Special Section:
Resilient Decision-making for a Riskier World

Key Points:
- Agricultural sector engagement is essential in securing sustainable integrated water resources management and planning at the regional level
- There is a need for equivalence in integrated water resources management processes to reflect the required levels of reliability and value of water within different sectors
- Under conditions of increasing water scarcity, opportunities for trade-offs are likely to exist between competing sectors, particularly in catchments where agricultural demand conflicts are most acute

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Identifying Trade-Offs and Reconciling Competing Demands for Water: Integrating Agriculture Into a Robust Decision-Making Framework

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Abstract Increasing demands for water, driven by population growth and socioeconomic development, environmental regulations and future climate uncertainty, are highlighting limitations on water supplies. This water-energy-food-environment nexus is not confined to semiarid regions but is emerging as a key business, societal, and economic risk in humid and temperate countries, where abundant water supplies and regulation have historically coped with fluctuating demands between industry, power generation, agriculture, domestic supply, and the environment. In the United Kingdom, irrigation is supplemental to rainfall, consumptive in use, and concentrated in the driest years and most resource-stressed catchments. This paper describes an empirical application of a mixed methods approach to integrate agriculture into a robust decision-making framework, focusing on a water-stressed region in England. The approach shows that competing demands between sectors can be reconciled and that potential options or portfolios compatible with multisectoral collaboration and investment can be identified. The methodological challenges in forecasting agricultural demand, defining acceptable *trade-offs*, managing scale and uncertainty issues, and the importance of engendering open dialogue between stakeholders are described. The study provides valuable insights for countries where similar emergent issues regarding conflicts over water demand exist.

1. Introduction

Given the need to understand the impacts of a changing climate on the hydrological balances in a river basin, the competing interests for increasingly limited water supplies, and the varying physical and socioeconomic drivers of demand that impact on specific sectors (domestic water supply, industry, and agriculture), it is not surprising that developing robust estimates of the magnitude and location of changes in future water demand are complex and often contested. They are, however, essential components in the strategic planning of water resources at both national and regional levels.

Many of the most severe impacts of climate change are reported to be water related (Stern, 2006) with river ecosystems and agriculture often highlighted as sectors highly sensitive to change (Kernan et al., 2010; Knox et al., 2010). Further global warming will likely impact the hydrological cycle, leading to changes in system response and increased drought risk (Bates et al., 2008; Giorgi et al., 2011) as well as exposure to resource stress (Watts et al., 2015). Indeed, in the first UK Climate Change Risk Assessment, three of the six identified risks requiring early intervention were water related, including specific aspects of natural ecosystems such as soils, biodiversity, and water resources management (Defra, 2012). However, while the importance of climate change on water is widely recognized and acknowledged at a national level in the United Kingdom, one of the major challenges is that at regional and local (catchment) levels, the nuances of the drivers on demand and impacts on hydrological water balances are less obvious (Watts et al., 2015). As a consequence, regional climate projections show much greater spatial and temporal variability, with disagreement in the direction of change in critical variables such as precipitation in some regions and seasons (Bates et al., 2008).

For water management, it is also at a regional level that most adaptation responses will need to be implemented. To develop and test appropriate adaptation actions, planners and decision-makers require robust understanding of the scale and scope of change and the uncertainties surrounding the projections. An absence of information, or perhaps just a perception of an absence of information, seems to be a major barrier to taking action (Moser & Ekstrom, 2010). Even when decision-makers deliberately choose approaches that favor flexible or low-regret solutions, such as scenario-neutral approaches (Wilby & Dessai, 2010) or

robust decision making (RDM; Lempert et al., 2006), they need a plausible extent of context-relevant futures against which they can test solutions (Adger et al., 2009). One of the major challenges in water management is therefore in quantifying the likely magnitudes of future demand within plausible envelopes of uncertainty and understanding how these differ through space and time between different sectors.

In England and Wales, all water companies (utilities) are legally required under the Water Industry Act (1991) to produce a Water Resources Management Plan (WRMP) and to submit these to government for scrutiny (Water UK, 2015). These plans set out the water company investment needs and priorities to deliver a secure and reliable supply of water under conditions of future climate and socioeconomic uncertainty. This is fundamentally important given that the WRMP process is regulated, with water companies having statutory responsibilities. These plans are updated on a 5-year rolling cycle to ensure there are sufficiently reliable supplies of water to meet anticipated demands from society and changing population demographics over a 25-year horizon.

The WRMPs also need to be resilient to the effects of climate and socioeconomic change even under conditions where water supplies are already stressed. During drought periods, or under exceptional circumstances when the risk of reductions in supply becomes significant, measures to reduce demand (e.g., through nonessential use bans, temporary use bans, or even the use of standpipes in extreme circumstances) or to allow increased abstraction, beyond levels permitted by an abstraction license, may be granted. Such measures can have a direct effect on both the general public (e.g., temporary use bans) and the environment (e.g., drought permits for temporary changes to abstraction licences) or indirectly on other sectors such as agriculture which can be subject to regulatory or *nonessential use* restrictions. Water companies therefore need to strike a socially and economically acceptable balance between the frequency and likelihood of occurrence of such interventions and the costs of implementing additional supply and/or demand measures to reduce their recurrence.

In the United Kingdom, water companies are required to specify the frequency with which such interventions will be permitted as specific targets in their WRMPs. These are known as *Levels of Service* (LoS) and constitute the benchmarks against which an individual company must strategically plan its future investment in schemes to increase available supply (e.g., storage reservoirs) or reduce customer demand in dry years. The LoS are formally agreed through a process of public consultation with customers, the water regulator (Environment Agency, EA) and Water Services Regulation Authority (Ofwat; Water UK, 2015). The overarching aim of a WRMP is thus to ensure that companies can meet customer demands for water in future dry years without exceeding the stated LoS. A core objective of a WRMP is to balance supply and demand in very dry years where water stress on the system's balance might require triggering one or more drought interventions. Detailed guidance is provided to water companies by the Environment Agency (2013), government, and Ofwat on how they should manage their future water resources, including drought plans and consideration of resilience and climate change. Guidance also encourages water companies to consider a longer planning horizon beyond the statutory 25-year minimum period; the regulator can also issue directions on minimum levels of resilience (Charlton & Arnell, 2001; Water UK, 2015).

