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Article

Handling Interdependencies in Climate Change Risk Assessment

Richard J. Dawson

School Civil Engineering & Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK; E-Mail: richard.dawson@newcastle.ac.uk; Tel: +44-(0)-191-208-6618

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Abstract: Typically, a climate change risk assessment focuses on individual sectors or hazards. However, interdependencies between climate risks manifest themselves via functional, physical, geographical, economic, policy and social mechanisms. These can occur over a range of spatial or temporal scales and with different strengths of coupling. Three case studies are used to demonstrate how interdependencies can significantly alter the nature and magnitude of risk, and, consequently, investment priorities for adaptation. The three examples explore interdependencies that arise from (1) climate loading dependence; (2) mediation of two climate impacts by physical processes operating over large spatial extents; and, (3) multiple risks that are influenced by shared climatic and socio-economic drivers. Drawing upon learning from these case studies, and other work, a framework for the analysis and consideration of interdependencies in climate change risk assessment has been developed. This is an iterative learning loop that involves defining the system, scoping interaction mechanisms, applying appropriate modelling tools, identifying vulnerabilities and opportunities, and assessing the performance of adaptation interventions.

Keywords: Interdependencies; Risk assessment; Flood; Urban; Coastal

1. Introduction

Typically, a climate change risk assessment might consider (i) what could go wrong (ii) the likelihood that it will go wrong, and (iii) the consequences if it does go wrong, in order to provide insight into managing risks by changing the state of the system to reduce vulnerability, improve resilience and lessen potential climate impacts. Climate risk assessments typically focus on individual sectors (e.g., [1,2]). However, the multiplicity of climatic variables, the spatial scale over which they manifest and their many points of interaction with human and physical systems inevitably leads to a range of complex interactions. For example, climate change may reduce precipitation and increase temperatures—both of which influence water availability and quality. Extending the impacts analysis further recognises interactions between different sectors—reduced water availability for cooling will affect the ability of inland power stations to generate electricity, as well as the role of softer systems such as the regulatory framework or the budget of energy and water customers. Thus, climate change has the potential to create new interdependencies, and to amplify existing interdependencies. Figure 1 highlights just a few of the complex interdependencies that can arise between long term drivers of change, the many processes through which they interact and the social, environmental and engineered systems that are impacted.

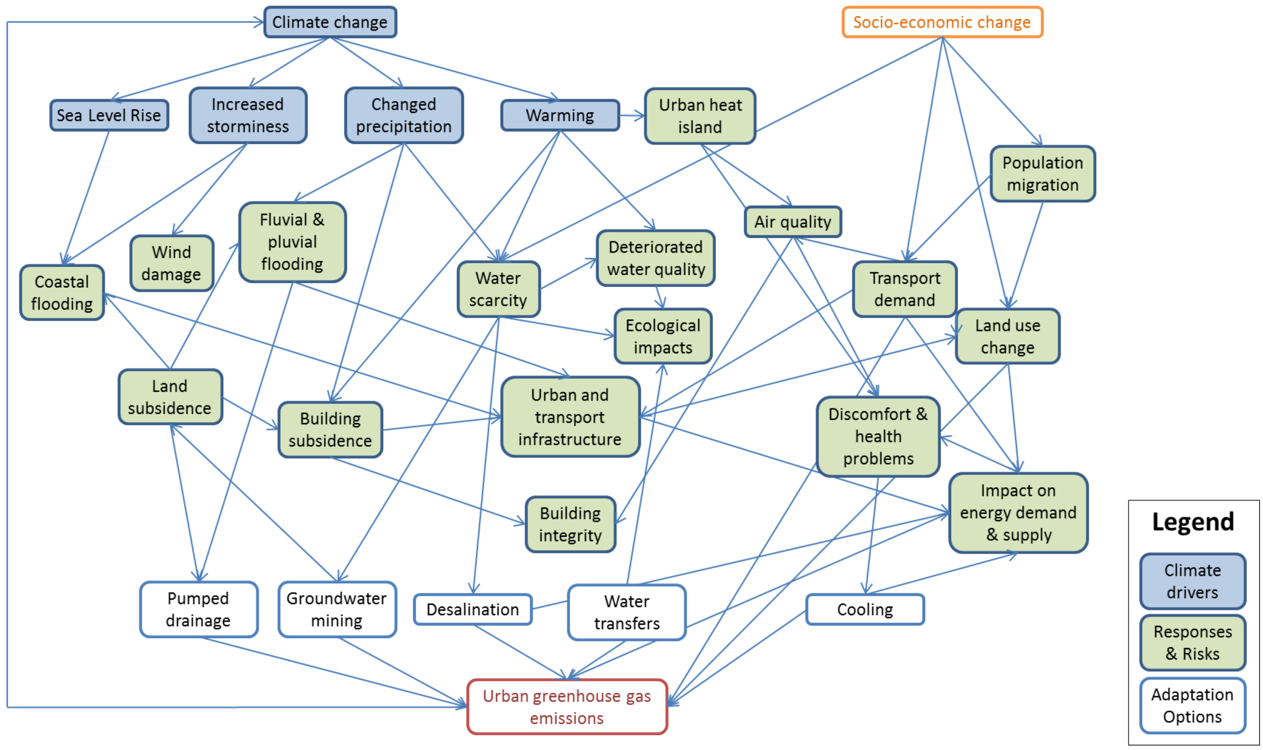


Figure 1. Some examples of interdependencies arising from climate change risks (adapted from [3]).

Climate change is therefore not only directly altering the risks to individual sectors, but also altering the nature and magnitude of these risks through the interdependencies that emerge from the dynamics of large-scale, highly interconnected complex systems. A climate change risk assessment that does not address such interconnections, and the possible loss or creation of interconnections, could lead to the miscalculation of risks. Furthermore, there are potential missed opportunities for adaptation, for over or under adaptation, or maladaptation (increased greenhouse gas emissions, or actions that inadvertently exacerbate climate risks such as increasing exposure or socio-economic vulnerability [4]).

