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Chapter 3

ADAPTING WATER SUPPLY SYSTEMS IN A CHANGING CLIMATE

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ABSTRACT

Climate is one of many external drivers which have the potential to significantly influence water supply systems. However, a changing climate is the main driver to affect the availability of raw water resources. Predominately changes in the timing, frequency and intensity of precipitation can have a significant impact on the entire hydrological system. For example, increasing temperature often results in increasing water demand and enhanced water losses due to intensified evaporation. While increasing precipitation can damage water supply systems, due to flooding or increased erosion and water abstraction can be affected due to high turbidity and decreased water quality. Less precipitation or shifting seasonal precipitation events can cause serve water shortages, in particular when water storage facilities are insufficient. To respond to current and future climatic challenges and other external drivers, water resource management plans are developed and constantly upgraded.

The traditional approach in water resource planning and management has been based on the assumption of stationarity of the hydrological system. However, the assumption that the past will be the key to the future is no longer valid. The climate and therefore the entire hydrological system is changing, and relying on the traditional planning approach increases the risk of mal-adaptation, water shortages and monetary losses. However, the methods to identify the future changes in water resources due to climate change are very uncertain. This cascade of uncertainty stems from the assumptions made about the state of future society and the greenhouse gas scenarios affiliated to these states. The uncertainty envelop expands further when the greenhouse gas scenarios are used to drive the global climate models, which are then downscaled to the regional models, and finally more uncertainty is added through local impact models. Such uncertain simulations are

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problematic when decisions on future adaptation have to be agreed upon to avoid expensive mal-adaptation.

This chapter examines climate change as emerging pressure on water supply and the evidence of climate change from climate records. Future impacts of climate change on water resources are highlighted and the challenge of adaptation is reflected on. Being confronted with deep uncertainty, the need for alternative approaches, shifting the paradigm away from the traditional "predict and provide" approach, seeking an optimum adaptation solution, is highlighted. Instead, alternative approaches are needed that allow the development of water supply systems that are robust to the uncertainty framing future changes in water resources. International examples of these approaches are described; including a case study of the Boyne catchment's water supply system in the east of Ireland. The uncertainties involved in generation of future catchment hydrology are discussed and the vulnerability of the case study water supply system to a changing climate is investigated. Where vulnerability exists, sample plausible future adaptation options are then assessed to their robustness to uncertainty, to quantify the water supply system response, to aid decision making. This chapter concludes that water managers will have to engage with alternative methods for climate change adaptation in conjunction with future observational evidence of change.

1. Climate Change as Emerging Pressure on Water Supply

Climate plays a central role in water resource management, as it influences the hydrological cycle at all stages. But the climate is changing. Increasing atmospheric temperature, due to increasing atmospheric concentrations of greenhouse gases, can lead to an intensification of the hydrological cycle, as evidence of several studies reviewed by Huntington, (2006) suggests. For example, as consequence of increasing temperature models suggest an approximate global average precipitation increase of 3.4% per degree Kelvin of temperature (Allen and Ingram, 2002), leading to more intense but less frequent precipitation periods.

However, effects of a changing climate will not be uniform on the earth and will differ at different locations. For example, climate models suggest a greater warming at high latitudes and less warming in the tropics (Hegerl *et al.*, 2007), while precipitation changes will not occur uniformly around the globe. On a regional scale, some locations will receive more rainfall, whereas others may suffer from extended drought periods. These changes in precipitation will also for example influence surface runoff, with an increase in higher latitudes (i.e. of North America and Eurasia) and a decrease in southern Europe, the Middle East, mid-latitude western North America, and southern Africa (Milly *et al.*, 2005).

Historically, pressure was put on water supply systems mainly from increasing water demand; however, with a change in climate, water demand could further increase while water supply may be reduced. Therefore, a changing climate is a key driver of the future availability of raw water resources. Predominately changes in the timing, frequency and intensity of precipitation can have a significant impact on the hydrological system. For example, the shifting of seasonal precipitation patterns or reduced precipitation can lead to reductions in stream flow and groundwater recharge rates, which can affect the quantity and quality of the available water. Increasing temperatures can result in higher evaporation losses and increasing water demand. Whereas increasing precipitation can damage water supply systems due to flooding or increased erosion, and water abstraction can be affected due to high turbidity and decreased water quality. Such climate-induced changes can pose a challenge in various ways to any water supply utility.

However, the effect of climate change on water resources and supply systems will not only depend on the location and the degree of chances in the hydrological system but also on the water supply system itself. Depending on the main characteristics of water supply systems, the same change in climate can have various effects on different water supply systems. For example, robust systems with plenty of excess headroom are likely to cope with large changes, but where water supply systems are already under pressure and operating at, or close to their design capacity, a small change can have a big impact. Therefore, an assessment of the balance of future water supply and demand of individual water supply systems or even a single water abstraction point is crucial taking future climate and the future development of non-climatic pressures into account. The quantity and/or the quality of the water resources can be affected by climate-independent factors such as population changes, increasing wealth, the political and legislative framework, economic activity, technological and monetary potential, land-use change and urbanisation. Demand increase due to population growth, the emergence of water-intense industry or agricultural practices for example reduces the overall water availability even without the occurrence of climatic change. Whereas, the introduction or rise of water charges (if water is already priced) can result in water saving, or the water loss reduction can increase the amount of water that can be provided to the individual water users. These key climatic and non-climatic factors need to be combined in an assessment to determine future vulnerabilities of a water supply system.

There is a consensus that climate change will have a small effect on water supply systems compared to growing demand over near term planning horizons. However, future hydrological simulations suggest that climate change will significantly alter catchment hydrology over medium and long time scales. In response to these anticipated changes; long-term adaptation has to take place locally, at the catchment scale. This need for adaptation is supported by the evidence of climate change from observations.

2. Evidence of Climate Change from Observations

Climate is the most central driver of the hydrological cycle. A change in either the climate system or water cycle would induce a change in the other due to their intimate association (Kundzewicz, 2004). The earth's climate system has changed since the pre-industrial period with an accumulation of evidence suggesting an anthropogenic increase of carbon dioxide being the very likely cause (IPCC, 2007). Global average surface temperature has increased, with warming accelerating to 0.13^{o}C per decade over the past 50 years (IPCC, 2007). The average atmospheric water vapour content has amplified since at least the 1980s over land and ocean and corresponds to long-term increasing trends in precipitation amount over North America, northern Europe and northern and central Asia (IPCC, 2007). Warming of the climate is in theory expected to bring about increases in evaporation and precipitation, leading to the hypotheses that one of the major consequences will be an intensification (or acceleration) of the water cycle (Held and Soden, 2000; Huntington, 2006). Huntington (2006) explains the theoretical basis for this intensification is summarised in the Clausius-

Clapyeron relation that implies specific humidity would increase approximately exponentially with temperature.

Globally, evidence of direct human influences on the hydrological cycle is now apparent (Gedney *et al.*, 2006; Huntington, 2006; IPCC, 2007; Barnett *et al.*, 2008). However, for a number of components of the water cycle, for example groundwater, the lack of data has made it impossible to determine whether their state has changed in the recent past due to climate change. Gedney *et al.*, (2006) suggest that raised carbon dioxide levels are already having a direct influence on the water balance at the land surface, increasing runoff and therefore freshwater availability. Increases of precipitation that occur outside the explanation of internal climate variability attributed to anthropogenic forcing have also been detectable with significance (Zhang *et al.*, 2001). Dai *et al.*, (2004) present large variations in yearly river flows for the world's 200 largest rivers but highlight that only about one third of the catchments show statistically significant trends over the study period 1948-2004. Furthermore, the majority of significant trends were associated with reductions in discharge. Trends were consistent with precipitation and modes of variability being driving forces, with the exception of Arctic drainage basins were increasing trends in flow are more likely associated with increasing temperatures (Dai *et al.*, 2004). Syntheses of evidence compiled by Huntington (2006) further defend the case for considerable global change in both key global climate and hydrological variables. Kundzewicz, (2004) highlight the role of climate change leading to the acceleration of the hydrological cycle and may cause increases in the frequency and severity of extreme hydrological events. Yet, to date, there is little concrete evidence of significant large-scale climate-induced change for floods and droughts (Kundzewicz, 2004), nor is it yet possible for rainfall trends below the global scale to be attributed to human influences (Lambert *et al.*, 2004; Fowler and Wilby, 2010).

