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Examination of climate risk using a modified uncertainty matrix framework—Applications in the water sector

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ABSTRACT

Previous climate risk assessments provide important methodological insights into how to derive tractable research questions and the appropriate use of data under uncertainty, as well as identifying steps that benefit from stakeholder involvement. Here we propose the use of a framework for the systematic and objective exploration of climate risk assessments. The matrix facilitates a breakdown of information about aim and context, main results, methodological choices, stakeholder involvement, sources and characteristics of uncertainties and overall weaknesses. We then apply the matrix to three risk assessments in the water sector to explore some methodological strengths and weaknesses of approaches strongly linked to climate model outputs (top-down) versus those that originate from local knowledge of climate exposures (bottom-up), and demonstrate that closer integration with social and physical sciences is more likely to yield robust climate risk assessments.

1. Introduction

Projected anthropogenic climate change could challenge current freshwater management practices (e.g., Wei et al., 2011), and has stimulated much research into different strategies for managing impacts on current hydrological regimes including changes to socio-economic pressures (e.g., Posey, 2009; Pandey et al., 2011). Whilst the physical component of water systems has received greater attention in climate change impact assessments, there is an urgent "need to look deeper into management systems to uncover the full array of costs and risks relevant to successful water delivery" (Dow et al., 2007, p. 236). This demands a shift of focus to the social dimensions of water management, or at least considering decision frameworks that are less dependent on climate change data when adapting to change (Dessai et al., 2009a; Beven, 2011).

Wilby et al. (2009) call for a twin-track approach involving development of: (i) scientific and economic capacity to identify critical thresholds leading to improved understanding and adaption to climate variability, and; (ii) climate scenario tools and data sets that reveal the longer-term changes in climate risk to inform adaptation planning. This echoes views found in the climate change vulnerability literature, where assessments are tending to move from science-driven assessments (impact-orientated research to enlighten mitigation policy) to policy-driven assessments (that identify options for adaptation policy) (Füssel and Klein, 2006).

The concept of *adaptive capacity* is extensively used in the climate change vulnerability and resilience literature albeit with different connotations. In the former case, the term refers to one of three dimensions that define vulnerability: 'exposure' and 'sensitivity' relate to climatic risks, and 'adaptive capacity' overcomes those risks (Ford, 2007, p. 11). Hence, adaptive capacity has a positive meaning. Conversely, in the resilience literature, adaptive capacity may be defined as a property that facilitates transformation of a system into a new state, which could be more or less desirable. In this case, adaptive capacity has a more complex meaning (e.g., Engle, 2011; Smit and Wandel, 2006). In this paper, we refer to the definition of adaptive capacity used by the Intergovernmental Panel on Climate Change (IPCC): "*The ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of*

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opportunities, or to cope with the consequences" (IPCC, 2007, p. 869). This is most closely aligned with the vulnerability perspective.

By considering adaptive capacity, vulnerability assessments can examine those factors that influence a system's ability to modify behaviour to better cope with external pressures, such as climate change. Füssel and Klein (2006) consider two types of adaptation activities: *facilitation* and *implementation;* both of which aim to reduce system vulnerability. The former refers to activities that enhance adaptive capacity (such as scientific research, data collection, awareness raising, capacity building, institutions and governance, information networks, and legal frameworks). The latter refers to activities that enable a system to reduce exposure or sensitivity to climatic hazards or alleviate non-climatic pressures. Information about both types of adaptation activity is meaningful to stakeholders in water management, but is difficult to elucidate in a model-driven impact approach. Furthermore, a focus solely on model-impact responses ignores contributions from non-climatic factors (such as agricultural practices, land-use change, new infrastructure, river regulation, areal and point pollutant discharges) to the outcomes of climate change (Bates et al., 2008).

Although the benefits of integrated approaches to climate risk assessment are increasingly recognised (i.e., using both impact and vulnerability information), historically the impact dimension has received more attention. This raises expectations that scientists should be providing projections of climate impacts at regional scales. Some climate and hydrological models produce high-resolution output at catchment scales but there is low confidence in the accuracy of such information. For example, in order to achieve high resolution, the United Kingdom (UK) Climate Impacts Programme 2002 (UKCIP02) scenarios were based on a single climate model, so were unable to quantify attendant uncertainties (Gawith et al., 2009), a weakness that was largely corrected in the subsequent probabilistic climate change projections for the UK (UKCIP09, http://ukclimateprojections.defra.gov.uk). Indeed, Knutti et al. (2010) assert that if model uncertainties are not well characterised in climate risk assessments, their usefulness is questionable.

The first step in understanding the value of a climate risk assessment is to describe the study design and associated uncertainties. Following Walker et al. (2003) we propose a modified version of their 'uncertainty matrix'. The matrix was designed as a tool for systematic uncertainty analysis in regulatory and management sciences and has proved to be a useful platform for communicating uncertainties amongst model operators, policy makers and stakeholders (Refsgaard et al., 2007). Here we combine core aspects of the uncertainty matrix with other descriptors to provide a framework with which to classify climate risk assessments. Key features of the matrix are descriptors of: (i) the context of the assessment (aim and main policy focus); (ii) theoretical strengths and weaknesses, including characteristics of uncertainties; (iii) level of integration of natural and social sciences through methodology choices; (iv) stakeholder involvement (how and when). To distinguish between the two versions, we refer to our framework as the 'climate risk matrix'.

The climate risk matrix is not a climate risk assessment framework, rather it offers a framework with which decision makers can evaluate the robustness of available climate risk information. For example, it can be used as a communication tool in collaboration with stakeholders when discussing the most appropriate pathway for addressing a particular climate threat, or as an information summary framework for distributors of climate change data to illustrate how different climate change data sets complement each other in terms of strengths and weaknesses. Risk assessment frameworks on the other hand, attempt to detail the risk characteristics of an adverse event, such as its nature, likelihood, severity and reversibility or preventability (USPCC RARM, 1997). Jones (2001) proposed a framework for risk assessments within a climate change context, involving the calculation of conditional probabilities for exceeding particular impact thresholds as agreed upon between researchers and stakeholders - the thresholds being either of the biophysical world or ones whose exceedance could trigger behavioural change. Others have proposed risk assessment frameworks for specific events such as flood frequency (Raff et al., 2009) or land-slides (Aaheim et al., 2010) in the context of climate change.

The following sections apply the climate risk matrix to three water sector studies intended to raise preparedness for climate change. The examples were chosen on the basis of differences in their methodology, context, and availability of data–providing useful tests of the versatility of the framework under varied circumstances. The next section provides a summary of the methodologies commonly used in climate risk assessments. Section 3 then describes the climate risk matrix in more detail, before outlining the three water case studies in Section 4. Section 5 evaluates the extent to which our matrix adds useful insights, and Section 6 provides concluding remarks and opportunities for future research.

2. Climate risk assessments

Climate risk assessments typically employ one or more IPCC scenarios to describe plausible future states of the world (IPCC, 2007). These scenarios define the rates of greenhouse gas emissions and corresponding global climate responses, as simulated by coupled Atmosphere-Ocean General Circulation Models (AOGCMs). The IPCC Task Group on data and scenario support for Impact and Climate Assessment (TGICA) describe two complementary pathways for applying AOGCM output in climate impact and adaptation assessment: "*. . . a top-down approach involving the interpretation and downscaling of global-scale scenarios to regional level, and a bottom-up approach, that builds scenarios by aggregating from the local to regional scales*" (IPCC-TGICA, 2007, p. 4).

Downscaling techniques translate coarse-resolution AOGCM output (typically on scales of 100–300 km) into higher resolution outputs, or even point estimates, over defined domains (Fowler et al., 2007a). Downscaling methods are conventionally described as either statistical or dynamical. The former are founded on empirical relationships between large scale atmospheric predictor variables and local surface variables. The latter involve the use of a Regional Climate Model (RCM) to simulate the climate over a limited spatial domain but at a higher spatial resolution than the host AOGCM. Having obtained local or regional scale climate scenarios (whether by statistical or dynamical means), the next step is to apply an impact (e.g., rainfall-runoff) model to assess potential hydrological responses to regional climate change. In most climate risk studies, only the impact modelling, or the downscaling and impact modelling are conducted in house, as AOGCM experiments require significant computing resources.

