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Towards best practice for assessing the impacts of climate change on groundwater

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1. Introduction

Groundwater is vital to human well being, providing two billion people with drinking water (Morris et al. 2003), supporting$210-$230 billion of annual global output of irrigated agricultural produce (Shah et al. 2000), and controlling the flows of water through the world's biomes (Alley et al. 2002). Given this importance, it is all the more disappointing that the Fourth Report of the Intergovernmental Panel on Climate Change (IPCC) still reports that there “has been very little research on the impact of climate change on groundwater" and that "the few studies of climate impacts on groundwater for various aquifers show very site-specific results" (Kundzewicz et al. 2007).

To contribute to addressing these perceived shortcomings and to maximize future study value, methodological recommendations are provided here for hydrogeologists to consider in groundwater-related climate change impact and adaptation studies.

2. Using climate model projections

Due to their current limitations, whether climate models produce climate projections that are fit for adapting to or managing the future is a matter of debate (Beven 2011). Although other approaches have been suggested (analogue regions, empirical models, projections based on historical responses – e.g. Dickinson et al. 2004), projections from global and regional climate models (GCMs and RCMs) are the default tool for generating future climate projections for input to recharge and hydrogeological models. If this approach is taken, the following are recommended:

Use climate scenarios from multiple GCM or RCMs. Many groundwater impact studies still use outputs from a single GCM or RCM, despite the recognized importance of climate model uncertainty in hydrological studies. Recently, the need for the groundwater community to use outputs from a range of GCMs or RCMs has been reemphasized (Toews and Allen 2009a; Goderniaux et al. 2009; Allen et al. 2010; Crosbie et al. 2011). For example, Jackson et al. (2011) found that the simulated changes in annual potential recharge to a UK Chalk aquifer using 13 GCMs ranged from -26% to +31% by the 2080s, with ten GCMs leading to predicted decreases and three to increases.

Use multiple emissions scenarios. A second major uncertainty in future climate is the emissions of greenhouse gases, which are expressed through the use of emissions scenarios, such as the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart 2000). As these are considered to be equally probable, groundwater impact studies should span the range of emissions scenarios (e.g. Rosenberg et al. 1999; Crosbie et al. 2010) to avoid overly certain and unduly pessimistic/optimistic results.

Consider the implications of the choice of downscaling method(s). GCM or RCM outputs of future climate are generally downscaled (Fowler et al. 2007) because the scales of climate and hydrological models are different and biases exist between simulated and observed climatic variables. The simplest downscaling method is the ‘perturbation’ or ‘delta-change’ method (e.g. Jackson et al. 2011), which implicitly assumes that the future climate is a perturbed version of the present, with weather that has the variability characteristics of the baseline weather but is slightly wetter/drier and warmer/cooler in each month. Many studies suggest however that the future variance within climate parameters will change, such that more complex downscaling techniques which allow the statistical distribution of climatic variables to be adjusted should be preferred (Goderniaux et al. 2009; Kilsby et al. 2007; Mitchell 2003; Salathé 2005). The use of more complex methods however imposes significant additional computational requirements and can contribute additional uncertainty (Stoll et al. 2011; Chen et al. 2011). Holman et al. (2009) suggest that they should be preferred in systems which may be sensitive to changes in the temporal sequencing and persistence of recharge droughts. Given the different assumptions underpinning downscaling techniques, the choice of technique(s) should be guided by the compatibility between these assumptions and the objectives of the project and to the sensitivity of the aquifer.

3. Improved hydrogeological coupling

In order to assess the impact of assumed future conditions (climate, landuse, demographics, adaptation feedbacks, etc.) on groundwater distribution and its quantity and quality, some kind of coupling between these forcings and the hydrogeology needs to be assumed. For example, this may be through empirical models which relate climatic factors to groundwater conditions (Bloomfield et al. 2003) or through the use of physically-based recharge models (e.g. Jyrkama and Sykes 2007; Scibek and Allen 2006; Toews and Allen 2009a) and groundwater flow models (e.g. Goderniaux et al. 2009; Nyenje and Batelaan 2009; Rozell and Wong 2010; Scibek et al. 2007; Toews and Allen 2009b; van Roosmalen et al. 2007). In this respect the recommendations are:

Properly consider hydrogeological model structural error and model uncertainty. All groundwater impact studies are influenced by the validity of their system representation and conceptualisation, so that particular attention must be devoted to properly identifying and representing water entering and leaving the groundwater system through recharge, river-aquifer interactions, pumping and boundaries. When different domains, such as surface and subsurface, are strongly interconnected with important feedbacks, using models integrating all systems should be considered. Model structural (conceptual) error, despite often being the main source of uncertainty in model predictions, is rarely considered (Refsgaard et al. 2006; Rojas et al. 2009). For example, it has been shown that different groundwater recharge models (e.g. soil moisture balance models, 1-D variably saturated flow models, and empirical rainfall-recharge relationships) may give similar long term historic recharge rates but may still respond very differently to changes in intensity of precipitation (Cuthbert and Tindimugaya 2010). When viable model structures cannot be invalidated, ensembles of climate projections should be coupled with ensembles of retained hydrogeological models to produce credible results.