Consideration of interdependencies in risk assessment therefore merits particular attention. Following this introduction, this review considers different types of interdependencies of relevance to climate change risk assessment before using three case studies that highlight the importance of considering them. The case studies demonstrate that there can be no "one size fits all" approach to account for interdependencies as it depends on the nature of interdependence and the approach taken to modelling and analysis. Therefore, drawing from these case studies and other work, a framework is presented for handling interdependencies in climate change risk assessment and adaptation planning.

2. Mechanisms of Interdependency

This sections builds upon a number of reviews of interdependencies (e.g., [5–9]), and considering the case studies below, to identify six key dimensions of interdependency in the context of climate change risk assessment. Each dimension requires a different response to address the risks resulting from these interdependencies. Table 1 describes a number of additional, complicitous, factors that need to be considered to fully characterise the nature of an interdependency.

1. *Functional interdependencies*—arise when one system is connected to, and relies on, another system to operate (e.g., water to cool power stations, energy to pump water through the water distribution infrastructure). Computerisation and automation of many systems has led to the proliferation of ICT related interdependencies.
2. *Physical interdependencies*—arise when systems interact through a physical process (e.g., hydrological processes), or through shared physical attributes (e.g., freight and passenger travel on railways is limited by a maximum capacity).
3. *Geographic interdependencies*—occur when geographic properties, such as proximity, lead to correlated responses in multiple systems. For example, a flood might impact upon multiple systems simultaneously within the floodplain, whilst damage to a single system might lead to wider disturbances as a result of geographical interdependencies (e.g., if a bridge collapses leading to the failure of ICT and electricity cables running over the bridge).
4. *Economic and financial interdependencies*—Shared markets result in sectors interacting through the same economic system which influences investment cycles, bond markets, pricing structures and the availability of credit to create "top down" economic interdependencies. Conversely, multiple sectors converge at the point of end-users (individuals, buildings, *etc.*) whose behaviour (e.g., demand for services such as energy and water, or potential to take certain actions during an extreme event) is likely to be subject to budgetary constraints—creating "bottom up" economic interdependencies.
5. *Institutional and policy interdependencies*—A shared regime (e.g., decarbonisation policy) where agencies may control and impact systems through policy, legal or regulatory means creates "top down" interdependencies amongst societal agents.
6. *Social interdependencies*—Conversely, from the "bottom-up", individuals and organisations interact locally, for example to communicate risks and build adaptive capacity.

Table 1. Additional factors that need to be considered to fully characterise an interdependency in the context of a climate change risk assessment.

Characteristic	**Implications for climate change risk assessment**
Spatial scale	Phenomena relevant to climate risks take place over a range of scales. Greenhouse gas emissions are altering climatic processes at global scales. Global teleconnections such as the El Nino Southern Oscillation (ENSO) influences extreme events around the world [10]. Other processes (e.g., the urban heat island) become more important for risk assessment at the scale of catchments, cities or lower spatial scales. Similarly, non-climatological processes play out at a range of spatial scales, including, for example, geopolitical issues such as competition for water resources, or availability of sea lanes for transport.
Temporal scale	The dynamics of processes and systems relevant to a climate risk assessment may vary from seconds (e.g., disturbances to power transmission systems) or individual events (e.g., a flood and associated responses) through decades (e.g., construction of major infrastructure) or centuries (e.g., commitment to sea level rise even if greenhouse gas emissions were to be ceased immediately [11]). Modelling and assessing risks for interdependent systems that interact over different timescales requires careful consideration.
Interaction strength	The nature of the interdependencies which include the strength of coupling, the directness of coupling and the (non-)linearity of interactions influences the propagation of climate risks through a system and the options available and priorities for adaptation. Tight coupling indicates a high degree of interaction between systems and typically a rapid response to changes. For example, a system reliant on electricity, with no backup generator, will immediately cease to operate if there is a failure in the power supply. Provision of onsite storage or generation capacity loosens the coupling of these systems.
Interaction complexity	The directness of coupling considers whether two systems interact directly or indirectly through one or more systems and processes. Complex interactions, in contrast to linear interdependencies, are those of unfamiliar sequences, or unplanned and unexpected sequences, and either not visible or not immediately comprehensible [12]. These complex sequences can lead to cascading failures across systems, or a gradual failure that is incrementally exacerbated by multiple system interactions.
System state	Social, environmental and engineered systems exhibit a range of behaviours according to their state and interconnectivity. Their response and interactions—and, therefore, the magnitude of climate risk, will be altered if systems (and their interconnections) are degraded or stressed. It is therefore crucial to analyse risk over a wide range of events and system conditions.
Socio-economic context	Climate risks are mediated by the attitudes, motivations, culture, values and different sets of concerns of individuals, organisations, government and society more generally. These can lead to different policy, procedural and behavioural responses to climate risks and acceptance of policies to manage these risks.

3. Case Studies

The many combinations of interdependency class, sectors and possible analytical methods prohibit a comprehensive set of examples that address each possible permutation of issues introduced previously. However, three case studies from the author's own experience are now reported to demonstrate how different types of interdependency can be captured in a risk analysis.

3.1. Flood Risk from Multiple Loading Sources

Managing urban flood risk represents a particular challenge because complex interactions between surface and sewer flows can result in flooding via a number of mechanisms that include intense pluvial runoff that leads to sewers surcharging and surface flows, fluvial flooding caused by high river flows, coastal storm surges and, perhaps, also groundwater floods. A given flood event could be caused by a single source, or several sources acting in combination. This case study draws from work first presented by [13].

The flooding system is described by a set of basic variables $X = (S,R)$ where S is a vector of climatic loading variables and R a vector of variables that describe the flood management infrastructure system that might include the height or other dimensions of dykes, the dimensions of surface water courses or the dimensions of the sewer system. The variability in the loading and resistance is described by a joint probability distribution $\rho(x):x \geq 0$.