In contrast to public water supply (PWS) and the energy sector, the agricultural sector in England and Wales is not formally required to submit plans regarding either its future water demands or any planned strategic investments. To date, agriculture's average share of water use, at about 2% of total national water abstraction, has not warranted special provisions but that demand is highly seasonally variable. Agriculture is also widely regarded as being one of the sectors most vulnerable to climate change (Falloon & Betts, 2010) due to the impact of increased temperatures, reduced rainfall, and increased frequency of extreme events, not only in semiarid environments but also in humid countries such as the United Kingdom (Knox et al., 2010). Here climate change is expected to impact on land suitability (Daccache et al., 2012) and the future viability of rainfed cropping and hence demand for irrigation. Furthermore, agriculture represents a consumptive use of water (in contrast to PWS), with relatively low immediate returns to local hydrological systems. Estimates of the magnitude and location of future irrigation demand are thus essential for strategic planning of water resources.

Despite its importance, agricultural demand forecasting is fraught with difficulty, as water use for supplementary irrigation is highly sensitive to changes in agroeconomic policy, agroclimate variability, and resources availability. There is much uncertainty regarding demand forecasts and *irrigation futures*, mainly with

respect to assumptions made regarding climate variability, agricultural management policies, and socioeconomic development, as well as changes in water regulation and available *headroom* on abstraction licences (permits). For both agriculture and PWS, the concept of headroom is also critical in water resources planning (Dessai & Hulme, 2007). It is a measure of the supply-demand balance, with *available headroom* defined as the difference between available water and demand, while *target headroom* corresponds to the minimum buffer that a business would allow between available water and demand to account for any uncertainties either in supply or demand. In recent years, guidance has focused more on maintaining or increasing headroom with demand management-oriented measures (Environment Agency, 2012). However, supply-side measures (e.g., increasing system connectivity and storage reservoirs), which were the traditional response, are usually considered more reliable, more certain, and effective in addressing supply/demand imbalances (Charlton & Arnell, 2011). In the United Kingdom, a *twin-track* approach which reflects a balance between resource development (e.g., new storage capacity) and demand management (such as promoting behavioral change, uptake of new technologies, reducing leakage, and implementing water efficiency measures) has evolved to incorporate both supply and demand measures to reduce pressure on water resources (Defra, 2008).

Within the scope of a broader initiative to develop an integrated water resources management (IWRM) strategy for the Anglian region in England, this paper describes an empirical study using a mixed methods approach to incorporate agricultural sector needs into a RDM framework to improve regional water resources allocation and management. The approach estimated likely changes in future water demand within specific sectors (including PWS, energy, and agriculture) to identify opportunities where potential *trade-offs* might be possible between competing sectors, recognizing the need to maintain environmental flow requirements. Through stakeholder engagement, a series of options or *portfolios* considered compatible with supporting multisector collaboration were identified. A long-term (up to the 2060s) water strategy for the region could then be developed to accommodate both future water demands to support sustainable socioeconomic development while also protecting environmental flows. Future water demands were assumed to be unconstrained by current regulations, with any future being relative to a 2015 baseline. The challenge of incorporating climate uncertainty was addressed through use of new stochastic climatology produced for the United Kingdom by Guillod et al. (2017).

The research focussed on eastern England, an area recognized as one of the most water-stressed regions in the United Kingdom, where the majority of irrigated agriculture is concentrated (accounting for >50% of the irrigated area and volume of water abstracted nationally) and where urban expansion and population growth is expected to have the most significant impact on household water use, rural land use, available water supplies, and the aquatic environment. The approach involved integrating a demand forecasting model to estimate the impacts of climate and socioeconomic change on agricultural water use, coupled with a regional water resources simulator to assess supply-demand balances and spatial changes in future water demand. Performance metrics were used to drive a multicriteria search analysis to identify supply and demand management portfolios and structured stakeholder workshops then used to identify opportunities for multisector collaboration. A brief description of the case study area is provided, together with the challenges associated with defining acceptable trade-offs, managing scalar (subregional) issues, modeling uncertainty, and engendering a trusted and inclusive approach to stakeholder engagement using a RDM framework.

The approach was directly aligned with the concept of IWRM as defined by the Global Water Partnership). Readers interested in a comprehensive description and critique of IWRM and its principles are referred to Swiss Agency for Development and Cooperation (2015). Also, of relevance here was recognition of the need for trade-offs to balance equity, environmental, and economic priorities (3E's) and compromising on the right combination of information, institutions, and infrastructure (3I's) required to achieve the desired outcome for the region, a process described by Sadoff and Muller (2015) as the 'art of adaptation' to reconcile the 3I's with 3Es for sustainable water management.

2. Case Study Region

The research focused on an area of 30,800 km^2 in eastern England that is experiencing rapid socioeconomic development and population growth that is predicted to continue over the coming three

decades. One water company (Anglian Water Services) is primarily responsible for the water supply and distribution network (although other companies including Affinity Water, Cambridge Water, and Essex and Suffolk Water) also operate within the region. In response to concerns regarding future water supply-demand imbalances, Anglian Water Services have recently initiated a multisector collaboration between PWS, energy, agriculture, and the environment to develop a long-term water strategy for the region through a partnership termed Water Resources East (WRE). The WRE rationale builds on experience from *Water Resources in the South East* (WRSE) an initiative led by the water regulator (EA) rather than the private sector. The aim of WRSE was to encourage a number of water supply companies in the southeast region to benefit from economies of scale and identify collaborative investment opportunities for joint capacity expansion to provide greater resilience to future supply-demand shocks (von Lany et al., 2013). While WRSE engaged individual water companies, it was not multisector, since agricultural, power generation and environmental demands were ignored. Based on IWRM principles, the objective of WRE was to pioneer a more collaborative approach to water resources planning rather than adopt the traditional approach in which water companies define their water resource plans for their respective areas in isolation from other sectoral needs. WRE therefore seeks to achieve a reliable, sustainable, and affordable system of water supply in the region and one that will be resilient to the effects of population growth and climate change. For the water company involved, the outputs will be used to inform submission of their 2019 WRMPs.

