01 - Climate change impacts on groundwater recharge to Irish fractured-bedrock aquifers

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Abstract

Groundwater recharge rates are affected by geological factors as well as meteorological variables. In the Irish context, there are two main geological features that limit groundwater recharge. Firstly, a significant part of the island is covered by glacial tills, so the permeability and thickness of these subsoils are major controls on the infiltration rates to the underlying bedrock aquifers. Secondly, two-thirds of the country is underlain by aquifers classified as 'Poorly Productive'. In these aquifers, groundwater flow is constrained by the properties of the fracture network, which results in limited groundwater storage and throughput capacity. A recharge assessment methodology previously developed takes into account these characteristics. In the present research, this methodology has been applied to three Irish catchments with different hydrogeological settings to carry out a sensitivity analysis to: (1) assess the possible impacts of climate change, and (2) determine how bedrock properties affect the response of these aquifers to present and future recharge. The sensitivity analysis included meteorological variables such as rainfall quantity, its intensity and seasonality, and also hydrogeological factors such as recharge coefficients and recharge caps. The results to date suggest that the effects of changes in climatic variables will be strongly influenced by the local hydrogeological settings. This would lead to an unequal impact of climate change across the country depending on the local hydrogeology.

1. INTRODUCTION

1.1. Climate change and Ireland

During the last 150 years the earth's global temperatures have experienced a significant increase, with temperature rises being more pronounced in the last half century. Whereas changes in climate were historically linked to tectonic processes, volcanic activity or changes in the incoming solar radiation, the changes experienced in the last century and a half are partly due to anthropogenic activities such as changes in land use and the enhancement of greenhouse gas and aerosol emissions (IPCC 2007). The long-term change in climate patterns due to the combination of these natural and anthropogenic drivers is known as global change.

There have been a number of studies carried out over the past decade which have focused on generating climate trends and projections for Ireland. McElwain and Sweeney (2007) found that the changes experienced by the Irish weather (temperature and precipitation) are consistent with those observed at global scale. Based on the prescribed set of emissions scenarios in the fourth IPCC report, Sweeney *et al*. (2008) generated climate projections for the 21st century in Ireland. In this study several variables were downscaled using a statistical method for different Global Circulation Models (GCMs) and emission scenarios. Ensembles of the downscaled results were then produced to evaluate the different model and emission uncertainties. The projections for temperature show a progressive warming during the last 100 years, leading to an overall predicted increase of between 2.1 and 2.7 ^{0}C by the 2080s. In addition, contrasts between seasons are likely to grow with the highest increases in temperatures predicted during the autumn period when the continental effect is more apparent. With regards to precipitation, the outcomes generally suggest a gradual rise in winter precipitation and a reduction in summer precipitation over the century.

Following a similar line of research, a project coordinated by Met Éireann generated updated simulations for Ireland, using the IPCC AR5 report (2013) as a baseline. The results obtained are similar to those found in the previous Sweeney *et al*. report: mean temperatures are likely to increase by approximately 1.5 ^{0}C by mid-century with respect to the reference period (1981-2000), and the warming is expected to be enhanced by the extremes. Regarding rainfall, winters are expected to be wetter and summers generally drier. Moreover, an increase in the frequency and intensity of rainfall events is predicted (Gleeson *et al*. 2013).

1.2. Groundwater recharge

Groundwater recharge can be defined as the 'the downward flow of water reaching the water table, adding to groundwater storage' (Healy 2010). It can originate from the direct infiltration of precipitation through the unsaturated zone into the water table (diffuse or direct recharge) – this is the main type of recharge in Ireland - or from infiltration of surface runoff via stream beds or swallow holes (localized, point or indirect recharge). In some environments irrigation return flows or leakage of water distribution systems can add significantly to recharge. Finally, recharge can also take place by lateral flow from one groundwater body to another.