Consider the indirect climate change-induced impacts on recharge. Climate change will affect recharge through indirect changes to evapotranspiration. For example, increased CO_2 can lead to partial closure of stomatal apertures on plant leaves suppressing transpiration (Field et al. 1995) but also to increased leaf area (LAI) which may result in an increase in transpiration and evaporation. The effects of such mechanisms have been detected in continental scale water balances (Gedney et al. 2006) and may produce an effect on global mean runoff that is comparable to that of radiatively forced climate change (Betts et al. 2007). Increased temperatures may also lead to changes in the timing of crop (e.g. emergence, senescence) or vegetation (e.g. bud burst, leaf fall) development. This suggests that recharge models should incorporate plant response to both elevated temperature and atmospheric CO_2 to enable the recharge significance of such physiological changes to be assessed (e.g. Rosenberg et al. 1999; Eckhardt and Ulbrich 2003; Green et al. 2007). Since this effect may be minimal under historic control periods in some parts of the world, this is an important illustration of where model structural uncertainty described above should be accounted for.

Evaluate across as wide as possible a range of groundwater levels and/or climate conditions. Calibration is very often neglected, but is crucial to provide credibility (Hill and Tiedeman, 2007). Simulated climate conditions often predict extremes (such as multi-year droughts) that are outside of the historical baseline climatology (Holman et al. 2009). It is important that impact models be calibrated across as wide a range of historic groundwater levels and/or climate conditions as possible to increase the possibility of model robustness for future conditions, even though it is acknowledged that this is an insufficient test (Beven 1989). Using different kinds of observations (groundwater levels, river flow rates etc.) allows a joint and better constrained calibration of groundwater levels, fluxes and water balance components, and decreases correlation between parameters (Ebel and Loague, 2006; Hill and Tiedeman, 2007). In climate impact studies, physically based models are often preferred to empirical models because they rely on physical parameters which can, in some cases, be measured directly, and may offer more reliability when future climate goes beyond the calibration range. Despite uncertainty analysis receiving increased attention (e.g. Refsgaard et al. 2007) it is still not standard practice in water resources modelling studies (Pappenberger and Beven 2006). The implications of uncertainty in input data and parameters should be quantified (e.g Refsgaard et al. 2007; Hill and Tiedeman, 2007) and compared to other sources, as Goderniaux et al. (2011) showed that it can be more important than that linked to climate models and downscaling.

4. Take account of socio-economic considerations

Just as it is unacceptable to consider that future climate will be identical to today's (Milly et al. 2007), it is also inappropriate to assume that societal, political and economic conditions will remain unchanged into the future. To focus on the direct (temperature and precipitation) impacts of climate change is to neglect the potentially important role of future policy, societal values and economic processes in shaping the landscape above aquifers (Holman 2006) and groundwater demand, including the feedback due to adaptation. The following are recommended:

Consider socio-economic change, in particular its effect on landuse change and water demand. Rural land use is a consequence of socio-economic elements which affect the relative profitability of crops, livestock or trees either directly (e.g. subsidies, prices) or indirectly (labour, input prices, etc.) (Audsley et al. 2008; Rounsevell et al. 2003). Whilst the direct impacts of climate on simulated recharge are generally most important, socio-economic factors do produce regional changes in recharge, which can locally be highly significant, especially where there are major land use changes (Holman 2006; van Roosmalen et al. 2009), or changes to the spatiotemporal distribution of groundwater abstraction. Future groundwater demand will also not solely be a function of climate. Irrigation demand will be affected by future crop areas, water pricing and abstraction licensing (Henriques et al. 2008; Zhou et al. 2010; Holman and Trawick 2011). Environment Agency (2001) suggested that future domestic water demand in the UK may change by between -28 and +33% between 1997 and 2025 depending on the socio-economic assumptions.

Consider the efficacy of adaptation responses. The representation of adaptation within modelling is a key uncertainty in understanding the likely impacts of climate change and other environmental changes (Adger et al. 2007). This arises as adaptations involve people, at local to national governmental levels (Holman and Trawick 2011), but it is commonly assumed that adaptation is immediate and effective. Groundwater adaptation studies need to consider: (1) the triggers or critical impacts which necessitate adaptation (i.e. the cause of adaptation); (2) the time-lags involved in a measure being implemented through policy and taken-up by users; (3) the extent to which a measure might be taken up (which is especially important for non-mandatory policy measures); and (4) the effectiveness of the measure in reducing impacts.

Consider adaptation within robust decision making paradigms. Given the many and significant spatio-temporal uncertainties in future impacts on groundwater discussed above, specifying adaptation responses which rely on a strong ability to predict future risks or to foresee the eventual outcomes of decisions is an inappropriate paradigm (Lempert and Collins 2007)- uncertain information is more useful than a wrong certainty (Blöschl & Montanari, 2011). Instead, groundwater management responses should be considered within alternative frameworks, such as robust decision-making and adaptive planning (e.g. Gleeson et al. 2011; Holman and Trawick 2011) or precautionary cost-benefit (Beven, 2011).

5. Concluding remarks

Given the vital importance of groundwater to human wellbeing and ecosystems, improved understanding of groundwater system behaviour in uncertain futures is required (Green et al. 2011). Whilst it is recognised that many of the recommendations outlined in this essay have time and computational costs, their appropriate implementation within the scope of a given study will afford a fuller appreciation of assessment uncertainty and an improved representation of adaptation responses. Such an holistic view will afford exciting opportunities for hydrogeologists to work more closely with a range of other disciplines including climate modelers, socio-economists, agricultural modellers and soil scientists.

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