University of Strathclyde Glasgow

A multi-agent approach to support decision-making uncertainty: optimising climate adaptation and resilience measures for the finfish aquaculture sector in Scotland.

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A thesis submitted for the degree of Doctor of Philosophy Glasgow, United Kingdom 2024

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Signed: *Joshua P*

Date: 17.02.2025

Acknowledgements

First and foremost, I would like to express my deepest gratitude to my two amazing supervisors, Dr. Jen Roberts and Prof. John Quigley. Their unwavering support, invaluable guidance, and profound knowledge have been instrumental in the completion of this thesis. I am deeply thankful for their patience, encouragement, and for consistently pushing me to achieve my best.

I would also like to extend my heartfelt thanks to all my fantastic friends who have made this journey enjoyable and memorable. To those I shared the office with, played football with, spent far too many lunch breaks attempting to learn roads of rural Bhutan with, and those whom I embarked on countless Dungeons & Dragons adventures with - you have all been a source of joy and camaraderie. Your friendship and support have been invaluable.

To my amazing family—Sharon, Wayne, Luke, and Lucy—thank you for your endless love and encouragement. Your belief in me has been a constant source of strength. To my partner, Sarah, your unwavering support, and understanding have been my anchor through the highs and lows of this journey. I am incredibly grateful for your love and patience.

Lastly, I would like to thank Nimbus, whose companionship kept me happy and warm during the long winter nights of writing. Your presence brought comfort and joy, making the challenging times more bearable.

Thank you all for being an integral part of this journey.

Abstract

Understanding and decision-making in complex systems can be significantly enhanced by decision-support tools that elicit and present data in an informative, accurate, applicable, and strategic manner (Wagener et al., 2022). Despite the widespread adoption of such tools, a gap persists: no existing tool effectively integrates multiple stakeholder perspectives, quantifies their values, and simultaneously addresses uncertainties in decision-making processes. This PhD research addresses this gap by developing a novel methodology and decision-support tool, SEAD (Stakeholder interaction, Elicitation, Analysis, Dialogue). By leveraging Multi-Agent Influence Diagrams (MAIDs) derived from Bayesian Networks, the SEAD methodology facilitates structured, quantified, and participatory decision-making processes. The innovation of SEAD lies in its adaptability across multi-stakeholder scenarios, particularly those characterized by significant uncertainty, such as climate change adaptation.

The thesis is organized to systematically address the research objectives. Chapter 2 reviews existing decision-making methodologies and identifies critical gaps, establishing the need for a tool like SEAD. Chapter 3 details the conceptualization and development of the SEAD methodology, emphasizing its novel integration of MAIDs for scenario evaluation and stakeholder engagement. Chapter 4 investigates climate change vulnerabilities within the freshwater aquaculture sector, providing the contextual foundation for SEAD's application. Chapters 5 through 8 present the case study application of SEAD to the Scottish freshwater finfish aquaculture industry, demonstrating its capacity to optimize decision-making under climate pressures and to identify adaptation and resilience measures. Finally, Chapter 9 explores broader adaptation and mitigation pathways, extending SEAD's implications beyond the case study.

The freshwater aquaculture sector was chosen as a case study due to its economic importance and vulnerability to climate change. Salmon is Scotland's leading food export, with exports worth £578m in 2022 (Salmon Scotland, 2023). The industry, comprising 108 freshwater aquaculture sites (Aquaculture Scotland, 2024), faces significant risks from climate change, including water shortages and temperature fluctuations. Adaptation decisions require input from diverse stakeholders—including insurers, regulators, and industry bodies—each with distinct priorities and risk perceptions. Such complexity often hampers timely and effective decision-making.

The SEAD method addresses this challenge by enabling real-time, participatory assessments of stakeholder values and priorities against customizable climate risk scenarios. In the case study, the tool engaged three key stakeholder groups from the aquaculture sector: insurance providers, regulatory bodies, and industry representatives. These stakeholders used SEAD to evaluate risks, explore cooperative pathways, and identify priority areas for intervention. The process not only facilitated consensus-building but also highlighted specific adaptation and mitigation measures.

