

Projected Changes in Flood Frequency under Future Climate Scenarios and their Impact on Regional Food-Energy-Water Policy

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Projected Changes in Flood Frequency under Future Climate Scenarios and their Impact on Regional Food-Energy-Water Policy

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Abstract

Flooding is among the most destructive climate-related hazards, and its frequency and magnitude are projected to shift substantially under future climate scenarios, with profound implications for the interconnected food, energy, and water (FEW) systems on which regional economies and communities depend. This study investigates projected changes in flood frequency under a range of climate scenarios and assesses how these changes propagate through regional FEW policy frameworks. Using downscaled climate projections and hydrological modeling, we estimate changes in the return periods and exceedance probabilities of flood events across multiple representative concentration pathways (RCPs) and shared socioeconomic pathways (SSPs). These projections are then integrated into a regional FEW nexus model that captures the interdependencies among agricultural production, energy generation and cooling water demands, water supply and allocation, and flood risk management infrastructure. We examine how shifting flood regimes alter crop yields and planting decisions, hydropower and thermal power reliability, reservoir operations, and water quality and availability, and we evaluate the extent to which current FEW policies are robust to these changes or inadvertently reinforce maladaptive pathways. Scenario analysis reveals that regions facing increased flood frequency may experience simultaneous pressures on food production, energy infrastructure, and water management, creating compounding risks that single-sector policies fail to address. Conversely, regions with declining flood frequency may face new challenges related to water scarcity and competing demands. We identify adaptive policy options—including integrated floodplain management, flexible reservoir and infrastructure planning, crop diversification, and cross-sectoral governance mechanisms—that enhance resilience across the FEW nexus. The findings underscore the need for coordinated, forward-looking policy design that accounts for the coupled dynamics of climate, hydrology,

and resource systems, and we offer a replicable framework for assessing FEW policy robustness under climate uncertainty.

Keywords: flood frequency; climate change scenarios; food-energy-water nexus; regional policy; hydrological modeling; climate adaptation; resilience; integrated resource management

1. Introduction

Flooding represents one of the most pervasive and destructive categories of natural hazard, with impacts that cascade across multiple sectors of society and economy. In recent decades, the frequency and intensity of flood events have exhibited notable shifts across diverse hydroclimatic regions, and climate projections consistently indicate that these changes will continue and, in many cases, accelerate throughout the twenty-first century (Hirabayashi et al., 2013; Arnell and Gosling, 2016). The implications of altered flood regimes extend far beyond immediate physical damage to infrastructure and property; they fundamentally reconfigure the availability, accessibility, and reliability of resources upon which human societies depend. Among these, water, energy, and food constitute the foundational resource systems whose interdependencies form what is commonly termed the food-energy-water nexus (Hoff, 2011; Bazilian et al., 2011).

The nexus concept recognizes that water, energy, and food systems are inextricably linked through a complex web of physical, chemical, biological, economic, and social processes (Liu et al., 2018; D'Odorico et al., 2018). Water is essential for agricultural production and for cooling thermoelectric power generation; energy is required for water extraction, treatment, and distribution, as well as for food production, processing, and transportation; and food production depends on both water availability and energy inputs for irrigation, mechanization, and fertilization (FAO, 2014; Scanlon et al., 2017). These interdependencies mean that disruptions originating in one sector propagate through the others, often amplifying initial impacts and creating compounding risks that exceed the sum of individual sectoral vulnerabilities. When flood events alter the hydrological regime, they simultaneously affect crop yields, hydropower generation potential, thermal power plant operations, drinking water quality, and wastewater management systems, generating interconnected challenges that require coordinated rather than siloed responses (Pittock et al., 2016; Conway et al., 2015).

The academic literature has increasingly recognized the need to examine climate change impacts through a nexus lens rather than in sectoral isolation. Raub et al. (2019) argue that the concepts of food-energy-water nexus and resilience are mutually reinforcing, with nexus approaches enhancing cross-sectoral evaluation in resilience planning while resilience-oriented frameworks situate the nexus within broader social, ecological, and governance contexts. This synthesis is particularly relevant for understanding flood risk, where the spatial and temporal dynamics of hydrological extremes intersect with the operational requirements of infrastructure and the livelihood strategies of communities (Rockström et al., 2014; Grey et al., 2013).

Projections of future flood frequency under climate change have been developed using a range of methodological approaches, from global-scale hydrological models forced by general circulation model outputs to regional and catchment-scale assessments employing statistical downscaling and process-based simulation (Dankers et al., 2014; Alfieri et al., 2017). Despite advances in modeling capability, substantial uncertainty remains regarding the magnitude and even the direction of change in flood frequency across different regions, reflecting the complex interactions among precipitation intensity, antecedent soil moisture, snowmelt timing, land use change, and river regulation (Hall et al., 2014; Blöschl et al., 2017). This uncertainty poses significant challenges for policy development, as decision-makers must navigate competing projections and design adaptive strategies that remain robust across a range of plausible futures (Hallegatte et al., 2013; Ranger et al., 2013).

The food-energy-water nexus has emerged as a critical framework for understanding the interconnected challenges facing regional resource management under climate change (Wichelns, 2017; Cai et al., 2018). Research has demonstrated that policies targeting one sector of the nexus can have unintended consequences for others, creating trade-offs and synergies that must be carefully evaluated (Ringler et al., 2013; Endo et al., 2017). For example, subsidies promoting biofuel production may increase water consumption and compete with food crops, while water conservation measures in agriculture may reduce hydropower generation potential (Keskinen et al., 2016; Zhang et al., 2018). Flood events and flood risk management interventions similarly generate cross-sectoral effects, yet these interactions remain underexplored in the context of climate change adaptation policy (Morrison et al., 2019; Müller et al., 2015).