At the scale most relevant for the effective management of water supply and water infrastructure, the detection of climate-driven trends is far more problematic due to high inter-annual and decadal variability of river flows (Burn and Hag Elnur, 2002; Wilby, 2006; Fowler and Wilby, 2010) and the effects of human intervention in natural catchment systems (Marsh, 2010). Detection of climate change at regional and local scales is inherently difficult because of the relatively weak climate change signal compared with large interannual variability of rainfall and river flows, the choice of index, spatial and temporal scale of aggregation, strengths and assumptions of statistical tests and significance testing and confounding factors such as land use change, channelization and arterial drainage, which all require careful consideration (Kundzewicz and Robson, 2004; Radziejewski and Kundzewicz, 2004; Legates *et al.*, 2005; Svensson *et al.*, 2005; Wilby *et al.*, 2008; Fowler and Wilby, 2010).

For example: The choice of indices can be monthly, seasonal, annual, based on river flow or water levels, maxima, minima, cumulative totals, counts of peaks over thresholds, point or area averages, based on individual records or pooled. The period of record has a huge bearing on derived trends where analysis of long records can refute the significance of trends from series of shorter duration that may be overly influenced by outliers or natural variability. The record length required to detect trends can vary depending on the strength of the trend, the variance about the trend, the probability of type one and type two errors. The power of statistical tests to detect trends (monotonic or step change) can vary hugely and in the case of hydrological data assumptions of tests may be violated and increase the likelihood of false identification of trend. Factors such as changes in site instrumentation, observing or recording practices, land cover change, water abstraction, arterial drainage, channel engineering can all confound the detection and interpretation of trend.

Short records have proven to be particularly problematic. The number of years of record needed to detect a statistically significant trend depends on: the strength of the trend; the amount of variance about the trend; the probability of erroneous detection (type 1 error); and the probability of missing a real trend (type 2 error). Preliminary estimates using data for river basins in the United States and the United Kingdom suggest that statistically robust, climate driven trends in seasonal runoff are unlikely to be found until the second half of the 21st century (Ziegler *et al.*, 2005; Wilby, 2006). In Australian river basins an even greater change may be required for detection as the interannual variability of flows is twice that of Northern Hemisphere river basins (Chiew and McMahon, 1993).

As shown by Wilby (2006) detection time relationships can also be inverted to estimate the strength of trend required for detection by specified time horizons. For example, analysis of UK winter and annual precipitation totals suggests that changes of ~25% would be needed for detection by the 2020s in the most sensitive basins (such as the River Tyne). Although attribution of changes is not yet possible at regional scales, techniques are being developed for detection of trends in indices at river basin scales, and for estimating the time taken for specified anthropogenic climate change signals to emerge from climate variability (Fowler and Wilby, 2010). For the moment at least it would appear that water managers will have to balance water demand and assess the functionality of supply systems for future climate, without any statistical evidence that climate change from local observations. Therefore, as discussed further below the challenge emerges of maintaining the functionality of critical supply systems under conditions of considerable uncertainty.

3. FUTURE IMPACTS ON WATER RESOURCES

Water resources will be one of the most affected sectors by changes in climate (Bates *et al.*, 2008). As discussed above, the main climatic drivers influencing the availability of the raw water resources are precipitation and temperature (especially where catchment hydrology is influenced by snow accumulation and snowmelt). Generally, by altering the hydrological cycle, climate change can have an effect on the quantity (intensity and frequency of flood, normal, or drought conditions) and quality of water resources (nutrient and oxygen content and, temperature) an their seasonal distribution. Changes in amount, intensity, and timing of precipitation, the type of precipitation (rain or snow) and evaporation determine stream flow, and water levels in lakes and wetland as well as groundwater levels and recharge rates, as do increased evapotranspiration and a reduction in soil moisture. This in turn determines how much freshwater can be utilised for ecosystem and human needs. Additionally, changes in vegetation cover resulting from changes in temperature and precipitation and consequently changes in land use management practices can also influence the hydrological cycle.

The future effects of climate change and non-climatic pressures on water resources with regard to their extremes and their likelihood of occurrence is summarised in Table 1 (after Bates *et al.*, 2008). Noticeable is the global scale at which results are summarised due to the confounding factors that moderate climate change at more local scales. As discussed later, as the resolution of climate change projections is increased to scales that are most relevant to assessing future impacts in water resources, the uncertainty of impacts grows considerably.

Climate change will impact both the available water resource through altering hydrological processes and the human water demand through increasing temperature. Other stresses are also likely to further increase the water demand such as increased competition for resources among water users, particularly for irrigation purposes. Further, additional water need to be allocated to ecosystems, where sensitive aquatic species have evolved which can only to deal with small changes in water temperature. At the catchment scale, changes in seasonality are likely to alter available resources while a change in the magnitude and frequency of extreme events are likely to result in increased risk of failure of critical infrastructure and increased maintenance cost. In relation to the latter for example, higher intensity rainfall is likely to increase the sediment load of rivers and therefore the rate of sedimentation in reservoirs, resulting in reduced water storage capacity. Catchment geology can play a strong role in offsetting large reductions in river flow, where permeable geologies and productive aquifers contribute to base flow to sustain river flow over dryer periods. However, where a reduction in rainfall in the recharge period occurs, drought conditions can be quite severe and long-lived.

Therefore, it is quite a complex issue to extract more catchment specific results. Indeed many have concluded (e.g. Prudhomme and Davies, 2007) that the complexity and uniqueness in response of individual catchments means that we need to assess climate change impacts on a catchment-by-catchment basis. The lessons we can gleam from such assessments is that, at the very least, water management is going to become a more complex issue in the future and the successful management of those resources will require adaptation to future climate.

Table 1. Future changes, their likelihood and effects on water resources (c.f. Bates *et al.*, 2008)

Change Projection	Likelihood (21st century)	Effects on water resources
Precipitation increases in high latitudes and parts of the tropics	*very likely and likely*	Increase in water resources.
Annual river runoff increase at high latitudes and in some wet tropical areas	*high confidence* (by the middle of the century)	More frequent and more serious floods
Precipitation decreases in some subtropical and lower mid-latitude regions	*likely*	Decrease in water resources
Annual river runoff decrease over some dry regions at mid-latitudes and in the dry tropics	*high confidence* (by the middle of the century)	More frequent and more serious droughts
The frequency of heavy precipitation events increase over most areas	*very likely*	Risk of rain-generated floods.
Increase in continental drying in summer (especially in the subtropics, low and mid-latitude)	*likely*	More frequent and more serious droughts

Decline in glaciers and snow cover (important in regions supplied by melt water)	*high confidence*	Reduced water availability (seasonal shift in stream flow, reductions in low flows)
Higher water temperatures and changes in extremes, including floods and droughts,	*high confidence*	water quality and exacerbate many forms of water pollution
Sea-level rise extends areas of salinisation of groundwater and estuaries,	*high confidence*	Decrease of freshwater availability in coastal areas.
Globally, increase in population and affluence and urbanisation;	*high confidence*	Growing water demand
Regionally, changes in irrigation needs due to climate change and land use change	*high confidence*	Growing irrigation water demand

4. Considering Adaptation

In order to accommodate future impacts of climatic change and meet future water demands, some degree of adaptation will have to take place within the water sector. Indeed adaptation is considered an important response option or strategy, along with mitigation efforts in the face of climate change. However, what is meant by adaptation is not entirely clear-cut. The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as: '*Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities*' (IPCC, 2007). Whereas, the United Nations Framework Convention on Climate Change (UNFCCC) defines adaptation as '*Actions taken to help communities and ecosystems cope with changing climate conditions, such as the construction of flood walls to protect property from stronger storms and heavier precipitation, or the planting of agricultural crops and trees more suited to warmer temperatures and drier soil conditions*'(UNFCCC, 1992). There are many other treatments and definitions of adaptation in the literature. UNFCCC treats adaptation in the narrowest sense — as actions taken in response to climate changes resulting from anthropogenic greenhouse-gas emissions. The dominant approach in dealing with adaptation in response to the UNFCCC definition has been the '*predict-then-act*' approach, where the key focus of assessments have been on climate and a predominantly scientific approach. In contrast, the stance taken by the IPCC tends to recognize other processes that act in conjunction with climate change in order to induce vulnerability to future change. Adaptation assessments based on the more human centred philosophy of the IPCC have been based on assessing vulnerability and resilience to climate change. The IPCC's definition of adaptation is probably more aligned to water system which can be viewed as an inherently socio-ecological system; sensitive to both changes in natural resources and human traditions and behaviours. Indeed, in many instances it can be difficult to differentiate between the two.