Impact is measured in terms of $d(x)$, which gives the flood damage in the system for a given system state x. For many states of the system $d(x) = 0$ and $d(x) > 0$ when S is large or when there are some inadequacies in system design or some failure, for example due to deterioration or blockage. If $\rho(x)$ is the annual probability, then the system risk, r, in terms of expected annual damages, is:

$$r = \int_0^\infty \rho(x) d(x) dx \tag{1}$$

Understanding the contribution of different dependent climatic variables and engineering components to risk, and, consequently, determining adaptation priorities involved the following steps:

1. Identify the drivers of flood risk and construct appropriate systems model (see Figure 2a)
2. Identify the components in the urban drainage system, shown in Figure 2b, (and associated model parameters) to which risk is to be attributed.
3. Identify the range of variation for each parameter.
4. Sample a range of values for each parameter. Replicated Latin Hypercube Sampling (rLHS), described in full by [14] was used to produce correlated inputs to capture interdependencies between variables.
5. Run the flood model for each sample and calculate the corresponding damage.
6. Analyse the sensitivity of the system to each parameter and attribute the risk accordingly.

Several approaches were applied to assess system sensitivity. These included a linear regression and a variance-based sensitivity analysis which calculates sensitivity indices [14]. First order sensitivity indices provide the proportion of the output variance attributable to a given input variable. Total sensitivity indices [15] measure the contribution to the output variance including all variance caused by the interactions with any other input variables.

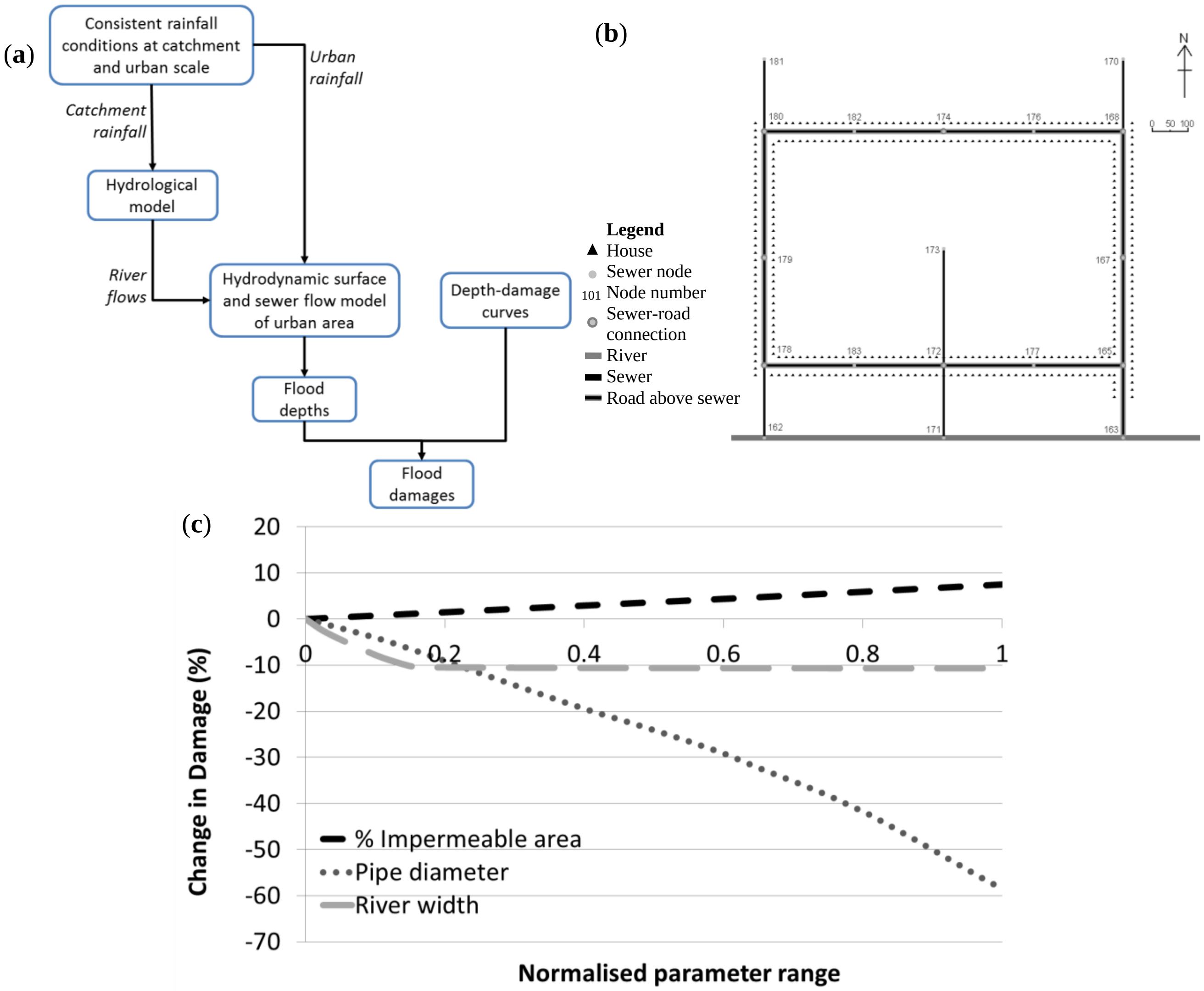


Figure 2. (**a**) Framework for assessing multiple sources of flood risk. (**b**) Overview of the urban area and drainage network case study. (**c**) Sensitivity of engineering variables (after [13]).

In this case study, flood risk is dominated by event duration, peak rainfall and pipe diameter. A linear regression analysis captures only 17% of the variance in risk, whilst analysis of the first order sensitivity indices provides only 29% of the variance—highlighting the importance of variable interactions in determining risk. Further inquiry reveals the effectiveness of different engineering adaptations at managing flood risk (Figure 2c)—with increased pipe diameter providing the most substantial risk reduction potential.

