CHANGING PRECIPITATION SCENARIOS: PRELIMINARY IMPLICATIONS FOR GROUNDWATER FLOW SYSTEMS AND PLANNING

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ABSTRACT

Statistical downscaling of a suite of three global climate models for two emission scenarios are used to produce precipitation scenarios for Ireland to 2090. One of these was used to drive a rainfall-runoff model for the River Boyne. The model was calibrated over the 1961-90 base period, validated using 1991-2000 data and run for three future time periods using downscaled GCM output. Significant changes in monthly flow regimes, soil moisture storage and groundwater storage were noted, with summer flows typically reduced by 20%. Negative changes in soil moisture storage also resulted, with soil moisture deficits increasingly extending into the Autumn as the century proceeds. Such a situation is seen to potentially compromise groundwater recharge in individual years and an increasing lag in groundwater recharge was detected. By the 2080s the groundwater recharge lag has developed to the extent that spring and early summer surface flows appear to be still benefiting from winter groundwater recharge while by late autumn groundwater is seriously depleted due to drier summer conditions. Serious implications for water yield from groundwater-fed sources would thus arise in the event of a dry winter being experienced. Greater conservatism in estimating water yields from groundwater sources would seem appropriate and may require to be formally incorporated into planning procedures.

1.0 INTRODUCTION

Although much of the concerns globally relating to future climate change focus on warming aspects, it is probable that the major impacts, as far as Ireland is concerned, will relate to precipitation changes. These are likely to have far-reaching implications in a range of sectors for which forward planning is required and a pressing strategic research objective exists in seeking to quantify the probable spatial and temporal precipitation changes likely to be experienced in coming decades. Indeed significant changes appear to be already underway; with marked winter increases observed in north western parts during the past century and marked summer decreases occurring in the south-east (Sweeney *et al*, 2002). Significant change points in Irish precipitation climatology have also been identified in the mid 1970s (Mills, 2001; Kiely, 1999) though these may at least partly relate to circulation frequency changes associated with the North Atlantic Oscillation. In any event it is clear that precipitation changes may have large and diverse consequences for water management and supply and this paper seeks to examine the consequences of these particularly for groundwater systems.

2.0 THE PRODUCTION OF PRECIPITATION SCENARIOS

The relatively coarse resolution (typically grid sizes >2.5^{o}) of Global Climate Model (GCM) output limits their utility for assessing the impacts of climate change, many of which require analysis at sub grid scale. Obtaining regional scenarios involves translating the GCM output to finer spatial scales, a technique known as downscaling. One of the most widespread approaches has been the incorporation of mesoscale predictor variables in an empirical statistical technique that establishes linkages between the GCM output and surface observations. This statistical downscaling technique is based on the assumption that GCMs simulate mesoscale aspects of climate better than surface variables such as temperature and pressure. The method involves firstly establishing relationships between conservatively changing upper air variables, such as geopotential temperatures and heights and local surface observations. Over a training period, the relationship between these sets of variables is established and assumed to be robust in a changing climate situation. Since the same mesoscale variables also are outputs of the GCM, the local surface variables in a changed climate situation may then be estimated via a transfer function. Downscaling is done for individual point locations both for the baseline and future runs of the model and the differences are applied to the observational data to provide a climate change scenario.

Previous downscaling work has indicated that substantial precipitation changes may occur in Ireland by mid century (Sweeney and Fealy, 2003). Overall increases in precipitation were projected for the winter months with up to 20% more rain in the northwest. In contrast, marked decreases during the summer months across eastern and central Ireland amounting to between 25-40% of present values were projected. It must be stressed that precipitation scenarios are inherently less reliable than temperature given the spatial variability of precipitation itself and the many uncertainties of GCMs in this area and in this case were based on output from a single Global Climate Model (Hadley CM3). To address this a suite of three GCMs has been employed in current work: the Canadian Climate model (CGCM2), the Australian Climate model (CSIRO) and the UK Met Office model (HADCM3) in combination with two emission scenarios A2 and B2. The former is a high emission scenario while the latter is indicative of a less carbon intensive world. Differences are apparent between the models in terms of seasonal precipitation projections for Irish stations. The current work examines 10 different catchments (Table 1) though for this paper, given the preliminary nature of results, only the HadCM3 A2 output was employed and results are presented only for the Boyne catchment.