In addition to considering definitions of adaptation, we can also think about how adaptation is likely to take place in time and the degree of strategic vision involved. Adaptation can take place with different levels of spontaneity, and can be distinguished into autonomous or planned adaptation (Bates *et al.*, 2008, Fankhauser *et al.*, 1999). Autonomous adaptation is not purposely designed to deal with climate change, but rather a non-coordinated mostly spontaneous response to changes by individuals or communities. Whereas planned, often policy driven, adaptation aims to directly make allowance for climate variability and climate change in order to reduce the negative impacts or gain from the changed conditions. The following paragraphs focus on planned adaptation to climate change impacts.

Adaptation can also be characterised depending on the timing, into reactive and anticipatory adaptation. Anticipatory adaptation predicts and responds to vulnerabilities before damages are incurred. Reactive adaptation limits the recurrence of damage only after effects have been felt and damage has been done. An example of an anticipatory adaptation is the construction of a reservoir to store winter rainfall to supply water during drier summer months. The goal of this anticipating adaptation is to minimize the impact of climate change by reducing vulnerability of the water supply to drier conditions. Reactive adaptation on the other hand is likely to lag persistently behind the emerging risks, which is particularly problematic when changes occur rapidly. The more rapid the rise in atmospheric greenhouse gas concentrations, the faster the rate of climate change and the less effective reactive adaptation is likely to be (Repetto, 2008).

In dealing with anticipatory, planned adaptation Arnell and Delaney (2006) highlight considerations that are important in adapting to climate change. In particular, they highlight the need for decision makers in the water sector to consider their adaptation strategy and what they term the ‘adaptation space’. The adaptation strategy defines what an organisation is seeking to achieve by adaptation and how this is intended to be achieve. Possible aims include continuing to provide the same standard of service or product to customers (using different methods if necessary), providing different products and services which broadly meet the same function, ceasing to provide the product or service at all, or ignoring climate change and relying on “muddling through”(Arnell and Delaney, 2006).

The adaptation space is defined as the set of options, which are potentially available to deal with possible climate and other changes. The need to adjust to changing pressures and climate variability over centuries and millennia has meant that the adaptation space for water management is considerably large. For simplicity, we might consider the adaptation space in terms of supply side options and demand side options. Examples of the former would include the building of new or enhanced reservoirs, inter-basin transfers, desalinization and new abstractions. Supply side options can also extend to improving resource utilization, such as increasing the connectedness of the network, seasonal forecasting and institutional behavioural change. Demand side options have been commonly used to reduce water use and in many cases have proven to be considerably less expensive than supply side solutions. Common strategies for demand reduction include the incentivisation of water efficient equipment and fittings, educational campaigns on behaviours to conserve water, controlling new development, encouraging the use of rainwater etc., the list is quite extensive.

Clearly some of the options within this adaptation space will be more feasible than others, for technical, legal, economic or cultural reasons, and some may not be perceived at all by an organization (Arnell and Delaney, 2006). The adaptation space is dynamic, as new options become available through, for example, technological development, and as understanding of the characteristics of change develops. In previous water management planning, the main focus was placed onto technical or so called ‘hard’ adaptation options, often involving engineering solutions, and less consideration was given to ‘soft’, non-technical options which are designed to influence socio-economic behaviour. In the situation where water management is ever more aware of the fact that humans are only one user of resources, the preference for soft strategies has increased. Soft strategies also have a lot to offer to climate change adaptation. The main advantage of 'soft' adaptation options is, that they are often more adaptable and more flexible than 'hard' adaptation. 'Soft' adaptation is therefore preferred more, as this form of adaptation keeps other options open and allows for modification as new information becomes available. 'Hard' technical adaptation options like new large infrastructural projects have a long lead-time and are designed for a long lifetime. They should only be considered carefully, as with the selection of such a 'hard' option the water supply system runs the risk of becoming dependant on a single future development path. This can easily result in expensive mal-adaptation, when the main assumptions of change on which such a project is based are over or underestimated.

To cope with the possible impacts of climate change on fresh water and water supply systems, careful consideration is required about how to plan, evaluate and prioritise adaptation action. Overall, it is important that the planned anticipatory adaptation measures are kept flexible to allow for further adaptation and not to be limited by our own actions. This is especially important for water supply systems where it is essential to balance between future water demand and future water supply. To maintain this balance, supply side as well as demand side measures can be adapted to abate climate change impacts. Supply side measures generally imply a supply increase whereas demand side measures aim to reduce the water demand. However, to agree upon a measure or a combination of measures to adapt to climate change still remains a challenging task.

5. The Challenge of Uncertainty

Within the water sector many decisions, particularly investment in new infrastructure and the protection of existing assets, come with long-term commitments, which can be very climate sensitive and require an estimate of what future conditions are going to be like over the design life of the investments (Hallegatte, 2009). Therefore, when building and designing water infrastructure to balance the supply and the demands of the future we need to account for the future changes that can be expected. The provision of this has proven to be a significant obstacle for climate science, particularly given the high levels of precision required by engineers in order to derive optimal solutions. This is a rather disconcerting position when it is contextualised by the fact that more than US$ 500 billion are invested every year in the water sector (Milly *et al.*, 2008). Additionally, the concept of stationarity, on which water systems throughout the developed world have been designed, cannot be retained as a foundational strategy for defining and designing optimum performance (Milly *et al.*, 2008). Changing climate variability, changes in extremes and means imply that water management cannot keep using the stationarity hypothesis for its investment decisions. An alternative approach is required.

Therefore, adaptation to climate change in the water sector is a challenging task and one that will perhaps require a paradigm shift in how we go about designing and operationalising the systems upon which so much of society depends. Producing future climate scenarios and future impacts of climate change in order to inform adaptation is by no means an exact science. Conventional approaches to adaptation have been driven by the scientific, scenario, or impacts led approaches. Such 'top-down' approaches can be characterised as a number of discrete steps as follow;

1. Scenarios of the evolution of future climate are derived from Global Climate Model.
2. In the majority of cases, some approach is used to downscale these scenarios to scales relevant of catchment scale hydrological processes. These approaches range from simple change factor approaches, through statistical downscaling, to the deployment of complex regional climate models.
3. Following downscaling these scenarios are used to force impacts models, most commonly conceptual rainfall-runoff models, which have been trained to capture the dynamics of a specific catchments hydrology.
4. Finally outputs from of hydrological response have been used as a means to inform policy and decision making in adapting to future changes.

Wilby and Dessai (2010) note that while there is an abundance of such applications that follow the 'top-down' approach or a similar framework, the number of such studies that have resulted in tangible adaptation strategies being implemented has been rather limited. A key reason for this is the large uncertainty associated with impact projections, as a result of the cascade of uncertainty in the methodological steps identified (see Figure 1).

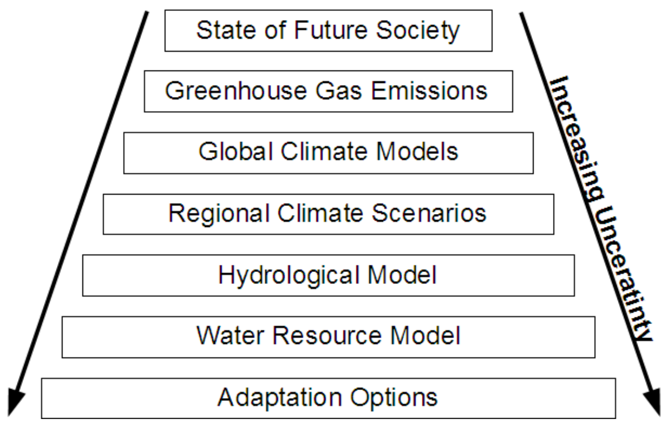

Figure 1. Cascade of Uncertainty (modified after Wilby and Dessai, 2010).

The largest source of uncertainty is associated with Global Climate Models (GCMs). These models, developed using fundamental laws of physics, differ in the number of grid cells used to represent the land surface, atmosphere and oceans. They also differ in the way they aggregate or parameterise climatic processes in space and time. Stainforth *et al*. (2005) show the range of simulations for equally acceptable GCMs in simulating the global climate sensitivity, defined as the temperature change at a doubling of carbon dioxide concentrations. Furthermore, Prudhomme *et al*. (2003) show that future projections of water resources are very much dependent upon the choice of GCM. Many techniques such as Reliability Ensemble Averaging (REA) (Giorgi and Mearns, 2002) and the Impact Relevant Climate Prediction Index (IRCPI) (Wilby and Harris, 2006) have aimed at catering for such uncertainties in future climate. Others have sought to develop large scale modelling experiments that assess inter- and intra-model uncertainty, examples being climateprediction.net and the Coupled Model Inter-Comparison Project (CMIP) to account for uncertainty in GCMs.