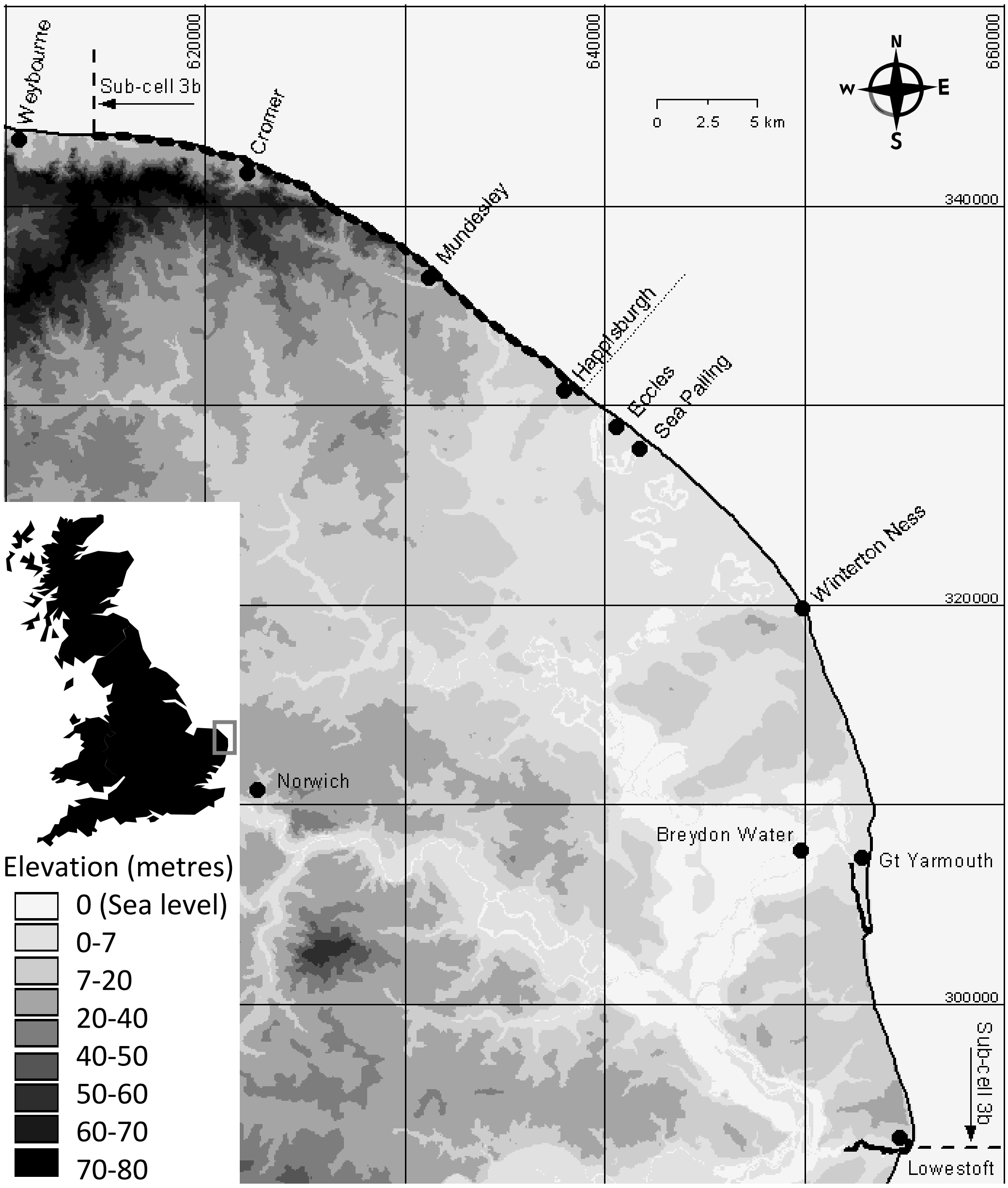
Here, the main interactions considered were (i) geographic dependence between loadings that arrive directly onto the urban catchment and those that are mediated by the hydrology of the upstream catchment and arrive after a time lag, and (ii) physical interactions between engineering measures that manage surface water. Consideration and analysis of these interactions, and their impact on risk, enables better targeting of interventions to manage risks from multiple sources. Variants of this approach have also been used to explore other types of interdependencies, including those between flood defence systems [16], time-dependent processes such as degradation [17], correlated climatic loadings [18], and between catchments [19].

3.2. Sediment Movements Mediating Two Coastal Risks

The risks to human populations in coastal areas are changing due to climate and socio-economic changes, and these trends are likely to accelerate during the 21st century. Due to their complexity, risks such as flooding and coastal erosion are usually managed separately, yet frequently these issues are interconnected—by mechanisms such as longshore exchange of sediments, rising sea levels, development and planning policies and the resulting broad scale morphological system behaviour. To understand these changing risks, and the resulting choices and pathways to successful management and adaptation, broad-scale integrated assessment is essential. Over a number of years, the Tyndall Centre for Climate Change Research developed an ambitious integrated assessment of 72 km of shoreline for the 21st century on the East Anglian Coast of England (Figure 3a). This case study draws from this extensive analysis, reported in [20,21].