The regional scale is particularly important for food-energy-water nexus analysis because the interdependencies among resource systems manifest most concretely at sub-national levels, where infrastructure, institutions, and resource endowments create specific configurations of vulnerability and capacity (Lant et al., 2019; Scott et al., 2015). Regional policies governing water allocation, energy generation, agricultural land use, and flood risk management are developed and implemented within specific geographic, political, and economic contexts that shape both the nature of nexus interactions and the feasibility of policy responses (Pahl-Wostl, 2019; Benson et al., 2015). Understanding how projected changes in flood frequency will affect regional food-energy-water systems, and how policy frameworks can be designed to enhance resilience across these systems, requires integrated analysis that bridges hydrological modeling, resource system assessment, and policy evaluation (Bhaduri et al., 2016; Howarth and Monasterolo, 2017).

This study addresses three interrelated research questions. First, how are flood frequencies projected to change under different climate scenarios across selected regional case study areas, and what is the range of uncertainty associated with these projections? Second, how do these projected changes in flood frequency propagate through regional food-energy-water systems, affecting agricultural production, energy generation, water supply, and the infrastructure that supports these functions? Third, what policy options exist at the regional level to enhance food-energy-water resilience in the face of changing flood regimes, and how robust are these options across the range of plausible climate futures?

The significance of these questions extends beyond academic inquiry to practical policy development. As climate change continues to alter hydrological regimes, regional decision-makers require evidence-based guidance on how to anticipate and prepare for changing flood risks and their cascading effects on interconnected resource systems. The costs of inaction are substantial: unmitigated flood impacts can devastate agricultural livelihoods, disrupt energy supplies, contaminate water sources, and trigger cascading economic and social crises (Willner et al., 2018; Jongman et al., 2015). Conversely, well-designed adaptation policies can reduce vulnerability, enhance resilience, and create co-benefits across multiple sectors (Kates et al., 2012; Aerts et al., 2018). Understanding the conditions under which different policy approaches succeed or fail is therefore essential for effective climate adaptation.

The novelty of this research lies in its integration of three analytical domains that are typically treated separately: climate-driven flood frequency projection, food-energy-water nexus modeling, and regional policy analysis. By connecting these domains within a single analytical framework, the study provides a more comprehensive understanding of how climate change impacts on hydrological extremes translate into policy-relevant outcomes across interconnected resource systems. This integration is methodologically challenging but analytically necessary, as the siloed treatment of climate projections, resource systems, and policy has limited the development of effective adaptation strategies (Liu et al., 2021; Albrecht et al., 2018).

The paper proceeds as follows. Section 2 reviews the relevant literature across three interconnected bodies of scholarship: projections of flood frequency under climate change, food-energy-water nexus analysis, and regional climate adaptation policy. Section 3 describes the methodological framework, including the selection of case study regions, the climate and hydrological modeling approaches, the nexus assessment methodology, and the policy analysis framework. Section 4 presents results from the integrated analysis, organized around the three research questions. Section 5 discusses the findings in relation to existing literature, identifies policy implications, and considers limitations and future research directions. Section 6 concludes with a synthesis of key contributions and recommendations for policy and practice.

2. Literature Review

2.1 Flood Frequency Projections under Climate Change

The scientific understanding of how climate change will affect flood frequency has advanced considerably over the past two decades, yet significant uncertainties and methodological challenges remain. Early assessments relied primarily on global-scale hydrological models forced by outputs from general circulation models, providing broad-brush estimates of changing flood risk at continental and global scales (Hirabayashi et al., 2013; Dankers et al., 2014). These studies generally projected increases in flood frequency across large portions of Asia, northern Europe, and parts of Africa and South America, with decreases projected in some Mediterranean and semi-arid regions. However, the coarse spatial resolution of these analyses limited their utility for regional and local decision-making, and the treatment of

hydrological processes such as snowmelt, soil moisture dynamics, and river routing was often simplified (Arnell and Gosling, 2016; Alfieri et al., 2017).

Subsequent research has employed more refined modeling approaches, including statistical downscaling of climate projections, process-based catchment modeling, and hybrid statistical-dynamical methods (Hall et al., 2014; Blöschl et al., 2017). These studies have provided more detailed insights into regional patterns of change and have highlighted the importance of considering multiple drivers of flood risk beyond precipitation alone. For example, changes in snowmelt timing can alter the seasonality of flooding even where total annual precipitation changes little, and shifts in land use and land cover can modify runoff generation and flood propagation (Blöschl et al., 2017; Viglione et al., 2016). The interaction of these drivers creates complex and sometimes counterintuitive patterns of change that require careful analysis.

Uncertainty in flood frequency projections arises from multiple sources, including the choice of climate model, emissions scenario, downscaling method, hydrological model structure, and parameter estimation approach (Hall et al., 2014; Kundzewicz et al., 2017). Model intercomparison studies have revealed substantial spread among projections, particularly for extreme events and for regions where hydrological processes are poorly constrained by observations (Giuntoli et al., 2018; Thober et al., 2018). This uncertainty poses fundamental challenges for adaptation planning, as decision-makers must make choices about infrastructure investments, land use regulations, and emergency preparedness in the face of incomplete and contested information (Hallegatte et al., 2013; Ranger et al., 2013).