While the outputs from GCMs reproduce the global and continental scale climate well, they are not so successful at higher resolutions (national. regional or local scales), the scales most appropriate for impact assessment (Wilby and Wigley, 1997). In dealing with this, limitation numerous regionalisation approaches have been developed ranging in complexity from the application of complex dynamical Regional Climate Models (RCMs), through empirical statistical downscaling to change factor analysis where changes in simulated future time series are applied to observations. Both regional climate modelling and statistical downscaling have been the most widely applied with pros and cons associated with each; most notably the computational costs and data demands of RCMs and the assumption that statistical links between local and large scale climatic variables will remain consistent under future, changed climate conditions. No one method has emerged as the optimum, as all approaches are subject to considerable assumptions.

Conceptual Rainfall Runoff (CRR) models have been the most widely applied models for assessing local scale hydrological impacts. Such models are characterised as simplified representations of catchment hydrology using conceptual stores to represent different components of catchment storage and response. Despite their widespread use such models are also subject to uncertainties given that they represent complex, dynamic catchment systems. Key uncertainties in the application of CRR models include input data uncertainty, particularly rainfall, as well as model state, structure and parameter uncertainty. (Beven, 2000; Gupta *et al.*, 2003).Numerous approaches have been proposed for propagating uncertainty in CRR models, most common being the Generalised Likelihood Uncertainty Estimation (GLUE) method, based on the concept of equifinality, and Bayesian Model Averaging.

The outcome of such a propagation of uncertainty throughout the modelling process is shown in Figure 2, with the largest uncertainty ranges associated with the information used for decision-making. Consequently, Hall, (2007) draws attention to the heavy criticisms proffered to the ranges of future changes presented in the IPCCs fourth assessment report, for not providing sufficient information on which to base decisions about the future and the conception that uncertainty ranges are so large as to be useless (Hall, 2007).

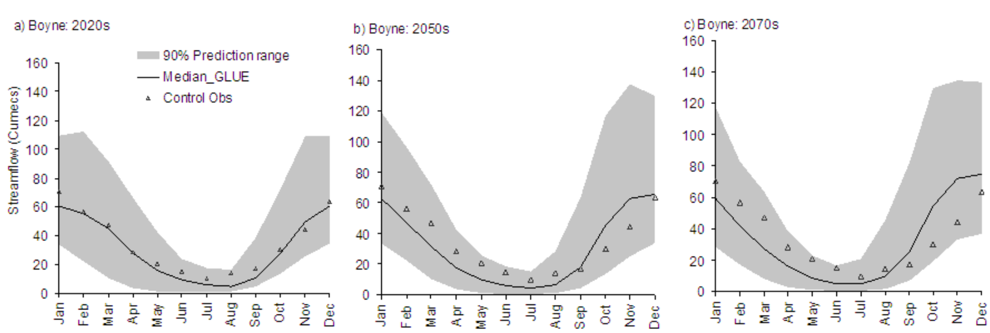

Figure 2. Uncertainty in future simulated monthly flow regimes derived from six climate scenarios and four hydrological models for the river Boyne in Ireland for three time periods (2020s, 2050s and 2080s) using Generalized Likelihood Uncertainty Estimation method (GLUE) (Bastola *et al*., unpublished).

In light of the criticisms of the scenario approach, many practitioners, particularly in the water sector, have called for probabilities to be associated with future impacts projections. However, given the uncertainties outlined above, probabilistic approaches are subject to the same difficulties as the scenario approaches presented, particularly epistemic uncertainty, and can only represent a fraction of the uncertainty space. Hall (2007) highlights that probabilistic outputs are highly conditional on the assumptions made in their construction, the models used and even the statistical methods adopted. For example, two commonly applied techniques for propagating uncertainty in hydrological models are Bayesian Model Averaging and the Generalised Likelihood Uncertainty Estimation (GLUE) method. A recent study by Bastola *et al.*, (2011) for a selection of catchments in Ireland has applied both of these approaches using the same regional climate scenarios and hydrological models as employed below and derived quite different ranges of outcomes depending on the technique used. Fundamentally, Hall (2007) highlights that the traditional use of probabilities in engineering for optimisation of performance in design is potentially dangerous in the context of climate change if the severe ambiguities in the information they present are not made transparent. Indeed, he also highlights that the calls to reduce all of the uncertainty in climate change impacts modelling to a single probability distribution function are to misrepresent and place unrealistic demands on current scientific knowledge.

As a result of uncertainties, adaptation to climate change in the water sector has been hindered by decision makers procrastinating on making commitments until either uncertainty is reduced, or until a clearer picture of which simulations are correct emerges as climate change signals become detectable within observational records. While it is agreed that early detection of climate change is essential for minimising adverse environmental and societal impacts (Ziegler *et al.*, 2005), it is becoming clear that waiting for climate change signals to emerge from records is unacceptable as an adaptation approach. As noted above, robust attribution of changes in hydrology at the catchment scale is not feasible at present. However, techniques have emerged for estimating the time horizons for formal detection of trends. Preliminary estimates using data for river basins in the US and UK suggest that statistically robust climate driven trends in seasonal runoff are unlikely to be found until at least the second half of the 21^{st} century (Zeigler *et al.*, 2005; Wilby, 2006). In such situations adaptation will have to take place in the face of uncertainty and well in advance of change being detected.

Moreover, the additive nature of uncertainties in climate change modelling and impact assessment means that it is highly unlikely that we can reduce uncertainties significantly in the time scale required for implementing adaptation options. This conclusion is supported by Dessai *et al.*, (2009) who draw attention to the fact that after in excess of twenty years intense study, the uncertainty ranges for climate sensitivity (temperature response of the global climate to a doubling of carbon dioxide levels in the atmosphere) has not been significantly reduced. In fact, the outcome of further developments in understanding key processes and feedbacks is likely to result in the opposite case where unveiling limits to our knowledge will result in further unknown processes, thereby increasing uncertainty. Recently this is evidenced by the increased uncertainty associated with sea level rise due to the discovery of previously unknown processes involved in the melting of large land based ice sheets.

6. Robust Adaptation

In spite of the adaptation challenges presented, adaptation to anticipated climate changes has to take place, as uncertainty cannot be avoided or eliminated through more research (Langsdale, 2008). The traditional framework of approaching such challenges *('predict-then-act'* framework (Lempert *et al.*, 2004)) is rooted in the assumption that the future is predictable. In this framework, different adaptation options are evaluated against probabilistic scenarios and a few options or a single optimal adaptation solution are selected with the help of evaluation criteria.

However, being confronted with deep uncertainties in a climate change vulnerability assessment, where no subjective likelihood judgments should be assigned and risk is not quantifiable; such an approach is no longer valid. Additionally, probabilistic scenarios are not capable of capturing the full uncertainty extent and therefore only represent a part of the total uncertainty (Hall, 2007). This is particularly problematic when, like in the water resource sector, extremes (low flows (droughts) and floods) are important planning components and adaptation decisions are made based on probabilities, without taking the total uncertainties into account. Not adequately considering the residuals of potential future outcomes, can result in non-appropriate adaptation decisions and may result in mal-adaptation. Hallegatte, (2009) additionally states that uncertainties in future climate change impacts are so large that traditional planning approaches, often seeking an optimum solution when designing infrastructure and other long-lived investments, are insufficient. For example, depending on the models used to predict impacts on water supply systems, the optimal adaptation strategy can differ considerably.

In such a setting, adaptation to climate change impacts is manly about dealing with uncertainties as precise climate change impacts on water supply systems are not available and will not be feasible in the near term future, making the quest for an optimum strategy infeasible. Therefore, it is important that the deep uncertainty surrounding the challenge of selecting adaptation options is communicated to decision makers, to enable them to understand and base their decisions on adaptation strategies that reflect the deep uncertainty encountered.

Consequently, new approaches other than the traditional '*predict-then*-act' or *'predict-then-adapt*' methodology to anticipatory climate change adaptation are required and need to be established. For example, Lempert and Schlesinger, (2000) suggest that adaptation strategies should be sought that are robust against a wide range of plausible climate change futures. This means that alternative future strategies need to be evaluated against a wide range of plausible futures to determine those that are insensitive to future uncertainties. Adder *et al.*, (2005) also identify robustness to uncertainty as one of the two key indicators of effectiveness of an adaptation option, besides the flexibility or the ability of a system to respond to changes. Possible adaptation strategies that improve robustness to uncertainties and challenges presented before have been highlighted in international literature. A review of the some leading papers in this area highlights some important characteristics of robust adaptation options as follows (Fankhauser *et al.*, 1999; Lempert and Schlesinger, 2000; Adger *et al.*, 2005; Hallegatte, 2009; Wilby and Dessai, 2010).

Development Path Independency

Measures taken do not compromise other future adaptation options.

