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Using high-resolution climate change information in water management: a decision makers' perspective

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Abstract

The UK Climate Change Act, requires the Environment Agency to report the risks it faces from climate change and actions taken to address these. Derived information from projections is critical to understanding likely impacts in water management.

In 2019 the UK published an ensemble of high-resolution model simulations. The UKCP Local (2.2 km) projections can resolve smaller scale physical processes that determine rainfall and other variables at sub-daily timescales with the potential to provide new insights in extreme events, storm runoff and drainage management. However, simulations also need to inform adaptation.

The challenge ahead is to identify and provide derived products without the need for further analysis by decision makers. These include a wider evaluation of uncertainty, narratives about rainfall change across the projections and bias corrected datasets. Future flood maps, peak rainfall estimates, uplift factors and future design storm profiles also need detailed guidance to support their use. Central government support is justified in the provision of up-to-date impacts information to inform flood risk management given the large risks and exposure of all sectors.

The further development of projections would benefit from greater focus and earlier scoping with industry representatives, operational tool developers and end users.

Key words: adaptation, high intensity rainfall, flood risk.

1. Introduction

In the UK, many people are likely to experience climate change through its impacts on water, whether through flooding, water shortages or water quality issues [1]. Climate change has been considered in flood risk assessments and water resource planning in the UK for several decades [2][3][4][5]. Most risk assessments have used coarse resolution projections downscaled from climate models not able to resolve many of the important physical and dynamical processes responsible for local to regional scale flooding. This lack of capability has been a strong driver in pursuing higher-resolution climate change information. High-resolution models are generally more skilful in simulating extremes such as heavy precipitation, strong winds, and severe storms and by explicitly simulating convection provide an opportunity to illuminate physical behaviour that previously was represented by parameterizations with large uncertainties [6]. Convection-permitting models (CPMs) provide information with the potential to better understand future flash floods in urban areas, steep and small catchments, in managing transport hazards, infrastructure and energy systems [7].

The latest UK climate projections (UKCP18) included a new product, which, for the first time internationally, used a climate model at a spatial resolution on a par with operational weather forecast models, for national climate scenarios [8][9]. The local projections ("UKCP Local (2.2 km)"), a 12-member ensemble driven by the Met Office Hadley Centre global model for a high emissions scenario (RCP 8.5), are expected to be the primary source of information for users interested in daily rainfall extremes in summer or changes on hourly timescales. This will allow examination of the risk of extreme weather events in local areas for the coming decades [8].

These new local projections will enable greater investigation of the climate change impact of surface water (pluvial) flooding. The risks from this form of flooding are increasing [10], with intense rainfall events (≥30 mm per hour) expected to become more likely in the future [11]. The potential threats from pluvial flooding entered the public consciousness relatively recently, in particular after major floods in 2007 [12]. These floods prompted the first UK maps of surface water flood risk published in 2013 [13]. There are not yet maps of future flood risk in the UK to complement those for the present day.

New climate information requires translation into impact assessments before information can be shared in a useable format to industry and public organisations. Even where scientists have provided improved information there is no guarantee that it will lead to better decision-making [14]. Therefore, products that inform on future change need to capture all relevant aspects of change and be curated by organisations with capability to support maintenance and service user uptake. Boundary organisations such as the Environment Agency also need to grow capacity and skills to use the information in their own and others future planning. This is not a new issue and there has been considerable research on the need for translation and research on how science can support decisions [15].

In this paper we consider the drive for high-resolution climate information, what it provides, some of the scientific challenges, the potential applications and practical steps needed to provide the right information to 'enable' adaptation and, specifically, 'implementation' [16].

2. Why do we want higher resolution climate information?

An important scientific endeavour has been to provide more credible, accurate and local (downscaled effectively) projections about plausible future climates [17][18]. The primary motivation for developing high-resolution projections in the UK has been to try and better capture the processes that lead to intense rainfall and extreme events, particularly to better understand flood risk and the direction of change in summer rainfall extremes [19][20][21]. This finer scale information not only resolves local-scale convection, but also improves climate model simulation along sharp environmental boundaries (e.g. coasts) and over complex terrain [22]; all relevant in a UK context.