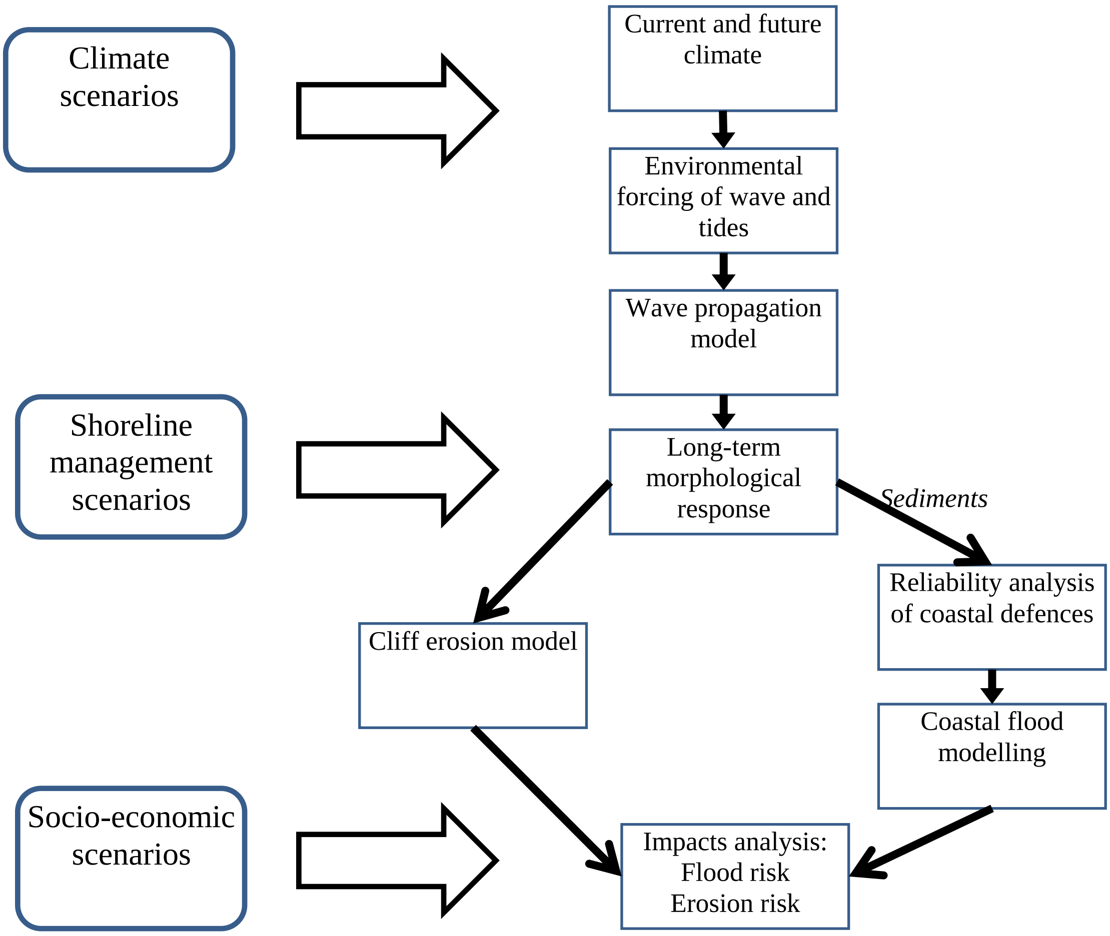
There are currently almost 20,000 properties at risk of flooding in the model domain, over 3000 of which are non-residential. Furthermore, over half the floodplain of 340 km^2 is premium agricultural land and over a third is designated as being environmentally sensitive. Along the 32 km stretch of eroding coastline there are almost 1400 properties within 100 m of the cliff top. The study area has a long history of erosion and flooding, but climate change exacerbates both these risks in terms of loss of buildings on the cliff coast, and increased flood risk in the coastal lowlands. As with any beach, if its level falls, flood risk in adjacent low-lying hinterland increases and *vice versa*. However, the beach protecting the Norfolk Broads benefits from sediments from eroding cliffs to its North, thus creating a mechanism for physical dependency between these two risks in East Anglia. Within this area, correlated climatic loadings and shared planning processes created additional geographical and institutional interdependencies, respectively. These interdependencies are captured in the modelling framework shown in Figure 3b through use of consistent scenarios and correlated climate loadings across the model domain and representation of key mechanisms of interaction (e.g., between morphology and reliability of coastal defences).

The flood risk is shown to be an order of magnitude greater than the erosion risk in the base year and grows exponentially during the latter half of the 21st century, whilst the erosion risk is predicted to remain relatively constant through the 21st century (assuming no change in socio-economic vulnerability). Differences between the risks can be partially explained because erosion is concentrated in a narrow band along the coast whereas a flood can impact a much larger area. Moreover, properties can be flooded on multiple occasions leading to repeat damages, whereas a property can only be eroded once. Although sea level rise increases the area at risk of flooding, as well as the depth of inundation, for a given return period, its influence is more complex as accelerated cliff recession generates additional sediment which can reduce recession rates elsewhere along the coastline [22]. Figure 4 illustrates the trade-off between different cliff management options that disrupt sediment movements. Whilst cliff protection reduces erosion risks (at a cost), it also reduces sediment supply to the flood-prone down-drift coast, leading to (assuming no improvement in flood defence infrastructure) rapidly increasing flood risks over the 21st century. Removal of cliff protection results in increasingly severe economic losses on the cliffed coastline according to the amount of protection lost. On the other hand, the gains are usually of an order of magnitude greater, in terms of risk reduction, on the flood-prone coast.



(a)

Figure 3. *Cont.*



(**b**)

Figure 3. (**a**) Location of the study area in eastern England, showing the location of the major settlements and land elevation. The area of cliff erosion is indicated by the dotted line (from [20]). (**b**) Overview of the coastal flood and erosion climate change risk assessment methodology

Interdependencies arising from shared loadings and planning policies were simulated by propagating consistent information through the integrated assessment framework using climate and socio-economic scenarios. [23] hypothesised the importance of this interaction some time ago from analysis of cliff top erosion and monitoring of beach levels in front of the cliffs. Here, the effect of waves and tides on littoral sediment transport and erosion of the soft coastal cliffs and platform was simulated using the SCAPE model [22,24]. The identification and modelling of these processes was central to the simulation of the sediment movement and capturing this dependency between erosion and flood risks.