Recharge estimations are an essential element of water balance calculations at all scales, and vital for water-resources assessments and groundwater vulnerability studies (Misstear *et al*. 2017). As noted by Risser *et al*. (2005), it is almost impossible to make direct measurements of recharge, so recharge must be approximated using indirect calculations. Due to the intrinsic uncertainty of groundwater recharge calculations, it is strongly advised to apply multiple techniques to estimate it and compare the results (Healy 2010). The selection of the methods to use has a number of implications, and several factors must be taken into account. Thus, the choice of the techniques in each study depends on the conceptual model of the flow system and the accuracy required (Misstear 2000).

1.3. Climate change and groundwater resources

Climate change impact assessment studies have mainly focused on surface water due to its visibility and the clear flooding risks involved. Notwithstanding the importance of groundwater resources in providing water supplies and in sustaining environmental flows, the impacts of climate change on groundwater resources have received much less attention in the scientific literature until relatively recently.

The fourth IPCC report (2007) stated that there had been little research regarding the impacts of climate change on groundwater and the few studies available at that time provided results for very specific areas and conditions. In response to this knowledge gap, there has been an increasing focus on climate change in relation to groundwater in more recent years (Green *et al*. 2011, Crosbie *et al*. 2013, Taylor *et al*. 2013). Holman *et al*. (2012) highlighted that no standardized methodology existed to carry out this type of research, referring to the large number of approaches that are potentially available to evaluate climate change impacts on groundwater. In the same work, a number of recommendations for hydrogeologists to address groundwater-related climate change impact studies were presented. Subsequently, some researchers have considered some of these recommendations in their research projects (e.g: Dams *et al*. 2012, Kidmose *et al*. 2013, Kurylyk and MacQuarrie 2013, Raposo *et al*. 2013).
In the more recent fifth IPCC report (2013) it is clear that the number of studies regarding the impacts of climate change on groundwater has increased significantly since the previous report, even if most of the studies have still been at a local scale. Just a few projects have tried to assess the impacts on a large scale: e.g. Portmann *et al*. (2013), at global scale, and Crosbie *et al*. (2013) at continental scale, in Australia.

The same trend can be observed in Irish studies: whilst there have been several research projects centred on generating climate projections and their impacts on surface water (Charlton *et al*. 2006, Steele-Dunne *et al*. 2008, Sweeney *et al*. 2008, Bastola *et al*. 2012, Gleeson *et al*. 2013), just a few studies have tried to address the impacts on groundwater (e.g. Murphy and Charlton 2006, Sweeney *et al*. 2008). In both these papers changes in catchment storage are analysed by applying a conceptual rainfall-runoff (CRR) model HYSIM in nine selected Irish catchments. This CRR model uses daily rainfall and potential evapotranspiration data to simulate river flow, and it is combined with the generalized likelihood uncertainty estimation (GLUE) method to quantify the uncertainty associated with the overall modelling process. The results are analysed catchment by catchment and, as a general conclusion, it is stated that changes in rainfall and temperature are likely to lead to significant changes in groundwater hydrology. The aim of a paper by Hunter Williams and Lee (2010) was not to quantify the impacts but to assess them qualitatively; Irish aquifer characteristics, national water usage, groundwater recharge and groundwater environmental needs are evaluated with respect to the possible impacts of climate change, including changes in rainfall patterns and groundwater recharge (among others). In summary, the studies that have been carried out in Ireland are fairly general assessments of the possible impacts of climate change on groundwater resources and hence a more detailed quantitative research on this topic is now needed.

1.4. Research Aims

The main aims are to determine how the properties of fractured bedrock aquifers in Ireland influence recharge, and to evaluate the possible impacts of climate change on future groundwater resources. This research is part of a PhD project funded through iCRAG (the Irish Centre for Research in Applied Geosciences), which includes a number of interlinked research projects focused on improving our understanding of groundwater resources and groundwater quality in Ireland.