Economic Efficiency

Adaptation measure that result in benefits, which exceed the costs. However, non-monetary benefits are often difficult to relate to costs (Adger *et al.*, 2005).

Flexibility and Reversibility

According to Adger *et al.*, (2005) two key indicators of effectiveness of an adaptation option are flexibility and reversibility. These indictors need to be considered when planning for adaptation measures. Flexible and/or reversible adaptation measures are dynamic by design to allow changes or to withdraw the adaptation strategy, as new climate change information evolves or when boundary conditions change.

Functional under Wide Uncertainty Ranges

Uncertain futures require robust adaptation strategies that aim to be insensitive to the wide range of climate change uncertainties. Robustness to uncertainty is one of the key indicators of the effectiveness of an adaptation action (Dessai and Hume, 2007). Robustness to uncertainty helps to ensure benefits and satisfactory performance under various future presumptions and scenarios.

Low/No-Regrets

Adaptation options with low implementation costs that are projected to have large benefit under various future scenarios. The Low or no-regrets adaptation criterion is important for infrastructural development considerations. No-regrets measurements are cost-effective and effective under current and projected climate given their long life design (Hallegatte, 2009.)

Reduced Decision Horizon

Lifetime reduction and therefore cost reduction of possible climate change vulnerable projects (Fankhauser *et al.*, 1999, Hallegatte, 2009)

Safety Margins

Strategies that can reduce climate change vulnerability by adding extra safety margins at null or low costs in current infrastructure or allow for easy retrofitting (Hallegatte, 2009).

Win-Win

Adaptation to climate change requires the implementation of management options and policies that reduce the vulnerabilities caused by climate change, but also offer the most benefits from changed conditions.

The key to identify robust adaptations strategies, which are both insensitive to specific future states of the system and are beneficial under a wide range of possible futures, is a paradigm shift away from the '*predict-then-act'* approach. As an alternative, the '*assess-risk-of-policy'* approach (Lempert *et al.*, 2004) overcomes the need to assign (subjective) probabilities to climate change and model outputs, as this approach does not aim to identify the optimum adaptation solution. Instead, a robust decision making framework aims to assess the robustness to uncertainty of a wide range of adaptation actions, without any likelihood judgment attached to them. Such decision making is mainly coherent with established optimum seeking analysis, but the traditional assessment order of uncertainty assessment and adaptation decision is reversed (Groves and Lempert, 2007). Thus robust approaches have often been characterised as bottom up assessments, in contrast to the top-down '*predict-then-act'* approach.

Bottom-up approaches begin with an identification of vulnerabilities. If vulnerabilities exist, the consideration of future adaptation options becomes necessary. In the robust decision making framework, an inventory of different adaptation options is compiled (see paragraph 5). Then through an exploratory modelling approach, the performance of selected adaptation measures is appraised against a wide range of future scenarios (Wilby and Dessai, 2010), with the aim of finding strategies which perform well and are insensitive to the most significant uncertainties. Whereas, the traditional top-down approach examines the variability of model outcomes against different (uncertain) input variables and ranks the options according to their performance. A robust decision making framework also has an iterative and flexible component, which evolves over time in response to emergence of new information or scenarios ensuring adaptivity of adaptation decisions.

Adaptation strategies have to be evaluated regularly according to the newest knowledge available and reconsidered if necessary. This ensures flexibility and the ability to respond to changes, to ensure that future adaptation options are not development path dependent and constrained by previous adaptation decisions, reducing the risk of mal-adaptation. Matthews and Le Quesne, (2009) therefore support the application of a process-oriented "vulnerability thinking" instead of "impacts thinking" approach in adaptation planning. A vulnerability thinking approach combines flexibility of planning over longer time horizons and monitoring with adaptive management, recognising the uncertainty in projected future hydrological changes.

It needs to be noted that different water supply systems might show a different degree of sensitivity to different uncertainties in climate change and hydrology models. Therefore, an individual exploratory modelling approach to identify robust adaptation options for each water supply system might be necessary. This is especially important, as climate change is only one of several factors and it is difficult to separate climate change adaptation decisions or actions from actions triggered by other social or economic events (Adger *et al.*, 2005). Therefore, robustness (insensitivity) to key uncertainties needs to be implemented as an important criterion for adaptation strategy decision making.

7. Some Best Practice Case Studies

In meeting the challenges of uncertainty, a number of approaches are emerging within the international literature, which are showing significant potential. In relation to engineering safety margins into the design of new infrastructure, Prudhomme *et al.*, (2010) have developed a novel framework for undertaking climate change impact studies, which can be used for testing the robustness of precautionary climate change allowances used in engineering design. In analysing the functionality of the UK Governments 20% increase on peak flows strategy, the authors employ a change factor analysis of the IPCC AR4 GCMs and the UKCP09 RCMs to analyse the sensitivity of catchment responses to a plausible range of climate changes. By combining current understanding of likelihood of the climate change hazard with knowledge of the sensitivity of a given catchment, as indicated by its response signal, Prudhomme *et al.*, (2010) contend that it is possible to evaluate the fraction of climate model projections that would not be accommodated by specified safety margins. This approach enables rapid appraisal of existing or new precautionary allowances for a set of climate change projections, but also for any new set of climate change projections for example arising from a new generation of climate models as soon as they are available, or when focusing on a different planning time horizon, without the need for undertaking a new climate change impact analysis with the new scenarios.

In Ireland, Hall and Murphy, (2010) using measures of vulnerability of public water supply infrastructure and the use of natural resources have produced a vulnerability analysis of future public water supply for the Moy catchment over the coming decades by accounting for the design capacity of current infrastructure, population growth, changing patterns of water demand and usage. Where vulnerability hotspots were found to exist potential adaptation options were screened for robustness using exploratory modelling to assess the robustness and functionality of adaptation options identified for the catchment. In the case of the Moy catchment, a realistic reduction of losses from leaking water infrastructure greatly reduced the vulnerability identified under all climate scenarios investigated up to mid century; a low regret strategy that is robust to uncertainty (Hall and Murphy, 2010).

In a similar study of the Wimbleball water resource zone in southwest England, Lopez *et al.*, (2009) used the ensemble of the ClimatePrediction.net experiment to test the performance of different adaptation options under climate change. By analyzing the frequency of failures to meet peak water demand it was concluded that the previously identified option of increasing reservoir capacity was not enough to tackle successive dry years and that demand reduction measures were also needed (Lopez *et al.*, 2009).

Evident from these studies is that adaptation measures have to be context specific, as one set of adaptation options may work in one region but may not be applicable in another. Adaptation has to be planned and implemented on international (for trans-boundary river basins), national and regional (basin) level. National planning and water management at the river basin scale can help to understand current and future vulnerabilities and insufficiencies which need to be recognised and subsequently addressed (Stakhiv, 1998). Individual river basins are the level at which detailed adaptation plans have to be implemented. The fine-tuning of these plans ideally takes place with a broad range of stakeholder involvement, to ensure that all possible options are considered. With stakeholder involvement, adaptation can allow water users to influence the adaptation process, enhancing the likelihood of success. However, formulating a final adaptation strategy remains complicated because of the number actors involved as well as range of measures available. The definition of the criteria for success of an adaptation strategy is always context specific and final decisions can always be argued (Dessai and Hume, 2007).

8. A Closer Look at Robust Adaptation to Climate Change: a Case Study from Ireland

The case study presented in this chapter is based on the assumption that the deep uncertainties in climate change and hydrological modelling are not quantifiable and therefore have no likelihood judgement (subjective probabilities) attached. Therefore, a robust decision making framework is applied aiming to assess the robustness to uncertainty of adaptation options through an exploratory modelling approach.

The application of a robust adaptation decision making framework is presented using the case study of the Boyne catchment's water supply system in the east of Ireland (Figure 3). Ireland has a moist, temperate, maritime climate, mainly influenced by the moderating influence of the Atlantic Ocean and the Gulf Stream's northern extension towards Europe, the North Atlantic Drift, which carries warm water towards the coast of Ireland. Climate data from the synoptic station at Mullingar is used to drive the Boyne catchments hydrology. The 30 year-annual average climatology (1961-1990) is about 931mm for precipitation and 8.8° C mean temperature (Met Éireann, 2010).

In Ireland, the majority of public drinking water (83.7%) originates from surface water (abstractions from rivers and lakes) (EPA, 2009). As surface water abstractions are directly influenced by changes in catchment hydrology induced by a changing climate and are the bulk source of drinking water, this case study focuses on river abstractions in the Boyne Catchment. The six surface water abstraction points shown in Table 2, are assessed to identify their vulnerability to climate change and if vulnerability is indicated, the robustness of adaptation options is assessed.