Stakeholders found SEAD to be both innovative and practical, praising its ability to provide structured and actionable insights. However, feedback indicated that future development should streamline the methodology and enhance the usability of the tool's interface. The next phase of this research involves applying SEAD to specific sites to optimise climate resilience interventions and assess the tool's effectiveness. Further studies will explore variability within stakeholder groups by engaging different participants and extend the SEAD methodology to other sectors and applications, broadening its utility in addressing complex, uncertain decision-making scenarios.

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Abbreviations

BN: Bayesian Network

CID: Causal Influence Diagram

COP: Conference of the Parties

CPT: Conditional Probability Table

DEFRA: Department for Environment, Food & Rural Affairs

DAG: Directed Acyclic Graph

DST: Decision-Support Tool

IDEA: Investigate, Discuss, Estimate Aggregate

IPCC: International Panel on Climate Change

FAO: Food and Agriculture Organization

MA: United Nations' Millennium Ecosystem Assessment

MAID: Multi-Agent Influence Diagram

PGI: Protected Geographical Indication

RAS: Recirculating Aquaculture Systems

RCP: Representative Concentration Pathways

SCCAF: Scotland Climate Change Adaptation Framework

SEAD: Stakeholder Interaction, Elicitation, Analysis, Dialogue

SEPA: Scotland Environmental Protection Agency

SHELF: Sheffield Elicitation Framework

UNFCC: United Nations Framework Convention on Climate Change

WRMP: Water Resource Management Plan

Chapter 1: Introduction

1.1 Overview and research motivation

Understanding and decision-making on complex systems often require decision-support tools (Box 1) which elicit (Box 1) and present data in an informative, accurate, applicable, and strategic way (Wagener et al., 2022). Despite decision-support tools' widespread use, existing decision-support tools face limitations when it comes to addressing multi stakeholder scenarios and quantifying stakeholder perceptions while managing uncertainties. This thesis focuses on addressing these gaps through the conceptualisation and development of a novel decision-support methodology, applicable to scenarios with significant uncertainty and diverse stakeholder priorities, such as those posed by climate change. Climate change is a pressing challenge requiring simultaneous mitigation and adaptation efforts.

Box 1: Definitions:

Decision-support tool: A system or application designed to assist individuals or organisations in making informed decisions by analysing data, presenting options, or offering recommendations (Hanea et al., 2022).

Elicit: To draw out or bring forth a response, information, or reaction, often through questioning or prompting (Quigley et al., 2018).

To test, and synthesise a methodology for; data collection, structure building, and stakeholder use – of a proposed decision-support tool a case study was needed. For this, the Scottish freshwater aquaculture industry was selected. The decision and thought behind the case study selection are outlined below and explored in further detail within Chapter 3. For industries like Scottish freshwater aquaculture, which are vital to the economy and face specific climate-related vulnerabilities, robust adaptation and resilience measures are essential. The aquaculture industry contributes an estimated £1.8 billion annually to the Scottish economy, with ambitious targets to double this by 2030 (Aquaculture - Gov.Scot, 2022). The impact of climate change, including increased frequency of droughts and floods (Visser-Quinn et al., 2021), poses significant risks to

freshwater availability and aquaculture sustainability. Addressing such wicked problems (Box 2), characteristics that integrate technical data and stakeholder inputs.

Box 2: Definition: Wicked problem.

"*A class of social system problems which are ill-formulated, where the information is confusing, where there are many clients and decision makers with conflicting values, and where the ramifications in the whole system are thoroughly confusing.*" (Churchman, 1967, p. 141).