The top-down approach is largely model driven and intrinsically linked to global emissions scenarios, whereas the bottom-up approach focuses on local scales, and often requires geographically explicit information. Smit and Wandel (2006) characterise bottom-up approaches as those where variables that represent exposure to climate change are sought empirically from the community rather than presumed by the researcher. They further note that the bottom-up approach "*. . . employs the experience and knowledge of community members to characterize pertinent conditions, community sensitivities, adaptive strategies, and decision-making process related to adaptive capacity or resilience. . .*" and "*. . . identifies and documents the decision-making process into which adaptations to climate change can be integrated*" (Smit and Wandel (2006, p. 285). Thus, understanding the system at risk is central to the bottom-up approach and the basis for evaluating appropriate pathways for action.

A major limitation of top-down approaches is the compounding epistemic (knowledge-related) and/or stochastic uncertainty at each step. Schneider (1983) described this conceptually as a 'cascading pyramid of uncertainties'; a construct that has been developed by later authors. For example, Giorgi (2005) adds interactions and feedbacks within the model steps, as well as inter-linkages between the sources of uncertainty and the policy responses (on adaptation or mitigation). Characterisation of these uncertainties is non-trivial, but increasing computer power enables the generation of large ensembles of different AOGCMs structures (e.g., Tebaldi and Knutti, 2007) and/or perturbed-physics experiments (e.g., Stainforth et al., 2005). Similarly, ensembles of different impact model structures and parameter sets have also been constructed (e.g., Wilby and Harris, 2006). Whilst the AOGCM is generally regarded as the main source of uncertainty in top-down approaches (Fowler and Ekström, 2009), uncertainty due to choice of downscaling method(s) can be of comparable magnitude (e.g., Chen et al., 2011). Indeed, some assert that higher precision from downscaling does not necessarily translate into higher accuracy; therefore RCMs are best used for evaluating sensitivity to climate risks or improving process understanding (Dessai et al., 2009b; Pielke Sr and Wilby, 2012).

Bottom-up approaches are less dependent on outputs from AOGCMs, but are exposed to other method-related uncertainties. Work typically begins by establishing the context and defining the assessment goals, then by identifying current risk exposures, sensitivities and adaptive capacity using semi-structured interviews, participant observation, focus groups, information from local stakeholders, and published and un-published literature (Smit and Wandel, 2006; Johnson and Weaver, 2009). Having established current risk exposures of the community, information from other scientists, policy analysts and decision-makers can be integrated into the analysis to identify what future risks the community may face and how they plan to respond. The methods favoured by bottom-up studies are also subject to epistemic uncertainty as well as to linguistic uncertainties (ambiguity, interdeterminacy, under-specificity, vagueness, context dependencies), and uncertainty due to variability in the data assessed or population sampled (Hayes, 2011). Additionally, methods for ranking climatic risks and prioritising adaptation strategies may not be robust.

Top-down and bottom-up approaches have their respective strengths and weaknesses but there are only a few studies where they have been combined. For example, Brown et al. (2012) applied a 'decision-scaling' method that introduces climate model output towards the end of the analysis to assess the likelihood of exceeding identified thresholds or different adaptation pathways. The Global Change of the Water Cycle (GLOWA) Danube project is a practical example of a modelling framework that considers both physical and social responses of domestic water consumption to climate change (Barthel et al., 2008; Soboll et al., 2011). Central to the programme is the simulation framework DANUBIA which links 16 natural and social science models (Soboll et al., 2011).

Barthel et al. (2008) suggest that it is necessary to simulate both physical and social processes because (i) consumers adapt their consumption with decreasing resources (saving water), (ii) water suppliers may increase resources by merging resources from different catchments, or, (iii) the number of consumers might decrease because water intensive industries close down. The primary purpose of the modelling is to identify interdependencies between relevant processes rather than management solutions per se. Value lies in raising awareness of how natural and social systems interact and in elucidating costs to natural systems (Barthel et al., 2008). For example, using three multi-agent models embedded in DANUBIA (Water Supply, Household and Tourism), Soboll et al. (2011) show feedbacks between different water users and the environment under climate change scenarios and help show the extent to which interventions could become necessary in the future. However, this level of analysis is generally not feasible for most organisations due to the substantial data demands and complexity of a multidisciplinary modelling infrastructure. Furthermore, human responses (and their consequences for the environment) are not readily incorporated into climate change impact studies and are thus ignored in most water-focused scenarios.

3. Defining a climate risk matrix

When constructing a model it is often necessary to make simplifying assumptions, even when there is sound understanding about the underlying processes (Brugnach et al., 2008). Hence, models can incorporate and manifest uncertainties in many different ways. Walker et al. (2003, p. 15) provide a tool that helps to "*... identify, estimate, assess and prioritise all important contributions to uncertainty associated with the outcome of interest in a systematic manner*". In their original matrix, uncertainty was defined as "*any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system*" (Walker et al., 2003, p. 5) and can be characterised by its: (i) *location* – where uncertainty manifests itself within the model system; (ii) *level* – a spectrum ranging between deterministic knowledge to total ignorance, and; (iii) *nature* – whether uncertainty is due to imperfect knowledge or the inherent variability of the phenomena being described.

Each uncertainty dimension can be sub-divided. 'Location' uncertainty can be classed as: context, input data, model structure, model technical and parameters (Walker et al., 2003). 'Context' refers to factors outside the model boundary that affect the results such as choice of model type or physical boundary conditions. 'Input data' uncertainties reflect measurement error or spatial and temporal patchiness in data used to drive the model. For the purpose of climate risk assessments, we broaden 'input' to include information provided via surveys or interviews. 'Model structure' and 'model technical' refer to the mathematical algorithms and numerical aspects of the software used to describe the mathematical relationships. 'Parameters' refer to uncertainty in definition or derivation of model parameters.

The second dimension classifies the 'level' of uncertainty as: statistical, scenario, qualitative, or recognised ignorance (Walker et al., 2003). The 'statistical' level is assigned to uncertainties that can be expressed numerically, such as probabilities. 'Scenario' captures uncertainties that reflect different outcomes but, unlike the statistical level, cannot be quantified. 'Qualitative' uncertainty refers to uncertainties that are expressed in terms of expert opinion: linguistic probabilities. 'Recognised ignorance' is used when it is impossible to assign a value to the uncertainty.

The third dimension describes the 'nature' of the uncertainty, classed as: epistemic, natural variability or ambiguity (Walker et al., 2003; Warmink et al., 2010). 'Epistemic' uncertainty results from imperfections in knowledge whilst natural variability implies variance due to the chaotic nature of natural systems. 'Ambiguity' is used to describe the situation when there are many equally valid choices of method or model. Whilst Walker et al. (2003) included ambiguity as part of epistemic uncertainty – implying that it can be reduced through more research –, Warmink et al. (2010) treated ambiguity as a separate class, recognising that in management practise, decision making often has to deal with situations where there is no universally accepted truth. Here, we apply the definition of Warmink et al. (2010), but broaden it to include how different people may understand information (such as how an interviewee interprets the questions and how the interviewer interprets the responses).

The uncertainty matrix details the location, level and nature of each study element. However, this approach is not feasible for climate risk assessments as the sheer number of uncertainties would render the matrix too cumbersome to use. Furthermore, researchers or stakeholders could find it difficult to correctly identify each source of uncertainty. Instead, we reduce the level of detail and provide a list of those factors (e.g., models, methods or data) that are associated with each dimensional class. For example, in a top-down approach the IPCC story lines could be considered as contextual uncertainties. The matrix then provides a general overview of what types of uncertainties are associated with each study without being swamped by detail.

In climate risk assessments, other types of information may be relevant, such as the specific aim(s) of the assessment, the circumstances under which the study was conducted, and any important caveats. In our climate risk matrix these are recorded under the descriptors 'Aim and genesis' and 'Recognised weaknesses'. Following Füssel and Klein (2006) we also capture the stages of climate change vulnerability assessments under: 'Main policy focus', 'Main results', 'Time horizon', 'Spatial scale', 'Analytical approach', 'Consideration of climate variability, non-climatic factors and adaptation', 'Consideration of uncertainties', 'Integration of natural and social sciences' and 'Degree of stakeholder involvement'. To classify how future climate change data were derived (e.g., via downscaling or re-sampling of previous historical events), how exposures investigated in the climate risk assessment were chosen (by the researcher with/or after an investigative-exercise) and how the particular impacts on the system or decisions at focus were conducted (e.g., qualitative or quantitative methods) we also apply the three titles 'Methodology used to derive climate change scenario data', 'Methodology used to identify climate exposures' and 'Methodology used to identify system or decision sensitivities' respectively. The organisation of the different elements into a matrix can be viewed in our Table 3.

