05 - ASSESSING THE VULNERABILITY OF GROUNDWATER FLOODS IN IRELAND TO A CHANGING CLIMATE

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Abstract

Climate change is expected to increase high impact weather events in Ireland, such as prolonged dry periods, heavy rain episodes and extended warm spells, and thus become a major driving force in shaping Ireland's water resources and natural environment in coming decades. It will pose significant risks to water management, exacerbating existing pressures in terms of water supply, quality, flooding and drought. Early detection of these pressures in hydrological regimes is key to informing adaptation strategies and minimizing adverse environmental and societal impacts. In 2020 Geological Survey Ireland (GSI) initiated a new project (GWClimate, 2020-2022), in collaboration with South East Technological University (SETU) to evaluate the impact that climate change may have on Irish groundwater resources. In this study we focused on groundwater flooding, a geohazard prevalent in the limestone lowlands of Ireland that affects many rural communities in Ireland. First, the potential for groundwater flood forecasting was evaluated with the aim of addressing acute groundwater-related issues that can be impacted by climate events. Second, a quantitative approach was developed to assess the impact of climate change to groundwater flooding in Ireland focusing on changes in terms of flood duration, frequency, and seasonality in relation to the reference period (1976-2005). Preliminary results showed significantly worse conditions during Autumn and Winter months with a clear trend towards increase in flood durations and intensity, as well as increase in frequency of the floods. These results help us to improve our understanding on climate change impacts on groundwater floods, improve the reliability of adaptation planning and predictions in the groundwater sector, and tackle the challenges resulting from climate and global change.

1. INTRODUCTION

It is now accepted beyond doubt that anthropogenic greenhouse gas emissions are significantly altering the Earth's climate (IPCC reports, 2013,2021). Globally a rise in average temperature of between 0.3 and 4.8°C is projected by the late 21st century, while IPCC estimates the frequency and proportion of heavy precipitation will likely increase and droughts intensify in the 21st century in many regions (Seneviratne et. al., 2017). In an Irish context, there has been a 0.5°C increase in mean annual air temperature during the period 1981-2010 compared to 1961-1990 (Walsh, 2012). Analysis of high-resolution regional climate simulations shows this trend continuing with a projected increase in annual temperatures of 1.24°C (RCP4.5) and 1.6°C (RCP8.5) by mid-century (O'Sullivan et al., 2016). Studies have also shown that a warming climate will result in an increase in high-impact weather events such as prolonged dry periods, heavy rain episodes and prolonged warm spells (Nolan et al., 2017; O'Sullivan et al., 2016). Climate change will thus be a major driving force in shaping Ireland's water resources and environment in coming decades, exacerbating existing pressures in terms of water supply, quality, flooding, and drought. Early detection of these pressures is key to informing adaptation strategies and minimizing adverse environmental and societal impacts. In order to set out a national strategy for addressing current and future risks posed by a changing climate to groundwater resources, the Department of Communications, Climate Action and Environment, created the National Adaptation Framework (NAF), and in 2020 Geological Survey Ireland (GSI) commenced a new project (GWClimate, 2020-2022), in collaboration to South East Technological University (SETU), to evaluate the impact that climate change may have on Irish groundwater resources, with a particular focus on groundwater floods.

In this study we focused on groundwater flooding in Ireland. Attention on groundwater flooding as a geohazard has increased in recent decades due to an increased frequency of extreme groundwater flood events across Europe (Finch et al., 2004; Naughton et al., 2017; Pinault et al., 2005). In Ireland, the dramatic floods during the winters of 2009/2010 and 2015/2016 caused widespread damage and disruption to communities across the country, particularly in the extensive karstic limestone lowlands on the western seaboard. In these regions, homes were flooded or cut off, roads submerged, and agriculture disrupted, with some affected areas remaining inundated for months after flooding had subsided elsewhere. The introduction of the EU Floods Directive (2007/60/EC), requiring States to consider flooding from groundwater sources, has reinforced the need to improve our understanding of the processes influencing this phenomenon and to assess how groundwater floods will behave in a changing climate scenario to promote adaptation to the upcoming changes. In this study two main areas were considered to promote adaptation to changes in the groundwater flood patterns: 1) capacity to address up to 10 days groundwater flood forecasting, and 2) assessment of long-term challenges (decades) in groundwater floods.