When planning for the effects of climate change, impact scenarios and adaptation decisions to mitigate them must be considered (Molenveld et al., 2020). However, as a wicked problem there are complexities associated with measuring these and it is important to consider input from key stakeholders when making final decisions (Pretorius, 2016). Climate change impact scenarios vary spatially and temporally and have uncertainties associated with them (Robins et al., 2017). Climate change adaptation decisions are complex and often involve more than one party, each with their own desired outcomes. Moreover, differences in priorities, resource capacity, and risk appetites within and between decision-makers and stakeholders, from sector-wide to individual personnel convolute issues further (Dowling et al., 2016). Adaptation decisions must be informed by reliable and up-to-date data, this is fundamental to adapt to potential impacts instigated by climate change and must incorporate and balance a range of stakeholder values; decision-making that is largely informed by technical expertise can neglect issues of public concern. A decision-support tool was developed to challenge these complexities and to combine impact scenarios, adaptation decisions and stakeholders. The SEAD (<u>S</u>takeholder interaction, <u>E</u>licitation, <u>A</u>nalysis, <u>D</u>iscussion) decision-support tool is used by stakeholders to identify:

1. Vulnerable areas within a risk system.
2. Cooperative decision paths - decisions which benefit all agents which only work by being cooperative.
3. The most effective or acceptable adaptation practices.
4. Mitigation strategies for reducing the stakeholder's future contribution to risk vulnerabilities.

Scotland is projected to become increasingly vulnerable to periods of dry weather and extended periods of wet weather (Visser-Quinn et al., 2021; Werritty & Sugden, 2012; Gov.Scot, 2019). This in turn puts pressure on water users and the environment, and potential adverse effects include water quality issues and decreased water supply (Blasco et al., 2015). Visser-Quinn et al. (2021) investigated these spatial shifts and concluded there could be between two and seven more additional dry periods per year by 2050, varying by location. Visser-Quinn et al. (2021) further state

that abstraction within Scotland will put pressure on the water supply potentially leading to water shortages and abstraction restrictions, which would hamper the industry. Research presented in in Chapter 3 corroborates Visser-Quinn's findings.

For the proposed decision-support tool to be suitable an unmet need a criterion was established based on the characterisation of the case study, doing so makes the tool applicable to problems with the same characteristics, justification is further explored in Chapter 3.

Any decision-support tool developed in this research must be able to:

Criterion 1: Highlight uncertainty - to deal with multiple scenarios and unknowns.

Criterion 2: Incorporate multiple stakeholder inputs – alleviating problems caused by multiple stakeholder priorities.

Criterion 3: Suited to handling wicked problems (Box 2)

The foundation of the tool was chosen to be a Bayesian Network (Box 3), Bayesian Networks are further detailed within Section 2.4. The ability of Bayesian Networks to quantify uncertainty, learn causal effects from observational data and present themselves in a user-friendly interface means they have gained traction in many industries (Scutari & Denis, 2021). Bayesian Networks fit two of the three set criteria (Criteria 1 & 3), but not all, as Bayesian Networks cannot incorporate multiple stakeholders (Criterion 2). The options and justification for a suitable decision-support tool are explored within Chapter 2 but, in short, this tool – known as a MAID (Multi-Agent Influence Diagram) was based on Bayesian Networks although was further adapted to incorporate multiple stakeholder perspectives. Previously MAIDs had not been used in a decision-support setting and there is no established method for doing so. This is a critical research gap that this thesis aimed to fill.

1.2 Research scope

> **Box 3**: Definition: Bayesian Network.
>
> A graphical model that represents probabilistic relationships among a set of variables using nodes (for variables) and directed edges (for dependencies). It is used for reasoning under uncertainty and making predictions based on given evidence (Jensen, 2009).

The scope for this research is split into two, first (1.2.1) the scope of the creation of the tool, and methodology for applying the tool. Then (1.2.2) the scope of the case study, which is explored and justified further.

1.2.1 Creating a decision-support tool

The purpose of the study was to create a generalised decision-support tool which could be applied to a climate-vulnerable industry. The decision-support tool developed (called SEAD) sets out a methodology for;

1) selecting stakeholders (who are seen to share the burden of risk).
2) Eliciting data from stakeholders, to build a structure, and inform the underlying data of the tool.
3) Modelling the structure and the data.
4) Using the completed decision-support tool to discuss potential risk mitigation or adaptation pathways.

The study also explores alternative methodologies, justifying the chosen approach and refining the tool through iterative testing and stakeholder feedback. These processes are detailed in Chapter 3.