Catchment	Area (Km^2)	Gauge	Data (days)	Mean Rainfall (mm)	Mean ET (mm)	Mean Discharge (cumecs)	Land use	Soil Texture
Suir	*3556.00*	*Clonmel*	*14610*	*2.7*	*1.27*	*48.2*	*Pasture*	*Loam*
Blackwater	*3245.70*	*Ballyduff*	*14610*	*3.1*	*1.5*	*62.3*	*Pasture*	*Loam*
Boyne	*2670.50*	*Slane*	*14610*	*2.4*	*1.22*	*35.4*	*Pasture*	*Loam*
Moy	*1980.87*	*Rahans*	*9862*	*3.9*	*1.22*	*57.9*	*Peat Bogs*	*Loam*
Barrow	*2956.00*	*Levitstown*	*11688*	*2.5*	*1.27*	*20.9*	*Pasture*	*Sandy Loam*
Brosna	*1082.50*	*Ferbane*	*14610*	*2.4*	*1.22*	*17.1*	*Pasture*	*Loam*
Inny	*1072.50*	*Ballymahon*	*10227*	*2.6*	*1.22*	*18.7*	*Pasture*	*Loam*
Suck	*1050.00*	*Bellagill*	*9498*	*2.8*	*1.22*	*25.2*	*Pasture*	*Loam*
Bonet	*371.57*	*Dromahair*	*14516*	*3.3*	*1.2*	*11.2*	*Natural*	*Clay Loam*
Ryewater	*213.90*	*Leixlip*	*14610*	*2.2*	*1.5*	*2.3*	*Pasture*	*Clay Loam*

Table 1:Catchments studied and their location

3.0 THE RAINFALL-RUNOFF MODEL

The rainfall-runoff model employed is HYSIM (Manley, 1993). This is a conceptual rainfall-runoff model, which uses rainfall and potential evaporation data to simulate river flow using parameters for hydrology and hydraulics that define the river basin and channels in a realistic way. Although spatially lumped and hydrologically conceptual in nature, the model contains a number of parameters that can be measured from physical reality. The model is built around two sub-routines; the first of these simulates catchment hydrology while the second simulates channel hydraulics. The complete flow diagram of the structure of the model is given in Figure 1. In relation to the hydrology routine seven natural stores are represented. These include snow storage, interception storage, from which evaporation takes place at the potential rate, the upper soil horizon, the lower soil horizon, transitional groundwater, groundwater and minor channel storage.

To gain an insight into the functioning of the model it is beneficial to take a more in-depth look at how these stores function and interact. Given the small amount of snowfall recorded in Ireland this store is not utilised. Interception storage represents the storage of moisture by the vegetation canopy. Evaporation accounts for losses from this store. Any moisture in excess of storage, determined by vegetation type, is passed on to the upper soil horizon. The upper soil horizon represents the moisture held in the upper (A) horizon or topsoil and has a finite storage capacity equal to the depth of the A horizon multiplied by its porosity. A limit on the rate at which moisture can enter the upper soil store is applied based on its potential infiltration rate. Losses are met by evaporation, interflow and percolation to the lower soil horizon. Evaporation is controlled by the forces of capillary suction, while interflow is a function of the effective horizontal permeability of the soil layer. The lower soil horizon represents moisture below the upper horizon but still within the rooting depth of vegetation. Again evaporation and interflow account for losses from this store as well as percolation to groundwater.