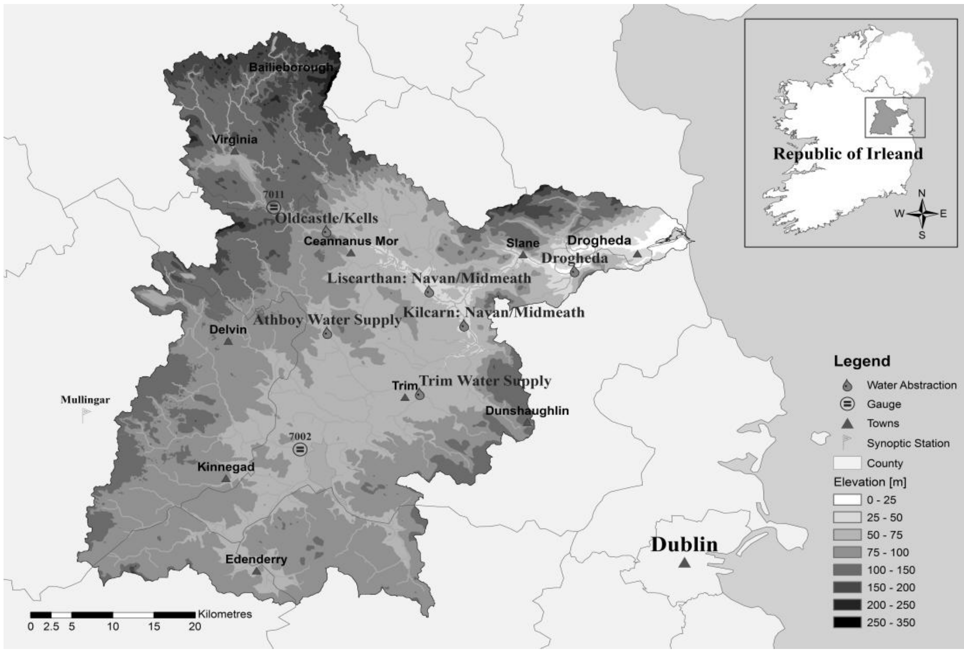

Figure 3. Study Area - The Boyne Catchment. Including Water Abstractions, Stream flow Gauges, Synoptic Stations, Towns and Catchment Elevation.

Table 2. Boyne Catchment Surface Abstractions studied and Water Supply Information (CDM, 2009, EPA, 2009)

Scheme Name	Scheme Code	Population Served	Volume (m^3/day)
Athboy Water Supply	2300PUB1001	3000	2200
Drogheda	2100PUB1019	23077	27692
Kilcarn: Navan/Midmeath	2300PUB1016	5600	2800
Liscarthan: Navan/Midmeath	2300PUB1016	22400	11200
Oldcastle / Kells	2300PUB1011	2024	1447
Trim Water Supply	2300PUB1009	8000	3200

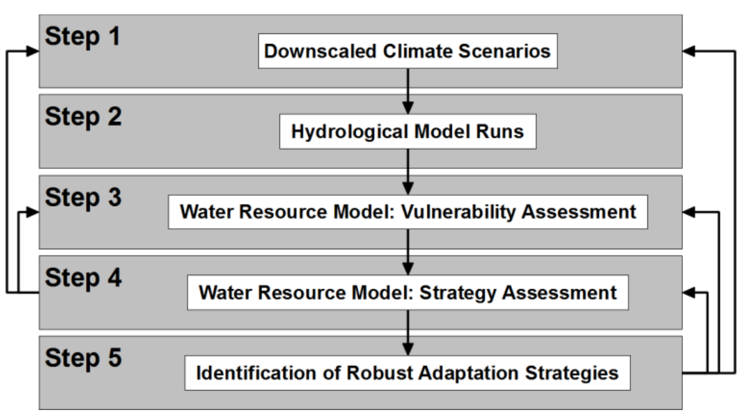

Figure 4. Flow chart of the case study modelling approach.

A stepwise modelling approach is applied (Figure 4) aiming to incorporate uncertainties from climate and hydrological models into the robust decision making framework.

Step 1: Regional climate scenarios for Ireland were derived from a combination of two greenhouse gas emission scenarios (A2 and B2) and statistically downscaled output from three Global Climate Models (GCM) (HadCM3, CCCma and CSIRO) which were modelled in previous research (see Fealy and Sweeney, 2007 and Fealy and Sweeney, 2008 for details) to incorporate climate model uncertainty.

Step 2: To additionally include hydrological model structure and parametric (model parameters) uncertainty, 500 Monte Carlo sampled behavioural hydrological model runs (generated with the Hydrological Simulation Model (HYSIM)) are driven by the six climate scenarios of step 1 for two future time slices: the *2020s* (average of 2010-2039), *2050s* (2040-2069). This approach increases the possible uncertainty space from six plausible futures (if only one hydrological future is modelled) to an ensemble of 3,000 possible future hydrological time series.

Step 3: Vulnerability assessment of the water supply system with the help of a water resource model (Water Evaluation and Planning model Version 21 (WEAP21) Yates *et al.*, 2005). The current features of water supply systems in the catchment are extrapolated into the future (Business as Usual-Scenario (BAU)). The performance of the system is assessed under the range of future hydrological conditions (3,000 plausible futures) generated in step 2.

Step 4: Where vulnerability under the BAU-Scenario exists, the key steps in the robust decision making framework, step four and five, are modelled. In step four different adaptation options are modelled and these strategies are assessed with regard to their robustness to uncertainty over the wide range of hydrological scenarios.

Step 5: The final step in this modelling approach involves the identification of robust adaptation strategies, which function well across the wide range of possible future hydrological scenarios, according to the performance measures selected. Robust adaptation strategies can then result in an adaptation option/policy options. The identified adaptation measures are flexible and can be revised as soon as new criteria are selected, new scenarios emerge or the characteristic of the water resource system change.

The following section focuses on the detailed assessment of step three to step five.

Step 3: Vulnerability Assessment

To assess the vulnerability of the water supply systems in the Boyne catchment, with the help of a water resource model, current characteristics of the system are extrapolated into the future as follows. The future *Business-As-Usual (BAU)* scenario for the water supply systems is based on the population growth rate projections from the Irish Central Statistics Office's (CSO) Report on *Population and Labour Force Projections* (CSO, 2008), the estimates of unaccounted for water (leakage) are derived from the *Assessment of water and waste water services for enterprise* (Forfás, 2008).

Scenario A —'Business as Usual'. The population of 2008 of the water supply system is extrapolated into the future using the projected annual average change of the CSO. The per capita water abstractions and the supply infrastructure remain constant. The amount of unaccounted for water (water lost through leakage) is of the national average of 43%.

The vulnerability of the water abstraction points is assessed using the Water Use-to-Resource Ratio (URR) (Raskin, 1997).The URR vulnerability measure is used to determine a quantitative indication of the pressure (water stress) imposed on the water supply system. This physical vulnerability index is the ratio of the water used (withdraws) to the available water supply on average (Raskin, 1997 and Arnell, 1999), and provides a local index of water stress (Vörösmarty *et al.*, 2000). The original URR-index is adjusted to the Irish water resource context, where on average over 80% of municipal water abstractions are taken from surface water with pronounced seasonality of water availability, and no water storage facilities. To take these characteristics of the Irish water supply system into account, the original URR-index is refined using monthly totals, compared to the original index which is calculated on an annual basis, (Hall and Murphy, 2010).

The URR-index is divided into four *Water Stress* classes, ranging from *No Water Stress* to *High Water Stress,* as shown in Table 3. A ratio of withdrawal to available water resources greater than 20% can 'begin to be a limiting factor for economic development', whereas the other stress classes are literature-based estimates by Raskin (1997).

Table 3. Monthly Water Use-to-Resource Ratio (URR) Classes (adapted from Raskin, 1997)

URR	<10%	10%–20%	20%–40%	>40%
Classification	No Stress	Low Stress	Medium Stress	High Stress

In the case study area, vulnerability is analysed for each abstraction point individually, using 3,000 future hydrology scenarios previously created in step two. Monthly URR indices are calculated and then analysed over seasonal periods (Winter (Dec, Jan, Feb), Spring (Mar, Apr, May), Summer (Jun, Jul. Aug), Autumn (Sep, Oct Nov)).