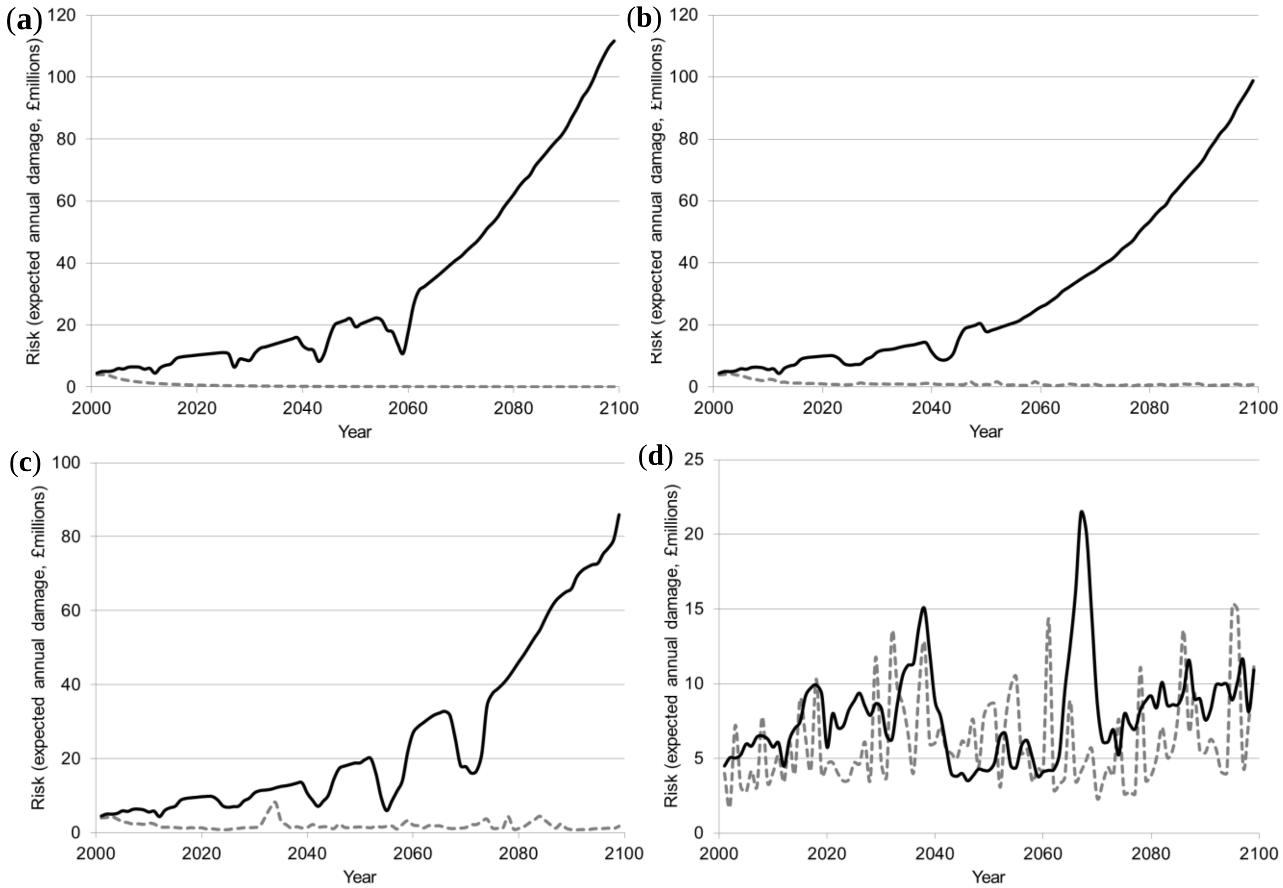


Figure 4. Comparison of the evolution of erosion (dashed lines) and flood risks (solid lines) in the 21st century under a high climate change scenario and assuming no change in socio-economic vulnerability for different levels of engineered cliff protection: (**a**) 100%, (**b**) 71% (corresponding to the current situation), (**c**) 34% and (**d**) 0%.

3.3. Spatial Planning and Multiple Risks in an Urban Area

Urban areas concentrate people, buildings, infrastructure and economic activity—making them potential hotspots of climate risks [25,26]. Other issues such as poverty and poor air quality can exacerbate these risks [27]. Because of the confluence of issues and sectors, adaptation of cities requires integrated thinking that encompasses a whole range of urban functions. Assessing measures of adaptation to climate risks (and indeed mitigation to curb greenhouse gas emissions) needs to occur in an integrated manner [28]. Within cities, interactions occur through land use, infrastructure systems and the built environment. Interactions between different urban functions and objectives occur at a range of scales from individual buildings to whole cities and even beyond (as shown in Figure 1). This case study briefly introduces an Urban Integrated Assessment Facility (UIAF), developed by the Tyndall Centre for Climate Change Research, and considers how land use change acts as a mechanism of interdependency between risks in cities. Further methodological detail and analyses are reported by [3,29,30].

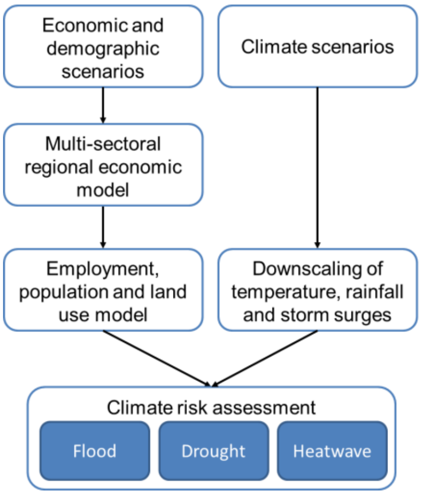


Figure 5. Overview of a multi-sector framework for urban climate risk assessment.

The UIAF (Figure 5) is driven by national scale economic and demographic scenarios (e.g., forecasts from the Office for National Statistics). These are used as a driver in the production of possible multi-sector UK regional economic futures [31]. Similarly, scenarios from UKC09 climate simulations [32] were downscaled using a stochastic weather generator [33] to drive a number of hazard models—in this case, heatwaves, droughts and flooding.

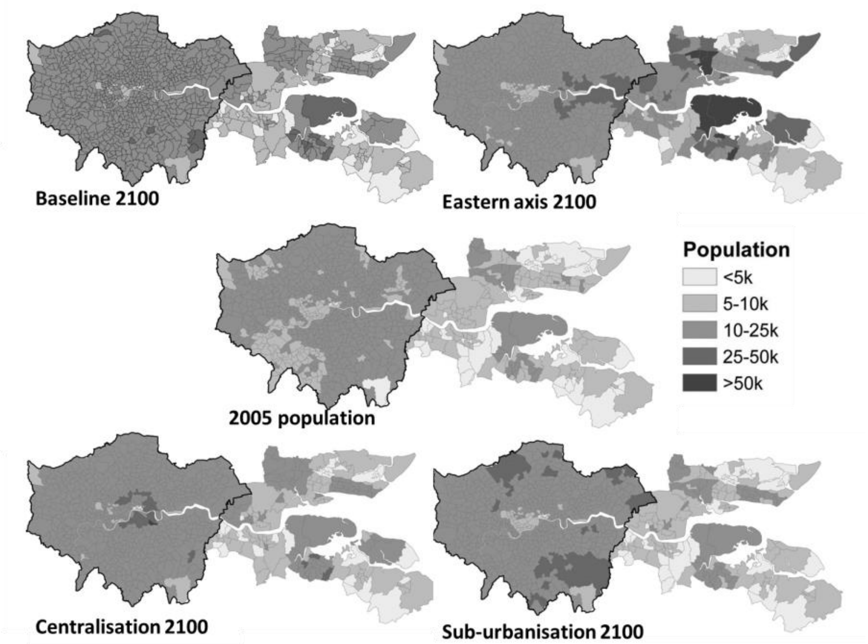
A spatial interaction module of land use change provides spatial scenarios of population and employment change for each census ward, or more detailed resolution for impacts analysis if required. The model uses information on infrastructure location, spatial attractors (e.g., location of schools), and other planning policies to provide city-wide mapping of future spatial distributions of population and employment, under alternative socio-economic and planning policy futures. Outputs from the economic and land-use change models can be used to estimate current and future greenhouse gas emissions under a range of alternative energy and transport policies. Similarly, the land use simulations provide information on future vulnerability which, when integrated with information on hazard from the climate downscaling, enables calculation of climate risks. The effectiveness in terms of risk reduction (and greenhouse gas emissions reduction) of a range of urban adaptation (and mitigation) policies can tested against different climatic and socio-economic futures.

