

Robust adaptation assessment–climate change and water supply

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Abstract

Purpose – This research aims to develop a framework to assist the identification of robust adaptation options that account for uncertainty in future climate change impacts for the water sector.

Design/Methodology/Approach – The Water Evaluation and Planning tool (WEAP), is to identify future water resource vulnerability in the Glone sub-catchment within the Moy catchment in the West of Ireland. Where water stress is evident, a detailed hydrological modelling approach is developed to enable an assessment of the robustness to uncertainty of future adaptation decisions. WEAP is coupled with a rainfall runoff model (HYSIM), and forced using climate scenarios, statistically downscaled from three Global Climate Models to account for the key sources of uncertainty. While hydrological models are widely applied, they are subject to uncertainties derived from model structure and the parameterisation of the catchment. Here, random sampling of key parameters is employed to incorporate uncertainty from the hydrological modelling process. Behavioural parameter sets are used to generate multiple future streamflow series to determine the bounds within future hydrological regimes may lie and the ranges within which future adaptation policy pathways need to function.

Findings – This framework allows the identification of adaptation options that are robust to uncertainty in future simulations.

Research limitations/implications – Future research will focus on the development of more site-specific adaptation options including soft and hard adaptation strategies. This approach will be applied to multiple water resource regions within Ireland.

Originality/Value – A robust adaptation assessment decreases the risk of expensive and/or mal-adaptations in a critical sector for society, the economy and the aquatic environment.

Key words Climate Change, Water Supply, Uncertainty, Robustness, Adaptation Options, Water-Stress-Index.

Paper Type Research Paper

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Introduction

Following the Intergovernmental Panel on Climate Change's (IPCC) latest assessment of "Climate Change and Water", the warming observed over the past several decades is consistently associated with changes in a number of components of the hydrological cycle (Bates *et al.*, 2008). Subsequently, climate change has the potential to alter river flow regimes and water resources considerably. The consequences of climate change will be added onto the weather variations that occur from year to year and onto inter-decadal climatic variations (Arnell, 2003). Hence, the traditional approach of the past being the key to the future in water resource planning and management will no longer be applicable, as historical streamflows and groundwater recharge rates are likely to be altered.

For Ireland, previous studies on the impacts of climate change on catchment hydrology consistently indicate increasing river flows during winter and spring, as well as reductions in streamflow in late summer and autumn by the middle and end of this century (Charlton & Moore, 2003). Additionally, Hall & Murphy, (2010) highlight the existence of vulnerability within the public water supply to climate change impacts in the west of Ireland.

Climate change is only one among many other pressures on water resources and an appraisal of adaptation options to future climatic and non-climatic pressures is essential. An assessment is particularly important for Ireland, as it currently has the highest population growth rate within the EU (CSO, 2009), while water supply has been identified as a potential limit on enterprise over the coming years (Forfás, 2008). The increasing population will result in a growing water demand. On top of this growth, there are no monetary incentives to reduce domestic water demand, as public water and sewage charges for domestic water use were brought to an end in 1997. Another challenge for Ireland is the current high value of unaccounted for water. Nationally, on average more than 43 % of the processed water added to the supply system is presently lost due to leakages in an aging water infrastructure (Forfás, 2008). Furthermore, legislation such as the Water Framework Directive has meant that ambitious targets for achieving good water quality status are driving the management of these pressures. The effects of climatic change will be added to these existing and expected challenges for water resource planning and management.

For these reasons, it is prudent to alter the current decision-making procedure and to include climate change in future water resource management plans. However, a cascade of uncertainties is encountered throughout each stage of the modelling process in an assessment of climate change impact on water resources. The uncertainty starts with the construction of possible states of the future society and future emission scenarios and accumulates over the climate models employed and the impact assessment. Therefore, an appraisal of the robustness to this wide range of uncertainties for possible adaptation options is needed.

This research presents the development of a vulnerability assessment and an adaptation option appraisal for meeting the challenges of climate change in the context of uncertainties as well as current and future pressures. The paper begins by examining the importance of incorporating uncertainty into adaptation assessment. Secondly, the development of a robust modelling framework is presented through a sample application for the Glore sub-catchment located in the Moy catchment, western Ireland.

1. Uncertainty and Robust Adaptation

A cascade of uncertainty propagates and accumulates throughout all stages of climate change predictions and impact assessments. The uncertainty stems from different socio-economic scenarios; from their transformation into greenhouse gas (GHG) concentrations, from their outcomes in global and regional climate models, and from their translation into local hydrological impact models and possible adaptation options. This implies that depending on the techniques used to drive potential future hydrological impacts the results can vary considerably (Wilby & Dessai, 2010). Therefore, it is not possible to give one single deterministic value of predicted streamflow change on which to base future planning decisions. Furthermore, the use of probabilistic climate change scenarios is questionable, as statistical probabilities of future changes are highly dependant on the methodologies used to generate the probabilities. Different methodologies can result in different pdfs (probability density functions) with large differences in their tails (extreme values). Consequently, probabilistic scenarios cannot capture the total uncertainty ranges and therefore only represent a part of the total uncertainties (Hall, 2007). This is particularly problematic in the water resource sector, where extremes (high flows (floods) or low flows (droughts)) are important to adaptation decisions. Insufficient consideration of the residuals of possible future outcomes, can result in inappropriate adaptation decisions and mal-adaptation.

Additionally, no objective measures to constrain uncertainties have been developed and the construction of probabilities of projected impacts remains subjective. Allied to this is the fact that for many catchments, particularly those characterised by high levels of variance under natural conditions, climate change signals may not be statistically detectable for many decades to come (Wilby & Harris, 2006). Given the dynamic and complex nature of both the climatic and hydrological systems being modelled, prospects for significantly reducing uncertainty over the required decision making horizons are limited. Therefore, the philosophy of deriving optimal solutions to the adaptation problem has to be questioned.

An uncertain future requires robust adaptation strategies, which are designed to be insensitive to a wide range of climate change uncertainties. Robustness to uncertainty is one of the key indicators of the effectiveness of an adaptation

action, along with the ability and flexibility to change (Adger *et al.*, 2005). An approach to adaptation based on the robustness of options to uncertainty holds significant potential. Under the development of robust options, uncertainty, rather than being viewed as a limit to adaptation, can be used in an exploratory modelling approach to explore the potential success or failure of adaptation decisions. This allows stress-testing of different adaptation strategies to assess their reliability under a wide range of assumptions and uncertainties. Robust adaptation options are insensitive to the resolution of uncertainties and function across a broad range of possible future outcomes. In robust decision making, different adaptation strategies are appraised without relying on precise and accurate predictions of future climate and hydrology as a key-step in adaptation decision-making. Robustness to uncertainty can aid the design of measures that perform satisfactorily under various future assumptions and scenarios. This also reduces the risk of mal-adaptive action which will be expensive and significantly constrain our future possibilities (Matthews & Le Quesne, 2009).