2. STUDY AREA

In Ireland, groundwater flooding is primarily associated with the limestone areas of the western lowlands. The prevalence of groundwater flooding in these regions is mostly due to the purity of the limestones, rendering it to more soluble and susceptible to a high degree of karstification, and to the limestones being well bedded and well jointed, which is important as it provides the initial pathways along which bedrock dissolution can occur and groundwater flow paths develop. Groundwater flow systems in these areas are characterised by high spatial heterogeneity, low storage, high diffusivity, and extensive interactions between groundwater and surface water, which leaves them susceptible to groundwater flooding (Naughton et al., 2018). During intense or prolonged rainfall, the solutionally-enlarged flow paths are unable to drain recharge and available sub-surface storage rapidly reaches capacity. Consequently, surface flooding occurs in low-lying topographic depressions known as turloughs, which represent the principal form of extensive, recurrent groundwater flooding in Ireland (MacDonald, 2010; Naughton et al., 2012). Unlike fluvial flooding where the flood is typically caused by high intensity rainfall, groundwater flooding is primarily driven by cumulative rainfall over a prolonged period. It is this accumulation of water over a period of weeks or months that determines flood severity and duration. Although it rarely poses a risk to life, it commonly causes prolonged damage and disruption because of the relatively long flood duration (Cobby et al., 2009; Morris et al., 2008) and it represents a significant flood hazard for many Irish communities in limestone regions (Naughton et al., 2018, 2017). In addition, potential changes in the behaviours of groundwater floods due to a changing climate are likely to have an impact in the wetland ecosystems that rely on groundwater to sustain habitat structure and function (Bhatnagar et al., 2021; Morrissey et al., 2021). For the purposes of this study, a set of four representative sites (Figure 1) were considered to assess the potential for groundwater flood forecasting and to evaluate the vulnerability of groundwater floods in Ireland to a changing climate. Study sites were chosen to be broadly representative of the continuum of flood behaviour recorded in Irish karst groundwater systems (Naughton et al., 2012). Lough Aleenaun (Site A), lying in the Burren uplands of Co. Clare, shows one of the most dynamic flood regimes recorded in any turlough (Figure 1A) and so represents the fast-response end of the flooding spectrum. Caherglassaun (site B) lies at the lower end of the Gort Lowlands chain of interconnected turloughs and has long been studied due to a sequence of major flood events in the region stretching back to the 1990s (Gill et al., 2013). Ballycar Lough (site C), Co. Clare, over the past 15 years has severely disrupted railway services on the main Limerick-Galway railway line, causing closures of up to 20 weeks. Finally, Ballygalda turlough (site D) is located south of Roscommon town and it was known to flood homes during the 2016 flood events and is characterised as having relatively slow responding flood regime.