Several approaches have been developed to manage uncertainty in flood risk assessment and adaptation planning. Scenario-based approaches explore a range of plausible futures to identify robust strategies that perform reasonably well across multiple scenarios (Lempert et al., 2003; Haasnoot et al., 2013). Adaptive management frameworks emphasize iterative learning and flexible responses that can be adjusted as new information becomes available (Pahl-Wostl, 2007; Allen et al., 2011). Real options analysis provides a framework for valuing flexibility and staging investments in ways that preserve future options (Dixit and Pindyck, 1994; Hertzler, 2007). These approaches have been applied to flood risk management in various contexts, though their integration with food-energy-water nexus analysis remains limited (Morrison et al., 2019; Zeff et al., 2016).

The attribution of observed changes in flood frequency to anthropogenic climate change has been an active area of research, with studies employing both statistical detection and attribution methods and process-based modeling approaches (Pall et al., 2011; Min et al., 2011). While attribution of individual flood events remains challenging due to the multiple factors involved, there is increasing evidence that human-induced warming has already influenced flood risk in some regions (Schaller et al., 2016; Otto et al., 2018). This evidence strengthens the case for incorporating climate change considerations into flood risk management and adaptation policy.

2.2 Food-Energy-Water Nexus Analysis

The food-energy-water nexus has emerged as a prominent framework for analyzing the interdependencies among resource systems and for identifying strategies to enhance resource

security and sustainability (Hoff, 2011; Bazilian et al., 2011). The nexus concept recognizes that water, energy, and food systems are coupled through physical, chemical, biological, economic, and social processes, and that policies and interventions in one sector can have significant implications for the others (Liu et al., 2018; D'Odorico et al., 2018). This recognition has led to calls for integrated approaches to resource management that transcend traditional sectoral boundaries and that account for trade-offs and synergies across systems (Ringler et al., 2013; Endo et al., 2017).

Research on the food-energy-water nexus has proceeded along multiple methodological lines. Quantitative modeling approaches use mathematical representations of resource flows and interactions to simulate the effects of changes in one sector on others, often employing optimization or simulation techniques (Cai et al., 2018; Zhang et al., 2018). Qualitative and participatory approaches emphasize stakeholder engagement, institutional analysis, and governance dimensions of nexus management (Pahl-Wostl, 2019; Benson et al., 2015). Integrated assessment frameworks combine quantitative and qualitative methods to provide comprehensive analyses of nexus dynamics and policy options (Bhaduri et al., 2016; Howarth and Monasterolo, 2017).

The nexus literature has identified numerous examples of interdependencies and trade-offs among food, energy, and water systems. Bioenergy production, for instance, requires water for irrigation and processing and may compete with food crops for land and water resources (Keskinen et al., 2016; Zhang et al., 2018). Hydropower generation depends on water availability and timing, and reservoir operations for hydropower can affect downstream water availability for agriculture and ecosystems (Conway et al., 2015; Pittock et al., 2016). Agricultural intensification often increases energy inputs for irrigation, mechanization, and fertilization, creating additional demands on energy systems (Scanlon et al., 2017; FAO, 2014). Water treatment and distribution require energy, and energy generation requires water for cooling, creating a bidirectional dependency between these sectors (Liu et al., 2018; Sanders and Webber, 2012).

Climate change adds additional dimensions to nexus analysis by altering the availability, timing, and quality of water resources, changing energy demand patterns, and affecting agricultural productivity (Conway et al., 2015; Howarth and Monasterolo, 2017). Extreme events such as floods and droughts can create acute nexus challenges by simultaneously disrupting multiple resource systems and triggering cascading failures (Morrison et al., 2019; Willner et al., 2018). The interconnected nature of nexus systems means that climate impacts can propagate through multiple pathways, creating compounding risks that are difficult to anticipate and manage through sectoral approaches alone (Liu et al., 2021; Albrecht et al., 2018).

Resilience has emerged as a key concept in nexus analysis, providing a framework for understanding how resource systems respond to shocks and stresses and for identifying strategies to enhance adaptive capacity (Raub et al., 2019; Lant et al., 2019). Resilience thinking emphasizes the importance of diversity, redundancy, flexibility, and learning in resource systems, and highlights the need to consider social, institutional, and governance

dimensions alongside technical and infrastructural factors (Folke, 2006; Walker et al., 2004). Applying resilience concepts to food-energy-water nexus analysis requires attention to the multiple scales at which resource systems operate, the diverse actors involved in resource management, and the ways in which power and inequality shape access to resources and exposure to risks (Mehta et al., 2019; Allouche et al., 2019).

2.3 Regional Climate Adaptation Policy

Regional climate adaptation policy encompasses the laws, regulations, programs, and governance arrangements through which sub-national jurisdictions prepare for and respond to climate change impacts (Bierbaum et al., 2013; Moser and Boykoff, 2013). The regional scale is critical for adaptation because many of the decisions that shape vulnerability and resilience are made at sub-national levels, including land use planning, infrastructure investment, water allocation, and emergency management (Kates et al., 2012; Aerts et al., 2018). Regional governments are often on the front lines of climate adaptation, yet they face significant capacity constraints, competing priorities, and political challenges that can impede effective action (Measham et al., 2011; Biesbroek et al., 2013).

Research on regional climate adaptation has identified a range of factors that influence adaptive capacity and the effectiveness of adaptation policies. Institutional capacity, including technical expertise, financial resources, and administrative systems, is a fundamental determinant of adaptation potential (Ford and King, 2015; Eisenack et al., 2014). Political leadership and public support can enable or constrain adaptation action, particularly when adaptation requires difficult trade-offs or conflicts with entrenched interests (Moser and Ekstrom, 2010; Biesbroek et al., 2013). Information and knowledge, including climate projections, vulnerability assessments, and monitoring systems, are essential inputs to adaptation planning, though the translation of scientific information into policy action remains challenging (Lemos et al., 2012; Kirchhoff et al., 2013).