The transitional groundwater store is an infinite linear reservoir, which serves to represent the first stage of groundwater storage. This store has greatest importance in catchments with permeable geologies where many of the fissures and fractures holding moisture may interact with the stream channel rather than with deeper groundwater. Losses from this store are controlled by a discharge coefficient and by the proportion of the moisture leaving storage that enters the river channel. Groundwater is also represented as an infinite linear reservoir, assumed to have a constant discharge coefficient. Groundwater parameters include the groundwater recession rate, the proportion of the catchment with no groundwater, transitional recession, the proportion of the recession that is transitional and the ratio of groundwater to surface catchment. The most sensitive of the groundwater parameters is the groundwater recession rate, computed from observed flow by studying periods in a dry summer when little or no rain has fallen. The ratio of groundwater to surface catchment also shows a high sensitivity, its value being derived from the geological survey of Ireland's Aquifer map (GSI, 2003). The final conceptual store represented by HYSIM is minor channel storage. This component represents the routing of flows in minor streams and ditches.

4.0 MODEL CALIBRATION AND VALIDATION

Before running the model with the downscaled data, HYSIM was calibrated and validated on observed records. Daily precipitation and PE data were obtained from Met Éireann for a baseline period of forty years (1961-2000). Daily streamflow data for this period were obtained from the Office of Public Works (OPW). A split sample procedure was adopted for calibration and validation. The first thirty years of the baseline data set (1961-90) were used for calibration so that the model could be trained on as much variability in streamflow as possible. Validation was conducted for the period 1991-2000. This decade has been the warmest globally, with 1998 being the warmest year in the global instrumental record while in Ireland the warmest year was recorded in 1997. Furthermore, the ten years 1991-2000 have presented some of the largest flood peaks on record in Ireland, such as the November 2000 floods and thus provide a good test of model performance, with conditions being more akin to those expected under climate change than at any other period in the baseline data set.

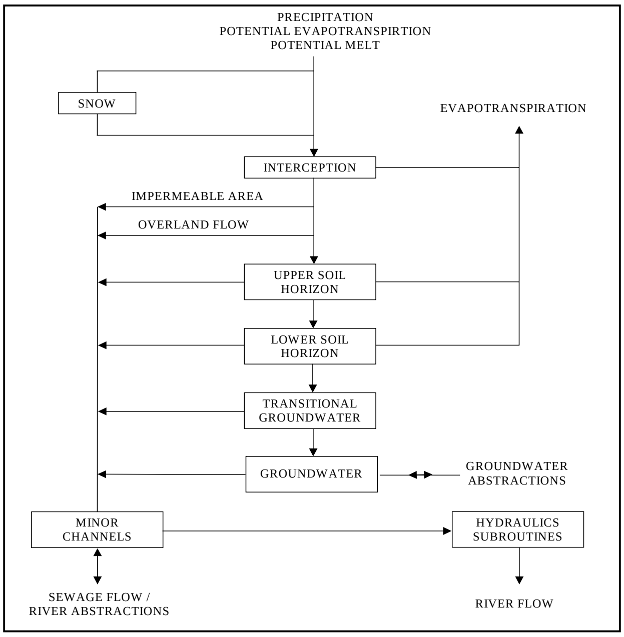

Figure 1: Hysim model structure

When assessing the impacts of climate change on water resources there is a cascade of uncertainty that begins when future socio-economic storylines are converted to future emissions scenarios and ends in impact modelling (Wilby, in press). While an analysis of uncertainty is beyond the scope of this paper, conceptual rainfall-runoff models are subject to a number of simplifications that give rise to uncertainty (e.g. Parameter uncertainty). In order to take account of this uncertainty one hundred parameter sets were generated for each catchment during the calibration period with each of these being validated for the 1990s.

In order to determine the degree of accuracy obtained during calibration and validation two 'goodness-of-fit' measures were employed, the Nash-Sutcliffe Efficiency Criterion (NS) and the Percent Bias (PBIAS). In terms of the entire calibration period results ranged from 0.73 to 0.86 for NS, with a value of 1 being indicative of a perfect fit, and from -1.81 to -1.11% in terms of PBIAS. Validation results ranged from 0.70 to 0.85 for NS while results ranging from 1.65 to 3.01 were obtained for PBIAS. Given that the validation period provides the closest surrogate possible for future conditions, the results achieved give increased confidence to the transference of parameter sets from current to changed climate conditions. However, there is the caveat that land use and soil textural characteristics will remain the same under a changed climate.