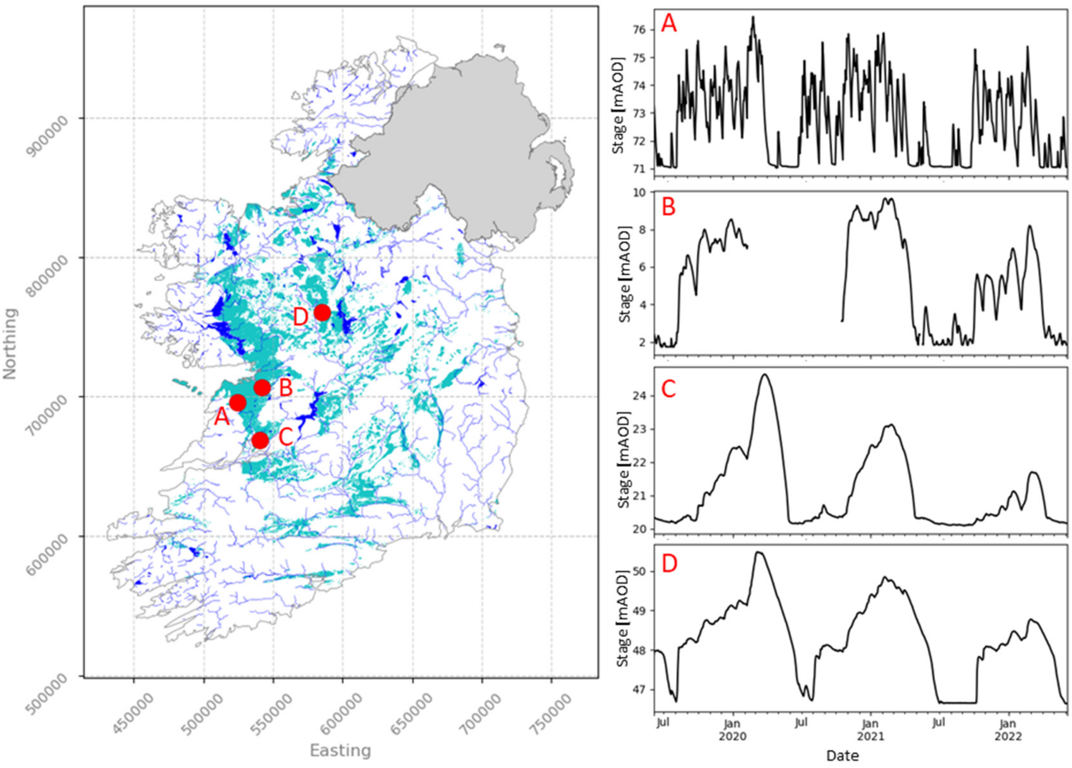


Figure 1: *Left: Location of the representative sites (red dots) on a map of Ireland with the presence of main water bodies and rivers (dark blue) and pure limestone areas (bright blue). Right: Hydrograph of the representative sites measured from gwlevel.ie between June 2019 and June 2022. The representative sites are: A) Lough Aleenaun (lat: 53.0055, lon: -9.1203), B) Caherglassaun (lat: 53.1045, lon: -8.8710), C) Ballycar Lough (lat:52.7623, lon: -9.1203), and D) Ballygalda Turlough (lat: 53.5971, lon: -8.2250).*

The following datasets were considered to evaluate the potential for groundwater flood forecasting and to assess the impacts of a changing climate to groundwater floods: 1) water level time series from the representative sites monitored by Geological Survey Ireland, which data is available at gwlevel.ie, 2) historical precipitation and evapotranspiration time series, and up to 10 days forecast precipitation time series provided by Irish Meteorological Service (Met Éireann, www.met.ie), and 3) climate change projections from five downscaled climate models (MIROC5, MPI-ESM-LR, CNRM-CM5, EC-EARTH, HadGEM2-ES) for RCPs 4.5 and 8.5 provided by the Irish Centre for High-end Computing (ICHECH). UISCEmod hydrological modelling software (Campanyà et al. *in prep.*) was used to assess the potential for groundwater flood forecasting and to assess the impact of climate change in groundwater floods.

3. FORECASTING

The potential for short-term forecasting for groundwater floods was evaluated using historical and forecast meteorological data from Met Éireann, and the associated hydrological models for the representative sites. The accuracy of the hydrological models at reproducing water levels time series was evaluated using Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970). The NSE assess how well the model explains the variance in the observations compared to using the mean of the observations as the prediction for every time-step and it can range from -∞ to 1, where negative values indicates that the modelled time series are worse than the average value, 0 that the modelled time series are as accurate as using the constant average value, and positive values that the modelled time series perform better than the average value, with 1 being the perfect fit. NSE values above 0.85 were obtained for the selected sites for calibration and validation datasets. The forecasting was performed by modelling the water levels up to the last day of the forecast precipitation data. Then the modelled time series were corrected at the start of the forecasting period to match current water levels measured from the monitoring network (gwlevel.ie). Figure 2 shows a conceptual diagram of the approach considered for groundwater flood forecasting. Uncertainties from forecasting precipitation values were defined by comparing 270 forecasts at each site with historic precipitation data during 2021.