Flood risk management has been a central focus of regional climate adaptation efforts, with strategies ranging from structural measures such as levees and floodwalls to non-structural approaches such as land use regulation, insurance, and early warning systems (Jongman et al., 2015; Aerts et al., 2018). Integrated flood risk management approaches combine multiple strategies and emphasize the importance of considering the full range of flood-related risks, including both direct damages and indirect and intangible impacts (Klijn et al., 2015; Morrison et al., 2018). Climate change adaptation adds additional complexity to flood risk management by requiring consideration of changing hazard probabilities, uncertain projections, and the potential for non-stationarity in flood regimes (Milly et al., 2008; Loehman et al., 2014).

The integration of food-energy-water nexus considerations into regional climate adaptation policy remains limited, despite growing recognition of the importance of nexus approaches (Morrison et al., 2019; Liu et al., 2021). Most adaptation planning processes remain organized along sectoral lines, with separate agencies and programs addressing water, energy, food, and flood risk management (Pahl-Wostl, 2019; Benson et al., 2015). This sectoral fragmentation can lead to policy incoherence, missed opportunities for synergy, and unintended consequences

across sectors (Ringler et al., 2013; Endo et al., 2017). Overcoming these barriers requires governance innovations that facilitate cross-sectoral coordination, integrated planning, and collaborative decision-making (Pahl-Wostl, 2019; Huitema et al., 2009).

3. Methodology

3.1 Research Design and Case Study Selection

This study employs a multi-case comparative research design that integrates climate modeling, hydrological simulation, nexus assessment, and policy analysis within a single analytical framework. The multi-case approach enables examination of how projected changes in flood frequency and their food-energy-water nexus implications vary across different regional contexts, providing insights into the conditions that shape vulnerability and adaptive capacity. Three regional case studies were selected to represent diverse hydroclimatic conditions, resource system configurations, and policy environments.

The selection criteria for case study regions included: (1) documented sensitivity to flood events, including historical flood damages and ongoing flood risk management challenges; (2) significant interdependence among food, energy, and water systems, as indicated by agricultural water use, thermoelectric power generation, and water supply infrastructure; (3) availability of downscaled climate projections and hydrological data sufficient to support modeling; (4) presence of regional policy institutions with responsibility for flood risk management, water allocation, energy planning, and agricultural policy; and (5) variation across cases in terms of climate regime, economic structure, and governance context to enable comparative analysis.

The three case study regions are: (1) the Mekong Delta region of Vietnam, characterized by intensive rice production, hydropower development, and complex water management infrastructure; (2) the Rhine River basin in Germany and the Netherlands, characterized by industrial agriculture, thermoelectric power generation, and advanced flood protection systems; and (3) the Murray-Darling Basin in Australia, characterized by irrigated agriculture, water trading systems, and significant climate variability. These regions represent different positions on the spectrum of economic development, institutional capacity, and climate vulnerability, enabling analysis of how these factors shape nexus dynamics and adaptation options.

3.2 Climate Projections and Downscaling

Climate projections for each case study region were derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6) ensemble, which provides simulations from multiple general circulation models under a range of shared socioeconomic pathway (SSP) scenarios (Eyring et al., 2016; O'Neill et al., 2016). Three scenarios were selected to span a range of plausible futures: SSP1-2.6, representing a sustainability-oriented pathway with strong mitigation; SSP2-4.5, representing a middle-of-the-road pathway with moderate emissions; and SSP5-8.5, representing a fossil-fuel-intensive pathway with high emissions. These

scenarios enable analysis of how different levels of climate forcing translate into changes in flood frequency and nexus outcomes.

Raw climate model outputs were downscaled to the spatial resolution required for hydrological modeling using a combination of statistical and dynamical methods. Statistical downscaling employed quantile mapping approaches that correct for biases in temperature and precipitation distributions while preserving the climate change signal from the parent general circulation model (Thiemeßl et al., 2011; Maraun, 2016). Dynamical downscaling using regional climate models was applied for selected sub-regions where topographic complexity or land-water interactions required higher-resolution simulation (Giorgi and Gutowski, 2015). The downscaling procedure produced daily temperature and precipitation time series at a spatial resolution of approximately 10 km for each case study region, covering the period 1980-2100.

Uncertainty in climate projections was characterized through the use of multiple general circulation models and multiple downscaling methods. Model weighting was applied based on performance in reproducing observed climate characteristics over the historical period, following approaches described by Christensen et al. (2010) and Knutti et al. (2017). The resulting ensemble of downscaled projections provides a basis for probabilistic analysis of changes in flood frequency and associated nexus impacts, while acknowledging the limitations and structural uncertainties inherent in climate modeling.

3.3 Hydrological Modeling and Flood Frequency Analysis

Hydrological modeling was conducted using the Soil and Water Assessment Tool (SWAT) for the Mekong Delta and Murray-Darling Basin case studies, and the Hydrologiska Byråns Vattenbalansavdelning (HBV) model for the Rhine River basin. These models were selected based on their suitability for the respective catchment characteristics, data availability, and prior application in each region (Arnold et al., 1998; Lindström et al., 1997). Both models simulate the major hydrological processes including precipitation, evapotranspiration, snowmelt, infiltration, surface runoff, groundwater recharge, and river routing, and have been widely used for climate change impact assessment.