5.0 FUTURE SIMULATIONS

By forcing the rainfall-runoff model with the downscaled output from each GCM, simulations were produced for three future time periods (2020s, 2050s and 2080s). HYSIM was used to assess changes in streamflow as well as in upper soil, lower soil, transitional and groundwater storage. The remainder of this paper presents the output from HYSIM for each of theses time slices using downscaled data from the HADCM3 A2 scenario. The output for each time slice is compared with GCM control conditions (illustrative of the 1961-1990 period) and the percent change is calculated. The results shown represent the average response once uncertainty is taken into account. Seasons are classified as Winter (DJF), Spring (MAM), Summer (JJA) and Autumn (SON).

5.1 Changes in monthly flow regimes

Within the Boyne catchment monthly flow regimes tend to follow the general patterns of change in precipitation (Figure 2) with a lag of approximately two months. Evidence for this lag is also present between recorded precipitation and streamflow, indicating that the model represents catchment storage quite well (Figure 2). By 2020 the river Boyne experiences a decrease in streamflow for all months with a maximum decrease of approximately 20% in the late Summer and early Autumn. By 2050 there is an increase in winter streamflow corresponding to the increasing rainfall suggested for this period. Reductions in monthly average streamflow are evident for the summer and early autumn months. This trend continues into the 2080s with further increases in winter streamflow, especially in the months of February and March with increases of up to 45%. This increase in winter precipitation is seen to increase and sustain streamflow for the Spring months where-after there is rapid drying and reductions of up to 20% in streamflow for the summer and the majority of the Autumn period. The continued reduction in autumn streamflow demonstrates that low flow conditions may extend later in the year than currently experienced.

5.2 Changes in Soil Storage

The amount of water stored in the soil is fundamentally important to agriculture and has an influence on the rate of actual evaporation, groundwater recharge, and the generation of runoff (IPCC, 2001). Gregory *et al.* (1997) show with the HadCM2 GCM that a rise in greenhouse gas (GHG) concentrations is associated with reduced soil moisture in Northern Hemisphere mid-latitude summers. The local effects of climate change on soil moisture, however, will vary not only with the degree of climate change but also with soil characteristics. The water-holding capacity of soil will affect possible changes in soil moisture deficits; the lower the capacity, the greater the sensitivity to climate change (IPCC, 2001). Both soil horizons within the Boyne catchment are characterised as having a loamy texture; classed as an "intermediate" soil between sands and clays, composed of many different sized soil particles that combine fertility and moisture-holding capacity with good drainage (Gardiner and Radford, 1980). In terms of the upper soil there is a decrease in storage for almost every month by the 2020s, the greatest decrease again being in late summer and autumn (Figure 2). This trend is continued for the 2050s but with greater reductions extending into spring as a result of decreases in precipitation. By 2080 the largest changes are seen in the summer months with reductions of 30% in the month of August. Again reductions are shown to extended into the autumn months. Over the range of time slices considered changes in upper soil storage are consistently negative, even in winter months for the 2080s where an increase in precipitation is evident. This may be due to the fact that effective rainfall is compensating in other stores. Such reductions may have large consequences for vegetation and agriculture.

The response of lower soil storage (Figure 3) is similar to upper soil storage. By the 2020s all months show a reduction of up to 6%. By the 2050s slight increases are evident for the Winter months but the extent of the decrease is greater for the remainder of the year. The 2080s show a continued exaggeration of this trend with continued decreases being experienced during the Summer and Autumn and continuing right into the Winter. Greatest decreases, in the order of 20% are evident for the months August, September and October. Under present conditions this part of the year is important for recharge purposes and significant reductions here could have a knock on effect on storage in other months. There is a degree of uncertainty associated with future simulations of soil storage as climate change also may affect soil characteristics, perhaps through changes in water logging or cracking, which in turn are likely to affect soil moisture storage properties. Furthermore, changes in land use may alter the amount of evapotranspiration accounting for losses from this store.