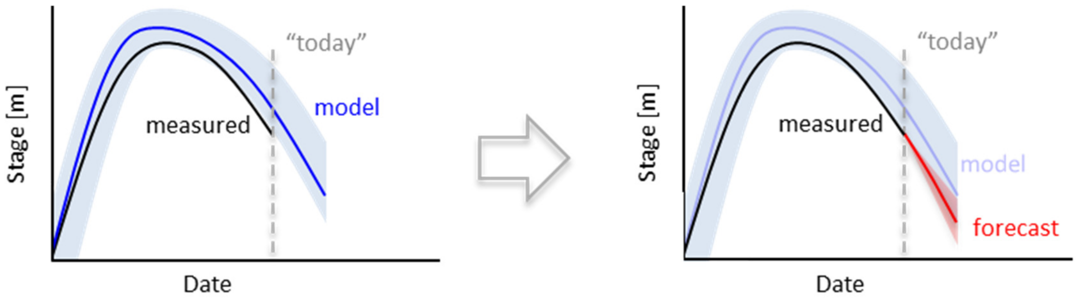
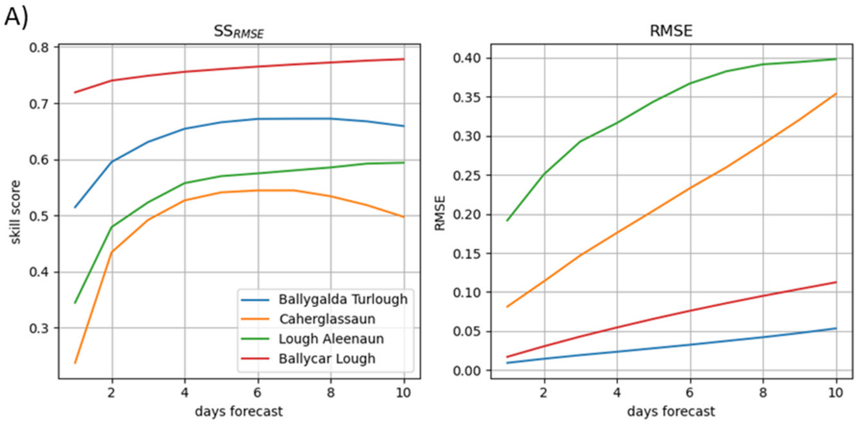


Figure 2: *Conceptual diagram of the approach for short-term groundwater flood forecasting.*

The potential for groundwater flood forecasting was assessed using the skill score metric based on the root mean square errors (SS_{RMSE}) comparing the representative values of the forecast time series, 50th percentile, with the benchmark of assuming that the water levels will remain constant during the forecast window (10 days). SS_{RMSE} below zero indicates that the considered approach for groundwater flood forecasting is less skilful than the benchmark, SS_{RMSE} above zero indicates that the considered approach for groundwater flood forecasting is more skilful than the benchmark, and SS_{RMSE} of 1 that the forecast perfectly reproduces the water levels. Figure 3a shows the SS_{RMSE} and RMSE versus the length of the forecasting for the representative sites considering a period range between September 2019 and September 2022. During the assessment of the potential for groundwater flood forecasting only periods of time associated with floods were considered, thus ignoring data related to dry periods. Figure 3b shows an example of groundwater flood forecasting at Ballycar Lough in February 2020, before the railway level (pink line) was exceeded, and in April 2020 before the flood went below the elevation of the railway.



B) Examples of groundwater flood forecasting at Ballycar Lough

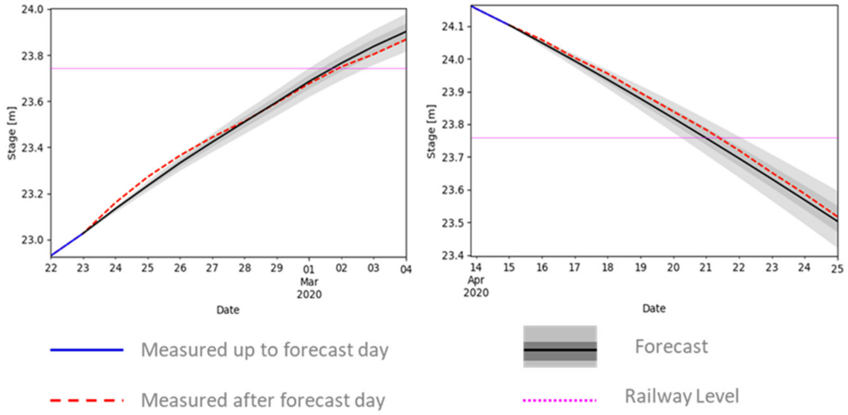


Figure 3: *A)Left: SS_{RMSE} vs length of the forecast for the four representative sites. Right: RMSE vs length of the forecast for the four representative sites. B) Example at forecasting water levels at Ballycar Lough.*

These results suggest that the presented approach has potential for groundwater flood forecasting in Ireland, showing SS_{RMSE} between 0.25 and 0.78 for the analysed sites and length of the forecast. The RMSE values are very dependent on the site and the amplitude of the floods at each site, with sites with larger amplitude of the floods, in terms of stage variability, and shorter memory showing larger RMSE.