Model calibration and validation followed standard procedures, using observed streamflow data from gauging stations within each case study region. Calibration was performed using the SUFI-2 algorithm for SWAT (Abbaspour et al., 2007) and manual calibration for HBV, with objective functions including Nash-Sutcliffe efficiency, coefficient of determination, and percent bias (Moriiasi et al., 2007). Validation was conducted using independent time periods not used in calibration, with performance metrics evaluated against established criteria. Uncertainty in model parameters was characterized through Monte Carlo simulation, generating ensembles of behavioral parameter sets for subsequent flood frequency analysis.

Flood frequency analysis was conducted using both annual maximum series and peaks-over-threshold approaches, with probability distributions fitted to simulated flood peaks for historical and future periods. The generalized extreme value distribution was used for annual maximum series analysis, while the generalized Pareto distribution was used for peaks-over-threshold analysis (Coles, 2001). Non-stationarity in flood frequency was assessed by allowing

distribution parameters to vary as functions of time or climate covariates, following approaches described by Katz et al. (2002) and Villarini et al. (2009). Changes in flood frequency were quantified as ratios of return period flows between future and historical periods, and as changes in the exceedance probability of historical design floods.

3.4 Food-Energy-Water Nexus Modeling

The food-energy-water nexus was modeled using an integrated assessment framework that couples sectoral models through a common set of scenario drivers and interaction terms. The framework includes: (1) an agricultural production model that simulates crop yields, irrigation water demand, and land use allocation as functions of climate, water availability, and economic conditions; (2) an energy system model that simulates electricity generation, cooling water demand, and hydropower potential as functions of water availability, energy demand, and infrastructure constraints; (3) a water resources model that simulates water supply, allocation among competing uses, and water quality as functions of hydrological conditions, infrastructure, and institutional rules; and (4) a flood impact module that translates flood frequency changes into damages to agricultural land, energy infrastructure, and water treatment and distribution systems.

The agricultural production model uses a combination of process-based crop simulation and econometric estimation to capture both biophysical and economic determinants of agricultural outcomes. Crop yields are simulated using the Environmental Policy Integrated Climate (EPIC) model (Williams et al., 1989), driven by climate projections, soil characteristics, and management practices. Land use allocation is modeled using a multinomial logit framework that responds to changes in relative profitability, water availability, and policy incentives (Lubowski et al., 2006). Irrigation water demand is calculated based on crop water requirements, effective precipitation, and irrigation efficiency, with adjustments for changes in water availability and allocation rules.

The energy system model represents electricity generation by technology, including thermal power plants (coal, natural gas, nuclear), hydropower, and renewable sources (wind, solar, biomass). Thermal power plant operations are modeled as functions of electricity demand, water availability for cooling, and environmental regulations on water temperature and withdrawal (Förster and Lilliestam, 2010; van Vliet et al., 2016). Hydropower generation is simulated based on reservoir operations, which balance multiple objectives including power generation, flood control, irrigation supply, and environmental flows (Labadie, 2004; Giuliani et al., 2014). The energy model is coupled to the water resources model through shared representation of reservoirs, water withdrawals, and return flows.

The water resources model allocates available water among agricultural, municipal, industrial, and environmental uses based on priority rules, infrastructure constraints, and institutional arrangements. Water allocation is modeled using a network flow optimization approach that represents the physical water system (rivers, reservoirs, canals, aquifers) and the institutional rules governing water rights and allocation priorities (Rosegrant et al., 2000; Yates et al., 2005). Water quality is simulated for key parameters including temperature, dissolved oxygen,

nutrients, and salinity, with implications for both ecosystem health and water treatment requirements. The flood impact module translates changes in flood frequency and magnitude into expected damages to agricultural land and crops, energy infrastructure, and water treatment and distribution systems, using damage functions derived from historical flood events and engineering assessments.

3.5 Policy Analysis Framework

Policy analysis was conducted using a combination of document review, key informant interviews, and policy simulation. Document review examined relevant legislation, regulations, plans, and programs at regional and national levels, focusing on policies related to flood risk management, water allocation, energy planning, agricultural support, and climate adaptation. Key informant interviews were conducted with representatives from government agencies, industry associations, environmental organizations, and academic institutions in each case study region, providing insights into policy processes, implementation challenges, and stakeholder perspectives.

Policy simulation used the integrated nexus model to evaluate the effects of alternative policy scenarios on food-energy-water outcomes under projected changes in flood frequency. Policy scenarios were developed based on the document review and interviews, and were designed to represent a range of approaches to nexus management, including: (1) sectoral approaches that address flood risk, water, energy, and food systems separately; (2) coordinated approaches that explicitly consider nexus interactions and seek to enhance synergies and minimize trade-offs; and (3) adaptive approaches that incorporate flexibility, learning, and iterative adjustment in response to new information. Each policy scenario was simulated under the three climate scenarios to assess robustness across climate futures.

3.6 Analytical Approach and Limitations

The integrated analytical framework enables assessment of how projected changes in flood frequency propagate through food-energy-water systems and how policy interventions can alter these outcomes. The framework acknowledges the complex, nonlinear, and uncertain nature of nexus dynamics and seeks to characterize rather than eliminate uncertainty. Scenario analysis explores a range of plausible futures rather than predicting a single outcome, and robustness analysis identifies policy options that perform reasonably well across multiple scenarios.

Several limitations of the methodology should be acknowledged. First, the integrated model, while comprehensive, necessarily simplifies the complex realities of food-energy-water systems, and model results should be interpreted as indicative rather than precise. Second, the climate projections used as inputs carry inherent uncertainties that propagate through the analysis, and the range of projections may not encompass all plausible futures. Third, the policy analysis focuses on formal policy instruments and may underrepresent informal governance arrangements and community-based adaptation strategies. Fourth, the case study approach, while providing depth and context, limits the generalizability of findings to other regions. These limitations are addressed in the interpretation of results and the discussion of policy implications.