1.2.2 Applying the decision-support tool to a case study.

To limit the scope of application, this research focuses on Scotland's freshwater finfish aquaculture industry. This sector was chosen due to its significant economic contribution and vulnerability to climate-related water challenges. Freshwater production, compared to saltwater, is particularly at risk due to issues like water scarcity and quality degradation, which directly threaten industry growth (Visser-Quinn et al., 2021). The sector's economic importance underscores the value of identifying adaptive measures to ensure its sustainability. Detailed justifications for this case study are provided in Chapter 4.

After applying the method to aquaculture using real agents, we extended the approach to the whisky industry in Scotland to test the feasibility of synthetic data. By leveraging synthetic data, we aimed to mirror the complexities and challenges faced by industry stakeholders, enabling us to validate the adaptability of the SEAD method. Paving the way for broader applications across diverse industries.

1.3 Research aims and objectives

This research aims to develop an approach that will enhance decision-making within environments characterised as wicked problems, where there are multiple stakeholders and high levels of uncertainty. The aim is to address the gap in existing decision-support tools by creating a novel approach that integrates stakeholder perceptions and quantifies uncertainties. The primary focus is on developing a versatile tool applicable to various multi-stakeholder decision scenarios, with particular emphasis on sectors vulnerable to climate change, such as the freshwater finfish

aquaculture industry, thereby optimizing decision-making under pressure from climate change impacts.

To achieve these research aims, four objectives were set out. The four objectives and the corresponding Chapters in which they are addressed are detailed in Table 1.1.

Table 1.1: *Summarising research objectives and thesis Chapters in which they are addressed.*

	Research Objective	Corresponding thesis Chapter(s)
1	Investigate decision-making methods and identify gaps in existing decision-making tools.	Chapter 2 presents a review of decision-support tools.
2	Develop a generalisable decision-support tool and associated methodology.	Chapter 3 details the construction and iterative development of the decision-support tool.
3	Identify a suitable case study to apply, test and refine the decision-support tool, with particular focus on climate change vulnerability.	Chapter 4 outlines the chosen case study (freshwater finfish aquaculture industry in Scotland) and sector vulnerability to climate change.
4	Apply, test and refine the decision-support tool using a synthetic case study and an empirical case study to explore emerging climate change adaptation and mitigation pathways.	Chapter 5 applies the decision-support tool to the chosen case study. Chapter 6 details the results, which are discussed in Chapter 7. A synthetic case study is examined in Chapter 8. Climate change adaptation pathways are then explored in Chapter 9.

Chapter 2 Literature Review

Chapter 2 examines primary literature, including peer-reviewed studies and government reports, to highlight challenges in planning for climate change and decision-making for mitigation and adaptation. The literature review establishes the need for the SEAD decision-support tool (DST) and outlines the rationale for selecting the Scottish Aquaculture industry as the primary case study to develop, test and apply SEAD.

The review is structured around two main themes which have the DST as its focal point:

1. *Theme 1 (Sections 2.1 – 2.4):* An overview of climate change adaptation issues - with a lens of how the chosen DST would benefit current mitigation and adaptation strategies, and specifically the chosen case study, Scottish freshwater finfish aquaculture. Theme 1 explores climate change adaptation, water, and the aquaculture industry, and shows how climate change impacts on water will have consequences for the aquaculture industry.

2. *Theme 2 (Sections 2.4 – 2.6):* Decision-making and decision-support tools, focusing on desired features while consistently linking back to issues from Theme 1. Theme 2 considers the perspective of the DST's intended users—either individual industry decision-makers or multidisciplinary collaborations – and explores decision science, multi-perspective approaches, and multi-agent influence diagrams, and highlighting a gap in existing DSTs suitable to the chosen case study.

2.1 Climate change adaptation

2.1.1 Anthropogenic Climate Change

The idea of mankind anthropogenically affecting the earth's atmosphere has been theorised since 1896 when a Swedish scientist, Svante Arrhenius, suggested that changes in carbon dioxide levels within the atmosphere could alter the earth's surface temperature (Arrhenius, 1896). Arrhenius' theory underwent multiple iterations until 1956, 62 years after Svante's first seminal paper, Gilbert Plass conceived the carbon dioxide theory of climate change which Plass, (1956) states that human activities such as those involved in the industrial process emitted CO_2 into the atmosphere, which within the present century had caused the earth's temperature to rise. Unlike previous iterations of the theory, Plass (1956) predicted that the suggested warming will persist, possibly for centuries. Since 1956, whilst the underlying theory has remained, the understanding of climate change has expanded, including insight into more 'greenhouse gasses', and a deeper understanding of the impacts, hazards, and risks.