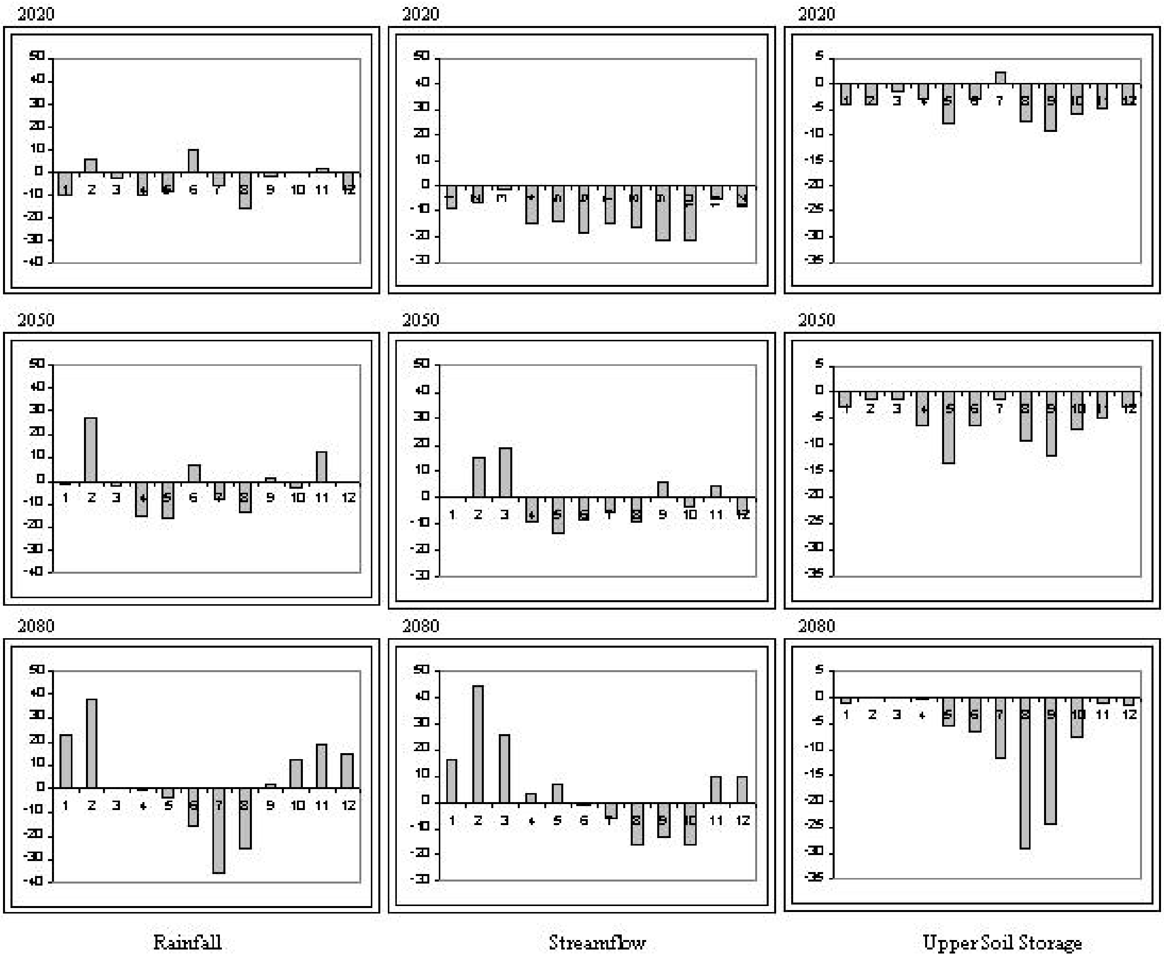

Figure 2: Percent change in monthly rainfall (left), streamflow (centre) and upper soil storage (right) for each future time slice.