4. Results

4.1 Projected Changes in Flood Frequency

Analysis of downscaled climate projections and hydrological simulations reveals substantial changes in flood frequency across all three case study regions, though the magnitude and direction of change vary by region, scenario, and flood magnitude. In the Mekong Delta, the ensemble mean projection indicates increases in the frequency of large floods, with the 100-year flood under historical conditions becoming approximately a 50-year flood by mid-century under SSP2-4.5 and a 30-year flood under SSP5-8.5. These changes reflect projected increases in monsoon precipitation intensity and shifts in the timing of peak flows, though considerable uncertainty exists across the model ensemble, with some models projecting smaller increases and a minority projecting decreases.

The Rhine River basin exhibits a more complex pattern of change, with increases in winter flood frequency and decreases in summer flood frequency projected under most scenarios. The 100-year winter flood is projected to become approximately a 70-year flood by mid-century under SSP2-4.5 and a 50-year flood under SSP5-8.5, reflecting increases in winter precipitation and earlier snowmelt. Summer flood frequency is projected to decrease due to reduced summer precipitation and increased evapotranspiration, though the magnitude of change is smaller than for winter floods. These seasonal shifts have important implications for flood risk management, as current infrastructure and emergency preparedness systems are typically designed around annual maximum flows without explicit consideration of seasonal timing.

In the Murray-Darling Basin, projections indicate decreases in flood frequency under most scenarios, reflecting projected declines in annual precipitation and increased evapotranspiration. The 100-year flood is projected to become approximately a 150-year flood by mid-century under SSP2-4.5 and a 200-year flood under SSP5-8.5, though uncertainty is particularly large in this region due to the influence of large-scale climate modes such as the El Niño-Southern Oscillation and the Indian Ocean Dipole. These projections suggest a shift toward drier conditions with fewer flood events, but also potential increases in the intensity of individual events when they do occur, reflecting the intensification of precipitation extremes even in regions with declining mean precipitation.

Uncertainty analysis reveals that the spread among climate model projections is substantial for all regions and scenarios, with the range of projected changes often exceeding the ensemble mean change. For the Mekong Delta, the ratio of 100-year flood return periods between future and historical periods ranges from 0.3 to 0.9 across the model ensemble under SSP5-8.5, indicating that even the direction of change is uncertain in some projections. This uncertainty underscores the need for adaptive approaches that can accommodate a range of possible futures rather than optimizing for a single projection.

4.2 Impacts on Food Systems

Changes in flood frequency have significant implications for agricultural production in all three case study regions, though the nature and magnitude of impacts vary depending on the timing

of floods relative to crop calendars, the vulnerability of different crops to flooding, and the capacity of farmers and institutions to adapt. In the Mekong Delta, increased flood frequency during the monsoon season poses risks to rice production, particularly for the summer-autumn crop that coincides with peak flood months. Model simulations indicate potential yield losses of 5-15 percent for rice under SSP2-4.5 and 10-25 percent under SSP5-8.5, depending on the timing and magnitude of flood events and the effectiveness of adaptation measures such as adjusted planting dates and flood-tolerant crop varieties.

The Rhine River basin experiences different agricultural impacts, with increased winter flood frequency affecting winter wheat and other cereal crops through waterlogging and soil erosion, while decreased summer flood frequency reduces the risk of flood damage to summer crops. Net impacts on agricultural production are mixed, with some crops benefiting from reduced summer flood risk and others suffering from increased winter flood risk. Adaptation options include changes in crop rotations, improved drainage systems, and adjusted planting dates, though the effectiveness of these measures varies depending on farm characteristics and access to resources.

In the Murray-Darling Basin, decreased flood frequency reduces the immediate risk of flood damage to crops but also reduces water availability for irrigation, as floods replenish soil moisture and recharge groundwater aquifers that support irrigation systems. The net effect on agricultural production depends on the balance between reduced flood damage and reduced water availability, with model simulations indicating potential declines in irrigated agricultural production of 10-30 percent under SSP2-4.5 and 20-50 percent under SSP5-8.5, primarily due to water scarcity rather than flood impacts. These results highlight the importance of considering both flood and drought risks in nexus analysis, as climate change may shift the balance between these hazards in ways that create new challenges for agricultural systems.

4.3 Impacts on Energy Systems

Energy systems in all three case study regions face significant challenges from projected changes in flood frequency, though the specific impacts vary depending on the composition of the energy mix, the location of energy infrastructure relative to flood zones, and the availability of alternative water sources for cooling. In the Mekong Delta, increased flood frequency poses risks to hydropower generation through both direct impacts on dam and reservoir infrastructure and indirect impacts through changes in reservoir sedimentation and water availability. Thermal power plants located in flood-prone areas face increased risk of inundation and disruption, while changes in water temperature and quality affect cooling efficiency and environmental compliance. Model simulations indicate potential reductions in hydropower generation of 5-20 percent under SSP2-4.5 and 10-30 percent under SSP5-8.5, with larger reductions during flood events when reservoir operations prioritize flood control over power generation.

The Rhine River basin experiences mixed impacts on energy systems, with increased winter flood frequency posing risks to thermal power plants located along the river and decreased summer flood frequency reducing the risk of summer flood disruptions. However, reduced

summer water availability may constrain thermal power plant cooling, particularly during heat waves when both electricity demand and water temperatures are high. Hydropower generation is affected by changes in flow timing, with increased winter flows and decreased summer flows creating seasonal imbalances that challenge reservoir management. The net effect on energy system reliability depends on the capacity to shift generation among technologies and to manage water resources across seasons.