4. Water sector studies explored in the climate risk matrix

Three studies were selected to test the ability of the climate risk matrix to elucidate strengths and weaknesses associated with the different assessment approaches. These studies are broadly representative of those with (i) heavy, (ii) moderate, and (iii) no reliance on climate change data. Furthermore, the chosen studies represent different geographical environments and hydrological challenges. Since all three studies are previously published, only brief summaries are given about the context, methodology and results; greater attention is paid to key outcomes. In Section 5, the three studies are explored using the climate risk matrix.

4.1. Study 1: adapting to increasing flood risks in the United Kingdom

The first study refers to an evaluation of when changes in UK extreme rainfall might be detectable and the extent to which precautionary allowances for flood risk are robust to projections of climate change. The work was commissioned by the Environment Agency and partly supported by a Research Council fellowship; the full methodology and results are described by Fowler and Wilby (2010).

4.1.1. Context

Following the summer 2007 flooding, the UK Government increased annual budgets for flood risk management to £800 million by 2010. Inevitably, higher spending on flood defence infrastructure prompted questions about *when* and *where* to prioritise the investment. Fowler and Wilby (2010) raised two related questions. First: when might any change in extreme precipitation be detectable at the scale of the UK? Changes in extreme precipitation events are, in theory, more robustly detectable than changes in mean precipitation (Frei and Schär, 2001) because as precipitation increases (under the greater water holding capacity of a warmer atmosphere) a greater proportion of rainfall is expected to fall as heavy events (Katz, 1999), increasing the signal-to-noise ratio. It is useful for policy makers to know whether they will have to make adaptation decisions in advance of formally detected changes in flood risk, or indeed, if formal detection is even possible within typical planning horizons.

The second question was: to what extent are existing precautionary allowances used for flood risk assessment robust to projected climate changes? UK Planning Policy Statement 25 (PPS25) includes precautionary allowances for climate change for use in flood risk assessments (DCLG, 2006). The Department for Communities and Local Government (DCLG, 2006) and Department for Environment, Food and Rural Affairs (DEFRA, 2006) use precautionary sensitivity ranges applied to changes in peak rainfall intensity informed by Ekström et al. (2005). In the light of new climate model integrations superseding those used in Ekström et al. (2005), it was deemed necessary to review existing guidance and climate change allowances used in flood risk management (Prudhomme et al., 2010).

4.1.2. Methodology

To investigate these questions, 13 RCM experiments from the European Union Framework Programme 5 (EU FP5) project "Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects" (PRUDENCE; Jacob et al., 2007) were used to develop scenarios of rainfall extremes for the UK (a list of RCMs included in the UK case study is found in the supplementary data of the online version, at doi:10.1016/j.gloenvcha.2012.11.003). The RCM ensemble comprised daily precipitation totals for control (1961–1990) and future (2071–2100) time slices (Christensen et al., 2007) following the A2 emission scenario of the IPCC Special Report on Emissions Scenarios (SRES) (Nakićenović et al., 2000). For comparison to observed data, a UK Meteorological Office dataset was produced at a comparable scale to the RCM outputs (Perry and Hollis, 2005a,b).

For each of the nine UK rainfall regions (Fig. 1), seasonal return values of precipitation totals with average recurrence of 10 and 50 years were estimated for 1-, 5- and 10-day durations. To estimate

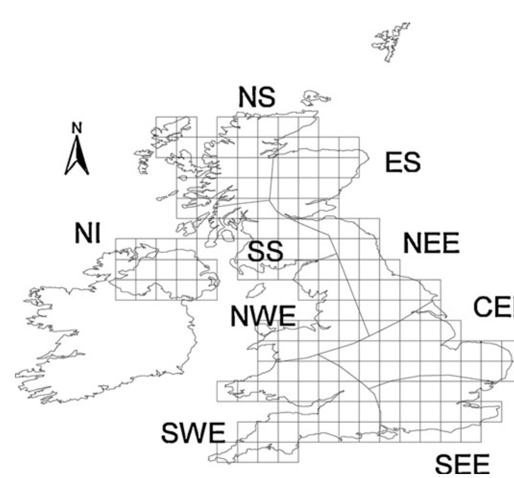

Fig. 1. The 0.5 × 0.5 regular RCM grid and the nine UK rainfall regions: Northern Scotland (NS), Eastern Scotland (ES), Northeast England (NEE), Central-East England (CEE), Southeast England (SEE), Southwest England (SWE), Northwest England (NWE), South Scotland (SS) and Northern Ireland (NI) (after Fowler et al., 2007b; their Fig. 1).

transient changes in the return values a conventional pattern scaling approach was applied to the data (Mitchell, 2003) based on the change in global mean temperature between control and future time periods.

Detectible increases in extreme precipitation, D_x, were defined as the year at which test statistics reject the null hypothesis 'the return level estimated for the 1961–1990 period is equal to year *x*' (where $x > 1990$). By applying equal weights to all RCMs, results were combined to provide probability distributions of estimated D_x values. The year beyond which the probability of detection is more likely than not arrives when more than 50% of the RCMs show significant change.

4.1.3. Key outcomes

The study provided a methodology for estimating detection times for changes in seasonal extremes. The results showed that for selected UK regions and extreme precipitation indices, climate change signal(s) in the PRUDENCE output could be detectable as early as the 2020s. Previous studies have suggested that coherent spatial patterns are rarely found for extreme precipitation in RCM ensembles due to the local scale of such events (Tebaldi et al., 2006). This view is supported by the findings for precipitation changes in summer which, for 1-day totals, are seldom detectable before the 2050s, in any region. By implication, consistent information about changes in the type of flash flooding witnessed in the UK in summer 2007, will not emerge for many decades unless marked improvements can be made in the modelling of such convective rainfall events. This depends on improved RCM resolution (allowing the explicit representation of convection, e.g., Kendon et al., 2012; Chan et al., in press) or improved parameterisation of convective processes in coarser resolution models. In the meantime, flood managers will have to make adaptation decisions about these types of extreme event in advance of formally detected changes in flood risk. However, the detectability of long-duration autumn and winter rainfall extremes was more promising. Changes in the magnitudes of 10-day totals with a 10-year return period were detectable in most regions before the 2040s and even within the next decade or so in some "sentinel" regions such as SW England. Consistent results were obtained when repeating this study using over 300 climate models from the climateprediction.net ensemble (Fowler et al., 2010). Results from these studies imply that different precautionary allowances are needed for sub-daily, daily and multi-day rainfall events.

The study also showed that the first set of UK climate change allowances used in flood risk management may not have been sufficiently robust for some regions, particularly for the earlier periods 1990–2025 and 2025–2055. The earliest year of potential exceedance of the 5% allowance was pre-2025 for Eastern Scotland and Northeast England; in other regions this allowance was typically exceeded between 2025 and 2040. Likewise, the earliest year of likely exceedance of the 10% allowance was pre-2055 for Eastern Scotland, Northeast England and also Northern Ireland; in other regions this allowance was exceeded between 2055 and 2070. For the 20% allowance the minimum year of likely exceedance was 2072 for Eastern Scotland and 2082 for Northeast England, so the allowance was not sufficiently precautionary in these two regions. For other regions the allowance was exceeded in the 2090s or, in the case of Southeast England, not until after 2100.

4.2. Study 2: climate change scenarios for water supply in the Murray Darling Basin, Australia

The Australian Murray-Darling Basin Sustainable Yields (MDBSY) Project was commissioned by state and federal authorities following consecutive drought years during the late 1990s and early 2000s that reduced water supplies with devastating consequences for agriculture and the natural environment (Murphy and Timbal, 2008). The project was undertaken by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and is described in a summarised project report (CSIRO, 2008) and also detailed in 18 regional reports plus more than 40 technical reports available at: http://www.csiro.au/partnerships/MDBSY.html.