However, increasing resolution in isolation does not necessarily equate to a better representation of future change [23]. Confidence in climate projections generally declines with higher temporal and spatial scales due to the introduction of further sources of uncertainty. Uncertainty associated with large-scale dynamics has a significant impact on the local-scale, such as the impact of stratosphere-troposphere coupling [24], so that it has been hard to provide meaningful information at daily time-steps, for example. Understanding the influence of method shortcomings on downscaled outputs becomes increasingly difficult to predict and quantify; perhaps only detectable using systematic comparisons of different models for different climates and environmental characteristics [25].

Another driver for local-scale projections is that they are also attractive to users of climate change information. With strong similarity to observed datasets, there is a feeling that local-scale information is more relevant. For example, Local Authorities wanted more information in the UK Climate Projections on the risk of higher intensity and frequency of storms in order to understand local flood risk [26]. Uncertainty in river flow estimations used in water resources planning arises from the lack of consideration of changes in daily rainfall and its year to year variability when using traditional approaches that incorporate climate change in river flow factors based on long term average changes [27]. Reconciling issues such as these have in part driven the demand for higher resolution climate change information. But, uncertainty also arises from the water resource models structures and parameterisations, plus assumed stationarity of catchment rainfall-runoff processes, land use and management.

The desire for high-resolution change information, particularly in the water sector, also arises from the typical operational scale of hydrological research, shaped by the need to resolve the heterogeneities of the land surface. Discipline-specific interests remain focused on understanding the causes of hydrological variability and extremes at all space- and time-scales in a process-based way [28]. However, whilst weather patterns vary over very short distances, the climatic drivers behind them are not readily captured at small scales. Hence, compounding uncertainties at multiple scales on the local-scale can result in a large envelope of possible futures, which is hard to work with. Indeed, the challenge to act on information associated with great uncertainty suggests that robust adaptation may be best served by enabling ‘adaptation options appraisal to take centre stage, rather than climate change scenarios’ [29]. Other proposed approaches include ‘tales of future weather’ developing narratives based on weather modelling in hypothetical future climates [30] and storylines to understand plausible pathways for extreme events [31].

Irrespective of approach, it is important that scientists can explain the confidence they attribute to different model projections in ways that are meaningful to users. This should include open discussion between scientists and decision-makers on the relevance of the spatial and temporal resolution of climate change projections in decision-making, thereby reducing uncertainty about applicability. Broad directions of change may sometimes be sufficient but we may often need to plan for a range of futures, ignoring this could lead to undesirable outcomes and a lack of preparation.

3. Climate science issues around projections and uncertainty

High-resolution climate change information presents some unique challenges for application, whilst some challenges are common to climate change information more generally. When using regional climate projections for impact, adaptation and vulnerability studies three points need to be considered ([32]; p. 13): (1) what emission scenarios are considered, are these appropriate for the context of the study? (2) are simulations representing the uncertainty in models' ability to simulate the natural and forced climate variability, and (3) if relying on a downscaled dataset, are method capabilities known, such as representation of the change signal as simulated by the driving GCM and its abilities to add value to the GCM output? The authors also note issues that speak to the limitations of climate models, namely (1) is there a bias in the simulated climate relative to the observed climate? If the level of bias is unacceptable to the application then it may be preferable to use a technique of scaling observations, or else employ a bias correction technique, and (2) the importance of understanding the limitations of the model; models used to study bio-physical impacts (such as rainfall-runoff models) are optimised based on physical relationships, do these hold under climate change conditions or is there a risk for introducing method-related biases?

The UKCP Local (2.2 km) projections do not sample uncertainty in convection-permitting model physics, nor information from the wider global modelling community [9], hence under-sampling uncertainties in simulating processes at the local-scale, and in the plausible global response to climate change. Further, all ensemble members follow a single emission scenario, RCP8.5, i.e. the climate response following a very high emission scenario, near the 90th percentile of considered baseline scenarios (i.e. assuming no climate mitigation policy) [33]. This places the onus on users to consider the results from UKCP Local (2.2 km) in the wider context of other UKCP18 outputs (e.g. [9], p6).