In the Murray-Darling Basin, decreased flood frequency reduces the risk of flood damage to energy infrastructure but also reduces water availability for thermal power plant cooling and hydropower generation. Model simulations indicate potential reductions in thermal power generation of 5-15 percent under SSP2-4.5 and 10-25 percent under SSP5-8.5 due to water availability constraints, with larger reductions during drought periods. Hydropower generation is similarly affected by reduced water availability, though the magnitude of impact depends on reservoir management priorities and the availability of alternative water sources. These results highlight the vulnerability of energy systems to water availability constraints and the importance of considering water-energy interdependencies in climate adaptation planning.

4.4 Impacts on Water Systems

Water systems in all three case study regions face significant challenges from projected changes in flood frequency, with implications for water supply, water quality, and flood risk management infrastructure. In the Mekong Delta, increased flood frequency poses risks to water treatment and distribution infrastructure through inundation and damage, while also creating challenges for water quality management through increased pollutant loads and saltwater intrusion. Model simulations indicate increased treatment costs and reduced reliability of water supply under both SSP2-4.5 and SSP5-8.5, with particularly severe impacts in areas where water infrastructure is already stressed by population growth and economic development.

The Rhine River basin experiences changes in both flood and drought risks, with increased winter flood frequency and decreased summer water availability creating challenges for water management across seasons. Flood risk management infrastructure designed for historical conditions may become increasingly inadequate under changed flood regimes, requiring investments in upgrading or redesigning defenses. Water quality is affected by changes in flow regimes, with increased winter flows diluting pollutants but also mobilizing contaminants from urban and agricultural areas, and decreased summer flows concentrating pollutants and increasing water treatment requirements.

In the Murray-Darling Basin, decreased flood frequency reduces flood risk but also reduces water availability for environmental flows, irrigation, and urban supply. Water allocation systems designed around historical flow regimes may become increasingly stressed as water availability declines, requiring difficult trade-offs among competing uses. Model simulations indicate increased frequency and severity of water shortages under both SSP2-4.5 and SSP5-8.5, with implications for agricultural production, urban water supply, and ecosystem health. These results highlight the interconnected nature of water, food, and energy systems and the

importance of integrated approaches to water management that consider the full range of nexus interactions.

4.5 Policy Analysis Results

Policy simulation results reveal significant variation in the effectiveness of alternative policy approaches across case study regions and climate scenarios. Sectoral approaches that address flood risk, water, energy, and food systems separately perform poorly in managing nexus interactions, often creating unintended consequences in other sectors. For example, flood risk management policies that prioritize structural defenses may reduce flood damages to agricultural land but also disconnect floodplains from rivers, reducing groundwater recharge and water availability for irrigation and energy generation. Similarly, water conservation policies that reduce agricultural water use may increase water availability for energy generation but reduce food production, creating trade-offs that sectoral approaches fail to recognize or manage.

Coordinated approaches that explicitly consider nexus interactions perform better in managing trade-offs and enhancing synergies, though their effectiveness depends on the specific policy mix and implementation context. Integrated flood risk management that combines structural and non-structural measures with land use planning and ecosystem-based approaches can reduce flood damages while maintaining groundwater recharge and water availability. Water allocation policies that consider the water requirements of food, energy, and environmental systems can balance competing demands more effectively than sectoral allocation rules. Energy policies that promote diversification and flexibility can enhance resilience to both flood and drought impacts on water availability. However, coordinated approaches face significant implementation challenges, including institutional fragmentation, conflicting mandates, and political resistance from sectoral interests.

Adaptive approaches that incorporate flexibility, learning, and iterative adjustment perform best across the range of climate scenarios, though they require significant institutional capacity and commitment to ongoing monitoring and evaluation. Adaptive flood risk management that adjusts infrastructure investments and management strategies in response to observed changes can avoid the risks of both under-investment and over-investment in flood defenses. Adaptive water allocation that adjusts rules and priorities in response to changing conditions can balance competing demands more effectively than fixed allocation systems. Adaptive energy planning that maintains flexibility in generation portfolios and water sourcing can enhance resilience to uncertain changes in water availability. However, adaptive approaches require sustained political commitment and resources, and may be difficult to implement in contexts where short-term pressures dominate decision-making.

5. Discussion of Findings

5.1 Interpretation in Relation to Existing Literature

The findings of this study are broadly consistent with existing literature on projected changes in flood frequency under climate change, while providing new insights into the propagation of

these changes through food-energy-water systems and the implications for regional policy. The projected increases in flood frequency in the Mekong Delta align with earlier global and regional assessments that identified Southeast Asia as a hotspot of increased flood risk under climate change (Hirabayashi et al., 2013; Arnell and Gosling, 2016). The seasonal shifts in flood frequency in the Rhine River basin are consistent with studies that have identified changes in flood seasonality as a key dimension of climate change impacts on hydrological regimes (Blöschl et al., 2017; Viglione et al., 2016). The projected decreases in flood frequency in the Murray-Darling Basin align with assessments that identify the Mediterranean and semi-arid regions as areas of declining flood risk under climate change (Dankers et al., 2014; Alfieri et al., 2017).

The finding that flood frequency changes propagate through food-energy-water systems in complex and sometimes counterintuitive ways supports the growing recognition of the need for nexus approaches to climate impact assessment (Liu et al., 2018; D'Odorico et al., 2018). The results demonstrate that sectoral assessments that focus on individual systems can miss important interactions and trade-offs, and that integrated assessment can reveal policy options that enhance outcomes across multiple systems (Ringler et al., 2013; Endo et al., 2017). The finding that policy approaches differ in their effectiveness across climate scenarios and regional contexts is consistent with literature on adaptive and robust decision-making under uncertainty (Hallegatte et al., 2013; Ranger et al., 2013).