4.2.1. Context

The Murray-Darling Basin (MDB) covers more than 1 million km^2 and is bounded by the Great Dividing Range in the south and east (Fig. 2). The MDB is home to over two million people including the national capital, Canberra, and is often referred to as Australia's 'food basket' with agriculture accounting for more than 80% of the Basin's area and two-thirds of Australia's total agricultural water consumption (ABS, 2008). The MDB is, however, located in a region characterised by large natural variability in climate and stream-flow with recurrent and persistent dry spells (Peel et al., 2004; Potter et al., 2010). Indeed, the southern MDB, where most of the runoff is generated, has recently emerged from prolonged drought, often referred to as the 'Millennium drought', with annual rainfall and runoff for the years 1997–2008 respectively ~10% and ~40% lower than long-term average (Chiew et al., 2009). The MDBSY was commissioned to improve estimates of sustainable yields of surface and groundwater systems within the MDB (CSIRO, 2008).

4.2.2. Methodology

To investigate impacts of climate risks and catchment development on water resources, the MDBSY developed three regional climate change scenarios (A, B and C) as input to operational hydrological models. Note that whilst the term 'scenario' usually denotes information about a future world, the MDBSY also used the term to describe different baseline climates:

- Scenario A was based on 112 years of daily climate data (1895–2006) and used as a baseline for comparison with other scenarios. The 1895–2006 period was considered suitable for hydrologic analysis as the period captures a large range of hydroclimate conditions including three prolonged drought periods (circa 1900, 1940, and 1997–2009).
- Scenario B was also a baseline climate series of 112 years, but was generated by stochastic re-sampling of climate data from the period 1997–2006. This second baseline series was motivated by

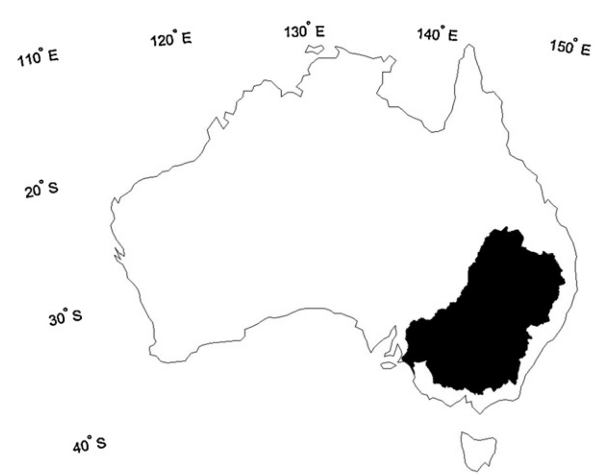

Fig. 2. Outline of the Murray-Darling Basin in Southeast Australia.

the need to assess the impacts on future climate risk relative to a continuation of the Millennium drought.

- Scenario C considers climate change by the year 2030. The future daily climate series was obtained by scaling the 1895–2006 historical daily rainfall (and monthly potential evaporation) by the changes shown in 15 AOGCMs under three levels of global warming. The three levels represent projections of the global temperature change by 2030s relative to 1990s and correspond to the low end of IPCC SRES B1 and the high end of IPCC SRES A1T respectively (Nakićenović et al., 2000; Chiew et al., 2008). The middle level is simply the mean of the low and high end scenarios. Scaling factors for each of the three global warming levels were derived for each GCM, thus yielding an ensemble of 45 future climates (i.e., 15 GCMs × 3 scenarios).

Rainfall-runoff modelling was carried out at ~5 km grids to estimate daily runoff at ~40,000 grid cells across the MDB. The hydrological model was calibrated against 1975–2006 streamflow data (representing current land-use conditions) for 240 largely unregulated catchments (mainly located in areas of high runoff generation). The modelled runoff was aggregated to provide inflows into river system models, which include irrigation water balance, flow routing, local inflow, agricultural and urban water demand (Van Dijk et al., 2008) and rainfall-recharge to estimate diffuse recharge into groundwater (Richardson et al., 2008). Most of these model components were previously developed by the Murray-Darling Basin Authority (MDBA) and state water agencies to represent the existing river network, water sharing and management plans.

4.2.3. Key outcomes

Several key insights of sustainable water use under current and future climates emerged in the MDBSY. There was large uncertainty in future rainfall projections, with general disagreement between the AOGCMs in the direction of rainfall change in the north. In the southern region, agreement amongst models was stronger pointing towards an overall drier future. The project showed that under current water sharing arrangements, the environment would be the biggest loser in a changed climate as surface water and groundwater use was expected to significantly increase and, although expansion of commercial forestry may not cause major impacts on rivers in the MDB, there could be significant impact on sub-catchment stream-flows.

Project output served a critical role in informing the government on water resource planning. In particular, the MDBA used project results to guide development of the first Murray-Darling 'Basin Plan' (http://www.mdba.gov.au/basin_plan) – an umbrella water resource plan to guide the sustainable management of the entire water resources of the MDB in the national interest. Through the MDBSY and subsequent work, the MDBA built technical capacity and applied modelling tools to the policy arena. The two key improvements to the river modelling framework to support the Basin Plan were the incorporation of flexible approaches for representing environmental water demands in the river models, and greatly improved model post-processing routines and data management processes. The former enabled rapid specification of alternative water sharing scenarios, reflecting different environmental water demands. The second provided a greater ability to report key metrics based on raw model output. Further, results from the disparate river models were stored in accessible and consistent databases that support structured queries and information requests submitted by stakeholders via the Internet.

Despite the overall success of the MDBSY, there were aspects of the work that required further attention. For example, better representation of the river and groundwater systems as well as improvements in methodologies for generating regional climate variables. Furthermore, experiences from the MDBSY highlighted the need for better understanding of the environmental flow requirements. Recent advances in this regard include ecological research into the estuarine components of the MDB (the Coorong, Lower Lakes and Murray Mouth) undertaken as a collaborative research programme spanning CSIRO, Universities and Government Agencies. From this work hydrodynamic and ecosystem response models (applied to the Coorong) have been developed, linked to the river system models and used in water-planning scenario-assessments (Lester et al., 2011).

4.3. Study 3: enhancing adaptive capacity of water management in Kiribati

Kuruppu (2009a) examined the process of adapting water resource management to climate change in five communities across three islands in Kiribati (formerly known as the Gilbert Islands) located in Micronesia (South Tarawa ~1.4°N, 173.1°E; Butaritari ~3.17°N, 172.815°E and Tabiteuea North ~1.37°S, 174.850°E). The core of this case study is drawn from the PhD thesis of Kuruppu (2009a), which contributed to the national Kiribati Adaptation Project (KAP) administrated by the World Bank. Some of the research is available in Kuruppu (2009b) and Kuruppu and Liverman (2011) but due to limited exposure to date, more detail is given below about the study context and methodology in comparison to the other cases.

4.3.1. Context

Small Island Developing States (SIDS) in the Pacific region, such as the Republic of Kiribati, are categorised, internationally, as Least Developed Countries (LDCs) because of their low incomes and other development indicators. These island communities are particularly vulnerable to climate change due to their physical size, their vulnerability to natural disasters, the extreme openness of their economies, and their low adaptive capacity (Barnett and Adger, 2001; Mimura et al., 2007). The thirty-two atolls in Kiribati are, on average, just 450 m wide and 2–3 m above sea level. The primary sources of freshwater for low-lying atolls in the central Pacific such as Kiribati are freshwater lenses floating above denser, salty groundwater. The freshwater lenses are recharged naturally through rainfall but during dry periods the lenses may turn brackish – a process that may be exacerbated by over-abstraction and poor land management. On small islands the freshwater outflow is minimal and it can take months to 'flush out' saltwater that intrudes into the freshwater zone (Falkland and Brunel, 1993). Across Kiribati, the water resources of many communities are already affected by saltwater intrusion into groundwater as well as by frequent coastal inundation and accelerated coastal erosion (Hay and Mimura, 2005).