In order to enable planned anticipatory adaptation despite uncertainty, a scenario-based approach is useful to provide decision makers with a range of possible and plausible future outcomes. The main idea of a scenario-based planning approach is to consider a variety of possible alternative futures based on different, equally plausible assumptions about the future. This approach is a way of including the uncertainties, which are difficult to quantify. Thus, these 'If/Then' scenarios for different adaptation strategies illustrate possible future outcomes and move the focus of decision making away from the need to accurately predict a single outcome. Instead, the focus is placed on exploring how different strategies perform across wide range of assumptions and uncertainties. However, scenarios cannot be taken as definitive future predictions but rather as approximate indications of what the different futures could be. A vulnerability assessment in combination with analysing the robustness to uncertainty of adaptation scenarios can provide planners, decision-makers and policy-makers with information where vulnerability is likely to emerge and therefore further adaptation measures might be needed. Such a decision-making framework is mainly consistent with the traditional optimum seeking analysis, but the assessment order of uncertainty and adaptation decision is the other way around (Groves & Lempert, 2007). In a robust adaptation option appraisal, the different options/scenarios are identified first and are then assessed against their robustness to uncertainty.

However, there is no guarantee that the selected range of scenarios accurately reflects the entire possible future range. Therefore, policy makers, water planners and managers need to realise that it is impossible to eliminate all uncertainties, and make use of the scenario supported planning to base their decisions on. Vulnerability assessments should be an ongoing adaptation process that should be undertaken on a regular basis to incorporate new information and knowledge (Matthews & Le Quesne, 2009). Constant monitoring and appropriate feedback into scenarios and models, and thereafter into management procedures and policies, are required for successful adaptation (Stakhiv, 1998).

2. Development of a Modelling Framework for Robust Hydrological Modelling

The following modelling framework was developed to allow the assessment of future vulnerabilities of the water supply system and to appraise different adaptation options to aid decision-making. This framework samples the key sources of uncertainty by employing statistically downscaled climate scenarios on a daily time-step derived from 3 GCMs forced with two GHG emission scenarios (A2 and B2) to drive the Hydrological Simulation Model (HYSIM), a conceptual rainfall runoff model. Uncertainty in the hydrological model is accounted for by using Monte Carlo random sampling to sample uncertain model parameters. The model performance is evaluated using two objective functions. Pareto rankings are obtained to make allowance for the uncertainty associated with the selection of objective functions during the model calibration and validation process. The behavioural parameter sets are then used to generate multiple future streamflow series driven by the statistically downscaled regional climate scenarios. The resulting stream flow series are then used as input to drive the water resource model WEAP. In WEAP, the current and future architecture and rules of the water supply system, including current and emerging pressures, are integrated and modelled. Vulnerabilities in the water supply system are identified and possible adaptation options are appraised according to their robustness to uncertainty.

3. Sample Application: Public Water Supply in the Glore Catchment

The modelling approach described above is applied to the River Glore sub-catchment located in the River Moy catchment, in the West of Ireland (Figure 1). The Glore catchment has an area of 64.72 km² and the elevation varies from 52m to 156m. The main land cover of the Moy catchment is pasture (44%) with 22% peat bogs (O'Sullivan, 1994). The dominant soils present in the catchment are well drained degraded grey brown podzolics (47.7%), shallow brown earths (19.3%) and podzols (10.3%) as well as poorly drained basin peat (19.1%) (Gardiner & Radford, 1980). The catchment is underlain by 'regionally and locally important aquifers' but groundwater recharge rates are generally low with most of the catchment receiving 100–200 mm of replenishment per year (Working Group on Groundwater, 2008). The surface water abstraction site investigated in this study withdraws on average 814 m³ per day and serves a population of 3,989 people, resulting in an average daily water supply of 204 litres per capita (including losses through leakages).

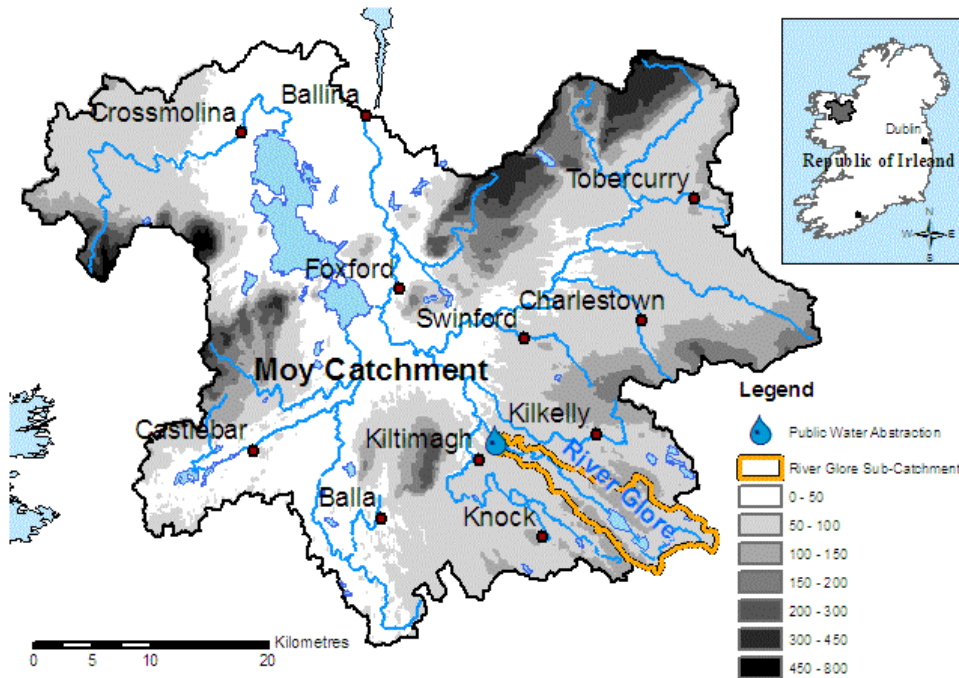


Figure 1: The River Glore Sub-Catchment in the Moy Catchment, Western Ireland, showing the Surface Water Abstraction Site described in Analysis; Elevation, Towns and Rivers.

3.1. Methodology and Data

The water supply system of the Glore Catchment case study is modelled using the Water Evaluation And Planning (WEAP) software. Data input into the WEAP tool include both the water resource system characteristics (water abstractions, leakage level and population served) and the monthly stream flow series at the surface water abstraction site. The following section specifies the generation of the stream flow series input data, using climate scenarios to drive the rainfall runoff model HYSIM. The subsequent section describes the WEAP model and its application to the River Glore sub-catchment.

3.2. HYSIM Model Conditioning

The Hydrological Simulation Model (HYSIM), is a physically-based lumped conceptual rainfall runoff model (Manley, 1978). HYSIM has been successfully used for climate change impact assessments on water resources in Ireland and the UK (Charlton & Moore, 2003, Charlton *et al.*, 2006, Pilling & Jones, 1999, Pilling & Jones, 2002). Details on the HSYIM model itself can be found in Manley (1978 and 2006).

Generally, HYSIM is forced with daily precipitation and potential evapotranspiration data input to return a river flow series. The hydrological

routing within HYSIM (Figure 2) consists of seven internal storages: snow, interception, upper soil horizon, lower soil horizon, transitional groundwater, groundwater and minor channel storage. Although HYSIM is a lumped model, the majority of parameters are physically realistic and can be measured from field observations or spatial datasets. This makes HYSIM particularly suitable for the application to ungauged catchments, as in this study where no measured streamflow record exists at the abstraction point. Five model parameters within HYSIM (two permeability & two interflow parameters and the rooting depth) are free and require fitting during model calibration. The investigated abstraction point in the Glore Catchment has no measured streamflow record. Therefore, the model parameters had to be conditioned in two proxy-basin catchments located within the Moy catchment and then subsequently transferred to the abstraction site.