The study extends existing literature by providing an integrated analytical framework that connects climate projections, hydrological modeling, nexus assessment, and policy analysis within a single study. While previous research has addressed individual components of this framework, few studies have integrated all four dimensions in a comparative multi-case design. The framework developed here provides a template for future research that seeks to understand how climate change impacts on hydrological extremes translate into policy-relevant outcomes across interconnected resource systems.

5.2 Policy Implications

The findings have several important implications for regional policy development. First, the substantial uncertainty in flood frequency projections, even under a single climate scenario, implies that policy approaches should emphasize robustness across a range of plausible futures rather than optimization for a single projection. This suggests the value of adaptive approaches that can be adjusted as new information becomes available, and the importance of avoiding lock-in to specific infrastructure or institutional arrangements that may prove maladaptive under changed conditions.

Second, the interconnected nature of food-energy-water systems implies that policies in one sector can have significant implications for others, and that policy development should explicitly consider these interactions. This suggests the need for cross-sectoral coordination mechanisms, integrated planning processes, and governance arrangements that facilitate collaboration among agencies and stakeholders with responsibility for different components of the nexus. While such coordination is challenging in practice, the costs of failing to coordinate

may be substantial, as sectoral policies that ignore nexus interactions can create unintended consequences that undermine overall system performance.

Third, the finding that adaptive approaches perform best across climate scenarios suggests the importance of building adaptive capacity at regional levels. This includes technical capacity for monitoring and assessment, institutional capacity for learning and adjustment, and financial capacity for incremental investments that preserve future options. Building adaptive capacity is particularly important in regions where climate impacts are expected to be severe and where existing capacity is limited, as these regions may face the greatest challenges in adapting to changing conditions.

Fourth, the regional variation in flood frequency projections and nexus impacts implies that policy responses should be tailored to specific regional contexts rather than applied uniformly across regions. The Mekong Delta, Rhine River basin, and Murray-Darling Basin face different combinations of flood and drought risks, different configurations of food-energy-water systems, and different institutional and governance contexts. Policy approaches that work well in one region may not be appropriate in another, and effective adaptation requires attention to local conditions and priorities.

5.3 Limitations and Future Research

Several limitations of this study should be acknowledged, and these limitations suggest directions for future research. First, the integrated model, while comprehensive, necessarily simplifies the complex realities of food-energy-water systems. Future research could extend the model to include additional dimensions of nexus interactions, such as land use change, biodiversity, and social equity, and could incorporate more detailed representation of infrastructure systems and institutional arrangements.

Second, the climate projections used as inputs carry inherent uncertainties that propagate through the analysis. While the use of multiple models and scenarios provides a basis for probabilistic analysis, the range of projections may not encompass all plausible futures, and the downscaling methods introduce additional uncertainties. Future research could explore alternative approaches to uncertainty characterization, including the use of large ensembles and the development of storylines that represent different combinations of climate and socioeconomic conditions.

Third, the policy analysis focuses on formal policy instruments and may underrepresent informal governance arrangements and community-based adaptation strategies. Future research could examine how informal institutions and social networks shape adaptive capacity and how they interact with formal policy processes. Additionally, future research could examine the political economy of nexus policy development, including the factors that enable or constrain policy change and the strategies that actors use to advance or block reforms.

Fourth, the case study approach, while providing depth and context, limits the generalizability of findings to other regions. Future research could extend the analysis to additional case study regions representing different hydroclimatic conditions, resource system configurations, and

policy environments, enabling broader comparative analysis and the identification of generalizable patterns and principles.

6. Conclusion

This study has examined projected changes in flood frequency under future climate scenarios and their implications for regional food-energy-water policy through an integrated analysis of three case study regions: the Mekong Delta, the Rhine River basin, and the Murray-Darling Basin. The findings reveal substantial changes in flood frequency across all regions, with increases projected in the Mekong Delta, seasonal shifts projected in the Rhine River basin, and decreases projected in the Murray-Darling Basin. These changes propagate through food-energy-water systems in complex ways, affecting agricultural production, energy generation, water supply, and flood risk management infrastructure, with implications for regional policy development.

The key contributions of this study are threefold. First, it provides an integrated analytical framework that connects climate projections, hydrological modeling, nexus assessment, and policy analysis within a single study, demonstrating the value of integrated approaches for understanding climate change impacts on interconnected resource systems. Second, it demonstrates the importance of considering nexus interactions in climate adaptation policy, showing that sectoral approaches can create unintended consequences and that coordinated approaches can enhance outcomes across multiple systems. Third, it identifies adaptive approaches as most robust across climate scenarios, while acknowledging the institutional and political challenges of implementing adaptive approaches in practice.

The policy implications of these findings are significant. Regional decision-makers should emphasize robustness across a range of plausible futures rather than optimization for a single projection, should develop cross-sectoral coordination mechanisms to manage nexus interactions, should build adaptive capacity for monitoring, learning, and adjustment, and should tailor policy responses to specific regional contexts. These recommendations are particularly urgent in regions where climate impacts are expected to be severe and where existing capacity is limited.

Future research should extend the integrated analytical framework to additional regions and dimensions, explore alternative approaches to uncertainty characterization, examine the political economy of nexus policy development, and investigate the role of informal institutions and community-based adaptation strategies. By building on the findings of this study, future research can contribute to the development of more effective and equitable climate adaptation policies that enhance food-energy-water security in a changing climate.

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