The water resources of these communities are expected to experience increased stress as climate projections suggest negative impacts on both the quantity and quality of the groundwater linked to variations in precipitation and rising sea level (Alam and Falkland, 1997; White et al., 2007). For example, more intense rainfall events could increase pollutant runoff, which could contaminate groundwater and exacerbate rates of water-borne diseases. Rising sea levels could push shallow water tables on coral atolls closer to the surface and, when coupled with increasing temperatures, groundwater will become vulnerable to greater rates of evaporation (Burns, 2002). For areas with shallow water tables, groundwater recharge is likely to be influenced more by higher temperatures than lower precipitation (Chen and Osadetz, 2004).

Kiribati commenced formal adaptation planning in 1995 after ratifying the United Nations Framework Convention on Climate Change and was an early member of the Alliance of Small Island

States. Since then, Kiribati has initiated two national adaptation programmes, the Kiribati Adaptation Programme (KAP) and the National Adaptation Programme of Action (NAPA). These programmes aim to integrate adaptation into vulnerable sectors, including water, to address long-term (via KAP) and short-term (through NAPA) adaptation needs. Whilst the NAPA seeks funding approval for its various priority action areas, the KAP has been in operation since 2000 and is now in the third phase which commenced in late 2011. The PhD research was conducted under the second phase of KAP, with the aim of examining processes for enhancing the adaptive capacity of water management in Kiribati.

4.3.2. Methodology

A key obstacle to adaptive planning for climate change was the lack of capacity for climate monitoring and modelling at the Meteorology Office in Tarawa. As a consequence there was heavy reliance on external assistance to provide climate change projections (Kuruppu, 2009a). Given these obstacles, a bottom-up approach was considered essential to complement top-down approaches for adaptation planning in the water sector. A shift in the starting point of analysis is required in extending hydrology to the social sciences and adopting a bottom-up approach to understand vulnerability. Instead of asking *how much water needs to be supplied to meet projected climate changes* the question becomes *what patterns of development and socioeconomic activity are sustainable and will reduce water related risks of climate variability and change* (Moench, 2007)? With people and their livelihoods as the starting point, embedded within the context of organisations and institutions, the study developed a conceptual framework (Fig. 3) in which understanding of adaptive capacity is central to reducing vulnerabilities and exposure of water management systems to climate change and other stresses (IPCC, 2007). These approaches stand to complement studies that aim to develop scenarios and project water needs to communities under a changing climate.

Whilst adaptive capacity varies across regions and communities, defined by those conditions that enable or prevent planned or autonomous adaptation (Cohen et al., 2006), it can generally be enhanced by "*investing in information and knowledge; encouraging institutions that permit change and learning; and increasing the level of resources such as income and education to those in which they are presently lacking*" (Janssen and Ostrom, 2006 in Lemos et al., 2007, p. 1). However, what is adaptive at one point in time, under a given set of circumstances may become maladaptive on a different occasion (Paine, 2001). Thus, it was essential that the framework identified context-specific determinants that enhance adaptive capacity and linked these to improved adaptation outcomes.

These determinants may be either objective or subjective, where the former constitute drivers that are external to the person or community, and the latter constitute those that add to the psychological dimension of adaptive capacity and aim to shed light on people's perceptions of climatic risks, their knowledge of the causes and their ability to respond to these risks (Lorenzoni et al., 2000; Milne et al., 2008). Recognition of these drivers includes changing the social or technical arrangements that constrain the choices that are open to communities when dealing with certain stresses (Grasso, 2006). Furthermore, theories from political ecology provide an understanding of the factors that constrain the adaptive capacity of actors and water management organisations. A political ecology approach to examining adaptive capacity commences with the premise that nature and society are inextricable linked with both forces constantly working together to produce reality (Hewitt, 1995). For example, Blaikie and Brookfield (1987) demonstrated how political and economic marginalisation push disempowered people into marginal/unstable landscapes that were unproductive and as a consequence required people to work the land harder to overcome and cope with lower yields. This results in a cycle of both environmental and social degradation; a landscape that provides people with less return and thus pushes people further into poverty (Robbins, 2004). This conceptualisation draws attention to the struggles over the relationship between human and non-human agents, mediated through social relations and institutions (Scoones, 1997; Hartmann, 1998). With this theory in mind, the following research questions were posed by the Kiribati case study (Kuruppu, 2009a):

(a) What are the initial barriers and opportunities associated with implementing national adaptation programmes in Kiribati?

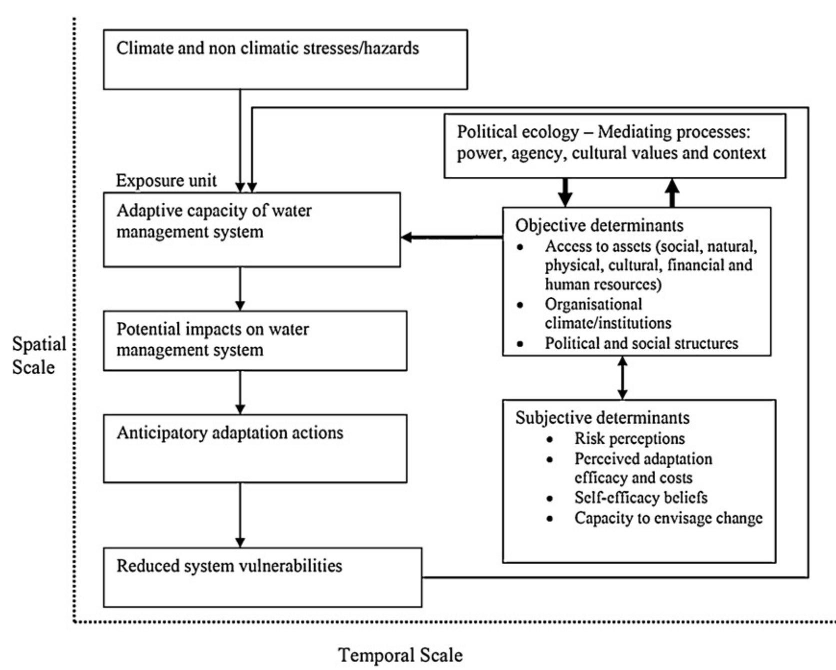

Fig. 3. A framework for conceptualising adaptive capacity. Dotted lines in figure signify the dynamic nature across space and time of adaptive capacity; its determinants and processes shaping its determinants as well as the adaptation process in general.

(b) To what extent do the formal adaptation interventions of water organisations enhance the adaptive capacity of water management systems?
(c) How do people's perceptions of climate risks to water resources and their capacity to adapt to these stresses shape the uptake of anticipatory adaptation actions?
(d) What are the key factors that impede the diversification of household water supplies (as an adaptation strategy)?

Household level surveys were conducted across five communities on three islands in Kiribati. Key informant interviews were conducted with organisations involved in water management and climate adaptation planning. The study employed qualitative methods, such as semi-structured interviews of 98 key informants (representing government and non-government actors) plus a survey of 132 households in five villages on three islands of the Gilbert group. Secondary data included national and local policy documents, archive materials, local census data, health statistics, climate data and water management reports. Data in Kiribati were collected over a 6-month period from November 2005 to May 2006.

To capture the range of resources/assets representing each household's particular access level, the survey was based on the Sustainable Livelihoods Framework designed by the UK Government's Department for International Development (DFID) (DFID, 2000). This determines the extent of access to natural, social, physical, human and financial assets needed to produce livelihood outcomes at the micro- (i.e., household or individual) level. The survey was designed to explore how these assets are (or can be) deployed to expand adaptive capacity to current and expected water stress despite being exposed to mediating policies/institutions. To examine the subjective dimensions of adaptive capacity, questions about perceptions of climate change impacts on water resources and on ability to adapt to these changes were incorporated in the survey (Table 1).

4.3.3. Key outcomes

This case study reached four conclusions (Kuruppu, 2009a; Kuruppu and Liverman, 2011); these are similar to those of Adger et al. (2004). First, successful adaptation depends on integrated approaches and adaptive capacity across multiple scales from the local to national and international. This reflects the embedded

Table 1
Extract of key household survey questions used in case study 3 (Kuruppu, 2009a).