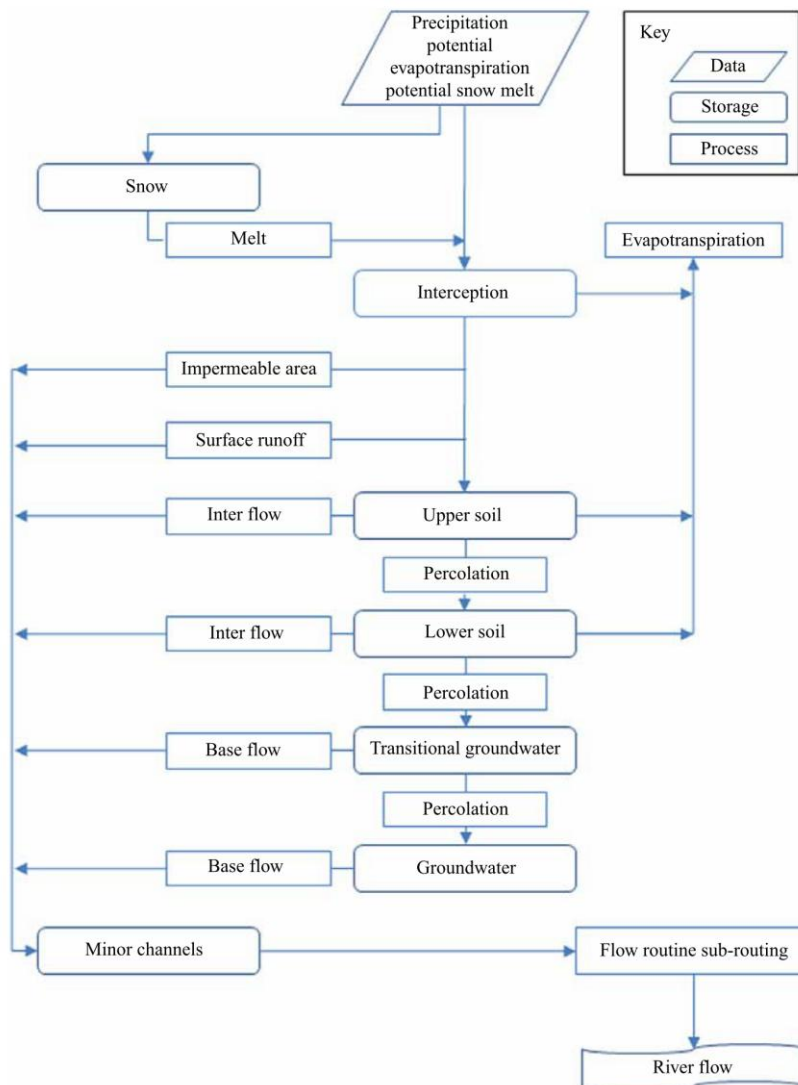


Figure 2: Conceptual structure of HYSIM. Flowchart showing the inputs, the storages and the processes modelled (Manley, 2006).

The hydrological model performance is evaluated using two methods: a split-sample test and a proxy-basin test (geographical transferability of model parameters) (Klemeš, 1986). In the split-sample test, the available streamflow record is split into two segments with 70% of the record (16 years) used for model calibration (1973-1989) and the last 30% (6 years) (1990-1996) for model validation. The hydrological model parameters are calibrated against observed historical streamflow in two sub-catchments (Gauge No. 34009 at Curraghbonaun and 34024 at Kiltimagh) within the River Moy catchment. These sub-catchments are similar in their characteristics to the Gloré and are located on tributaries of the River Moy. Their upstream location ensures low influence of major settlements on their water abstractions.

When testing the transferability of the free HYSIM model parameters within the Moy catchment, the proxy-basin split sample test is applied (Figure 3). Two catchments with similar soil and land use characteristics are cross-checked during calibration and validation. The model is calibrated for one catchment and then run with the obtained behavioural parameter sets in the other catchment for validation and vice versa. The equifinal behavioural free parameter sets obtained in both validation periods are combined and are applied together with the physical model parameters for future hydrological simulations at the ungauged abstraction.

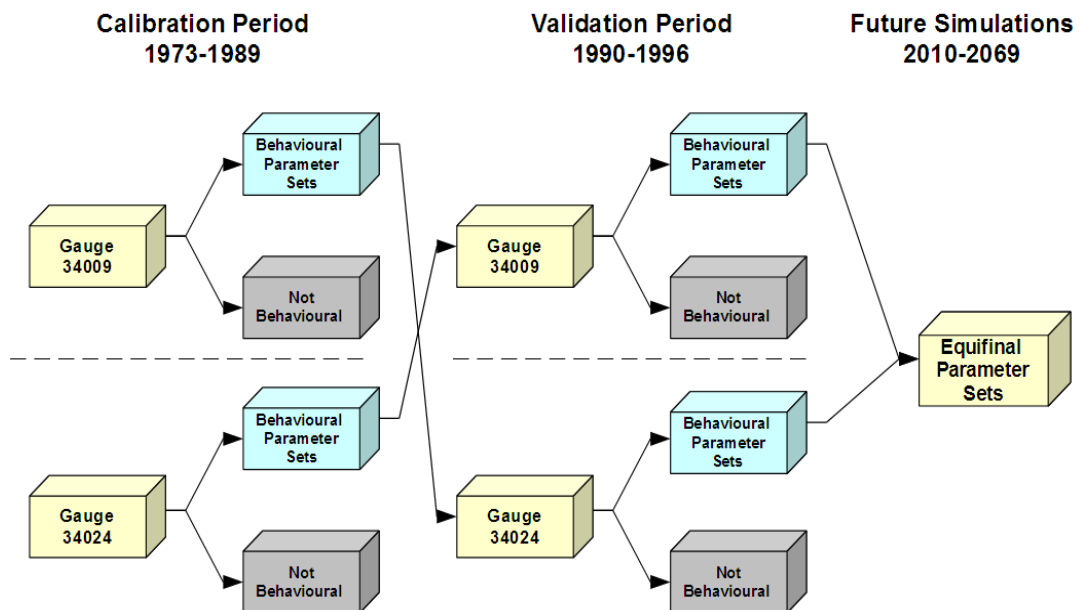


Figure 3: Schematic of split-sample test and a proxy-basin test to obtain parameters

To force the hydrological model during the conditioning process, historical daily climate data (precipitation and evapotranspiration) were used. The data was taken from the synoptic weather station in Claremorris, which is located ~5 km to the south of Moy catchment boundary. The physically based hydrological model parameters for each sub-catchment were selected according to known sub-

catchment characteristics, with the help of a Geographical Information System, which provided information on elevation, soils, land covers and aquifers. Having defined the physical parameters for each sub-catchment, values for the five process parameters were sampled using Monte Carlo Random Sampling. 20,000 Monte Carlo random parameter values were obtained from plausible parameter ranges, defined as the lowest possible parameter value and twice the manual calibrated optimum parameter (Wilby, 2005).