In current risk assessments, RCP8.5 is a common choice of emission scenario as, from a climate impacts perspective, the change signal will be strongest for a far-future time horizon under a high-emission scenario. For many purposes, exploring what this change looks like is a meaningful approach to understand future risks. For example, when providing guidance on water supply for the state of Victoria, analysis focused only on RCP8.5 as regional stakeholders wished to represent the worst case scenario, noting also the close agreement in observed and RCP8.5 emission rates [34]. In England, the latest sea level allowances for flood [35] and the new National Framework for water resources [36] have also used this pathway. However, studies wishing to demonstrate the avoided damages of mitigation may want to illustrate the impacts associated with lower cumulative emissions and policy targets, for example to limit warming to 1.5°C or 2°C [37]. Pattern-scaling is a practise where the climate response to high mitigation scenarios (e.g. RCP 2.6) can be derived from no, or low mitigation scenarios such as RCP8.5. This technique assumes the change signal to be a near linear function of the global mean surface temperature [38][39]; noting that pattern-scaling can inadvertently act to reduce the inter-model spread or suppress the internal variability [39]. Such additional datasets would ideally be provided centrally for the benefit of users.

How one could consider projections from the additional UKCP18 products together with UKCP Local (2.2 km) is not obvious, as neither the global nor probabilistic projections sample local-scale modelling uncertainty, and there are no links between the different products (scaling factors for example) provided in the UKCP18 user guidance. Whilst model verification can provide guidance on model biases relative to the observed climate, understanding uncertainty in projecting change at local scales would necessitate the comprehensive sampling of parameter and structural uncertainty, currently unavailable at the CPM scale for the UK. Some variables remain parameterized even in CPM models for example the exchange/transfer of heat and moisture fluxes between the land surface model the atmospheric surface layer and the planetary boundary layer, urban canopy physics and land use. Prein et al. [22] call for coordinated modelling programs to advance parameterizations of unresolved physics and to assess the full potential of CPMs.

Better chances exist to address the limitations in representing uncertainty in natural and forced variability, as simulated by different GCMs. Both probabilistic and global projections provide improvements in this regard, considering change information from a subset of GCMs from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) [40][41], and via a statistical emulator for the probabilistic projections [42]. A practical challenge is how a user would go about comparing the outputs from the different products, so far this is only available for mean changes [9].

If there is a discrepancy between products, how would a user assess what amount of discrepancy is problematic, or what is reasonable given the scale differences? Further, many impact studies are not concerned with the climate variables *per se*, but in a secondary product drawing on multiple variables as input, such as the computation of runoff requiring estimates of potential evapotranspiration as well as precipitation (the former potentially requiring many variables depending on the estimation method). Attempting to draw conclusions on how discrepancies in one, or several, variables could influence the final output is unlikely to be straightforward, particularly if relationships are non-linear. Finally, most impact models require climate projections to be bias-corrected prior to computation [43][44]; a necessity because impact models are assessed in a real-world context where absolute values matter [45][46]. Observations of the real world are also in a sense probabilistic and yield different benchmark conditions depending on the source of the data whether point, gridded or from variable time periods for example.

Because the CPM provides a more detailed simulation compared to coarser-resolution RCMs, different large biases may arise due to a model inadequacy. Therefore, absolute values, and indeed spatial coherence, of the local projections are likely to be modified in the process of bias-correction. Hence, when comparing the local projections with global projections, comparison should be done on uncorrected data. Comparison is needed with the driving GCMs to understand how the downscaling has modified the change signal (if different, is this due to added value or method bias in downscaling?), and with the range provided by the CMIP5 GCM sample (to inform on GCM sampling uncertainty). An example for such a comparison is provided in the projection guidance material for England and Scotland on seasonal resolution for mean temperature and rainfall (e.g. [9], Fig. 5.1-5.3). The guidance material encourages use of the CPM projections in combination with other UKCP18 products that provide a wider sampling of uncertainty.

A final issue to consider with respect to the local projections concerns the length of the simulations, currently provided as 20-year time-slices (1981-2000; 2021-2040 and 2061-2080). The positioning of these time-slices is meaningful, representing a near-future and a far-future horizon. However, in using a relatively short time-slice, the analysis of extreme events becomes somewhat restricted to relatively common events, though this ‘restriction’ is strongly linked to the driving global climate model’s ability to capture observed decadal and multi-decadal natural variability in the first place. If poor, longer downscaled runs may not provide a better sample of extreme events. Irrespective of the GCMs’ ability to capture uncertainty in natural variability, researchers and practitioners interested in very rare events need to carefully consider the relevance of results from extreme value analysis for very rare events given the limited opportunity to sample such events in such short time-series. The short length of the simulation timeslices also implies the change signal is impacted more by internal model variability rather than the forced GHG change. This is especially important for the 2021-2040 slice since that will become verifiable soon. If the driving GCM is out of phase with observations for key interannual to multi-decadal oscillations like El Niño-Sothern Oscillation (ENSO) or the North Atlantic Oscillation (NAO), the change signal may well be driven primarily by that model discrepancy.

