climate studies: A study undertaken by Nerantzaki & Nikolaidis (2020) which was similar in nature (i.e use of GCM and RCM data with karst models) and indicated that a reduction of karst spring flow of between 14 - 25% could occur under climate change scenarios (authors used a blended rainfall spectrum from RCP2.6 and RCP8.5). This range is comparable to some of the results observed in this study. Similarly, other studies focused on the impacts of karst aquifer due to climate change utilise GCM/RCM and various emissions scenarios (Pardo-Igúzquiza et al., 2019) but are concerned with impacts to recharge (and spring water availability) and flooding/eco-hydrology are not considered. It is therefore difficult to provide direct comparisons with this current study, however the authors are confident the projections reported in this study are broadly in line with other international studies.

Do the projected karst hydrological changes agree with the conceptual understanding

of the lowland karst? The study catchment has been investigated by the authors for almost 20 years and we have gained valuable insight into how the system responds to various rainfall patterns and intensities. In this regard the outcomes of this study are in line with our conceptual understanding of the lowland karst. Slightly higher intensity rainfall events in the winter when the system is flooded will lead to higher flooding which is slower to drain to the sea. Text to reflect this stance can be added to the final version of the paper if the reviewer feels it is necessary.

The discussion about ecohydrology could be a bit more specific. Which negative specific consequences may occur? Which plants/animals are affected most? Maybe one or two specific examples would help. In parallel to this work there has also been a multi-disciplinary team of ecologists and water quality experts investigating these turloughs, with the results contained in (Irvine et al., 2018 and Waldren et al., 2015). This work has been continued in an ongoing project which has used a combination of more advanced spatial analysis in relation to long term hydrological data (over 298 years) as well as satellite data to define the ecohydrological metrics of relevance to different vegetation habitats. This is the subject of a new paper on ecohydrology which has just been submitted. Unfortunately, we can't provide a reference for this yet as it is still under review, but we will include some examples for specific vegetation communities that are sensitive to changes in the flooding regime. Also, we show some of the plots that have been generated from the recent work to back up the statistics presented (see below). The following text will be added to the Implications for mean and recurrent flood levels and eco-hydrology section from line 346.

The spatial distribution of different vegetation communities in such wetlands is intimately entwined with the hydrological conditions (flood duration, flood depth, time of year of flood recession etc.), which change on a gradient moving up from the base of the turloughs. These ecohydrological relationships have been researched in multidisciplinary studies on these turloughs investigating links between the fluctuating hydrological regime and vegetation habitats, invertebrates, soil properties, land use and water quality (Kimberley et al., 2012; Irvine et al., 2018; Waldren et al., 2015) from which metrics have then be defined for the different key wetland habitats. For example, recent ecohydrological analysis the spatial distribution of vegetation habitats on four turloughs in this karst network (Blackrock, Coy, Garryland and Caherglassaun) over a 28 year period has revealed distinct differences between vegetation communities, from Eleocharis acicularis found at the base of the turlough typically experiencing 6 to 7 months of inundation per year compared to the limestone pavement community at the top fringes of the turloughs only flooded from 1 to 2 months per year. These differences in flood depth and duration are also reflected in a gradient of times across the early growing season (spring) when the communities emerge from the flood waters (and associated changes in air temperature and solar radiation). Other investigations on invertebrates in the turloughs (Porst and Irvine 2009, Porst et al., 2012) have shown that hydroperiod (flood duration) has a significant effect on macroinvertebrate taxon richness, with short hydroperiods supporting low faunal diversity. The study demonstrates how different colonisation cycles occur in response to the seasonal hydrological disturbances.

Figure XX. Annual flood duration spatial profiles for Blackrock turlough over 28-year period.

Figure XX. The statistics of flood duration as a metric across the range of turlough vegetation communities averaged over four turloughs over a 28-yr period.

Figure 4: please enlarge x-/y-axis label font sizes This is complete – see below.

Figure 4. – revised version to be incorporated into the paper.

Line 325: Typo “Figure 5illuminates” This typo has been corrected.

Please also note the supplement to this comment:
https://hess.copernicus.org/preprints/hess-2020-203/hess-2020-203-AC1-supplement.pdf

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