To account for the uncertainty in the selection of the objective function and the definition of behavioural parameter sets, two objective functions were used. Multi-objective function evaluation aims to achieve a compromise between the Nash-Sutcliffe Efficiency Criterion (CE) (Equation 1) proposed by Nash & Sutcliffe, 1970), which is biased towards higher flows, and the relative Nash-Sutcliffe Efficiency Criterion (CE_{rel}) (Equation 2) that gives good calibration results for lower flows (Krause *et al.*, 2005). Both objective functions have a maximum value of 1 and are defined as follows:

$$CE = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad \text{(Equation 1)}$$

$$CE_{rel} = 1 - \frac{\sum_{i=1}^n \left(\frac{O_i - P_i}{O_i}\right)^2}{\sum_{i=1}^n \left(\frac{O_i - \bar{O}}{\bar{O}}\right)^2} \quad \text{(Equation 2)}$$

where O is the observed flow, P is the predicted flow, and \bar{O} is the average of all observed flows.

To evaluate model performance using more than one objective function, Pareto ranking is applied. This ranking approach is based on the assumption that there is no single optimum parameter set. A ranking approach has to be applied, as different parameter sets can perform with different levels of success under the criteria used to evaluate them. When using multiple criteria to evaluate model performance, improving one objective can offset the other objective function, which makes it difficult to identify which sets are better than others. Pareto ranking assigns ranks to different parameter sets according to their performance for both objective functions (Figure 4). The lower the rank, the better the individual parameter sets.

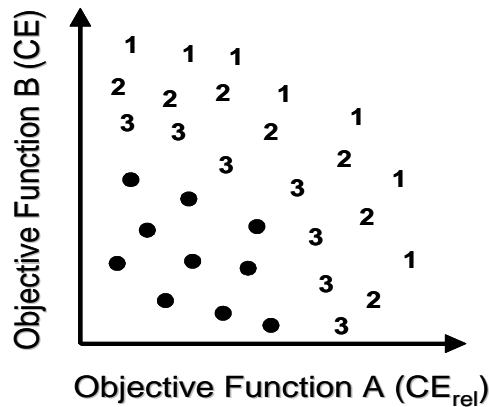


Figure 4: Illustration of Pareto Ranking according to two different objective functions

To allow for the uncertainty in the definition acceptable parameter sets, Pareto ranks one to twenty were selected for each sub-catchment individually. This sample of behavioural parameter sets adds robustness to the modelling approach as the number of behavioural simulations is high but still results in acceptable simulations for both high and low streamflow series.

Figure 5 illustrates the distribution of the scores obtained for the 20,000 random parameter sets when CE is plotted against CE_{rel} and the Pareto Ranks 1-20 for sub-catchment 7002 during the calibration period. For sub-catchment calibration of gauge No. 34009, there were 1,094 parameter sets within Pareto Rank 1-20. For gauge No. 34024 there were 1,481 parameter sets used for the proxy-basin-validation. After validating the behavioural parameter sets of gauge No. 34009 in the 34024 sub-catchment and the behavioural parameter of gauge No. 34024 parameters validated in the sub-catchment No. 34009, 270 combined validation parameter sets within Pareto rank 1-20 were regarded acceptable and were used to generate the ensemble of future streamflow series.

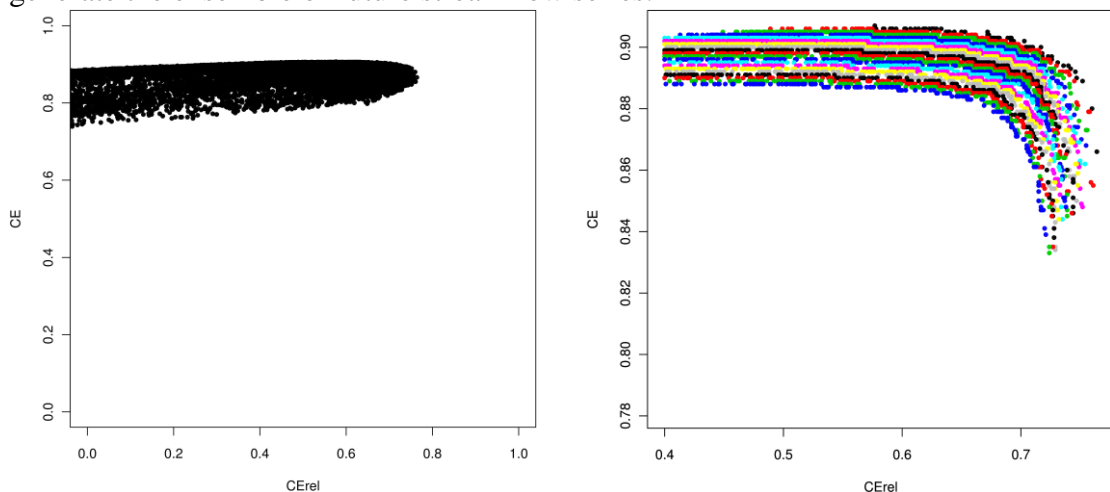


Figure 5: Random Parameter Space and Pareto Ranks 1-20 for the Gauge 34024

3.3. HYSIM generation of future stream flow series

Upon model conditioning, the 270 behavioural parameter sets are used in HYSIM to simulate future streamflow of the ungauged catchment supplying the water abstraction points driven by future climate data input. The physical and the free model parameters sets were assumed to remain unchanged under future conditions for all future model runs. This commonly held assumption in rainfall–runoff modelling for environmental change impact assessment implies that possible feedback effects are not considered (Bronstert, 2004).

The future flow regime was modelled using an un-weighted ensemble of six future climate scenarios (Fealy & Sweeney, 2008). This data consists of statistically downscaled climate scenarios from three different Global Climate Models (GCMs) (HadCM3, CGCM2 and CSIROMark 2) forced with two emissions scenarios. The future greenhouse gas emissions were taken from the IPCC Special Report on Emission Scenarios (SRES). The A2 (medium–high) and B2 (medium–low) emission scenarios both predict a more regional future development with either a more economical (A2) or environmental (B2) focus (IPCC, 2000.) The coarse grid solution of the six different GCM data was then empirically statistically downscaled for the Claremorris synoptic station, adjacent to the Moy catchment (Fealy & Sweeney, 2008). The methodology employed by Fealy and Sweeney, (2008), was primarily focused on generating scenarios, which are able to mean climate state. Therefore, it is likely that extremes (high and low) in temperature and precipitation are underestimated. However, the significant trends shown for precipitation and temperature are consistent with expected changes as suggested by the GCMs (Sweeney *et al.*, 2008).

The resulting HYSIM monthly streamflow series for the abstraction point for each of the parameter sets and combination of climate scenarios was then used as input to drive the future water resource model in WEAP as described in the next section.

3.4. Water Resource Model WEAP of the Glore Catchment

The water resource model used in this assessment is the Water Evaluation and Planning model (WEAP). WEAP is a forecasting tool for integrated catchment hydrology and water supply modelling, assessment and planning based on the water accounting principle (Yates *et al.*, 2005). The water mass balances are calculated on node structures, which are linked to water supply and demand sites. WEAP is designed as a comparative analysis tool, in which alternative sets of assumptions and the resulting behaviour of the whole water system, within the river basin, can be investigated. Details on the water accounting procedures can be found in (Yates *et al.*, 2005).

The first step is to set up the “*Current Accounts*” in the WEAP modelling framework. This is a snapshot of the water demand, supplies and abstractions in the river basin at one specific moment in time. This setup serves as a baseline on which future projections are based. The future water demand model of this study is based on the 2009 average water consumption (204 litres per capita and day), which is extrapolated into the future as described below.