Using the framework outlined above, four land use futures, driven by distinctive sets of planning and infrastructure policies, were generated (Figure 6a) in order to explore the implications of contrasting development trajectories:

1. *Baseline*: Population and employment tend towards existing settlements with transport infrastructure capacity increasing in response to demand only to ensure existing infrastructure is unhindered by capacity constraints.
2. *Eastern axis*: The Olympics and Thames Gateway Development Corporation serve as stimulus for long term investment, including new transport infrastructure, in East London and along the estuary.
3. *Centralisation*: High density living and working becomes the main style of new development with population and employment concentrating in the city of London and adjacent areas. Expansion of the greenbelt discourages further suburban sprawl.

4. *Suburbanisation*: Employment remains strong in the centre, but growth is focused around major suburban hubs. New radial routes, and local walking and cycling infrastructure support shorter commutes. Restrictions on tall buildings limit population growth in central areas.

(**a**)



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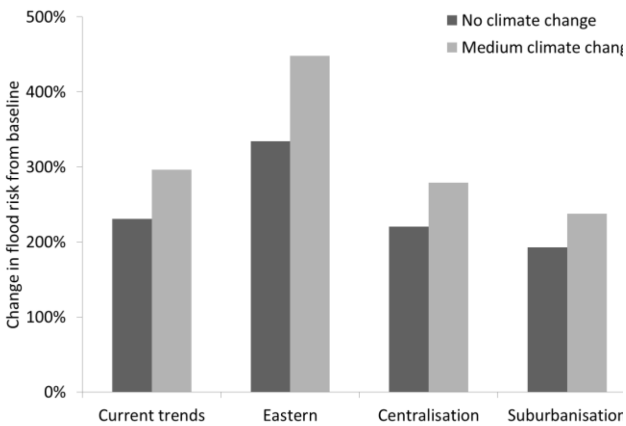

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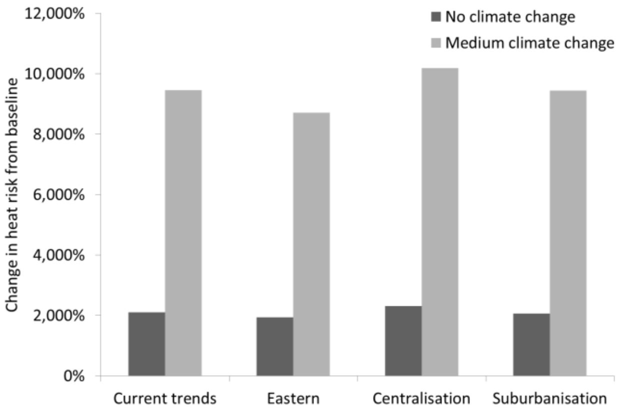

Figure 6. (**a**) Different land use scenarios and their impact on (**b**) flood risk and (**c**) heat risk in 2100 under a UKCP09 medium climate change scenario, and a no climate change scenario.

Flood risk is measured in terms of expected annual damages, and calculated by integrating the extreme value distribution of water levels along the estuary, information on the crest level and structural reliability of flood defences and functions that relate flood depth and duration to economic damage [18,30]. Heat risk is calculated as the expected number of vulnerable people (defined as people aged younger than 4 and older than 65) exposed to a heat wave event (defined in London as two consecutive days where T_{max} > 32 °C and the night in between T_{min} > 18 °C [34]). Further development by [35] quantifies the contribution to the intensity of the urban heat island from changes in land use (e.g., loss of greenspace) or increased energy use (e.g., from air conditioning) which enables further interactions between land use change and climate risk to be captured.

To demonstrate the influence of land use planning in mediating climate risks, the percentage growth in flood and heat risks is compared in Figure 6b. The analysis shows considerable variability between risks and spatial development futures, with flood risk being more sensitive to land use change, and heat risk showing greater sensitivity to climatic change. The UIAF allows geographical, physical and policy interdependencies to be explored in an urban climate risks context.

4. Guidance for Handing Interdependency in Climate Change Risk Assessment

Many climate change risk assessments require an understanding of how, and to what degree, constituent subsystems are interdependent. The three examples above capture just some of the range of interdependencies relevant to climate change risk assessment. However, they do all demonstrate how interactions between climate hazards, physical processes operating over long distances, and shared climatic and non-climatic drivers can impact upon risk and, consequently, adaptation decisions that may be required as a result of a risk assessment.

A climate change risk assessment can provide diverse evidence. The number of processes and interactions that could be incorporated in the analysis could be overwhelming. By eliciting the learning and experience from these case studies, and many other examples (e.g., [36–41), a number of general steps are now proposed as a means of handling interdependencies in a climate change risk assessment. Whilst many of the risk analyses here, and the steps below, are presented in linear terms, in practice the process is implemented iteratively via interaction and learning between decision makers and analysts (Figure 7). Furthermore, although many risk analyses focus on the methodology and assessment process, this framework aims to encourage the necessary collective learning to tackle the challenge of managing interdependencies between climate change risks.