5.3 Changes in Groundwater Storage

Groundwater storage is an important natural resource with about 20-25% of freshwater supplies in Ireland being derived from this source (Daly & Warren, 1998). However, relatively little research has been conducted on the effects of climate change on groundwater supplies. Increased winter rainfall—as projected under most scenarios for mid-latitudes—is likely to result in increased groundwater recharge (IPCC, 2001). However, as has been shown for the Boyne, soil moisture deficits tend to commence earlier in Spring and persist later into the Autumn, thus having the potential of offsetting the amount of effective rainfall available for groundwater recharge. Such changes are also capable of altering the timing and duration of the recharge period. As with changes in soil storage, changes in groundwater storage due to anthropogenic climate change for a particular catchment are largely dependent on individual catchment characteristics and the type of aquifer under consideration. The Boyne catchment is predominantly underlain with impure limestones interspersed with sandstones, shales and undifferentiated sedimentary strata (EPA, 2004). There are few regionally important aquifers within the Boyne catchment due to the unbedded nature of the underlying limestone. However a large proportion of the catchment is underlain with locally important aquifers (approximately 67%)

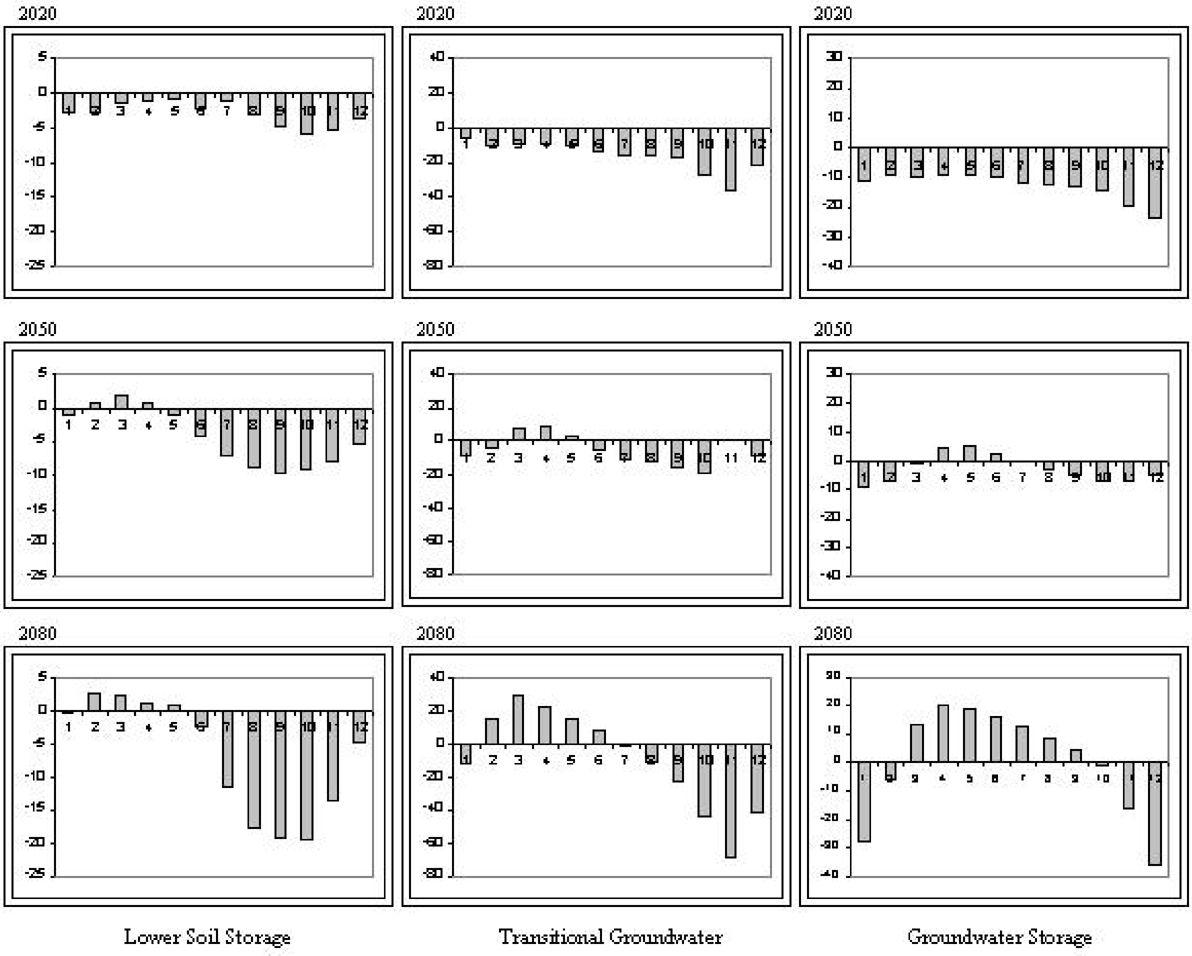

Figure 3: Percent change in monthly lower soil storage (left), transitional groundwater storage (centre) and groundwater storage (left) for each future time slice

Known locally important sand and gravel aquifers of glacial origin within the catchment have been shown to have a rather low transmissivity (EPA, 2004). The transitional groundwater store serves to represent the first stage of groundwater storage. By the 2020s there is a reduction in transitional groundwater storage in all months, largest in the autumn with reductions of up to 40% in November (Figure 3). These reductions are reduced by 2050 due to short-term increases in summer and autumn precipitation. Slight increases in storage are also evident during the spring. This increasing trend in Spring storage is extended to the 2080s with increases in storage developing into the early Summer. However, most evident by the 2080s are the large reductions in transitional groundwater storage during the late summer, autumn and winter seasons. Indeed, it is the winter decrease in storage that is most prominent, with a reduction of over 70% in November. This decrease in winter storage exists even though increases in precipitation of up to 20% and 30% are projected for autumn and winter respectively by the 2080s. This again highlights the potential that changes in the timing, duration and extent of soil moisture deficits can have in offsetting the amount of effective rainfall available for groundwater recharge.