In this study, four sample ‘what-if-scenarios’ (business as usual, supply or/ and demand reduction measures) are explored to appraise their robustness to uncertainty and to investigate vulnerability of the abstraction point. The hydrology of the scenarios is driven by the multiple future streamflow series generated within HYSIM as described in the previous section. The population growth forecast was derived from the Irish Central Statistics Office’s (CSO) Regional Population Projections (CSO, 2008). It is assumed that population growth is constant across the scenarios. After the CSO’s M2F1 traditional scenario, the population is expected to increase by 1.5% per annum in the period to 2026 (CSO, 2008). The projected trends are extrapolated from 2009 up to 2069.

WEAP21 is employed to test the robustness of adaptation options to the range of climate projections and streamflow series. The effects of supply and demand reduction adaptation measure on the water resource system are compared to trend extrapolation (business as Usual):

- Scenario A—‘*Business as Usual*’. Current population trends are extrapolated into the future. Per capita water demand and supply infrastructure remain constant. It is assumed that the level of unaccounted for water is of the national average of 43%.
- Scenario B—‘*Reduced Water Demand*’. Increasing awareness in water conservation results in a stepwise per capita water demand reduction up to 5% by 2020. The level of unaccounted for water remains unchanged by 43%.
- Scenario C—‘*Reduced Leakages*’. Improved water supply infrastructure results in a stepwise-reduced leakage level from 43% to 25% by 2020. Daily per capita water demand remains unchanged on its current level.
- Scenario D—‘*Combined Reduction Measures*’ Reduction of the per capita water demand and leakage reduction, as described above.

The future water scenarios were assessed for the current planning horizon of the 2020s (2010-2039) and the 2050s (2040-2069). The water resource stress index (Raskin, 1997) was applied to analyse the model outputs. This index is a measure of vulnerability and is used to derive a quantitative indication of the water resources pressure imposed on the examined areas and to test the robustness of different options within the system. This physical index of vulnerability is the ratio of average water use divided by the average available water supply (Arnell, 1999; Raskin, 1997). A ratio of greater than 20% can ‘begin to be a limiting factor for economic development’; whereas the other categories are literature-based stress class, estimates by Raskin, (1997). The vulnerability index is divided into four categories as shown in Table 1.

Table 1: Water-use-to-resource-ratio classes (Raskin, 1997)

Use-to-Resource-Ratio	<10%	10%–20%	20%–40%	>40%
Stress class	No stress	Low stress	Medium stress	High stress

4. Results

The results of the modelling example of the water abstraction point in the River Glore sub-catchment were analysed with respect to the 0.05-Quantile, the median and the 0.95-Quantile of all model outcomes for each water scenario. For the 2020s and the 2050s, no water stress was detected in the 0.05-Quantile and in the median of all flows. Water stress was only apparent in the 0.95-Quantile (Table 2). During the examination period of the 2020s, Low-Water-Stress was detected for 11 out of 360 months in the investigated Business-As-Usual Scenario A, whereas due to the demand reductions in Scenario B the occurrences dropped to 8 months. Leakage Reduction (Scenario C) and the combination of Demand and Leakage Reduction in Scenario D lead to less occurring water stress.

Table 2: Occurance of Water Stress Threshold Exedance for the 0.95-Quantile

Water Stress	2020s				2050s			
	A	B	C	D	A	B	C	D
No stress	348	349	352	354	308	315	335	336
Low stress	12	11	8	6	42	36	19	20
Medium stress	0	0	0	0	9	8	5	4
High stress	0	0	0	0	1	1	1	0

Figure 6 illustrates that water stress increases in both frequency and magnitude in the scenarios in the 2050s when compared with the 2020s. For example in Scenario A, in the 2020s only 3.33 % of the months experienced some sort of water stress, whereas in the 2050s already 14.44 % of the months are affected. The same tendency is apparent when analysing the individual water resource scenarios. For example in the Business-As-Usual Scenario A, the percentage of total water stress in 2050s decreased from 14.44 % due to the leakage reduction in Scenario C to 6.94 %. When comparing the individual Scenarios for the 0.95-Quantile (Figure 6), it is evident that the all the modelled scenarios seem to be robust measures to reduce the occurrence of water stress, compared to the Business-As-Usual Scenario.

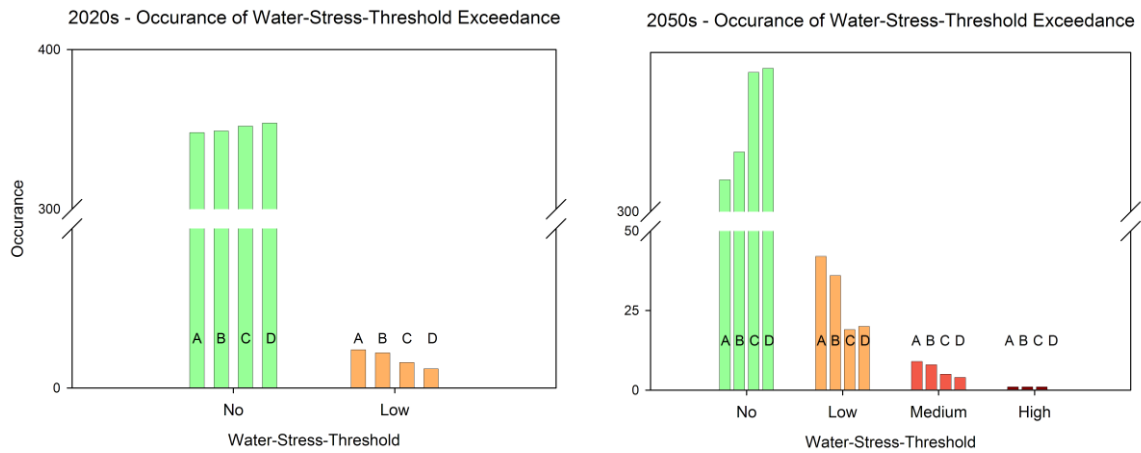


Figure 6: Water-Stress-Threshold Exceedance (Number of Months) of the 0.95-Quantile

With the help of the box and whisker plots shown in Figure 7 trends across all the climatic scenarios and hydrological simulations can be identified. For example, when comparing Scenario A with Scenario B for both the 2020s and the 2050s, the median number of No Water Stress increases in Scenario B, whereas the number of Low Water Stress decreases. The same decreasing pattern is apparent in the 2050s for Medium Water Stress. High Water Stress only occurs in the 2050s for outliers.

Additionally, a seasonal analysis was performed to obtain the entire uncertainty envelope of future simulations (Figure 8). The plots incorporate all climate scenarios and all behavioural hydrological model outputs. The range of the obtained values shown as lower quartile, median, upper quartile and the outliers of all model outcomes for each water resource scenario individually can provide some sense of the uncertainty range within which adaptation has to take place. Figure 8 also highlights the seasonality of Water Stress occurrences. In winter and spring (not shown) no Water Stress is occurring, while during summer and autumn some models indicated Water Stress. During autumn, no Water Stress is occurring for the median but for some outlier indicate Low and Medium Water Stress. In summer, some models (outlier) indicate the possibility of High Water Stress; for example in 2047, 2060 and 2066, as well as Medium and Low Water Stress. However, the median of all simulations remains below the Low Water Stress threshold.