2. METHODOLOGY

2.1. Approach

This research project is concerned with the hydrogeological and meteorological variables that influence groundwater recharge. As part of this ongoing research, a sensitivity analysis has been carried out for the three selected study catchments presented in Section 2.2 below. For this purpose, the GIS-based tool "Recharge map", described in Hunter Williams *et al*. (2013), has been applied to the study areas. First, the hydrologically-effective rainfall is calculated using a soil moisture budget approach. Then a recharge coefficient is applied which determines the proportion of the hydrologically-effective rainfall that forms potential recharge. The main factors influencing the recharge coefficient are: the hydraulic conductivity (permeability) and thickness of the subsoils; the drainage characteristics of the topsoils; the presence or absence of peat deposits; and the occurrence of karst features such as swallow holes. The potential recharge is then adjusted by taking account of the ability of the aquifer to accept the recharge water; for aquifers regarded as poorly productive (PPAs), the recharge caps of 100 mm/y or 200 mm/y are applied, the cap value being dependent on the particular aquifer category.
The recharge map tool has been used to calculate both the current recharge and to undertake the sensitivity analysis. The sensitivity tests performed include relevant hydrogeological features of the catchments and anticipated changes in rainfall patterns such as intensity and seasonality. In the sensitivity analysis, a variable is modified whilst fixing the other variables, so as to be able to determine how it constrains groundwater recharge. The larger the variation, the greater is the sensitivity to the studied variable.

A literature review was carried out to determine a realistic range of values in which to change both the hydrometeorological and hydrogeological variables. The modifications to recharge caps and coefficients were applied directly in the model parameters. To investigate the effects of the changes in rainfall intensity and seasonality, historical rainfall and potential evapotranspiration (PE) daily series were obtained from Met Éireann for a period of 30 years (1985-2015). These data were used to run a distributed soil moisture budget for the catchment and to estimate actual evapotranspiration (AE). The manipulation of the rainfall series to simulate climate changes has been carried out on a daily basis using the statistical downscaling method decision centric (SDSM-DC) software described by Wilby *et al*. (2002).

2.2 Study areas

Three Irish catchments with contrasting hydrogeological and climate properties were selected for the recharge sensitivity analysis: the Mattock (Co. Louth), Nuenna (Co. Kilkenny) and Dripsey (Co. Cork).

The Mattock and the Dripsey catchments are each underlain by a single aquifer type, where recharge caps of 100 mm/y and 200 mm/y, respectively, are applicable. The Nuenna, on the other hand, is mainly underlain by a regionally important limestone aquifer (where a recharge cap does not apply), whilst a relatively small fraction of this catchment is underlain by a PPA. A summary of the characteristics of the study areas is presented in Table 1.

Table 1*: Summary of the main characteristics of the selected catchments. The annual values presented are the average for the period 1985 to 2015*

	Nuenna	Mattock	Dripsey
Area (km^2)	35	16	82
Location	Co. Kilkenny	Co. Louth	Co.Cork
Underlying Aquifer	Regionally Important/ Poor Aquifer	Poor Aquifer	Locally Important Aquifer
Recharge Caps	Partially. 100 mm/a	100 m/a (all catchment)	200 m/a (all catchment)
Main land use	Pasture	Pasture	Pasture
Vulnerability Category	Extreme to Moderate. Locally low	Extreme to low	Extreme to moderate
Precipitation (mm/y)	1076	970	1227
PET (mm/y)	532	544	514
AE (mm/y)	475	493	465
AE/PET rate	0.89	0.9	0.9
Effective rainfall (mm/y)	600	478	761

3. RESULTS

The influence of hydrogeological properties on groundwater recharge in the Nuenna catchment has been discussed previously in Cantoni *et al*. (2017). This present paper will focus on the results obtained for the sensitivity analysis of hydrometeorological variables, for all three study catchments.