The scientific robustness of UKCP Local (2.2 km) is ultimately dependent on the application. Any guidance on future climate change impacts needs to reflect all the significant sources of uncertainty in employed methodological practices so that findings can be meaningfully used in decision-making. Crucially, guidance needs to capture the ‘relevant dominant uncertainty’ (RDU) described by Smith and Petersen [47] (p. 2) as the “ … *most likely known unknown limiting our ability to make a more informative … scientific probability distribution on some outcome of interest; perhaps preventing even the provision of a robust statement of subjective probabilities altogether*.” From a flood risk perspective this involves not only capturing the thermodynamic response of the atmosphere to increased warming and changes to the storm structure, but also changes that influence the strength and positioning of the jet stream, and blocking features that influence the frequency, speed and pathway of storms [48]. Ideally, users interested in UKCP18 for flood risk planning would want to know to what extent the broader suite of projections inform on all of these aspects of climate and how they might combine outputs from different products to create a coherent narrative about future change.

With all projections greater exposure of the limitations and caveats and issues in specific applications might streamline how and where to best use the available information.

4. Using the new high-resolution information with confidence

Notwithstanding the issues outlined above, UKCP Local (2.2 km) has potential applications in water management and beyond. In the following sections we discuss factors that affect the usability of these projections in impacts research and the development of decision-making tools.

4.1 What can high-resolution climate information help with?

High-resolution climate change information could inform decision-making through improvements to the modelling and estimation of extremes [7][49][50] and the added-value from improved process understanding [51][22]. These offer the opportunity for the provision of physically and geographically consistent high-resolution projections to support impacts modelling at relevant spatio-temporal scales beyond existing downscaling approaches, albeit with the inevitably increased uncertainty due to the addition of another layer of complex modelling (whilst all downscaling increases uncertainty, limitations and biases of simpler methods are perhaps easier to understand and quantify relative to that of dynamical models). Climate change impact assessments may be improved in any risk area that:

- Requires understanding and modelling at local scales;
- Already uses high-resolution impacts modelling in decision-making;
- Is sensitive to small-scale variability to climatic inputs;
- Is dominated by the short-term evolution of a process or event;
- Has a local climate strongly influenced by marked environmental features, such as orography, coastal proximity (marine or large lakes), or urban expansion.

Currently, the greatest potential rests upon those decisions that already make use of high-resolution modelling; much of this has previously used statistically-downscaled climate change information (e.g. using the UKCP09 weather generator [52]) rather than output from CPMs and is detailed in Table 1. Existing tools and approaches can also be incrementally improved, e.g. storm and design hydrographs and climate uplifts used in engineering design for drainage and waste water management (e.g. [53][54]). The Met Office lists several examples of how outputs from CPMs could be used [8].

Improved spatial and temporal resolution opens up new possibilities to decision-makers in exploring and applying new approaches and should help them to understand more comprehensively how change propagates through the entire system [28]. A refined understanding of where vulnerability exists, where particular management options may work or not, and identifying if the risk is shifting, provides important information for decision-makers. By using local-scale assessment in conjunction with larger-scale assessments, a more complete picture of risk could be developed. But the feeling that projections need to be “relevant” to a small geographical area of interest may not be justified if the spatial variability of results is low or hard to explain.

The greatest benefits are likely to be realised through greater temporal resolution; particularly where short-term events determine local risk, often driven by changes in rainfall intensity. Extreme events and water quality processes are frequently modelled on sub-daily timescales. Timescale, sequencing and seasonal to inter-annual variability are important to water availability. Event-based, local assessments using high-resolution input data could provide new information on hazards, potentially revealing new risk spaces and facilitating improved understanding of local resilience if greater insights into system function can be made. This could allow us to design and assess management solutions tailored to the particular location if we are better able to stress test interventions. Higher resolution modelling also has the potential to allow changes in temporal patterns to be identified, understood and prepared for.