The region is also recognized as being one of the driest and most water-stressed in England, with over half of all catchments defined by the EA, as being either overabstracted and/or overlicensed (Figure 1; Hess et al., 2010). Average annual rainfall is around 600 mm (less than 70% of the national average), and annual reference evapotranspiration (ET) averages 530 mm. Future climate projections show an increase in aridity due to rising temperatures and ET rates and higher rainfall seasonality, with drought periods occurring more frequently and with higher intensity (Rey et al., 2017). It also has critical socioeconomic importance given that three of the five fastest-growing cities in the United Kingdom (Cambridge, Milton Keynes, and Peterborough), the Thames Gateway, and three transport growth corridors are all within the WRE region. Demographic forecasts estimate that the population will increase by between 0.5 and 6.4 million above current levels (10.5 million) by 2100. Nearly 2×10^9-m^3 water is currently licensed for PWS of which near half (47%) is abstracted each year, of which approximately 85% is dedicated to meeting PWS needs and the remainder (15%) is for water transfers between river basins (Figure 1).

Agriculture dominates the landscape, representing over 80% land cover, within the region. Indeed, due to the favorable agroclimate, fertile soils, low-lying topography, and dominance of large-scale intensive farming systems, the region also contains the highest concentration of intensive agricultural and horticultural cropping, with most fresh fruit, potato, and vegetable enterprises being dependent on irrigation to deliver high quality, continuous supplies for premium produced to the major retailers and processors. Irrigation is used to buffer the effects of rainfall variability and to meet the quality assurance standards demanded by the retailers (supermarkets; Knox et al., 2000). High-value irrigated vegetable cropping typically abstracts 160×10^6 m^3 in a dry year (Weatherhead et al., 2015) with half the total irrigated area and 57% of the total volume of water applied concentrated in the region (Figure 1). Although, on average, the agricultural sector abstracts only 16% of the regional water resources for irrigation, it is predominantly consumptive in use and is highly seasonal. In summer months, daily irrigation abstraction can exceed the total volume abstracted for PWS use with negative consequences for habitats (Defra, 2008). In some catchments, agriculture is the only water abstractor. As a consequence, in many catchments in the region, summer water resources are already overcommitted and additional licenses for either surface or groundwater abstractions are no longer available (EA, 2013).

In economic terms, the agrifood and drink (AF&D) sector in the region accounts for 4% of national Gross Value Added and 30% of England's Gross Value Added from the AF&D sector (Office for National Statistics, 2016). The agricultural sector is most closely linked to the environment through its relationship with water; a reliable supply of sufficient quality is critical for growing crops, raising livestock, processing fresh produce, manufacturing food, and as an ingredient in beverages. Finally, the region is also renowned for the high concentration of national and internationally protected aquatic ecosystems (Figure 1) including SACs, RAMSARs, and SPARs (Natural England, 2013).
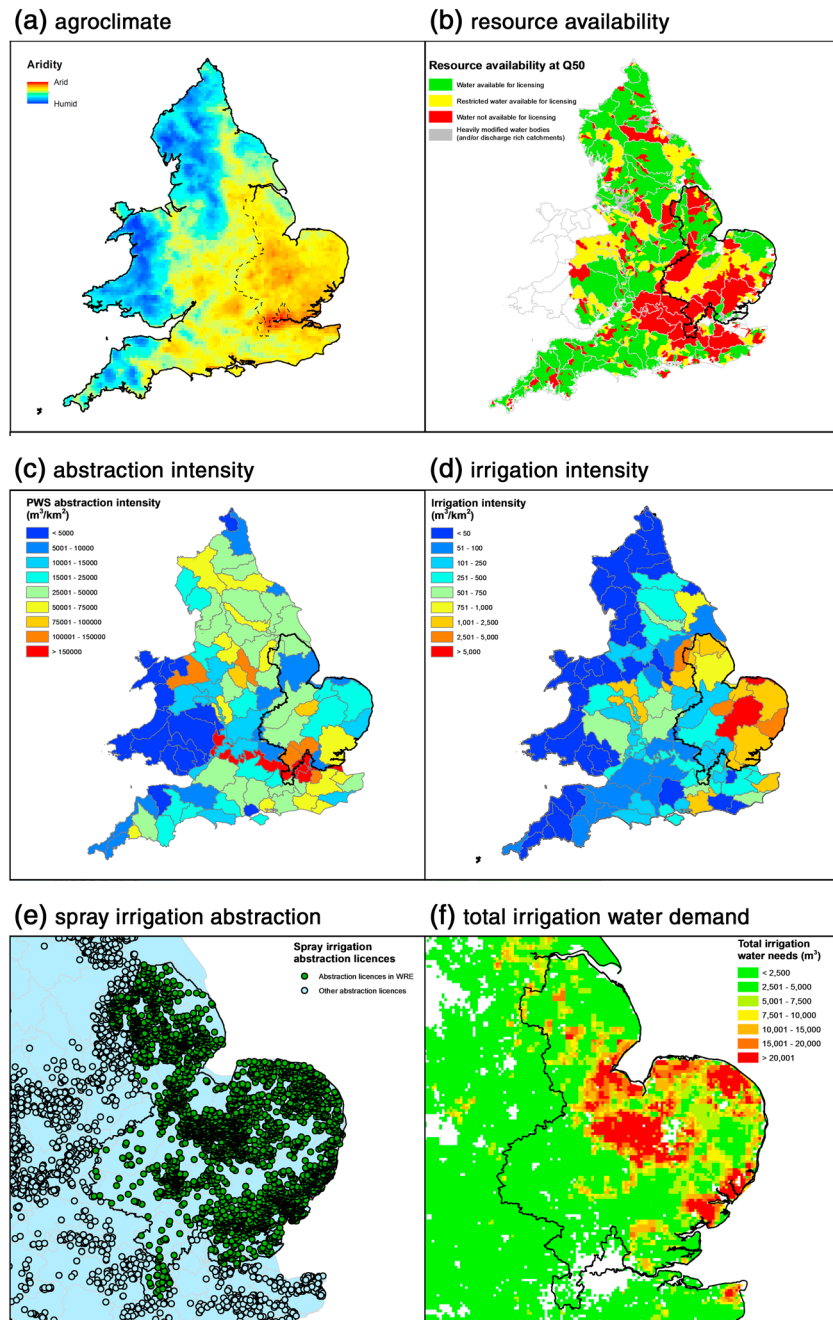
Figure 1. Regional variation in agroclimate using PSMD$_{max}$ as an aridity index (a), resource availability at Q50 (b), abstraction intensity (m^3/km^2) for public water supply (c), abstraction intensity (m^3/km^2) for irrigated agriculture (d), distribution of spray irrigation abstraction licenses in WRE region (e), and total irrigation demand (m^3/4 km^2). PSMD = potential soil moisture deficit; WRE = Water Resources East.