It is worth noticing that the forecast depends on the characteristics of the site and that a more extensive study with additional sites will help to corroborate if the presented approach can be applied at a national scale making use of recent advances for monitoring groundwater floods using satellite images (McCormack et al., under review). It is also worth noting that the presented analysis used historical gridded data, assuming that the precipitation up to the day of the forecast is available and accurate for the four analysed sites, which is not the current situation as some sites may be at more than 50 km from nearest synoptic station that could provide real-time precipitation data. In terms of practical applications for groundwater flood forecasting, further studies should be performed assessing the viability of groundwater flood forecasting with current resources highlighting regions where groundwater flood forecasting will benefit from new upgrades in the monitoring system, such as new meteorological stations closest to the location of the groundwater floods.

Finally, given the long duration typically associated with groundwater flooding, future work should focus on estimating the likely persistence of flooding in the medium-term (months) by considering best practices for medium-term groundwater flood forecasting applied national and internationally, and by integrating the sub-seasonal forecasting of precipitation from the Met Éireann into the groundwater flood medium-term estimates.

4. IMPACT OF CHANGING CLIMATE IN GROUNDWATER FLOODS

The assessment of the impact of a changing climate to groundwater floods was performed by considering the RCP4.5 and RCP8.5 scenarios. Recent studies suggest that currently the RCP8.5 scenario, often described as a business-as-usual, is the most likely scenario despite existing mitigation efforts (Schwalm et al., 2020), and that the RCP4.5 is still more ambitious than current nationally determined contributions under the Paris Agreement, according to UNFCCC8. RCP2.6 was not included in this study due to a lower amount of climate models including this scenario and because it is now assumed that these is a very unlikely scenario.

The meteorological data from the five climate models were post-processed for input for hydrological models. In order to include uncertainties from the climate projections, data from 3 × 3 cells around the site of interest were considered (i.e. Wunsch et al., 2022). The 9 selected time series were used to generate 500 time series of precipitation and evapotranspiration data for each site considering the variations between cells. Meteorological time series were then combined with hydrological models to generate 2500 volume time series between 1975 and 2100 for each site, also considering uncertainties from the hydrological models. During the climate analysis we focused on changes in volumes of the groundwater floods as they are representative of the amounts of water within the flood and are not influenced by the topography of the site. Conversion from volume to stage and area time series can be performed using stage-volume and area-volume curves that can be generated from digital terrain models (DTM). In addition, normalized volume time series were considered to facilitate comparison between sites. The normalized volume time series were then used to assess the impact of climate change in the representative groundwater floods looking at changes in: 1) flood duration, percentage of time a certain volume is equalled or exceeded, 2) frequency, percentage of years that a certain volume is equalled or exceeded, and 3) seasonality, changes in volume for different times of the year. Flood duration and seasonality analysis were assessed using the whole time series, while frequency analysis was performed by looking at annual maxima, considering only the maximum volume of the groundwater floods for each year.

The results of the climate change analysis are presented in Figure 4, with the solid lines representing the representative value, 50th percentile, and the shade areas the uncertainties based on the interquartile range, between 25th and 75th percentiles.