The impacts of this threat expand beyond simply a warming of the atmosphere. Climate change alters temporal and spatial weather patterns, leading to more frequent and intense extreme events. With increasing understanding of the impacts of climate change the phrase 'global warming' is now deemed redundant. Furthermore, globally the impacts of climate change are disproportionately skewed towards already vulnerable societies and peoples. Although some efforts have been made in recent years to adapt and mitigate these impacts, climate change has already altered both the human and natural planet irreversibly, putting strain on these adaptations (IPCC, 2018). The International Panel on Climate Change (IPCC) states that climate change harms both physical and mental health worldwide (IPCC, 2018), exasperating climate change impacts on economic and social conditions. Additionally, global infrastructure has been compromised, with transportation, water, sanitation, and energy stability under pressure or failing.

Despite knowledge of human-induced climate change being around for over a century, the impacts have only started to become prominent in recent decades (IPCC, 2018). Some theorise that we are beyond the tipping point of slowing or stopping climate change (IPCC, 2018). Despite this, efforts to adapt and mitigate have been mobilised, with efforts increasing continuously (IPCC*, 2018*). Headline statement A3 by the IPCC (2018) states "*Adaptation planning and implementation has progressed across all sectors and regions*". These adaptations are, naturally, not spatially equal, with regions with less economic access unable to provide the same amount of adaptation measures (Klimenko et al., 2019). As public perception of climate change is altering, policies are being implemented to reduce impacts, with 170 countries now including adaptation methods within their climate policies. Furthermore, climate services as well as decision-support tools and increasingly being used within these adaptation processes (IPCC, 2018).

Despite adaptation progress, there is still a difference between desired levels of adaptation to adequately reduce presented climate risk, and the adaptation currently observed. Observed adaptations are often not on a large scale and are often sector-specific (*IPCC,* 2018). There is no established answer as to the most efficient or theoretically most successful way to adapt to climate change, suggestions vary from a government-led approach to spontaneous adaptation (Molenveld et al., 2020). Other solutions include using tools such as that suggested by Kunapo et al. (2018) to allow for spatial planning to confront climate change issues or introducing climate change adaptation into societal protection (Kundo et al., 2021). Enhancing decision-making for adaptation solutions will reap benefits from heightened decision-support capabilities. Consequently, fostering innovation within decision-support tools will pave the way for more effective adaptation strategies.

2.1.2 Climate Policy Landscape

Policies and legislation are an essential component of any plan, their importance stems from their ability to address pertinent issues. In the case of climate change, it's clear that the difference between action and no action could be considerable, legislation and policies help to reduce the overall impacts climate change may have. A DST will be limited by legislation and may have to account for potential legislation scenarios. Therefore, understanding the current legislation is paramount for a DST. Furthermore, as the climate policy landscape is being continually updated, a DST must also be able to be updated or risk being out of calibration.

Climate change policy has been gaining traction since climate change was determined to be a global effort in the late 1980s, with the founding of the International Panel on Climate Change (IPCC) in 1988, followed shortly after by the United Nations Framework Convention on Climate Change (UNFCCC). The Rio Earth Summit set a foundation for a unionised global effort on climate change, which would become one of the most focused global policies (Klimenko et al., 2019). Many studies: (Klimenko et al., 2019; Miles, 2019; Vezirgiannidou, 2008; Eizenstat, 1998), amongst others, classify the Kyoto summit as the first major step in climate change legislation. The Kyoto summit aimed to set legislation which targeted fuel switching and carbon capture (UNFCCC, 1997). Following this the next major milestones included; Copenhagen 2009, which had a focus on atmospheric concentrations (United Nations, 2009), Durban 2011 and Doha 2012 which focused on cumulative budgets ("Essential Background - Durban outcomes | UNFCCC," 2012)("The Doha Climate Gateway | UNFCCC," 2013) and finally the Paris agreement which focused on the outcome temperature in future scenarios (UNFCCC, 2015). These agreements acknowledge the monumental task that is tackling climate change and that every country must be involved for it to be successful.