3. RDM Framework

With the increasing risk of drought and rising future demand for food, energy, and services, there is growing awareness and concern that a lack of water could severely limit economic growth and regional development. In response to these multiple water-related risks, the WRE initiative set out to develop an integrated, collaborative, and multisector approach to quantify future changes in water demand by sector and reconcile competing demands through trade-off analysis and stakeholder engagement. The plan was to identify more efficient, robust, resilient, and cost-effective solutions than would be offered through more traditional single

sector studies. For example, this might include reducing demand (by cutting leakage) and increasing supply by building new reservoirs, recycling, and reusing water, promoting water trading and desalination. It also set out to challenge current perceptions and attitudes regarding the potential benefits of collaborative water use, raising important questions such as (i) What levels of demand management are possible? (ii) How can environmental net benefits be maximized? (iii) How can the net benefits of sharing resources be maximized? (iv) How can stranded surpluses and the volume of inter-basin transfers be minimized? (v) How can water allocation flexibility be ensured for the power generation sector? and (vi) What kinds of funding mechanisms and investment portfolios might be required to meet and prioritize future agricultural demands? WRE was thus attempting to both articulate what was needed (objective outcomes) as well as the range of mechanisms by which change could be effected (water strategy, investment options, and actions). In this context, it represented the first attempt in the United Kingdom to investigate and critique competing water demands and investment options at a regional level through the lens of an IWRM perspective but most importantly considering agriculture as a key stakeholder and water-dependent sector.

The WRE study opted for a RDM approach. Such approaches are increasingly being applied in natural resources management to develop strategies for mitigating highly uncertain risks such as climate change, long-term population growth, and multiseason drought events. RDM has previously been applied in England and Wales (Borgomeo et al., 2014); Hall, Watts, et al., 2012b; Matrosov, Padula, et al., 2013a; Matrosov, Woods, et al., 2013b), California (Weaver et al., 2013), and the Lake Tana Basin (Shortridge et al., 2016) and have also been applied to support decision making in flood risk management (Hine & Hall, 2010; Sayers et al., 2012), the development of greenhouse gas emissions policies (Hall, Lempert, et al., 2012a), and national infrastructure planning (Otto et al., 2016). By combining a regional water resources simulation model with forecasts of future demand including the effects of climate change, the approach enables stakeholders and decision-makers to assess a wide spectrum of future resource management and investment strategies and screen those that would be more robust under a wide range of equally probable socioeconomic futures.

In this study, the method relied on a water resource simulator that explicitly represents the effects of changing water abstraction and use across the region. This simulator is a spatially distributed regional water resources allocation simulator model. It includes the natural (river network) and built water infrastructure (piped distribution network) to supply different resource zones and seasonal water demands for each sector. The model runs on a daily time step to assess the surface and groundwater balances for each catchment, sectoral water demands, and environmental flow requirements to meet EU Water Framework Directive (WFD 2000/60/EC) needs.

Multicriteria search optimization techniques were then used to quantify the relative performance of a set of metrics (approximately three for each sector), with analyses visually represented through parallel plotting software (Polyvis, www.polyvis.org). The optimization process resulted in a large number of options or portfolios with each reflecting a different combination of metrics at regional or subregional level. Using the Polyvis interface, key informants and stakeholders could then explore possible trade-offs between competing water demands, the environmental and engineering performance of different portfolios to address any supply-demand imbalances, and critique proposed interventions (infrastructure investments) that were shown to be robust under most plausible future socioeconomic scenarios. In contrast to other least-cost optimization techniques which are usually deterministic and assume only one or a limited number of possible *futures*, the advantages of the RDM approach here was that it included the capacity to simultaneously evaluate a much wider range of climate change, population growth, and water scarcity scenarios using stochastic modeling techniques to explicitly consider uncertainty in future water supply and demand (Padula et al., 2013), the ability to search for and test many different options for minimizing supply-demand risks and the likelihood of, for example, *stranded assets* due to lack of system connectivity. The RDM approach is also considered to provide much greater transparency in strategy development and to support inclusive multisectoral negotiation and decision making. This includes explicit evaluation of stakeholder preferences for the most appropriate balance between system resilience, environmental performance, and affordability.

3.1. Description of the RDM Approach

Lempert and Collins (2007) defined RDM as a long-term planning framework devised to help decision-makers define future robust management and investment alternatives under scenarios of deep uncertainty which
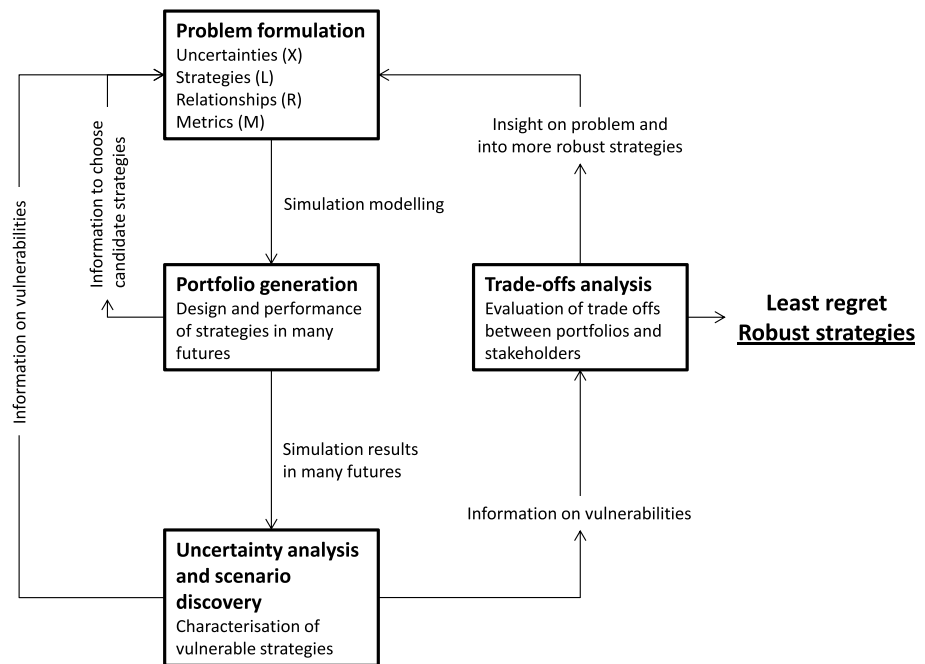
Figure 2. Steps in the robust decision making analysis (adapted from Lempert et al., 2013).