But realising these benefits for managing risk and improving incident response rests on how the information can be made usable. Although research possibilities are large; the decision-making applicability of UKCP Local (2.2 km) is currently small. Understanding the situations in which, and demonstrating where, these benefits may arise is a necessary prerequisite to developing decision-making tools based on these new high-resolution projections. It would be useful to take this forward as a partnership between the users and providers of this information. Some actions that might help are ready to use data sets and change factors. Current planning guidance advises the use of 70th and 95th percentiles of future peak river flow (driven by RCP8.5) by developers and promoters of flood schemes. Similar guidance for applications that make use short duration rainfall e.g. drainage design (as proposed by Dale, this issue) would benefit from the availability of datasets, change factors and perhaps design storm profiles.

Table 1. Examples of use or potential use of high-resolution climate change information to support adaptation decision-making. * using CPM outputs rather than statistical downscaling

Sector	Use	Examples
Urban and Building	Diurnal cycle for weather files – UKCP18 demonstration project	[55]*
	Analysing the urban heat island effect	[56][57]*
	Overheating	[58]
Hydrology: flooding and water resources	Calculating river flows and groundwater levels	[59]*; [60]
	Sewer design, drainage	Dale (this issue)*; [53]*[54]*[61]*
	Peak rainfall guidance	Dale (this issue)*; [53]*
	Extremes (flood and drought)	[59]*

	Changes in frequency of flash floods	Archer et al. (2017; 2019); Ming et al. (2020); [62][63][64][53]
	Inform flood management and incident response	
	Explore hydrological response, reservoir models, changes in abstraction volume	
	Waves, tides and storm surges	[65]
Infrastructure	Road, rail and exposure of critical infrastructure to flooding	[66][67]
	Implications of changing sediment, flow and channel changes for infrastructure and flood defences (erosion and deposition)	
Water quality, sediment and chemicals	Soil erosion, sediment and nutrient losses from land to water	[68][69]
	Algal blooms and management (sequencing)	[70]
	Species distribution and bioclimate-envelope modelling	[71][72]

4.2 Utilising high-resolution projections within current impacts information

Without a planned approach to the delivery of climate impacts information in the UK, our understanding of changes in rainfall and river flows have been developed in response to a number of drivers [73] and by a range of agencies with a diversity of priorities [14].

Lessons learned from significant environmental incidents such as wide-scale flooding [12] can lead to significant improvements in both policy and response. For example, the establishment of the joint Environment Agency and Met Office Flood Forecasting Centre in 2009, which has in turn influenced the latest generation of climate projections [42]. However, event-driven decision-making may, in many cases, risk being too short-termist to develop the partnerships and funding required to provide a comprehensive programme of climate impacts information. This may be due to the limited scope of disaster recovery, or because of the framing of risk as a static element [74], thereby missing the full range of future risks and plausible scenarios and potentially leading to maladaptation.

Another important driver of impacts information is the guidance for considering flood risk in development proposals and infrastructure design [75], which has relied on an iterative process between the science community, decision-makers and practitioners to create increasingly sophisticated and tailored uplifts for various sources of flood risk (Wasko et al., this issue). These allowances have to balance the complexity of use with the proportional risk posed by any proposed development or intervention.

Within this guidance, allowances for peak rainfall intensity have been derived from work carried out before the UKCP09 probabilistic projections on understanding extreme rainfall [76][77], but could reasonably be augmented with information from high-resolution CPMs to give a better representation of intense rainfall (e.g. [53]). In addition, allowances for future fluvial flood risk have the potential to be enhanced using high-resolution modelling, particularly for smaller, “flashier” catchments, where current models better represent larger catchments (Kay et al., in press).

4.3 Making information more useable

Climate hazard information is plentiful but the quantification and distribution of risk and information about adaptation options and solutions is more limited. We do not attempt to explain why adaptation practice and preparatory action lags behind theory, but instead consider where information has been provided that attempts to get closer to decision support. We also use examples to illustrate some issues that need to be overcome to help move climate change information from research into practice. These include accessibility, ease of use (e.g. clarity, size of datasets, sophistication of download functionality), which is often ‘grossly’ overestimated [78], relevance and importance of data or information.