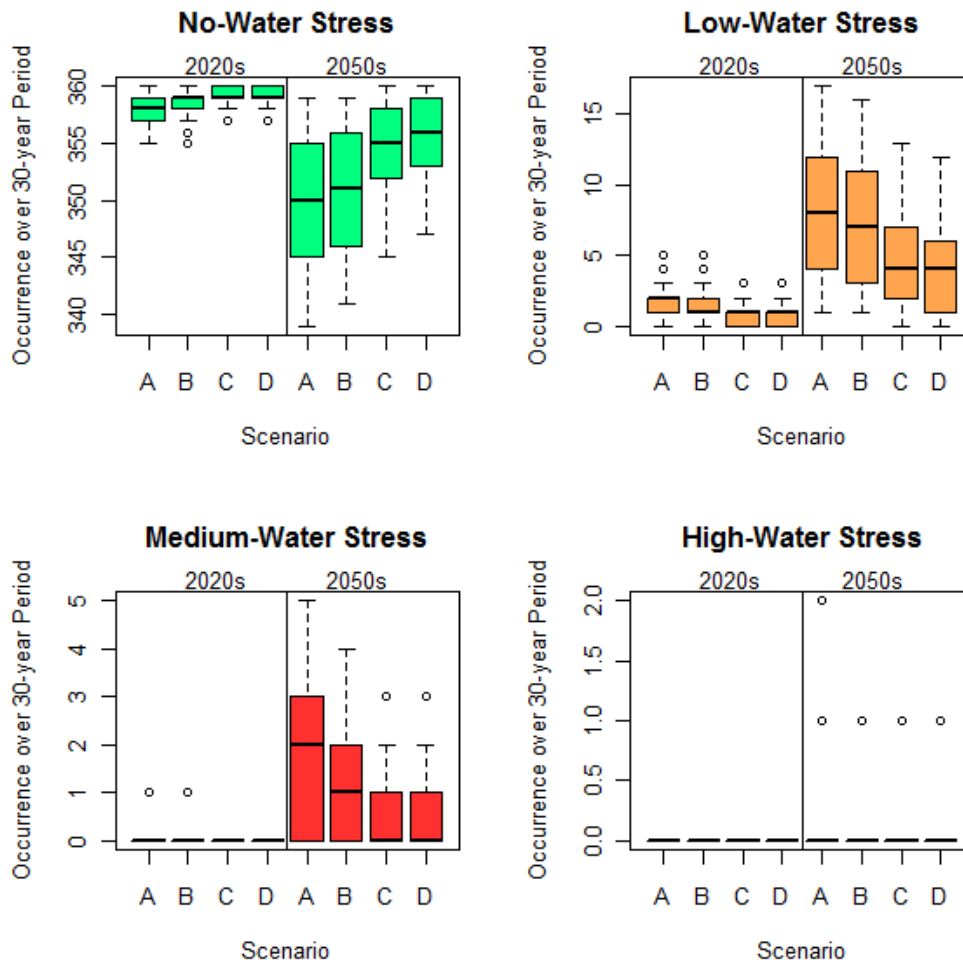
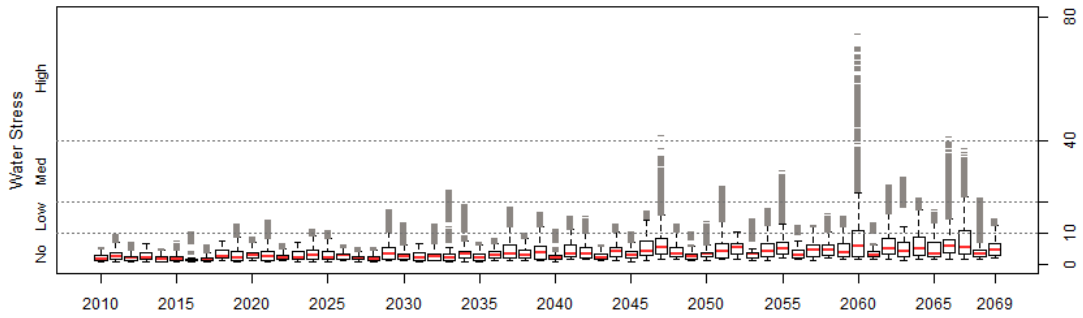


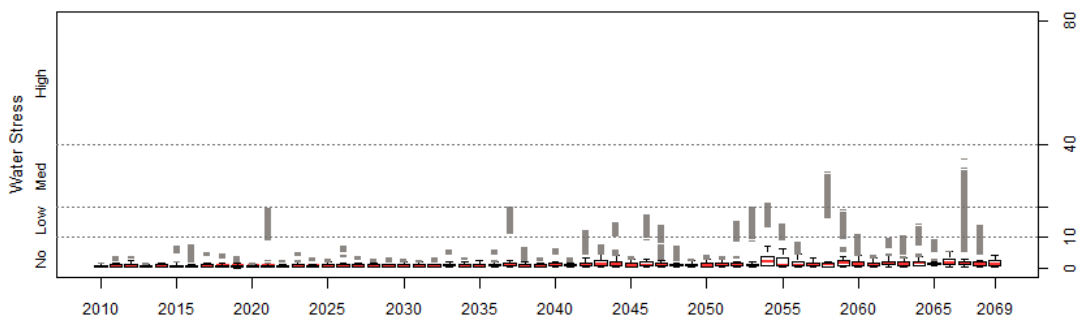
Figure 7: Box plot comparing the different Water-Stress levels for the 2020s and the 2050s. (The horizontal line indicates the median for the all the water stress values across all climate scenarios. The bottom and top of the box show the 25th and 75th percentiles respectively. Points indicate outliers, which are more than 1.5 times the interquartile range below the first quartile or above the third quartile.)