was assumed here to occur when the parties involved in a decision-making process do not know, or do not agree, on the likelihood of future events or the best approach for relating actions to consequences. RDM thus seeks robust, rather than optimal, strategies that satisfy or exceed minimum performance criteria across a broad range of plausible futures. In contrast with more traditional decision-making approaches that tend to follow a *predict-then-act* framework, the RDM approach executes the analysis in reverse order or *backward* starting with one or more alternatives and testing them against multiple scenarios to identify those that are critical to the plan's success using a vulnerability and response approach (Lempert et al., 2013). Ultimately, RDM can help decision-makers develop initially considered strategies into much more robust plans, or *least regret* strategies (Hall et al., 2012a, 2012b).

An RDM framework is typically divided into four steps (Figure 2). First, the *problem formulation* step conceptualizes the system under consideration, identifying critical uncertainties (referred to as X), preferred strategies (L), relationships (R), and metrics (M). This is similar to the Drivers-Pressures-State-Impact-Responses approach (European Environment Agency, 2014). Preferred strategies, or decision levers, quantify an option that can be used to influence the system. For example, building a new reservoir could substantially reduce system vulnerability against future drought events. Metrics are then used to quantify the performance of specific actions with regard to the various objectives being pursed in the decision-making process. Relationships represent the process or processes that determine the consequences of selected strategies quantified by the output metrics.

Second, in the *portfolio generation* step, a single strategy or combination of strategies that are initially selected are evaluated under a wide range of plausible futures (or scenarios) to identify under which combination of future conditions they fail to meet the performance criteria. The initial candidate strategies can be selected through a utility or regret analysis (Groves & Lempert, 2007); it can be one or the combination of more existing future plans, or it can even be the current policy (Matrosov et al., 2013a, 2013b). The behavior of one or more models of the system under study is systematically assessed and results stored in a database, forming a portfolio of strategies. Each run of the model is considered a success if it satisfies the minimum performance criteria or a failure if it does not. Thresholds are defined and can be either absolute or relative. In the first case, the strategy fails if the performance metric exceeds a certain limit. In the second case, the performance criteria are compared to the performance of a benchmark strategy.

Third, the *uncertainty analysis and scenario discovery* step characterizes the vulnerabilities of the candidate strategies by identifying sets of scenarios under which they would be under additional stress. Using a

scenario discovery approach, it is possible to summarize poorly performing cases with a smaller number of scenarios (Bryant & Lempert, 2010; Groves & Lempert, 2007).

Finally, the performance of individual portfolios for stakeholders is compared across the different metrics identified from the first step. This provides an additional source of information that decision-makers can use to design new alternatives that reduce the vulnerabilities of their initial preferred or candidate strategies. The four steps can be iterated until the different stakeholders or parties compromise on the most robust strategy or one that minimizes regret.

3.2. Integrating Agriculture Into the RDM Framework

Four discrete steps were required to integrate agriculture into the RDM framework; these are briefly outlined below. Drawing on earlier work (Knox et al., 2013; Weatherhead et al., 2015), a methodology was developed to estimate the future unconstrained irrigation water demand for each catchment in the Anglian region under a given set of climate change and socioeconomic scenarios. As a first step, agricultural irrigation water requirements from surface and groundwater sources were modeled for each catchment in the region. Historical weather data (Compo et al., 2011; Keller et al., 2015) and geospatial soils data for each catchment were integrated to estimate theoretical irrigation needs (depths applied) for the most important crop categories in using a soil water balance program (Hess, 1996). Total theoretical volumetric irrigation demand (Ml) was estimated by combining the theoretical needs (mm) with irrigated area (ha) data for each catchment. Irrigated areas were estimated from cropped areas reported by the government Regional Farm Business Survey (2010) and Irrigation Survey 2010 (Defra, 2011). In this way, estimates of unconstrained irrigation demand were derived for the 2015 baseline, assuming a *dry year* (defined as the year with a rainfall with an 80% probability of exceedance). The effect of climate change on irrigation demand was estimated from projections of future precipitation and reference evapotranspiration (ETo) and an agroclimate index representing maximum potential soil moisture deficit ($PSMD_{max}$). Regression equations that link $PSMD_{max}$ with crop water requirements (Knox et al., 1997) were then used to estimate annual unconstrained irrigation demand (Ml) for each catchment and for any future simulated year, taking into account the spatial variability of soils and agroclimate across the region.

A second step, drawing on earlier work (Weatherhead et al., 2015; Weatherhead & Knox, 2008), used scenario analysis techniques to explore four plausible futures for water demand in the Anglian region as a whole and within the irrigation sector. The four scenarios were based on two axes of social and economic change, ranging from sustainable to uncontrolled demand for material goods and services on one axis and from regionalization to globalization on the other (Environment Agency, 2009). These four scenarios were termed sustainable regionalization (SR), sustainable globalization, uncontrolled demand regionalization (UR), and uncontrolled demand globalization. Scenarios were supported by narratives and indicator values to reflect differences in the *drivers of change*, such as economic growth, water consumption behavior, environmental regulation, and investment and innovation. The scenarios were then interpreted for UK agriculture and agricultural policy, relative to the current 2017 situation. The regionalization strategies emphasize greater self-sufficiency in agricultural commodities, with SR assuming increased weight to social and environmental priorities at the local scale, compared with UR reflecting a mainly unconstrained production oriented approach. The globalization strategies involve greater international connectedness for UK agriculture, with sustainable globalization assuming targeted compliance with internationally agreed social and environmental standards, compared with uncontrolled demand globalization that assumes unconstrained world market agricultural *free trade*.