Question ID	Topic: climate change
1.1	What changes in climate and sea level have you experienced since living here? (a) High tide closer to the house (b) More storms (c) More/less wind (d) Hotter (e) Colder (f) Other (explain)
1.2	Which of the following changes have you noticed in your well water levels or quality in the last five years, especially during dry weather, heavy rains and high tide? (a) More salty well water (b) Less salty well water (c) Lower water level in well (d) Higher water level in well (e) Colour change (f) Change to its smell (g) Other (explain)
1.2.1	Do you know how people can change the climate? (a) People can't change climate (b) Burning fossil fuels (petrol, diesel, oil) in industry (c) Using a lot of electricity (d) Driving cars (e) Burning rubbish (f) Other (explain)
1.4	What actions do you think your family can take to prepare themselves for more frequent water shortages, drought events or saltier well water?
	Topic: natural capital – water quality and quantity
2.1.1	List each water source and the quantities your family uses *daily* and for what purposes?
2.4.1 (a)	What problems do you have with your water service?
2.4.2 (a)	Do you know anyone who wants a rainwater tank but can't get one?
(b)	What do you think can be done to help them?
3.0	Is there anything that you know can contribute to polluting/dirtying your water sources, e.g., pig waste?
3.1	What actions have you taken/can you undertake to protect your water sources from pollution? (if none, then why)
3.2	What do you want the Public Utilities Board and Betio council do to improve water quality in Betio?
	Topic: financial capital
4.0	What are the main sources of income for your household (rank if more than one): (a) government employment (b) remittances (c) rent (d) other (specify)
4.1	Where do you spend most of your money on (rank 1–6): water, education, health, food, church and entertainment, other (specify)?
4.3	If you were given money from the Government for improving water management in your village, what would you use it for?
	Topic: physical capital
5.0	Which of the following items does your household posses (quantify)? Land, car, bicycle, boat, canoe, fishing net, sewing machine, poultry/pigs, other (specify)
	Topic: human capital

Table 1 (*Continued*)

	Topic: human capital
6.0	In a given week, what activities do you spend most of your time on (rank 1–3)? (a) working (b) studying (c) domestic (d) leisure (e) church (f) fishing (g) sewing (h) children
6.1	What are the most important things in life for you (rank 1–3)? (a) family (b) health (c) money (d) clean water (e) education (f) religion (g) other (specify)
6.2 a)	How often a month do members of your family get diarrhoea?
b)	What do you think is causing this?

	Topic: social capital
9.1 a)	Which groups in your village or outside are you a part of or get together with to talk about village problems e.g., neighbours, church, women or youth group?
9.4	Which leaders in your village can you ask to help solve problems (e.g., water, fighting, drunkenness) concerning the village (please select)? Village councillor or warden, church leader, unimwane (village head), local MP, other (specify)
9.5	Do you agree or disagree that people here look out mainly for the welfare of their own families and they are not much concerned with the village/neighbourhood welfare? Strongly agree, Agree, Disagree, Strongly disagree, Other (explain)
9.6	Who should be responsible for water management in your village? Ministry of Public Works and Utilities (MPWU), Council, Health Ministry, Villagers, Everyone, Other (specify)

nature of water resources; requiring a network of actors and organisations for its management. For example, without a unified approach to administering national adaptation programmes, in-country tensions had led to a loss of interest in adaptation planning amongst water managers whilst limited adaptive capacity at the local government level had the potential to constrain the implementation of adaptation strategies of the water sector.

Second, adaptive capacity depends on deeper contextual factors such as culture, power relations and behavioural norms. The study found that a combination of these factors constrained the current adaptive choices available to water organisations in Kiribati. For example, the capacity to promote learning, memory and creativity within water organisations was constrained not only by a lack of qualified technicians and engineers but by the deeper processes responsible for prioritising the granting of training funds which were biased towards particular disciplines.

Third, people's belief in their own effectiveness in responding to water resource impacts from climate change depend more on past experience with water stress rather than on a detailed understanding of future climate risks. These over-confident beliefs may impede adaptation (Kuruppu and Liverman, 2011).

Fourth, cultural values and relations shape how resources/assets are used in pursuit of adaptation strategies to overcome water stress (Kuruppu, 2009a). For most respondents, the moral economy of the household was one in which livelihood assets were maintained to serve the wider purpose of sustaining and building personal relationships. For example, financial resources provided personal significance when they were spent on satisfying community obligations, particularly those related to the church. This limited the finance available to pursue adaptation and diversification strategies, such as purchasing rainwater tanks or measures to protect household wells.

Overall, this study showed that underlying contextual processes, such as local culture and social relations, influence people's agency[1] to convert resources to address water hardships. Individual's perceptions of their own ability to adapt to water stress, power inequalities within water management organisations and between international adaptation fund administrators, are critical to enhancing adaptive capacity of water management systems. These contextual processes were largely overlooked by informal national adaptation programmes which tended to concentrate on solutions promoting conventional supply and demand management strategies for the water sector, influenced largely by an impact-driven approach to vulnerability analysis. Many of these are technical and do little to change the social arrangements which affect people and influence the choices that are open to them in managing water stress; yet such interventions are necessary under a changing climate (Table 2). Adaptive strategies for the water sector such as raising community awareness of climate change coupled with providing access to rainwater tank loan schemes have been promoted amongst communities in Kiribati through the national adaptation projects.

Linkages to broader social policies that enhance the livelihood security of people are also pertinent. The requirement for policies that enhance adaptive capacity has been shown elsewhere (Eriksen et al., 2007; Heltberg et al., 2008). The Kiribati study showed wide disparities in resource access particularly in physical, financial and human capital amongst South Tarawa (urban) and outer islander (rural) respondents, which directly affect respondents' capacity to adapt to climate change (Kuruppu, 2009b). Thus, policies must open up access to economic, political, human and natural resources if the adaptive capacity of vulnerable people is to be enhanced. These, particularly in the rural islands, should provide alternative income-generating activities for vulnerable households and for women; bring about new opportunities in gaining vocational skills for youth; enable social groups to participate in local and national politics; encourage activities that protect existing water resources (e.g., cement lining open wells); and improve access to local technologies for overcoming water stress such as Tamana pumps. Many of these goals are addressed through social policies that target

[1] Agency is defined as "the ability of persons to act on behalf of goals that matter to them" (Sen 2002 in Devine et al., 2006, p. 7).

Table 2
Kiribati adaptation project strategies for the water sector (World Bank, 2006, p. 41 and 48).

Adaptation Strategy
<u>*Update water policy, standards and capabilities to include climate adaptation*</u>
Develop National Water Policy to provide a 20–30 year framework for freshwater resource planning;
Revise national building codes relating to freshwater management and sanitation; and development of guidelines on rainwater catchment, storage and use.
<u>*South Tarawa water planning, remedial actions and pilot projects*</u>
This sub-component will assist the Ministry of Public Works and Utilities (MPWU) and the Public Utility Board (PUB) to prepare a master plan for water in Tarawa atoll, carry out assessments and pilot projects and studies to identify and increase available resources.
Activities aimed at increasing future availability of freshwater will include pilot projects in rainwater collection and storage, and study of the feasibility of creating additional freshwater lens capacity by reclamation of land.
Undertake intensive repairs and other measures to reduce losses from the installed systems.
<u>*Outer Islands assessments and public and private system upgrades*</u>
Outer Islands freshwater systems are widely in need of repair and upgrading. This sub-component will enable this work to be undertaken incorporating climate variability and change factors.
A grant scheme to assist outer islander households to invest in rainwater catchment and storage—and possibly to install water-saving sanitation systems—will be piloted.

national development goals rather than water management policies per se.

5. Climate risk matrix

The characteristics of the three case studies are discussed with reference to the climate risk matrix in order to explore their respective aims and main policy foci, compare their theoretical strengths and weaknesses (such as characteristic uncertainties), and to gauge the degree of integration of stakeholder, natural and social sciences involvement.

The main policy focus of all the studies is adaptation (rather than mitigation) and whilst the aims are different, there are some similarities in genesis of two projects (Table 3, rows 1 and 2). The extreme rainfall study for the UK was commissioned by the Environment agency and the MDBSY by the Australian government; in both cases this is 'requested' research with very specific objectives. The third study on the other hand represents the work of a PhD thesis, for which research directions and outcomes are not as easily defined as they evolve during the course of the work. Is the genesis of a particular piece of work relevant in terms of adaptation research? Perhaps, since the origin of a study is suggestive of the intended outcomes. For example, work commissioned by a water regulator, agency or government institution addresses a perceived need by the client and therefore results from this type of work is more likely to be implemented in policy development or adaptation plans compared with results originating from academic research grants and PhD theses. Such direct links between commissioned work by Government regulators and policy implementation is perhaps best illustrated by the MDBSY, where results were directly implemented in guidance material and improvement of decision support tools (Table 3, row 3).