Glore: Scenario A - Business as Usual

Summer

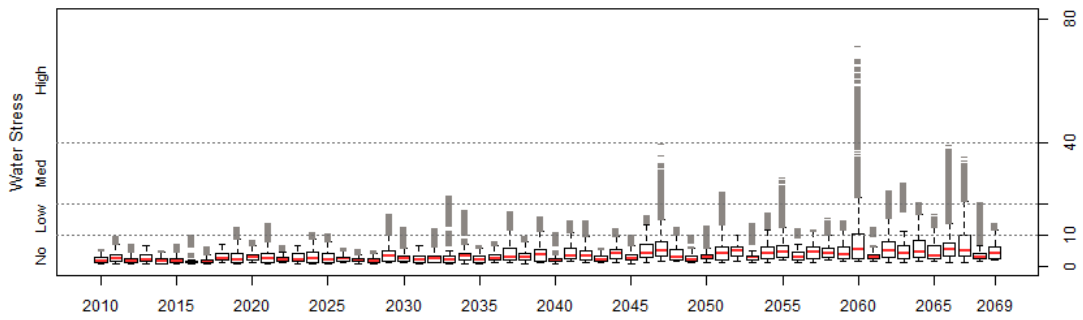


Autumn

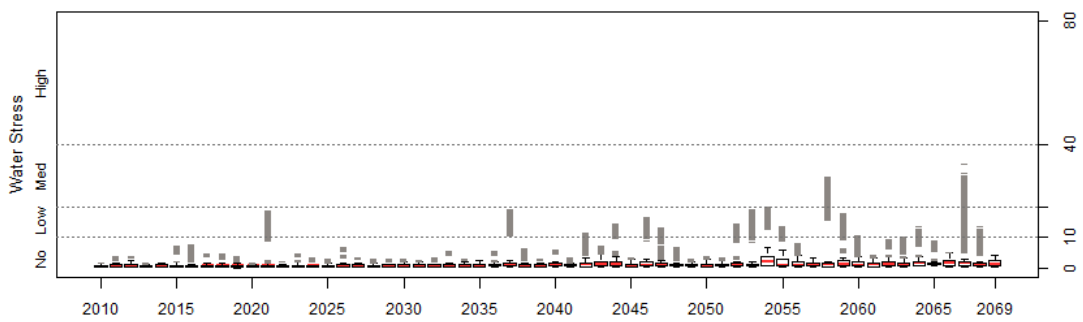


Glore: Scenario B - Reduced Water Demand

Summer

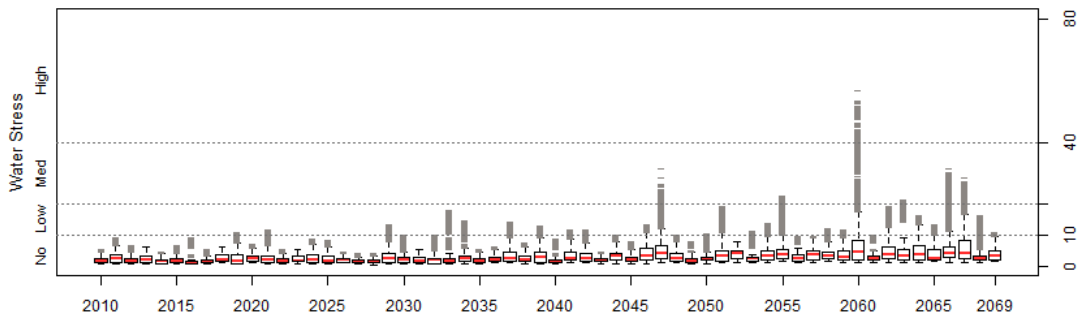


Autumn

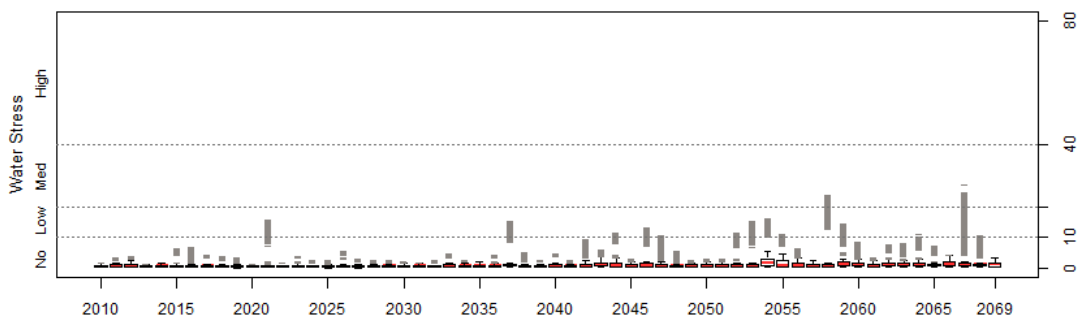


Glore: Scenario C - Reduced Leakages

Summer

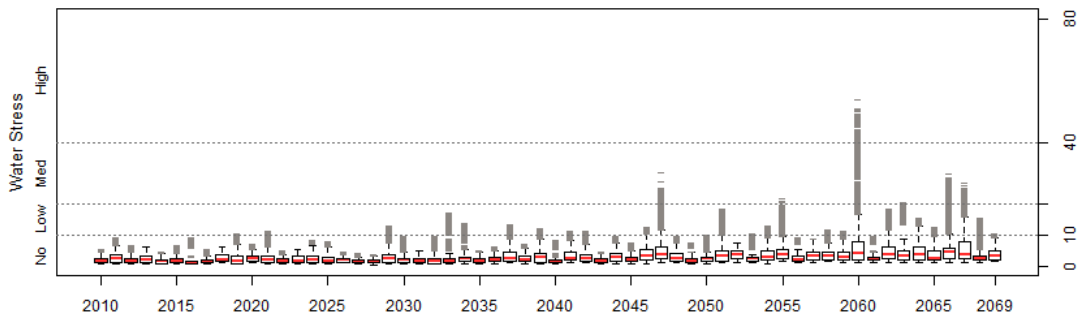


Autumn



Glore: Scenario D - Reduced Water Demand and Leakages

Summer



Autumn

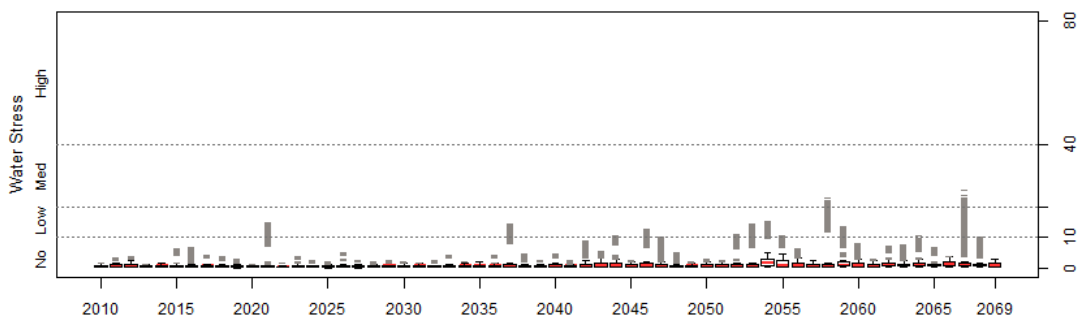


Figure 8: Boxplots all Water Resource Scenarios on a Seasonal Basis.

5. Discussion and Conclusion

This work describes the development of a framework for robust hydrological modelling using statistically downscaled regional climate scenarios to drive a conceptual rainfall runoff model (HYSIM) and an impact model (WEAP21). The investigation shows, that the modelling framework developed is able to appraise the robustness of different adaptation strategies. The appraisal of the water use scenarios in the Glone catchment has shown, that demand reduction, leakage reduction and the combination of both can be an important strategy to reduce pressure on the water resource system. All adaptation scenarios also show a robust performance under the uncertainties incorporated in this modelling framework. Uncertainty resulting from each individual modelling step is propagated and accumulated through the final water resource impact model. The scenarios investigated in this modelling exercise are used to test the framework developed above and to give an indication of the effect of such adaptation measures. It becomes apparent that the investigated adaptation measure will not be enough to remain below the medium water stress threshold for all simulations. In future work, more adaptation options including soft and hard adaptation strategies will be investigated and the approach will be applied to multiple water resource regions within Ireland.

Finally, it is important to integrate uncertainties into the modelling and decision-making process, as the effectiveness of measures strongly depends on the assumptions upon which they are based. Therefore, the robustness to uncertainty of future management decisions in the water sector should always be assessed to decrease the risk of expensive and/or mal-adaptations in a critical sector for society, the economy and the aquatic environment.