Vulnerability under the BAU-Scenario

The water abstractions at Drogheda, Kells and Liscarthan indicate various levels of Water stress. Figure 6 shows the Water Use-to-Resource Ratio for the summer and autumn season and for the abstraction points indicating *Water Stress.* The 3,000 model runs are presented using violin plots, which show the kernel density of the data at different values (similar to a histogram), and a marker for the median of the data at that time step. In summer and autumn, Drogheda Water Supply URR values ranging from *No Water Stress* to *Water Stress*, whereas for Kells and Liscarthan all *Water Stress Classes* are present. In winter and spring, all simulations for Drogheda, Kells and Liscarthan remain below the *Low Water Stress* threshold. The only exception was the year 2055 (not shown) where some simulations of the Kells and Liscarthan water supply system indicate *Low Water Stress* in spring. The remaining water abstraction points do not indicate any vulnerability (water stress) under the future simulations of the Business-As-Usual Scenario and are not included in any further analysis.

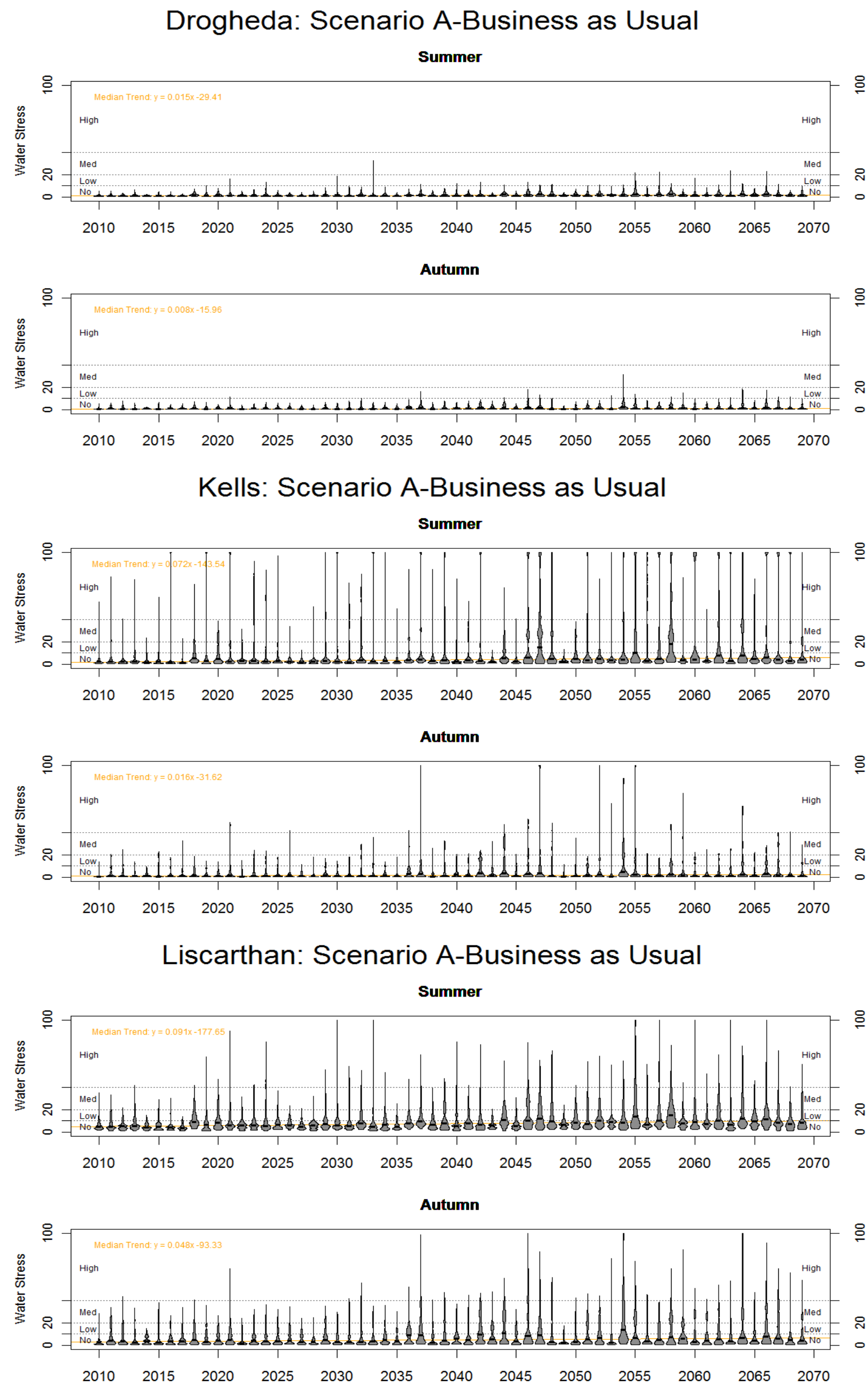

Figure 6. Use-to-Resource Ratio (URR)-Analysis (with median trend line) of abstraction points, in the *Low*, *Medium* or *High Water Stress Category*.

Step 4: Adaptation Strategy Assessment

For presentation purposes, only the results for the abstraction of the Kells water supply, which indicates the highest water stress, are presented and described from this step onwards.

Three future adaptation options different to the BAU-Scenario are constructed to allow for the evaluation of water management strategies/policy into the future. In this case study, scenario thinking is used as a planning tool to test and assess the future vulnerability of different strategies used in the water resource sector. The aim is to learn about the future by understanding the vulnerability of the different water supply systems. Therefore, the water resources modelling tool (WEAP21) is not used as an optimisation tool or as a planning tool for designing future water resource systems, but rather to indicate the robustness of different adaptation options to uncertainty by exploring possible future states of the water supply system.

Here, for each adaptation strategy described below, water abstractions are based on the same assumptions described for the BAU-scenario for each water supply system individually. The four future adaptation strategy scenarios' comprise of the *'no-measure'* (BAU-scenario), a '*demand side*', a '*supply side*' and an '*integrated*' measure shown in the Scenario Matrix (Figure 5). The aims of this exploratory scenario modelling approach are to assess the vulnerability of the abstraction point, to investigate the interaction between different measures and to evaluate their robustness to uncertainty as well as to compare the impacts of climate change to other non-climatic pressures.

The following is a brief description of the scenarios and assumptions made;

- Scenario A—'*Business as Usual'*. Extrapolation of the water supply system characteristics as described above.
- Scenario B—'*Reduced Water Demand'*. Increasing water conservation measures results in a stepwise per capita water demand reduction of 5% of the 2008 value by 2020. The level of unaccounted for water remains constant at 43%.
- Scenario C—'*Reduced Leakages'*. Water supply infrastructure improvements reduce the leakage level in annual steps from 43% to 25%, by the year 2015. Leakage reduction is based on the *Department of the Environment, Heritage and Local Government (DEHLG) Water Conservation Programme* estimates (CDM, 2004). The per capita water demand persists on its 2008 level.
- Scenario D—*'Reduced Demand and Reduced Leakages'* Combination of Scenario B and Scenario C. Water demand and leakage level reductions, as described above.

Step 4 - the Adaptation Strategy Assessment - of the modelling framework is conducted, which means that the future *demand side, supply side* and *integrated strategies* (Scenario B, C and D respectively) are modelled. The three alternative strategies/scenarios selected can be characterised as "low or no regrets" and "win-win-strategies", which are able to cope with climate uncertainty and provide benefits, even in absence of climate change (Hallegatte, 2009). Therefore, in uncertain conditions their application is to be favoured over high cost, potentially high regret strategies. In the following sections, the capacity of these strategies to successfully adapt to the vulnerabilities indicated in step three is assessed.

		Per Capita Water Demand	
		Constant Water Demand At 2008 Value	**Reduced Water Demand** 5 % Reduction of 2008 Value by 2020
Leakage Level	**Leakage Constant** National Average of 43%	**Scenario A** Business as Usual	**Scenario B** Reduced Water Demand
	Leakage Reduction Stepwise up to 25% by 2015	**Scenario C** Reduced Leakage	**Scenario D** Reduced Water Demand & Leakage

Figure 5. Scenario Matrix; showing the four investigated Adaptation Strategies.

Results for the Adaptation Strategy Assessment

The outcomes of the adaption-strategy assessment show that in summer and autumn all ranges of water stress can be found within the different adaptation scenarios modelled. Generally, throughout the simulated time periods, the water Use-to-Resource Ratio (URR) increases over all adaptation scenarios (also indicated by the median trend lines). Figure 6 and 7 show that as the simulation times increase so does the spread of the simulation outcomes. This increasing spread of data over time also represents the increasing uncertainty ranges. However, when looking at individual water resource scenarios there is a significant reduction of the spread of simulation outcomes with the implementation of *demand*, *supply*, and *integrated measures* compared to BAU-Scenario *('no-measures'*). Scenario A has the highest uncertainty ranges, which are subsequently reduced in Scenario B and C resulting in a significant reduction in Scenario D. The adaptation options can be classified as robust, since the adaptation measures have an effect on the vulnerability, especially on the values different from the median and on the extremes. The median of all simulations is also influenced by the adaptation measures. For example, the median values of the BAU-Scenario (A) show a statistically significantly increasing trend (line) of water Use-to-Resource Ratio. With the reductions in water demand and leakage, the exhibited increasing trend is mitigated (compare Figure 6 with Figure 7). The same applies to the median values in autumn.