The climate risk matrix also records the degree of stakeholder involvement (Table 3, row 4), a factor that may be relevant depending on the type of study. Of course, these three studies have different scope for stakeholder engagement; ranging from very little in the UK extremes case to high for MDBSY and Kiribati. For the UK extremes case, the scope is small as the research question and main results are fundamentally tied to a top-down modelling exercise to analyse impact on a particular characteristic of rainfall. The MDBSY looked at impacts on regulated water resources with foremost technical stakeholder involvement, such as drawing on the expertise from governmental bodies within the Australian states and territory that come together in the MDB. In Kiribati, the stakeholder involvement is also high, albeit of a different kind. Here the stakeholder knowledge was recorded using interviews and questionnaires, providing the data upon which conclusions about adaptation advice could be given.

The time horizon of the assessments also differs amongst the studies (Table 3, row 5). For the UK extremes study, analysis was carried out to the full extent of available climate model output to the 2100; for the MDBSY, short to near-term water management planning considered recent climate (past 10–20 years) and the 2030s, whilst the longer-term management planning focused solely on the 2030s; for the Kiribati study, the time horizon ranges from an unspecified short- to medium-term as the assessments rely mainly on recent and historical data and stakeholder life-time experiences.

In each study, the spatial scale is directly linked to the method choice (Table 3, row 6). For the UK extremes, the analysis could be conducted and presented on a grid cell basis; however, to provide more robust estimates, results were provided for 9 rainfall regions that have been shown to be homogeneous (Jones and Conway, 1997). The reporting regions of the MDBSY reflect the 18 major tributaries of the MDB, upon which current river system models and surface water sharing plans operate. Since impact analysis was conducted with current operational models, these reporting regions were deemed to be the appropriate scale for communicating results. Whilst establishing the spatial scale is relatively straightforward for model driven assessments, the same is not necessarily true for bottom-up approaches. Nevertheless, it is possible to consider the spatial scale at which the agents in the assessment operate. For example, an individual or a household could be considered to operate on a local scale. However, behaviour or principles that are non-local in characteristics are transferrable across larger communities, thus the spatial scale could also be deemed regional to national.

Next we consider various aspects of the study methodologies (Table 3, rows 7–10). The UK extremes and MDBSY assessments were scenario driven and used either direct or inferred impacts analysis to anticipate how climate change could affect systems/variables (i.e., a positive analytical approach). Conversely, the water management study of Kiribati focused on the social processes that shape the adaptive capacity of small islands to identify options for minimising potential impacts on communities (i.e., a normative analytical approach). The Kiribati study employed questionnaires and targeted interviews in combination with a review of health, social and water management documents to determine exposures and sensitivities to climate variability. In the other studies, the exposure units were pre-determined by researchers and project managers during the design-phase of the research. The UK case study was able to utilise RCM outputs from the EU funded project PRUDENCE in combination with advanced statistical theory to estimate sensitivities in modelled regional rainfall extremes to a climate change signal. Whilst Australia does have climate modelling capacity, data were not readily available for the MDBSY, and due to time constraints, a

Table 3
Three climate risk assessments evaluated using the climate risk matrix.

Description	Extreme rainfall, UK	Murray-Darling Basin, Australia	Water management, Kiribati
1. Aim and genesis	Physical impacts on rainfall extremes. Commissioned by the Environment Agency and also supported by NERC Postdoctoral Fellowship award	Physical impacts on water resources. Commissioned by Australian Government	Social processes linked to enhancing adaptive capacity for small islands. PhD thesis at the Environmental Change Institute, University of Oxford, UK
2. Main policy focus	Adaptation	Adaptation	Adaptation
3. Main results	Identification of possible time frames for when climate change becomes detectable in extreme rainfall series. Changes in the 1 in 10 year, 10-day totals may become detectable in most UK rainfall regions before the 2040s and in some regions in the 2020s. Recommends that different precautionary allowances are needed for sub-daily, daily and multi-day rainfall events in statutory guidance. Recommends that potential hotspots of emerging flood risk should be identified to provide a more targeted approach to monitoring and investment planning.	Government guidance material for strategic planning of short (10–20 years) and long term (2030s) water resource use. Provision of river-modelling platform for the Murray-Darling basin.	Identification of the importance of societal processes that can impede long term success of national adaptation plans. This includes the value of integrating across local and international scales, the importance of contextual factors shaping adaptive capacity, the importance of past experience to beliefs about effectiveness in responding to climate change impacts, and the importance of cultural values and relationships in determining how resources are used to overcome water stress.
4. Degree of stakeholder involvement	Little	Medium-High	High
5. Time horizon	1961–1990, 2071–2100 from RCMs, then 30 year periods centred on: 1975, 2025, 2055, 2085 using pattern scaling.	The 2030s	Short to near-term
6. Spatial scale	Regional (UK rainfall regions) to national	Local (catchments and river reaches) to regional (reporting regions)	Local (e.g., family unit) to national (e.g., national strategies)
7. Analytical approach	Positive	Positive	Normative
8. Methodology used to identify climate exposures	Determined by researcher	Determined by researcher	Investigation based on information in records and documents, health and climate statistics, interviews and questionnaires
9. Methodology used to derive climate change scenario data	Dynamical downscaling of IPCC SRES A2 emission scenario	Daily- and seasonal-scaling of historical climate data informed by GCM scaling factors that range from low IPCC SRES B1 to the high end of A1T.	N/A
10. Methodology used to identify system or decision sensitivities	Parametric and process based models (AOGCMs and RCMs) Statistical (extreme value theory)	Parametric and process based models (rainfall-runoff, river-flow and groundwater models)	Investigation based on information in records and documents, health and climate statistics, interviews and questionnaires
11. Consideration of climate variability, non-climatic factors and adaptation	Natural climate variability as represented by climate model output and by observations	Natural climate variability as represented in current climate time series; current water resource allocation schemes	Consideration of community pressures, operation under current climate variability; current and planned adaptation strategies.
12. Integration of natural and social sciences	None (natural sciences only)	None (natural sciences only)	Little (foremost social sciences)
Uncertainty description of climate risk framework			
13. Location			
Context	IPCC storylines (one)	IPCC storylines (two or more)	Assumptions determining outline of questionnaires, and conduct of interviews.
Input	Uncertainties in data used as input to various model steps.	Uncertainties in data used as input to various model steps.	Household level questionnaires, key informant interviews, national and local policy documents, archival documents, local consensus data, health statistics, climate data and water management reports
Model technical	Uncertainty in technical/numerical representation of physical processes	Uncertainty in technical/numerical representation of physical processes	N/A
Model structure	Uncertainties due to structural differences amongst models.	Uncertainties due to structural differences amongst models.	N/A
Parameter	Uncertainty in parameters and parameter schemes.	Uncertainty in parameters and parameter schemes.	N/A
14. Level			
Statistical	13 RCMs	15 AOGCMs	N/A

Table 3 (*Continued*)

Uncertainty description of climate risk framework			
Scenario	N/A	The use of two different baselines provides two alternative ways of viewing future changes. Emission scenarios.	N/A
Qualitative	AOGCM, emission scenario	Daily-scaling, impact models (one or couple, depending on variable)	132 household questionnaires across 5 villages on 3 islands, 98 semi-structured key informant interviews with government and non-government actors.
Recognised ignorance	Aspects of all model steps and IPCC story lines	Aspects of all model steps and IPCC story lines	N/A
15. Nature			
Natural variability	AOGCMs, RCMs	AOGCM, observed climate data	Sample population for questionnaires and interviews
Epistemic	Aspects of all model steps and IPCC story line	Aspects of all model steps and IPCC story lines	N/A
Ambiguity	N/A	N/A	Interpretation of questions in questionnaires and interviews by interviewees and interpretation of their responses by the researcher.
16. Recognised weaknesses	Not applicable to summer precipitation extremes as these are poorly resolved by RCMs. GCMs have large influence on magnitude of extremes; only two GCMs were used as lateral boundary conditions for the RCM ensemble. Only one SRES emission scenario limits the insights into range of possible impact levels.	Limitations in empirical downscaling technique are likely to give less variability in projected climate variables. Impact models require calibration to historical data and it is unclear how accurately these models perform under changed flow regimes.	Limited attention to physical aspects of water management that combine with the studied social processes. Limited scope for long term planning beyond the next couple of decades.

simple daily-scaling methodology was used to derive regional climate data. A range of operational hydrological models were then used to assess the sensitivities of the MDBA water resources to climate change. Although operational models provide results that are meaningful to water managers, there are two potential drawbacks when applying them to climate risk assessment: (1) it is assumed that the models are valid under changing environmental conditions (Jiang et al., 2007), and; (2) the 'lock in' of existing infrastructure could limit the scope for identifying alternative infrastructure solutions that maximise adaptation capacity (i.e., there is a risk of adopting an approach that imply only incremental adaptation whilst the optimal solution may involve a transformational approach (e.g., Kates et al., 2012)).