3.1. Rainfall intensity

The modification of the rainfall series has been achieved by preserving the annual totals and altering the percentage of occurrence of rain days. The addition and removal of rain days is done by a stochastic forcing, which is randomly based on the likelihood of events occurring in each month. In this way, wetter months have a greater chance to have a rainy day added and vice versa. The increment of intensity is performed by removing wet days while fixing the annual average, so the intensity of the remaining days needs to be higher in order to preserve the total. Four new precipitation scenarios have been generated: two in which rainfall intensity has been incremented by 10% and 20%, and two more in which the intensity has been reduced by the same percentages. The results suggest that an increase of rainfall intensity would lead to higher annual groundwater recharge (Figure 1).

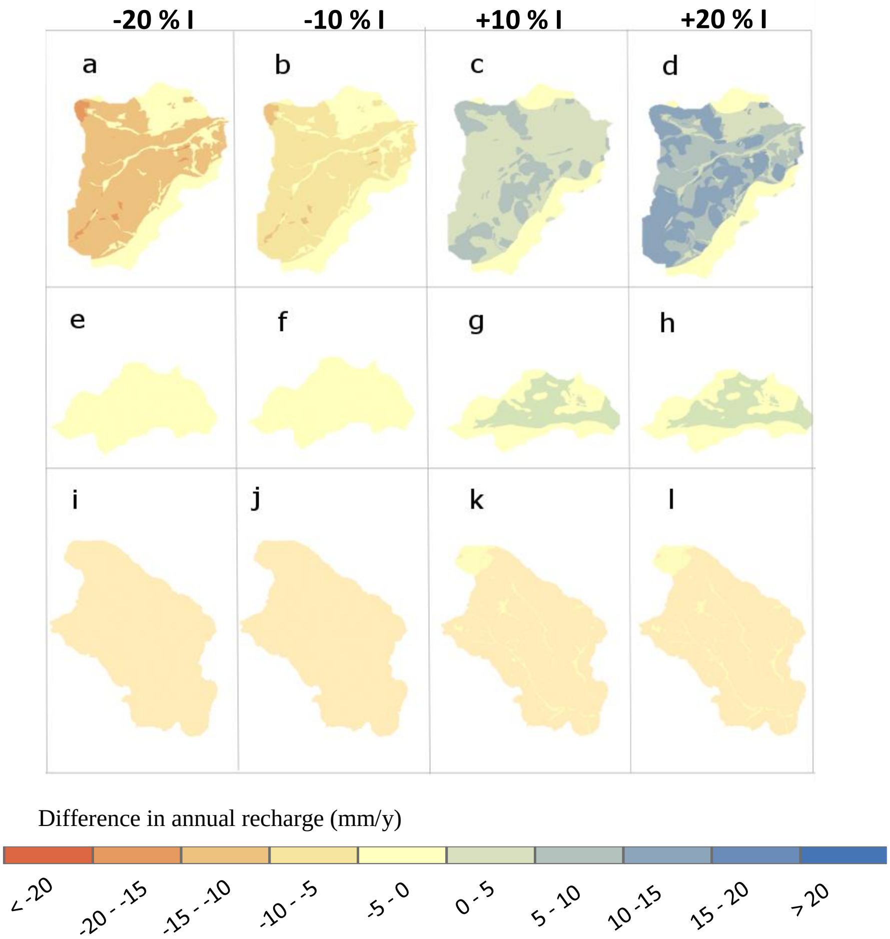

Figure 1: *Recharge scenarios for the Nuenna catchment (a,b,c,d), Mattock (e,f,g,h) and Dripsey (i,j,k,l) under changing rainfall intensities.*

Nevertheless, the effect of the changes of intensity only apparent in those areas that are not affected by recharge caps i.e. areas underlain by aquifers with good storage and throughput capacity, such as regionally important limestone aquifer that occupies the centre of the Nuenna catchment.

3.2. Rainfall seasonality

The alterations to the rainfall seasonality were performed in a similar manner to those presented above for rainfall intensity: by fixing the annual averages, then increasing the number of wet-days for the winter months (December, January and February), and reducing the number in the summer months (June, July and August), by a set percentage in each case.