Scenario-specific narratives and a set of metrics were then developed for the regional irrigated sector drawing on earlier work by the Environment Agency (2008) and Knox et al. (2013) to derive growth factors for irrigation demand for three main agricultural subsectors (arable, potatoes, and horticulture) under the four scenarios. For example, under SR the irrigated proportion of all crop subsectors is low, mainly involving traditional irrigation methods for the seasonal production of high value horticultural crops, constrained by limited available water. Under UR, however, high commodity prices and preferential access to water result in increased irrigation across all commodity groups in pursuit of high yields and output. In addition to overall population growth, the major drivers of irrigation demand were identified to be the national average annual consumption per head of the aforementioned agricultural commodity types, the proportion of total crop consumption grown domestically in England, the proportion irrigated, the average crop yields, irrigation

Table 1
Relative Strength and Direction of Drivers of Irrigation Demand and Growth Factors by Scenario for the WRE Region

Sector	National consumption per head	Proportion UK grown	Yield	Cropped area	Proportion irrigated	Irrigation depth	Irrigation efficiency	Irrigation growth factor		
								2040	2060	2080
Sustainable regionalization										
Arable	↑↑	↑↑	←→	↑↑	↓	↓	←→	1.13	1.04	0.71
Potatoes	↑	↑↑↑	←→	↑↑	↓	↓	←→	1.07	0.99	0.73
Horticulture	↑↑	↑↑	←→	↑↑	↓	↓	←→	1.70	1.87	1.42
Total growth								1.39	1.39	1.03
Sustainable globalization										
Arable	↑↑	←→	↑	↑	←→	↑	↑↑	1.06	1.09	1.04
Potatoes	←→	←→	↑	↑	↑	↑	↑↑	1.13	1.16	1.08
Horticulture	↑↑↑	←→	↑↑	↑↑	↑	↑	↑↑	2.35	3.42	4.62
Total growth								1.65	2.04	2.40
Uncontrolled demand, regionalization										
Arable	↑↑	↑	↑↑	↑	↑	↑↑	↓	1.34	1.70	3.57
Potatoes	↑	↑↑	↑	↑	↑	↑↑	↓	1.32	1.58	1.66
Horticulture	↑	←→	↑↑	↑	↑	↑↑	↓	2.40	3.85	5.65
Total growth								1.81	2.52	3.38
Uncontrolled demand, globalization										
Arable	↑	↓	↑↑	←→	↓	↑	↑	0.82	0.72	0.47
Potatoes	↓	↓	↑↑	↑↑	↑	↑	↑	0.95	0.86	0.70
Horticulture	↑↑	↓	↑↑	↑↑	↑↑	↑	↑	1.57	2.21	2.19
Total growth								1.24	1.39	1.25

Note. Total growth in water demand includes allowance for other agricultural irrigation, including biofuels. Irrigation growth factors relative to 2015 baseline (=1). Score: ↓↓↓ large decrease; ↓↓ moderate decrease; ↓ slight decrease; ←→ no change; ↑ slight increase; ↑↑ moderate increase; ↑↑↑ large increase. WRE = Water Resources East.

depths (relative to technical requirement), and the efficiency of irrigation water applied. A scoring framework was developed and validated using expert judgement by the researchers and key informants to assess the strength of *growth factors* affecting water demand relative to the 2015 baseline under each scenario (Table 1). The symbols (arrows) in Table 1 indicate the direction and magnitude of expected change, whether an increase, decrease, or no change, and whether the change was large, moderate, or slight. Historical trends analysis was used to determine a quantitative index of change relative to the baseline (=1) for each driver over the relevant direction and range of change. For example, indices of change were derived for food consumption statistics for the United Kingdom from FAOSTAT (2015), agricultural self-sufficiency from Defra (2014) statistics, trends in crop yield from Knox et al. (2016), and irrigated areas and depths from national irrigation surveys (Defra, 2011) and population estimates from the Office of National Statistics (Office for National Statistics, 2015).

In a third step, the scenario approach and demand estimates were tested in a 1-day workshop involving a dozen key informants specifically chosen to represent the diverse composition of the UK agricultural and horticultural sector. The aim of the workshop was to consider the main drivers of change and the uncertainties likely to impact on future irrigation water demand. The participants were from a mix of technical backgrounds and included representatives from the industry levy board (Agricultural and Horticultural Development Board), the National Farmers Union, UK Irrigation Association, independent growers, water user associations, water company (Anglian Water), and independent researchers with interests in agricultural water resources. Participants were in general agreement on the high-level drivers shaping future UK agricultural production and how these might translate into impacts within the irrigated sector. These included agricultural and rural policy, food markets and prices, environmental policy, farmer attitudes and motivation, and agricultural production and farming systems. Discussions also explored the regional dimensions of these drivers, particularly given the relative intensity of arable farming in the Anglian region. Workshop participants also identified major sources of uncertainty affecting irrigation growth factors. These included climate change and increasing drought risk in the United Kingdom, world market dynamics and global climate-related risks, and national and regional socioeconomic conditions and policies, including the proposed withdrawal from the EU Common Agricultural Policy. Participants then worked through selected scenarios to
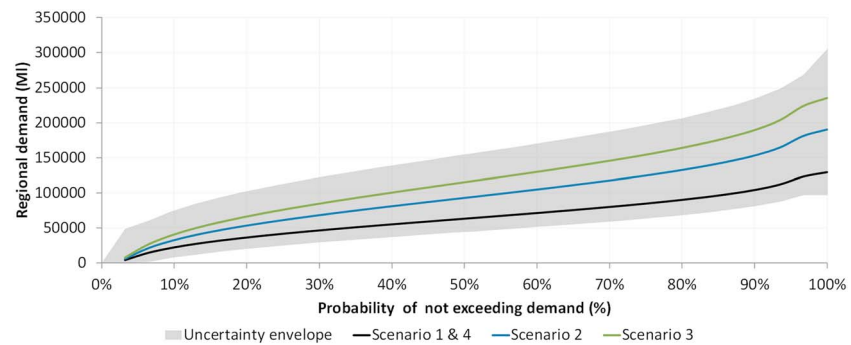
Figure 3. Average distribution function for total irrigation water demand (Ml) in the Water Resources East region for four selected socioeconomic scenarios under a near-future climatology signal (2020–2049).

reassess the growth factors previously generated by the researchers. While there was general agreement about the direction of change in growth factors for each scenario, views varied about the relative strength of factors, for example, relating to the degree of change in dietary preferences and in crop yields.