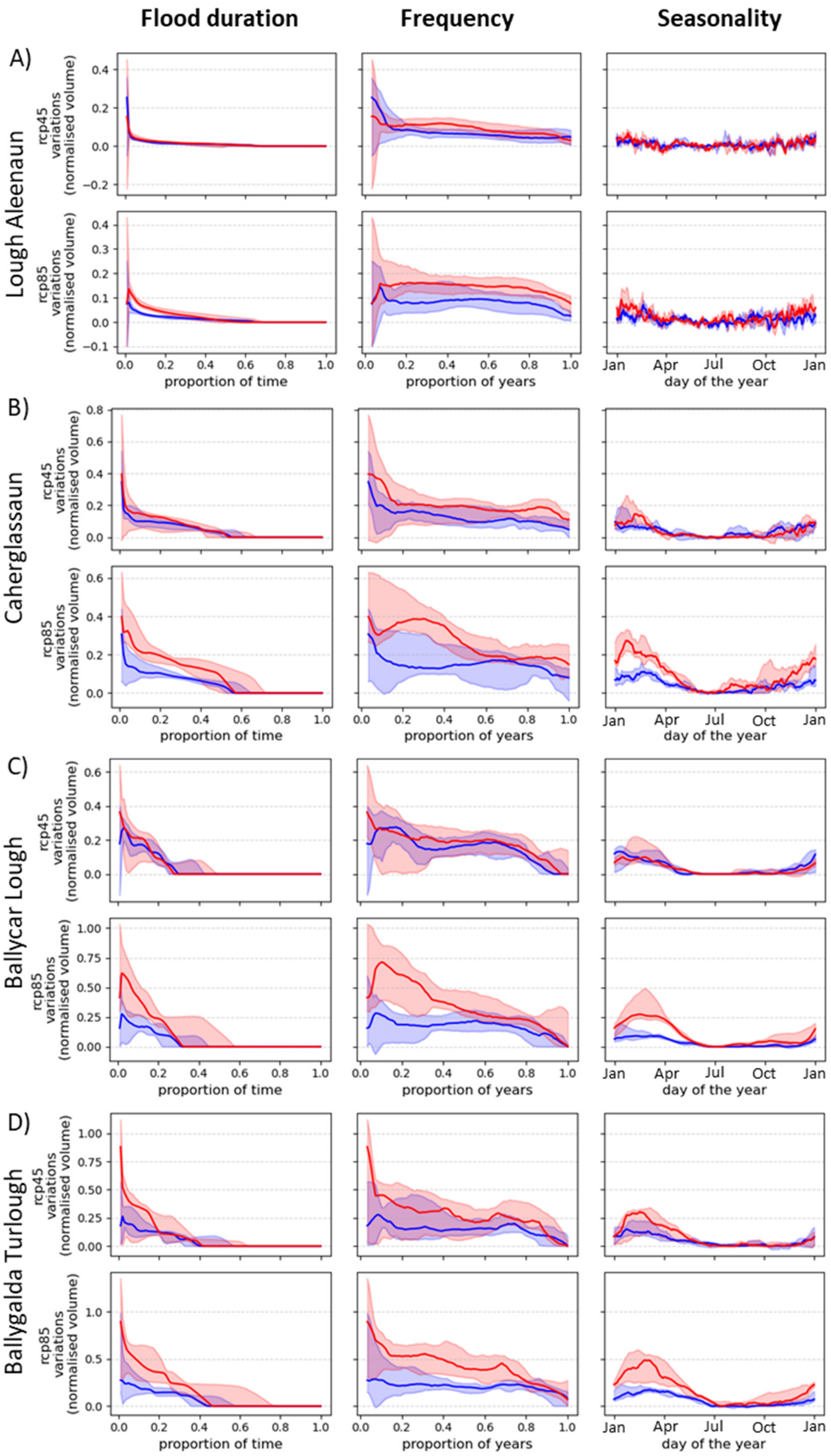


Figure 4: *Variations in flood duration, frequency of the floods and seasonality for the representative sites for RCP45 and RCP85 scenarios looking at changes between the reference period (1976-2005) and mid century (2035-2064, in blue), and between the reference period and the end of the century (2070-2099, in red).*

The results suggest a significant increase in the volumes of the floods, between 10% and 80%, which will also translate in an increase in flood duration and frequency of the floods, with the largest increases observed on extreme flood events. It is also observed that sites with longer memory (i.e. Ballygalda turlough) are likely to be more strongly affected by climate change than sites with shorter memory (i.e. Lough Aleenaun). In terms of changes in seasonality, climate change is likely to have the strongest impact in groundwater floods between December and April, and no significant changes are observed during summer months. In addition, no notorious temporal shift was observed in terms of when the peak of the floods may occur.

The assessment of the vulnerability of groundwater floods in Ireland to a changing climate was presented in terms of changes in the volume time series of the groundwater floods, which facilitate the analysis and comparison between sites. In order of facilitating their practical applications in terms of adaptation, the presented results can be converted to stage and area time series. Figure 5 shows an example at Ballycar Lough assessing changes in the frequency of the floods, which can be relevant in terms of constraining how often the railway, which can currently flood under large flood events, may flood in the upcoming years. The analysis shows that during the reference period (black) the flood was expected to reach the railway level every 12 to 14 years. Under RCP45 scenario, the return period is likely to increase to every 4 to 10 years by mid-century (blue), and to every 3 to 11 years by the end of the century (red) with the representative values suggesting every 4 to 5 years in both cases. Under the RCP85 scenario, the return period is likely to increase to every 4 to 14 years by mid-century and to every 2.8 to 4 years by the end of the century, with the representative values suggesting every 5 and every 3 years, respectively.