The results obtained suggest that, similar to rainfall intensity variations, an amplification of rainfall seasonality would lead to an increase of annual recharge due to a significant rise of recharge during winter in the areas not affected by recharge caps. The impacts on the catchments fully underlain by poorly productive aquifers are minimal.

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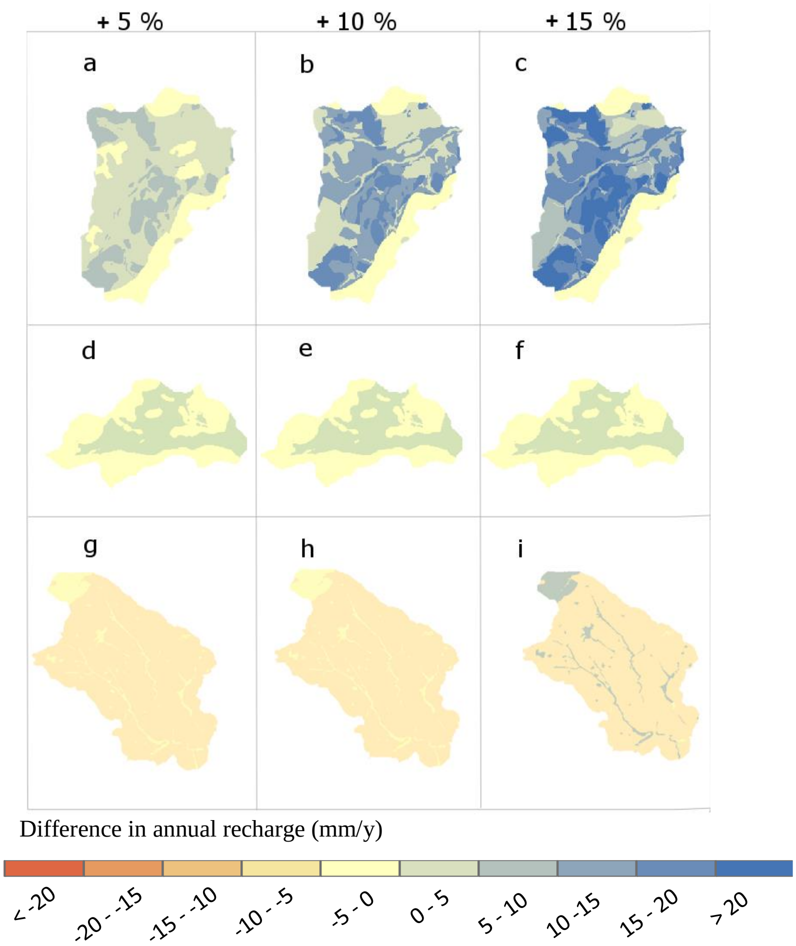

Figure 2: *Recharge scenarios for the Nuenna catchment (a,b,c,), Mattock (d,e,f) and Dripsey (g,h,i) under amplified rainfall seasonality scenarios*

4. CONCLUSIONS

The effect of changes in the hydrogeological and hydrometeorological variables that control groundwater recharge have been investigated in three study catchments. The results of this sensitivity analysis suggest that any increases in rainfall intensity or seasonality would lead to an increase in annual recharge due to a reduction in actual evapotranspiration. Furthermore, the effect of changing rainfall intensity or seasonality is most marked in areas with high recharge coefficients and in aquifers which are not affected by recharge caps.

The impact of changes in rainfall intensity and seasonality on recharge is strongly influenced by the local hydrogeological settings. Climate change will therefore have an unequal impact across the country, owing to the heterogeneous nature of the hydrogeology. These findings are useful for identifying the most sensitive areas, and thus for setting a framework for future work. Ongoing work is focused on characterizing recharge in fractured-bedrock aquifers to improve our understanding of the parameters that limit groundwater recharge within these types of aquifers. The findings will then be used in combination with future climate projections to assess the possible impacts of climate change on Irish groundwater resources.

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