With the task of resolving climate change a worldwide issue, each country has a responsibility to do what it can. This review covers the principal legislation elected by Scotland. As of the time of writing, the main legislation, although there are many frameworks, is the Scotland Climate Change Act of 2019, an update to the 2009 act by the same name. The principal objective of the Climate Change Act 2009 was to reduce emissions by 80% from the baseline by the year 2050. If relevant, this should be considered within decision-support tools, although a vast decrease for Scotland may be outweighed by larger countries not complying with similar regulations. This aim is broken down into actions throughout the years leading up to 2050, this will allow calibration of the decision-support tool, with current progress taken into mind. E.g. "*The Scottish Ministers must ensure that the net Scottish emissions account for the year 2020 is at least 42% lower than the baseline*." (Climate Change (Scotland) Act 2009, 2009). The Scottish Report on Progress Towards Meeting the Interim Target, (2015) was the first report assessing the progress toward the targets set out in the Climate

Change (Scotland) Act 2009, this report showed an annual breakdown of progress each year from 2010-2013, which was as far as the report showed, they met the targets set out as by 2013 they had reduced by 38.4%, which exceeded the 31.4% target by that year for them to meet the 42% by 2020.

The 2009 climate change act indicators are not from the 2009 baseline, but from the 1990 baseline. By the time the act was introduced, there was already roughly a 25% decrease. The progress towards the 2050 target should next be considered and checked annually within the proposed decision-support tool to allow the tool to stay calibrated.

Climate policy in Scotland is also affected by UK policy. The Climate Change Act 2008 (The Climate Change Act 2008 (2050 Target Amendment), 2019) is a cornerstone of the UK's approach, setting legally binding targets to reduce greenhouse gas emissions, initially aiming for an 80% reduction by 2050 (relative to 1990 levels) and later updated to net-zero emissions by 2050. This act underpins climate-related strategies across the UK, influencing policy and decision-making at both national and regional levels, including Scotland.

The Net Zero Strategy (Burnett et al., 2024) further elaborates on how the UK aims to achieve these targets, outlining economy-wide measures such as transitioning to renewable energy, enhancing energy efficiency, and supporting low-carbon industries. Recent developments, including enhanced emission reduction targets announced at COP29 and increased support for renewable energy adoption (e.g., grants for solar panel installations), reinforce the UK's commitment to leading on climate action. These UK wide policies, directly impact Scotland's industries and decision-making, ensuring consistency with national objectives while addressing unique regional needs.

2.1.3 Climate change projections in Scotland

In the context of climate change, the prevailing trend suggests that regions with higher latitudes, such as Scotland, are poised to encounter amplified winter precipitation levels. This phenomenon can be attributed to the heightened specific humidity of the warmer troposphere (*IPCC*, 2019). Increases in annual runoff are likely in the northern latitudes corresponding to large increases in winter and spring precipitation by the end of the 21st century (Döll et al., 2014). It is also predicted that while winter and spring precipitation will increase, hotter seasons will see a reduction in precipitation and an increased chance of drought (*IPCC*, 2019).

Scottish Government have laid out more details of the potential impacts of climate change on Scotland and what impacts this global issue is already having on the country. The main impacts stated are "Average temperatures will increase across all seasons, Typical summers will be warmer and drier, Typical winters will be milder and wetter, Intense, heavy rainfall events will increase in

both winter and summer, Sea levels will rise, Reduced frost and snowfall, Weather will remain variable and may become more variable." (Environment.Gov.Scot, 2022). Having multiple, different scenarios (in this case summer and winter), which pose different threats will have to be accounted for within the model, to insure year-round resilience.