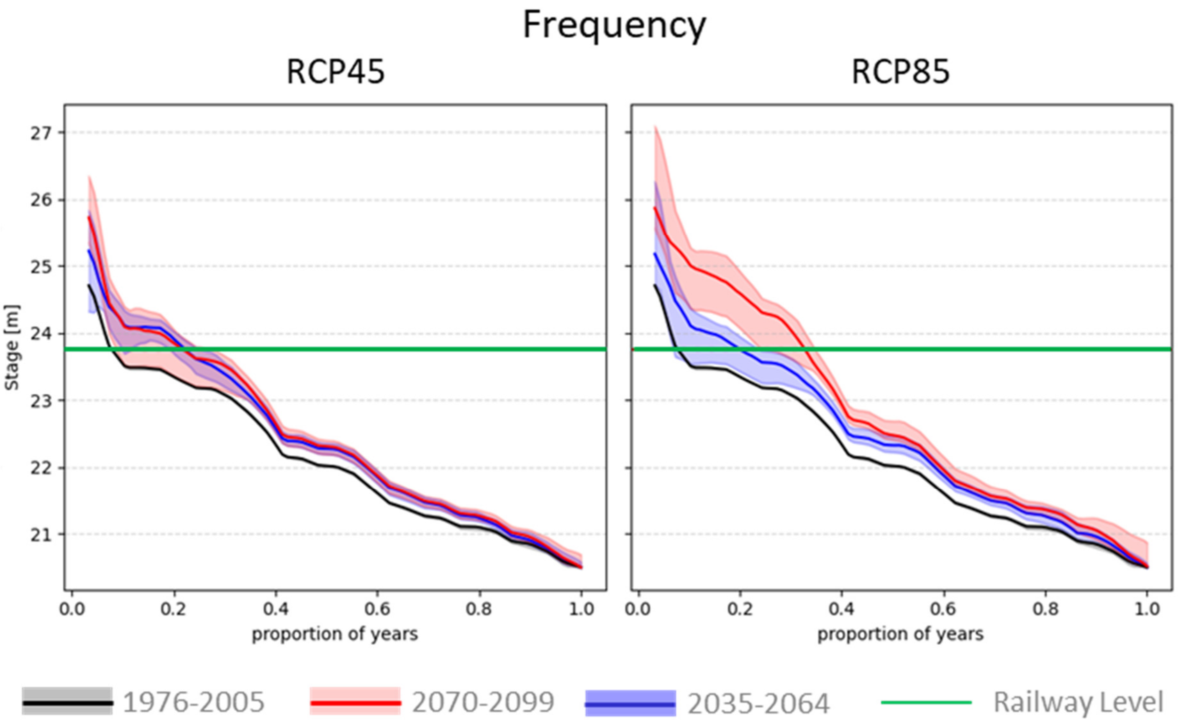


Figure 5: *Frequency plots for Ballycar Lough using stage time series for RCP45 and RCP85 scenarios. Black: reference period (1976-2005). Blue: mid century (2035-2064), Red: end of the century (2070-2099), and green the elevation of the railway.*

5. CONCLUSIONS

The potential for groundwater flood forecasting was evaluated with the aim of addressing acute groundwater-related issues that can be impacted by climate events showing positive results in terms of short-term groundwater flood forecasting (up to 10 days) with SS_{RMSE} values between 0.25 and 0.78 for the analysed sites and length of the forecast. In terms of assessing the impact of a changing climate a quantitative approach was developed to assess the impact of climate change to groundwater flooding in Ireland with results suggesting worsening groundwater flood conditions, in particular for the largest floods and for sites with longer memory. The results for the representative sites suggest increase in terms of flood duration, frequency of the floods and intensity of the floods. In addition, it shows that the impact is expected to be exacerbated between December and April.

The outputs of this study are contributing towards quantifying climate trend analysis and predictions in terms of groundwater floods, which are necessary to provide evidence based to inform relevant national policy-makers, planners and stakeholders of potential climate-related issues and enable the development of pre-emptive mitigation strategies as called for under the All of Government Climate Action Plan to Tackle Climate Breakdown.

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