To some extent the conditions that need to be met to use UKCP Local (2.2 km) will depend on the sensitivity of decisions. Where this is already known, it is helpful to provide material that demonstrates how the change signal differs relative to previous projections, or relative to other regionally-available products. For example, before UKCP18 users mainly derived local-scale information from the UKCP09 Weather Generator [52]. Existing tools may not need to be updated if they are insensitive to any changes in the newly available projections. This is often overlooked in the drive to use the latest science. Readily available comparisons and guidance on how to undertake sensitivity analyses would be useful here. It remains to be seem if the UKCP18 CPM outputs prove more supportive of local decision making than statistically downscaled tools such as weather generators or whether we will continue to need a range of products to meet the desire for local information.

Climate change projections are often the first stage in top-down studies of impacts. But even where bottom-up or decision-scaling approaches are adopted, usability issues are often shared. High-level narratives accompanying projections [79] can directly inform decision-making, where broad change is all that is required to stimulate action. Although, in the UK the often adopted headline of ‘warmer wetter winters and hotter drier summers’ could usefully be more nuanced. Alternatively, plausible extreme scenarios, similar to the H++ scenarios produced in UKCP09, can be used in sensitivity tests for particularly vulnerable or important assets. Other projection-related products will mainly be used by researchers and expert translators to develop a range of impact products over a period of years in the form of climate services or published studies and datasets [80] (e.g. [54]). This provide-and-wait service then leaves markets and sector representatives to develop their own products collectively, independently or perhaps not at all. The gaps in impacts information in many areas suggests that this is an imperfect model and that users need more support and guidance than is currently provided to make use of the range of UKCP products.

Other provide-and-wait services such as climate change report cards include authoritative syntheses of climate change observations and potential impacts in a specific area [81]. These are used for communicating the need for action and can be motivating narratives for organisations like the Environment Agency, but are insufficient for planning and implementation purposes.

Where there has been a collective effort to combine funding and expertise to develop targeted products, a more focussed provide-and-wait service can present significant opportunities for uptake. For example, the development of ‘Future Flows’, a data set (time series and maps) for river flows and groundwater levels across the UK up to 2050 [82] allowed a large community to access future hydrological information without the need for climate change expertise or additional analysis. This hydrological projections datasets have led to multiple impact studies in water resources (e.g. [83]), water quality (e.g. [70]) and ecosystems (e.g. [84][85]). Future Flows has also been used to inform national-scale assessments of groundwater recharge [86], to underpin UK water company assessments and regulation and to provide assessments of water availability across the UK for the National Climate Change Risk Assessment [87]. Users of Future Flows are clear that along with updated climate projections and new approaches to modelling flow changes there is a need for ready access to data, post-processed information and an easy to use interface. A demonstration product has been created for Europe based on dialogue between water decision makers about their needs and climate impact modellers [88] (Edge). Requested information included around 40 indicators of stream flow, groundwater, soil moisture, potential evaporation and temperature.

Some of the experiences to date in developing climate impacts information and tools should enable us as a society to increase the pace of action on climate change, at least where action can be helped with the right injection of scientific information. In particular, working across academia, industry and regulation to improve the information flow can really help. The responsibility for developing products for wide use would ideally be led by bodies with national agency but translation of the science is rarely coordinated by government. Impacts research is left to each sector to sort out, often leaning on the academic sector to act as a funding venue (via competitive research grants), making it hard to gain oversight, or to organise and implement a systematic approach. Additionally, the success factors of academic research (that underpin promotion) are not necessarily aligned with the operational constraints needed for the work to be accessible to users. Cutting-edge science is risky, often limited in testing (spatially or temporally) and is not readily scaled up for national application, as is required by many decision-makers. The most recent UK Climate Change Risk Assessment [10] again highlights the need for more action to address the high risk from flooding and coastal change and impacts of high temperatures. Given the impacts across the country to all sectors these should surely merit central government support for provision of up-to-date clear and accessible impacts data as a priority**.**

Decision-makers also invariably need to consider climate change information alongside other current and future pressures that may also be changing. Additional translation work is needed to streamline decision-making processes to include climate change as standard, rather than it being an extra, often separate, analysis.