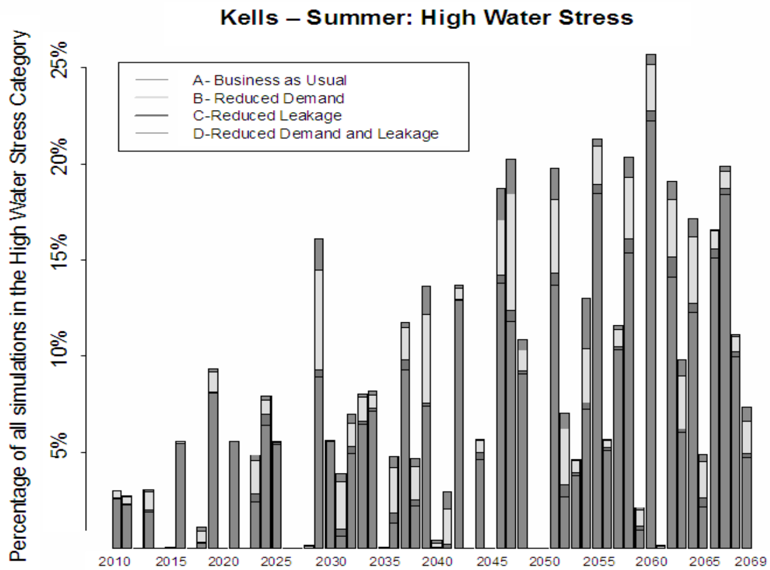

Figure 8. Kells-Summer: Percentage of all Simulations in the High Water Stress Category.

Figure 8 presents the increasing trend of the percentage of all summer simulations located in the High Water Stress Category for the Kells water supply system over the simulated time period. The effect of the different adaptation measures in reducing the amount of simulations showing high water stress is evident. However, even within Scenario D where integrated measures reduced water demand and leakage level, the percentages of simulations resulting in the High Water Stress Category are still considerably high. Especially for the water abstractions at Kells, in the time between 2049 and 2069, when 25% of the years have more than 15% of all their simulations reaching the High Water Stress Category.

Step 5: Identification of Robust Adaptation Strategies

Having completed the steps of this robust decision making framework, it can be concluded that all three adaptation measures (*demand*, *supply*, and *integrated measures*, Scenario B, C and D respectively) are robust to uncertainty, as they are all able to reduce the vulnerabilities compared to BAU- Scenario A ('*no-measures'*). However, there is an indication that the considered *No or Low Regret* water adaptations measures might not be enough to sufficiently reduce the vulnerability of the water supply system, as the W*ater Stress* levels still remain at a high level. An expansion of the inventory of the adaptation strategies considering for example additional adaptation scenarios/measures or higher water demand and leakage reduction is needed. This new menu of strategies can then again be assessed in step 4 to identify their capacity to decrease the vulnerability and increase the robustness of the investigated water supply systems.

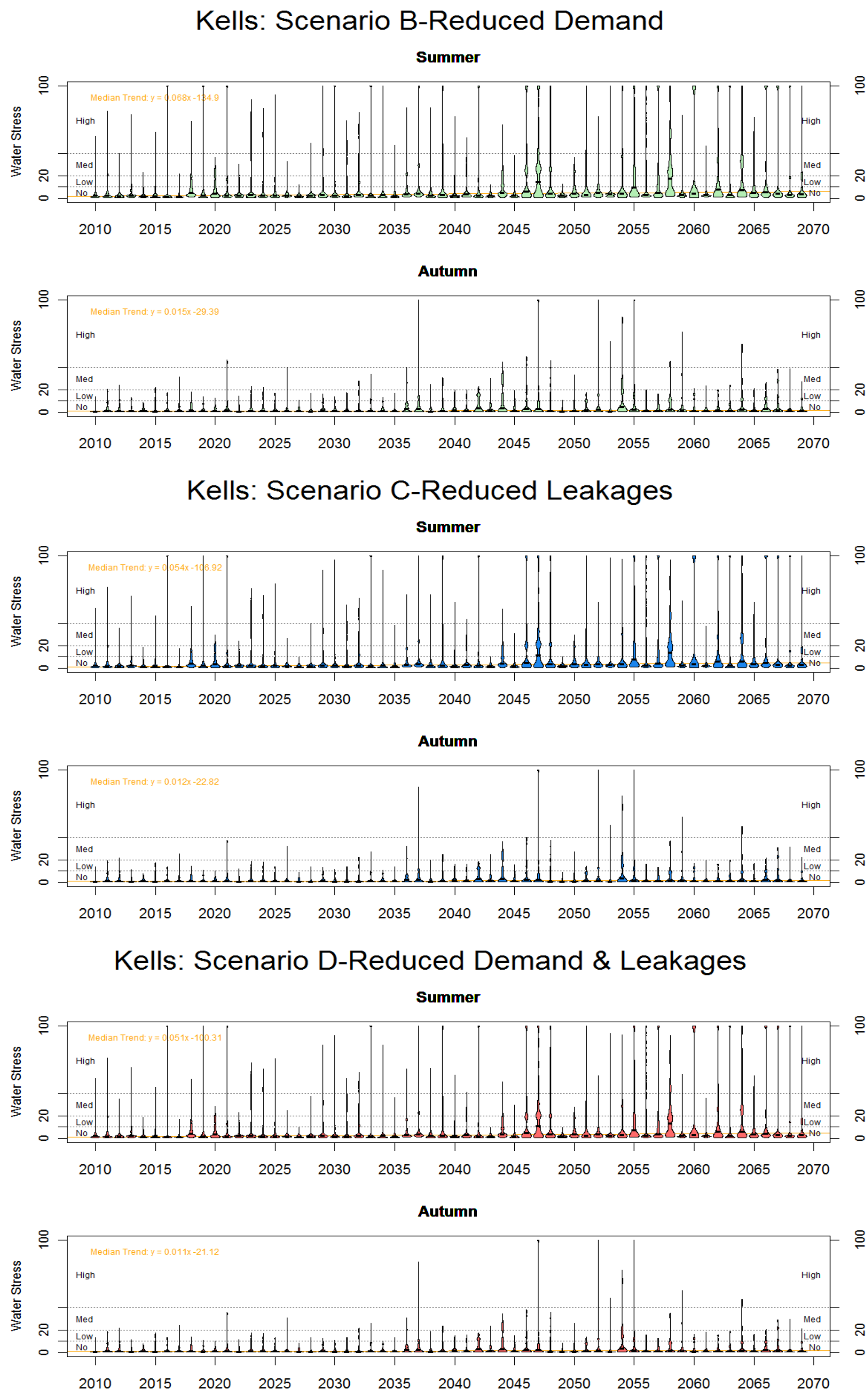

Figure 7. Kells - Adaptation Strategies: URR-Analysis (with median trend line).

Conclusion

Climate change presents significant challenges for water supply systems and their management. The results of such a change undermine the assumption of stationarity, on which adaptation in the water sector to past pressures such as population growth has been based. In addition, the future evolution of the climate system is inherently uncertain, with the likelihood of uncertainty being reduced within the timeframe needed for adaptation being small. Furthermore, the large variations in local scale hydrology and small climate change signals mean that it is unlikely that climate change signals will be statistically detected in river flows before the middle of the century. Therefore, water managers will have to engage with alternative methods for adapting to climate change. One such framework that has been gaining considerable attention in a range of sectors is robust adaptation. Under robust approaches, rather than being prescriptive, uncertain climate change scenarios are used for exploratory modelling to assess the functionality of identified adaptation strategies across the uncertainty space. These approaches offer considerable potential for progress in initiating anticipatory adaptation strategies. In the case study conducted here, an exploratory modelling framework is presented that enables the assessment of both demand and supply side options.

Looking to the future observational evidence will play a vital role in addressing uncertainties and achieving a fuller reconciliation between model-based scenarios and ground truth (Hannaford and Marsh, 2006). Hydrological monitoring programmes have an essential role to play in acquiring the hydrological data necessary to characterise variability and discern any emerging trends, while the identification and interpretation of these trends is a necessary foundation for the development of appropriate water policy and management responses to climate driven changes (Hannaford and Marsh, 2006) effecting the water supply sector.

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