In the final step, the researcher and workshop assessments were combined to estimate future irrigation demand under each scenario (Table 1). Taking the estimates for 2060, for example, the greatest expected growth in irrigation demand is projected to occur under the UR scenario reflecting strong positive increases across most drivers of demand change, including the proportion of crops irrigated and depths applied. Irrigation productivity (t/m^3 applied), however, falls due to incentives to maximize crop output rather than economize on water use. Under this scenario, irrigation demand is estimated to increase by a factor of 2.52 compared with the baseline. By comparison, sustainable globalization, characterized by healthier plant-based diets, retained levels of agricultural self-sufficiency, and increased irrigated areas and depths that are moderated by significant increases in irrigation productivity, has an overall growth factor of 2.04 for the 2060s. The equivalent 2060 estimate for the other two scenarios was 1.39 (Table 1). These estimates of change in demand (expressed as growth factors) were further combined with estimates of population growth for each socioeconomic scenario (Office for National Statistics, 2015) to derive irrigation demands for each subsector, under each of the future climate and socioeconomic scenario. The algorithms to calculate irrigation demand were then integrated into the WRE water resource simulator in order to estimate agricultural demand, both regionally and by catchment.

Figure 3 compares, for example, estimates of irrigation demand for each of the four socioeconomic scenarios under a near future (2020–2049) climate signal (Guillod et al., 2017) recognizing that for each distribution function there is an envelope of uncertainty. Irrigation demand under Scenarios 1 and 4 is expected to rarely exceed 130,000 Ml; in contrast, demand might reach 180,000 Ml in Scenario 2 and almost double to 240,000 Ml in Scenario 3. These probability distributions illustrate the high sensitivity of the demand forecasts to the assumed prevailing socioeconomic conditions.

Having integrated a module to forecast agriculture irrigation demand into the WRE water resource simulator, the remaining stages involved portfolio generation and trade-off analyses for a range of simulated interventions. These are briefly considered below, from an agricultural sector perspective.

4. Multicriteria Searches to Identify Multisector Portfolios and Trade-Offs

Using a set of performance metrics, the objective of the RDM process is to identify a robust or least regret strategy that performs well against a set of key criteria under a wide range of scenarios (Figure 2). In WRE, the strategy search and subsequent evaluation of intervention portfolios aimed to maximize the reliability of supply to a range of different water users (PWS, energy, and agriculture) while minimizing investment costs and negative environmental impact. In this context, strategies were formed by combining multiple interventions to ameliorate the supply-demand imbalances at the local, subregional, and regional scales. These interventions included construction of new reservoirs or increasing the capacity of existing storage, the use of desalination plants, increasing wastewater reuse, water transfers either between water resources zones within the region or from adjacent water companies, leakage reduction, and other efficiency-improving
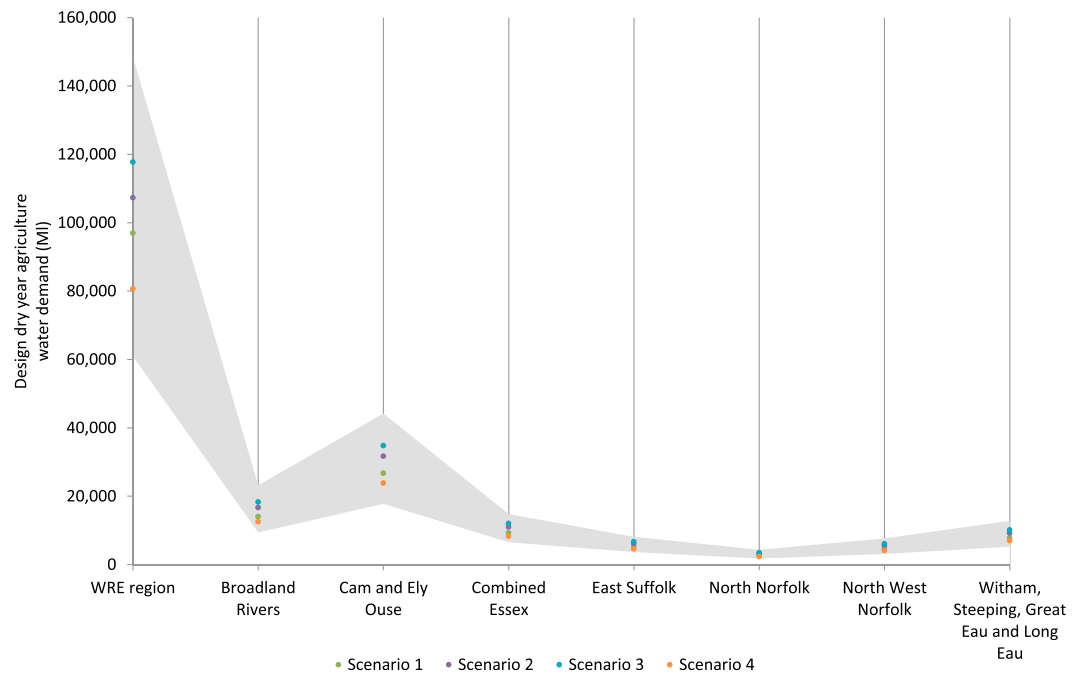
Figure 4. Modelled variability 'design' dry year agricultural irrigation demand under 2020–2049 climate conditions for the four socio-economic scenarios.

interventions. For irrigated agriculture, the performance of these individual interventions or their combination could be evaluated against their capacity to satisfy irrigation demand in a *design* dry year at regional and catchment levels while also minimizing any negative effects associated with reducing environmental flows or competing uses. These interventions also need to reflect reasonable implementation cost (both capital [CAPEX] and operational expense [OPEX]). Figure 4 shows the modelled spatial variation in 'dry year' irrigation water demand at both regional level and for selected catchments in the WRE region; the envelope highlights the associated uncertainty in agricultural demand linked to future agroclimate and agro-economic scenario (Table 1).