The bottom-up approach adopted by the Kiribati study provides a framework that readily considers influences on water management or regulation by factors other than climate change, as well as integrating results from both the physical and social sciences (Table 3, rows 11 and 12). However, the lack of data for the region meant that the study could not consider historical or future impacts of climate variability on regional water resources. Whilst little consideration was paid to the social sciences in the two top-down approaches, some accounting of natural variability was considered by both, as represented in the RCM ensemble for the UK extremes study and in the climate series used for daily-scaling in the MDBSY. The MDBSY further considered impacts due to water sharing infrastructure.

The remainder of the climate risk matrix focuses mainly on the characteristics of uncertainties associated with the three studies (Table 3, rows 13–15). For the purpose of providing a synthesis of uncertainties, the sources considered are the AOGCM, the downscaling method, analysis of observed time series, and questionnaires.

The two top-down approaches are both subject to contextual uncertainties (the IPCC storylines can be considered uncertainties outside the model boundary); input, technical and structural model uncertainties, and parameter uncertainty associated with all steps involved in the regional climate downscaling and hydrological modelling. Whilst some model related uncertainties can be quantified (for example by calculating the spread in the 13 RCMs of the UK Extremes and the 15 AOGMs of the MDBSY study), much uncertainty is due to lack of knowledge (recognised ignorance). For the MDBSY, different emission scenarios and different baselines were used to test the sensitivity of system behaviour (scenario uncertainty). The uncertainty associated with the daily-scaling and impact models, on the other hand, was not quantified but can be described (as qualitative uncertainty) or reflects limitations in knowledge (recognised ignorance). Some aspects of the uncertainties associated with emission scenarios as well as with AOGCMs can be drawn from other studies. For example, known biases in the positioning of storm tracks by the AOGCMs used in the UK extremes study does qualitatively account for some inter-model variability (Rowell, 2006). Although much of the uncertainty in the top-down studies is epistemic, a large proportion is also due to natural variability, particularly for rainfall (Hawkins and Sutton, 2011), as indicated by the observed climate data used for the baselines and scaling in the MDBSY.

Similar to the two top-down studies, the locations of uncertainties in the Kiribati study are in the assumptions underpinning the research questions (contextual) and in the inputs (survey data and records), but the study is not affected by model uncertainties. The level of uncertainty is largely qualitative, simply due to the type of data used in the analysis. The nature of uncertainties in the survey material depends partly on variability (e.g., due to the different opinions/beliefs held by the survey targets) and ambiguity (e.g., when working with historical records, policy documents, and survey material, there is scope for contradictory information). Ambiguity can also arise from interpretation of questions and results of surveys/interviews.

The final category in the climate risk matrix concerns recognised weaknesses (Table 3, row 16). For the physical climate change impact scenarios, these relate mainly to the shortcomings of the models as illustrated by the lack of ability to quantify or even qualify model uncertainties that are mainly epistemic in nature. For example, the UK study is constrained by RCM uncertainties. Other research shows that multi-day rainfall associated with large weather systems is reasonably well simulated by RCMs, but 1-day summer extremes associated with convective events are not (Fowler and Ekström, 2009). Thus, results for winter have greater credibility compared to those of the summer. Furthermore, although a large number of RCMs were used, the ensemble only used boundary and initial conditions from two GCMs – so uncertainty in the projected extremes will be understated.

In the MDBSY study, daily-scaling of historical time series cannot resolve possible changes in temporal dependence structures of future climate variables as in more sophisticated downscaling approaches (e.g., Chiew et al., 2010). Furthermore, although different hydrological models were applied, these were not originally designed for climate change impact studies and it is unclear whether these will properly simulate runoff for future environments (Jiang et al., 2007). For the Kiribati study the sole focus on societal processes could be considered to be a weakness since the long-term range of options is ultimately shaped by physical aspects of water management. On the other hand, as the Kiribati case study is based on information derived from real situations (rather than modelling frameworks) it could be regarded as having more 'ground truth' than the other studies. Perhaps in contexts such as SIDSs and LDCs, formal adaptation programmes for the water sector should place greater emphasis on building the capacity of water organisations by gathering long-term data that can complement bottom-up vulnerability studies. Such initiatives were overlooked in both the KAP and NAPA programmes.

By breaking down the climate risk assessment into its component features, we are able to synthesise and then explore the assessments in a systematic way. The matrix shows that the top-down approaches provided assessments that could readily be used to inform medium to long-term policy; however, it also shows that they are heavily associated with uncertainty of mainly epistemic nature of which only some can be quantified (e.g., based on RCM and/or AOGCM ensembles). The matrix also details uncertainties in the bottom-up framework; such as natural variability and ambiguity (types of uncertainties that are not remedied by improved knowledge, but can be reduced through improved sampling or design of qualitative surveys for instance). Comparing across studies can also inspire other actions that could result in a more robust assessment. For example, evaluating the cost of various adaptation options in the UK extremes study; using multiple downscaling techniques in the MDBSY (to change the level of uncertainty from qualitative to statistical); or undertaking climate change impact analysis on Kiribati water resources to test the fitness of management and regulatory policies.

6. Conclusions

Climate change strengthens the case for good practice in water management whilst adaptation offers opportunities to improve flexibility to meet new risks and demands on water systems (Dow et al., 2007; Muller, 2007). Top-down and bottom-up approaches provide useful insights that could ultimately shape water management infrastructure. Although the theoretical value of integrating both approaches is recognised, at least in the research literature, there is very little practical evidence of such work. This paper describes a tool with which climate risk assessments can be explored and hence modified to ensure appropriate stakeholder involvement, selection of informative methods to identify problem focus and tractable research questions, as well as ways to reduce the level of uncertainty.

By exploring three very different approaches to facilitate adaptation in the water sector we identified the following issues:

- Top-down methodologies that can provide future estimates of hydrological metrics are easily implemented in guidance material for organisations with a governance role.
- Operational models that rely on calibration against observed data may not be capable of estimating the full range of future conditions and carry the risk of 'lock-in' to existing infrastructure, which could constrain the scope of other adaptation options.
- Focusing on hydrological impacts provides information on potential changes in magnitude and timing of resources, but the outcomes are heavily conditioned by the characteristics and uncertainties of the models and scenarios chosen and these need regular revision to reflect rapidly evolving climate science.
- Bottom-up studies are not reliant on model projections. Instead, they investigate different communities' response to changes in water supply, which assists planners by revealing how different communities might react to future changes to their local environment.
- By detailing the location, level and nature of uncertainties, a developer of climate risk assessments can identify ways in which the level of uncertainty can be changed so that it becomes more informative (i.e., shifts from qualitative to scenario or statistical). Alternatively, the approach might be modified so that the data with the largest uncertainty is introduced towards the end of the analyses (as in Brown et al., 2012).
- Focusing solely on historical and contemporary societal processes limits the applicability of bottom-up results for long-term policy planning.
- Integrating climate change scenario data with conceptual or deterministic models of human/societal behaviour could offer tools that enable problem framing and analysis that ultimately leads to more robust adaptation planning.

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