1. *System definition*—When assessing climate risks in interdependent systems and providing insights for climate risk management, the first stage is to define the system of interest and the policy questions to be addressed:

    a. Identify the associated metrics by which climate risk is to be assessed.
    b. Explore, and potentially expand, the boundary of the system being analysed to include other “soft” (e.g., regulation) as well as “hard” systems (e.g., flood defences) that are relevant to the risk(s) to be assessed.
    c. Identify the processes of long term change, including climate change, that will influence the risk(s) and associated systems.

2. *Scope interaction mechanisms*—Crucial to reducing the complexity of this problem is the identification of the system interactions and processes most relevant to the objectives and decision-makers using the risk assessment. A number of approaches can support this process, including the use of influence diagrams (e.g., Figure 1) or matrix structures such as Lano’s N^2 chart [42] that structure interactions as an array where each row and column could represent one of the nodes in Figure 1.

3. *Apply appropriate modelling tools*—The three case studies used statistical and process based models to quantify interdependent relationships. Clearly, the modelling approach used must be appropriate to the system being analysed, and, in some instances, a combination of methods may be required. A range of approaches are available, including qualitative assessment [43], network analysis [44,45], dynamic simulations—for example of supply-demand [46] or system dynamics [47], Input-Output modelling [7] and agent-based modelling [48].
4. *Identify vulnerabilities and opportunities*—Use the systems analysis to identify beneficial interdependencies between drivers and sectors, as well as potentially problematic interactions (e.g., cross-sectoral antagonisms or vulnerabilities or pathways that could lead to cascading failures) that will need to be managed. As with any risk analysis, to identify and characterise a wide range of climate risks, the systems analysis must consider a full spectrum of threats, vulnerabilities and consequences:
    a. Subject the analysis to the full range of possible events and system states,
    b. Consider a range of possible futures, and alternative sectoral perspectives, and,
    c. Provide information on social, economic, environmental, technical and political risks.
5. *Assess the performance of adaptation measures*—Identify and assess the potential benefits of adaptation options by considering their performance against the full range of threats and drivers.

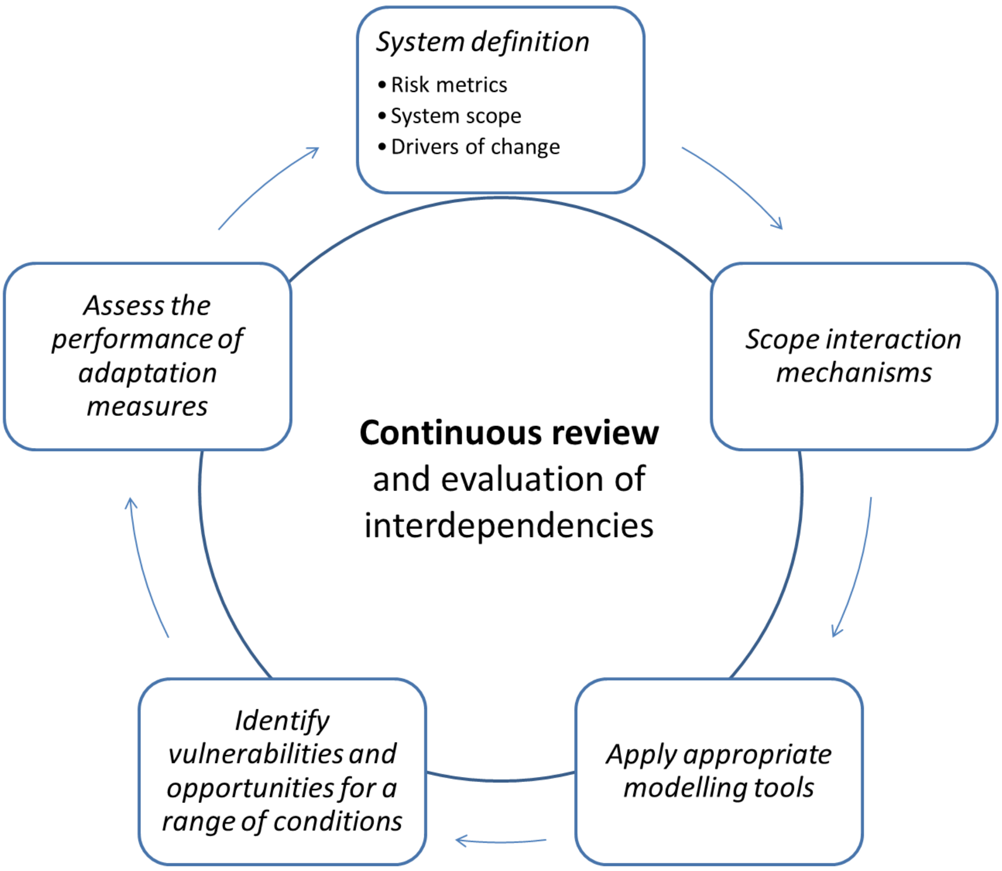

Figure 7. Framework for analysis and consideration of interdependencies in climate risk assessment.

Uncertainty about interdependencies, both now and under future socio-economic and climatic conditions, gives rise to risks but also provides opportunities. The three case studies highlight that the nature of these interdependencies is only partially apparent from a study of the geography of a region or physical connections between sectors. A systems approach enables the identification of interdependencies and provides a platform for the design and prioritisation of adaptation and resilience measures.

To exploit opportunities and effectively manage risks in interdependent systems, governance of climate risks must advance beyond single sector analyses and will require collaboration of a wide range of organisations and agents. The complexity of the systems being considered prohibits a "one size fits all" assessment tool, but the framework described above provides a basis for incorporating interdependency analysis into climate change risk assessment.

Continuous review of these risks is important. Not only are these systems dynamic, but monitoring and analysis typically focuses on specific sectors or systems rather than their interactions. This analysis highlights how it is important to use this process to enable cross-sectoral learning about climate risks and their interdependencies when assessing climate risks, implementing adaptation measures, or in acquiring new data and evidence.

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Conflicts of Interest

The author declares no conflict of interest.

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