Based on the demand forecast modeling, for irrigated agriculture it is important that any future investment portfolios or strategies for the region are capable of supplying up to 140,000 Ml/year at the regional level, but critically that local demand hot spots such as the Cam and Ely Ouse can also be accommodated (40,000 Ml/year), given their significant dependence on water for high value production. Conversely, some catchments would require modest future water allocations in order to secure future production levels. In theory, agricultural stakeholders would logically be expected to only select portfolios within a collaborative approach that maximized regional irrigation supplies. However, in eastern England, irrigation demand is highly concentrated within a few catchments, mainly due to the distribution of fertile soils and topography and the current availability of water resources. It is therefore critical not only to consider future water resource strategies that only meet total regional agricultural demand but also to scrutinize options that are also robust at subregional level to reduce future vulnerability in irrigation abstraction hot spot catchments; priorities for a regional water strategy thus need to reflect important local catchment demands. Furthermore, some future investment options would inevitably have a strong geographical focus, including desalination plants and wastewater reuse schemes, which would only support additional agricultural demand for farms in close proximity to coastal areas and/or near-sewage treatment plants, respectively.

5. Concluding Comments

The application of the multicriteria search and RDM approach has helped develop a more in-depth understanding of the water supply vulnerabilities the agricultural sector faces in the region and reconciling how other sectors (PWS, energy) and the environment are likely to be impacted by water scarcity. The RDM

approach adopted in the WRE study has also stimulated new and proactive cross-sectoral engagement with portfolios being selected that could facilitate multisector investment (particularly from those who otherwise would struggle to raise capital) as well as encouraging collective awareness and recognition of the future challenges facing abstractors from competing sectors. It is anticipated that this preliminary assessment will underpin further efforts to develop and implement an integrated approach to water resources planning and management in the region. Involving engagement from a spectrum of stakeholders with shared interests in water will not only help exploit opportunities for making efficiency gains across different investment programmes but will also reduce the likelihood of stranded assets or maladaptation strategies being implemented as a response to future drought and water scarcity risks. The RDM approach could be applied to other natural resource challenges including resolving land use change due to urban development or the consequences for water quality, soil, and nutrient management.

In the context of supporting improved water resources management though RDM, two aspects are critical. First, there is a need, particularly during periods of drought, for competing sectors to maintain open lines of communication and to recognize other sector's specific water needs, in terms of the importance of peak timing of water demand. Multisector stakeholder engagement has also identified the differences that exist in language and terminology and the importance of framing discussions where participants understand the fundamental differences between consumptive (agriculture) and nonconsumptive (PWS, energy) uses, supply versus consumption, as well as impacts of water efficiency interventions on water abstractions and return flows. Ultimately, at the catchment or river basin scale it is the different levels of consumption that need to be traded off against each other, but at certain locations, it is the abstractions (withdrawals) that are also important which often create difficulties in resolving allocation conflicts. Second, there is the issue regarding water source and for the WRE region the high dependence on groundwater for PWS and agriculture, particularly where groundwater fed streams support important aquatic ecosystems. There is also the role that aquifers in the region can provide a short-term (seasonal) buffer during drought events and their future utility as a bank or trading facility for supporting water markets. Although groundwater offers major scope in providing resilience to drought stress, initial modeling within the WRE study has identified that the volume of groundwater abstracted for agriculture and PWS may need to be substantially curtailed, in some cases, to levels that are half of that which is currently assumed available.

Through an empirical application, this paper has attempted to link ongoing debates surrounding long-term, multisector water resource strategies, the opportunity for trade-offs between competing sectors, and the need for collaborative investments and shared risks in water resources planning and management. This is fundamentally important because, despite being a key economic sector in the region, agriculture is often marginalized in water resources decision making due to its low demand and low perceived economic value compared to other sectors. However, the demand for irrigation in the region is predicted to increase significantly due to a changing climate and population growth, principally due to dietary changes linked with socio-economic development. In this context, the RDM approach helps provide valuable insights and a useful framework through which decision-makers and stakeholders can scrutinize competing demands and identify robust portfolios that meet multisector needs while providing appropriate levels of resilience under multiple future scenarios.

There is also a need for equivalence in the RDM process in terms of individual sector treatment, to reflect the LoS needed for PWS, the relative water values within different sectors, the environmental objectives assumed in the RDM approach (EFR could be viewed as a rather crude metric of environmental performance), and identification of business critical risks linked to water. For the agricultural sector, the importance of water in *adding value* needs clear recognition, and prioritization of water use between different sectors needs further consideration. Options for water trading and considering impacts of water investment in the region on the sustainability of rainfed versus irrigated production also warrant further attention. Finally, while fostering an increased level of collaboration between stakeholders, particularly between PWS and agriculture that was identified as a key priority at the outset, some concerns were raised regarding *rules of engagement* and the need to create common ground for understanding and building of trust. Historically, there have been tensions between the water companies and the agricultural sector, but the RDM approach in WRE was widely endorsed as a new opportunity to strengthen relationships and underpin long-term strategic collaboration. Under these conditions, there will be an onus on sharing and developing information, to explore in a transparent way the technical and economic viability of resource

investments and to recognize and understand the emergent water needs for agriculture, energy, and PWS sectors. Although rising demands will create tensions regarding water allocation and prioritization, it will inevitably be under drought conditions that the more thorny trade-offs between these competing sectors will take place. The fundamental question is whether collaboration and a genuine willingness to engage during periods of high water security can be maintained during periods of extreme resource scarcity. The RDM approach has not provided all the solutions, but a robust mechanism through which constructive progress can be evidenced.

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