Future work will therefore primarily need focus on site-specific development of adaptation options for abstraction sites where future water stress is likely to occur, in conjunction with the assessment of robustness to uncertainty of these measures to aid decision making in the area of water resources management. The results of a site-specific robustness assessment of adaptation options to climate change uncertainties can then be incorporated into future Water Resources Management Plans. These plans need to be robust to uncertainty and flexible to allow monitoring, reviewing and adaptation of water supply systems as soon as new pressures and vulnerabilities emerge.

References

- Adger, N.W. Arnell, N.W. and Tompkins, E.L. (2005), "Successful adaptation to climate change across scales", *Global Environmental Change*, Vol. 15, p. 77–86.
- Arnell, N. (1999), "Climate change and global water resources", *Global Environmental Change*, Vol. 9, p. S31-S49.
- Arnell, N.W. (2003), "Relative effects of multi-decadal climatic variability and changes in the mean and variability of climate due to global warming: future streamflows in Britain", *Journal of Hydrology*, Vol. 270, pp. 195-213.
- Bates, B.C. Kundzewicz, Z.W. Wu, S. and Palutikof, J.P. (2008), *Climate change and water*, IPCC Secretariat, Geneva, Switzerland, Technical Paper of the Intergovernmental Panel on Climate Change, 210 pp.
- Bronstert, A. (2004), "Rainfall-runoff modelling for assessing impacts of climate and land-use change", *Hydrological Processes*, Vol. 18, pp. 567-570.
- CSO (2008), "Regional Population Projections", Central Statistics Office, Dublin. available at: <http://www.cso.ie/releasespublications/documents/population/current/poppro.pdf> (accessed 30 March 2009).
- CSO (2009), "Census 2006 – Preliminary Report", Central Statistics Office, Dublin. available at: http://www.cso.ie/census/documents/2006_prelim_press_release.pdf (accessed 25 March 2009).
- Charlton, R. Fealy, R. Moore, S. Sweeney, J. and Murphy, C. (2006), "Assessing the impact of climate change on water supply and flood hazard in Ireland using statistical downscaling and hydrological modelling techniques", *Climatic Change*, Vol. 74, p. 475–491.
- Charlton, R. and Moore, S. (2003), "The impact of climate change on water resources in Ireland", in Sweeney J. (Ed.), *Climate change: Scenarios and impacts for Ireland - Final Report*, Environmental Protection Agency, Johnstown Castle, Co. Wexford, Ireland, pp. 81-102.
- Fealy, R. and Sweeney, J. (2008), "Statistical downscaling of temperature, radiation and potential evapotranspiration to produce a multiple GCM ensemble mean for a selection of sites in Ireland", *Irish Geography*, Vol. 41, pp. 1-27.
- Fealy, R. and Sweeney, J. (2008), "Climate Scenarios for Ireland", in Sweeney J. (Ed.), *Climate Change: Refining the Impacts for Ireland - Final Report*, Environmental Protection Agency, Johnstown Castle, Co. Wexford, Ireland, pp. 5-38.
- Forfás (2008), *Assessment of water and waste water services for enterprise*, Forfás, The National Policy and Advisory Board, Dublin.

- Gardiner, M.J. and Radford, T. (1980), *Soil Associations of Ireland and their Land Use Potential: Explanatory Bulletin to Soil Map of Ireland*, An Foras Talúntais, Soil Survey Bulletin 36. Dublin, Ireland.
- Groves, D.G. and Lempert, R.J. (2007), "A new analytic method for finding policy-relevant scenarios", *Global Environmental Change*, Vol. 17, pp. 73-85.
- Hall, J. (2007), "Probabilistic climate scenarios may misrepresent uncertainty and lead to bad adaptation decisions", *Hydrological Processes*, Vol. 21, pp. 1127-1129.
- Hall, J. and Murphy, C. (2010), "Vulnerability analysis of future public water supply under changing climate conditions: A study of the Moy catchment, Western Ireland", *Water Resource Management*, Vol. 24, p. 3527–3545.
- IPCC (2000), *Special Report on Emission Scenarios - Summary for Policymakers*, A Special Report of IPCC Working Group III. Intergovernmental Panel on Climate Change, Geneva, Switzerland, Nakicenovic, N.; Swart, R..
- Klemeš, V. (1986), "Operational testing of hydrological simulation models", *Hydrological Sciences Journal*, Vol. 31, pp. 13-24.
- Krause, P. Boyle, D.P. and Bäse, F. (2005), "Comparison of different efficiency criteria for hydrological model assessment", *Advances in Geosciences*, Vol. 5, pp. 89-97.
- Manley, R.E. (1978), "Simulation of flows in ungauged basins", *Hydrological Sciences Journal*, Vol. 23, pp. 85-101.
- Manley, R.E. (2006), *A guide to using HYSIM*, R. E. Manley and Water Resource Associates, Ltd.
- Matthews, J.H. and Le Quesne, T. (2009), *Adapting water management: A primer on coping with climate change*, WWF-UK, Surrey.
- Nash, J.E. and Sutcliffe, I.V. (1970), "River flow forecasting through conceptual models. Part I - A discussion of Principles", *Journal of Hydrology*, Vol. 10, pp. 282-290.
- O'Sullivan, G. (1994), *CORINE land cover project Ireland*, Ordnance Survey of Ireland, Project report. Dublin.
- Pilling, C.G. and Jones, J.A.A. (1999), "High resolution climate change scenarios: implications for British runoff", *Hydrological Processes*, Vol. 13, pp. 2877-2895.
- Pilling, C.G. and Jones, J.A.A. (2002), "The impact of future climate change on seasonal discharge, hydrological processes and the extreme flows in the Upper Wye experimental catchment, mid-Wales", *Hydrological Processes*, Vol. 16, pp. 1201-1213.
- Raskin, P. (1997), *Water Futures: Assessment of long-range patterns and problems. Background document to the Comprehensive Assessment of the Freshwater Resources of the World report*, Stockholm Environment institute, Stockholm, Sweden.

Stakhiv, E. (1998), "Policy implications of climate change on water resource management", *Water Policy*, Vol. 1, pp. 159-175.

Sweeney, J. Albanito, F. Brereton, A. Caffarra, A. Charlton, R. Donnelly, A. Fealy, R. Fitzgerald, J. Holden, N. Jones, M. et al. (2008), *CLIMATE CHANGE – Refining the Impacts for Ireland*, EPA STRIVE Programme, 2007–2013.

Wilby, R.L. (2005), "Uncertainty in water resource model parameters used for climate change impact assessment", *Hydrological Processes*, Vol. 19, pp. 3201-3219.

Wilby, R.L. and Dessai, S. (2010), "Robust adaptation to climate change", *Weather*, Vol. 65, pp. 180-185.

Wilby, R.L. and Harris, I. (2006), "A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK", *Water Resources Research*, Vol. 42, p. W02419.

Working Group on Groundwater (2008), *National recharge map of Ireland*, Environmental Protection Agency and River Basin Districts Coordinating Authorities, Dublin.

Yates, D. Sieber, J. Purkey, D. and Huber-Lee, A. (2005), "WEAP21-A demand-, priority- and preference-driven water planning model. Part 2: Aiding freshwater ecosystem service evaluation", *Water International*, Vol. 30, pp. 501-521.

Yates, D. Sieber, J. Purkey, D. and Huber-Lee, A. (2005), "WEAP21-A demand-, priority- and preference-driven water planning model. Part 1: Model characteristics", *Water International*, Vol. 30, pp. 487-500.