Groundwater storage is seen to reduce in all months by the 2020s with the largest decreases coming in autumn and winter, as stores are not being recharged (Figure 3). The greatest reduction is shown for December with a decrease of approximately 24% from current levels. This decrease is reduced by the 2050s, again due to the short-term increase in summer and autumn precipitation while April, May and June begin to see increases in groundwater storage. By the 2080s dramatic changes in groundwater storage become evident. Increases of up to 20% are evident for spring months while summer and early autumn also experience an increase, although this increase diminishes over time. The largest reductions in groundwater storage are evident in November as well as throughout the Winter period with decreases of as much as 35% in December groundwater storage. When changes in groundwater storage for the 2080s are compared with the percent change in rainfall for the same period a distinct lag is evident. It would seem that increases in precipitation during the autumn do not replenish groundwater stocks until spring. This may be due to the combination of increased deficits in soil storage offsetting increases in effective rainfall, as well as the poor transmissivity of the sand and gravel aquifers. On the other hand, increases in winter precipitation tend to supplement groundwater storage throughout the spring and summer. This characteristic is also evident in streamflow during the summer months where baseflow is critical in sustaining discharge.

6.0 CONCLUSION

Changes in Irish climate as a result of anthropogenic climate change are likely to have a significant impact on water resources. Such impacts have the potential to alter each element within the catchment water balance. Impact assessments are subject to uncertainty derived from emission scenario, Global Climate Model (GCM), downscaling technique as well as uncertainties derived from the impact model employed. This work uses statistically downscaled data from three GCMs using two emission scenarios. Rainfall-runoff model uncertainty is catered for and the presented results are based on the average changes. Given the preliminary nature of this work only output from one GCM using the A2 medium-high emission scenario for one catchment is presented. From this analysis it is evident that increases of precipitation in autumn and winter will be critical in sustaining water resources in the Boyne Catchment. The failure of precipitation in these months may mean that important stores are not replenished resulting in an increased risk of drought throughout the summer months.

7.0 ACKNOWLEDGEMENTS

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