A recent example of decision tool development for storm drainage design has involved the rapid uptake and interpretation of UKCP Local. An industry-led collaboration with researchers and expert users [53][54] was further developed by a well-timed and successful research council bid to update an existing tool with new information from UKCP Local. The model developers were involved in active discussions with a range of end users as well as expert tool developers to shape the project outputs to be useful for decision-making in the water industry.

It is currently unclear what best compels people to take adaptive action as it has proved hard to measure how much adaptation has taken place or is still needed. However, there is general agreement amongst information users and researchers that more focus on translating climate change information into usable products would support wider uptake. In particular, a central location for impact and adaptation information could lead to more rapid adaptation. An example of this from Finland – *Climateguide.fi* – provides guidance on climate mitigation, adaptation and solutions in a very accessible way, with data maps and graphs in a format that is directly of use in planning and examples of solutions in practice. But in some cases, sector-specific provision of information may enable better accommodation of cultural norms and the way different industries operate.

There are invariably a series of steps from understanding a change in climate and applying it to an impact relevant to a decision. Currently, the information informing these steps is often disjointed, separately funded and can involve different actors. We suggest that the decision-makers involved at the start of the process also need to reflect the diversity of users involved at its end. Since the opportunity to influence decision-making is often time bound and requires relevant, accessible information that has importance to the recipients, this flow of information can be quite complex and easily broken. For example, the release of the UK Climate Projections is not timed to interface with required updates to National Flood Risk Assessments. There is no formal mechanism for funding impacts research in the UK so that after the release of new climate change projections there can be a long gap before impacts modelling results emerge. This means that formal planning systems may not be able to make use of new science quickly [75]. Changing planning guidance too often creates issues for developers and the whole process may barely be complete before new climate information comes along. All of these factors contribute to the challenge of adopting the dynamical planning processes often advocated by climate change adaptation researchers [89].

5. Conclusions

High-resolution convection-permitting climate model simulations from UKCP Local (2.2 km) present new opportunities for research to investigate climate change hazards, risks and impacts, particularly around the changing magnitude, duration, frequency and spatial distribution of short-duration convective storms. Knowledge arising from such experiments provides an additional line of evidence when assessing plausible future climate change.

The added-value of UKCP Local (2.2 km) is likely to be where understanding at local scales is required, e.g. in urban areas and for processes dominated by short-duration events, e.g. storm drainage or where high-resolution impacts modelling is already used in decision-making. However, use of UKCP Local (2.2 km) for decision-making in the water sector is conditional on how knowledge gained can be assessed as value added. Hence, applications in decision-making require a series of translating tasks to support their wider use, including:

- A clear understanding of the range of uncertainty in UKCP Local (2.2 km) compared to other UKCP18 products. This includes whether differences in the broad findings support a different interpretation between the products and how to assess differences relative to concepts of ‘added-value’ or ‘model bias’.
- Storylines about changing rainfall patterns informed by this comparison, particularly on the changing magnitude, duration, frequency and spatial coverage of high intensity storms. These storylines could usefully include a low emission trajectory to indicate the impact of climate mitigation policy. If application focused, these storylines could be framed around a best, a worst and a model consensus (the ensemble mean mode) case (following [90]).
- The provision of readily accessible bias-corrected datasets with a similar level of usability to the Weather Generator provided with earlier UK climate projections.
- The development of products that can be directly used in planning and decision-making, for example, maps of future surface water flood risk would be a necessary screening/risk management tool. An understanding of changing rainfall intensity on flow regimes could inform runoff and pollution patterns. Design hyetographs/hydrographs would complement research on peak rainfall intensity for sewer design and surface water management.

A concerted effort is also needed to shift research funding from identifying hazards and risks to be more directly targeted towards the development of solutions. This could proceed by developing cross-industry-research consortia to help shape and translate research and develop tools, with decision-makers involved from the start. Creative approaches to ways of working together may be needed to make full use of knowledge exchange funding streams. Academic research could potentially play a greater role in translational science if career evaluation and promotion metrics better recognised the value of this activity in shaping practical decision making.

We conclude with a plea that the development of future projections and the further evolution of high-resolution climate change information be designed with the full involvement of impact scientists from a range of sectors. All outputs intended to inform decisions also need early scoping with industry representatives, operational tool developers and end users who are likely to be a different group. We also suggest that the development of translated products (as well as projections) include ongoing user acceptability testing.

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