A pivotal challenge in planning for future events revolves around the scarcity of quantifiable data, rendering it difficult to ascertain the validity and accuracy of any forthcoming plans. Given such uncertainty surrounding how these events may unfold, one strategy is to plan for multiple scenarios. Climate change scenarios are a range of outcomes which are influenced by a range of driving forces, such as; demographic development, socio-economic development, and technological change (IPCC, 2019). Decision makers and stakeholders aiming to adapt to climate change should carefully deliberate on all available scenarios (Lowe et al., 2018). Consequently, a decision-support tool addressing climate change forecasting must be equipped with the ability to effectively evaluate uncertainty.

Climate change is proving to be a problem which cannot simply be solved at an individual level, there is an evidential need for a global governmental effort. Climate change impacts are often inevitable for businesses (Doukas & Nikas., 2020). When a business, industry or government is looking at planning for climate change there are more obstacles than just the uncertainty they must consider. Uncertainty in climate change arises from various factors, notably, the ambiguity surrounding the global scale of actions to be undertaken and consequently the severity of forecasted changes. Understanding the implications of this uncertainty for sectoral transition is crucial. It necessitates significant transformations within sectors to achieve net zero emissions through climate change mitigation measures, as well as the implementation of adaptation measures. The decision maker must consider the adaptation strategy that suits their needs best, the severity of impacts that they wish to adapt to if their actions will be pre-emptive or adaptive and the fiscal implications of the above choices. An ideal DST should be adaptable to allow for uncertainty while utilising up-to-date data to make informed propositions.

2.2 Water in Scotland

2.2.1 Water distribution within Scotland
Scotland is abundant in freshwater resources, with numerous rivers, lochs (lakes), and reservoirs scattered across the landscape. The distribution of water in Scotland is influenced by various factors, including topography, precipitation patterns, and human activities. The Highlands and other mountainous regions receive ample rainfall, contributing to the formation of numerous rivers and

lochs (Marsh & Anderson, 2002; Martin-Ortega et al., 2013). These water bodies serve as natural reservoirs and play a crucial role in supplying water to both urban and rural areas.

When compared to the rest of the planet Scotland has an abundance of water resources, ranking as one of the wettest countries in Europe (Marsh & Anderson, 2002). Further, Scotland is said to have 90% of the UKs freshwater (Gov.Scot, 2014). These water resources are continual re-supplied through rainfall, caused by moist airflows and high relief throughout the country (Marsh & Anderson, 2002). Since these rainfalls are often tied to the Atlantic frontal system the west of Scotland sees a higher proportion of precipitation (R. J. Hall & Hanna, 2018).

Despite Scotland's "*abundant freshwater resources*" (Water Supply and Waste Water Sector Plan | Scottish Environment Protection Agency (SEPA), 2019) water systems face challenges due to their multiple competing uses and the "wicked problems" associated with water management. Scotland's water is used for various purposes, including public water supply, agriculture, aquaculture, energy production (e.g., hydroelectric power), recreation, and environmental conservation (Visser-Quinn et al., 2021). Balancing these diverse demands while ensuring sustainable use presents significant challenges, particularly as climate change and human activities exert increasing pressure on water availability and quality.

The wicked problems of water management in Scotland stem from the complex interplay of social, environmental, and economic factors. For example, agricultural practices can lead to nutrient runoff, affecting water quality, while hydropower development can alter river flow regimes, impacting ecosystems and fish migration. Additionally, conflicting stakeholder interests—such as the needs of urban water consumers versus rural agricultural users—complicate decision-making. Climate change further exacerbates these challenges, as shifting precipitation patterns may lead to periods of drought or intense flooding, increasing the difficulty of managing Scotland's freshwater resources equitably and sustainably. These complex issues highlight the need for integrated approaches to water governance that consider the interdependence of various users and the long-term resilience of water systems.

Climate change poses new challenges to water security in Scotland. SEPA warns that rising temperatures and changing precipitation patterns could lead to more frequent and severe droughts, particularly during summer months (SEPA, 2019). These drier conditions may strain water supplies, affecting agriculture, energy production, and ecosystems, despite Scotland's overall reputation for wet weather.

2.2.2 Water usage and management within Scotland

Understanding water usage and management in Scotland is crucial for contextualising the decision-support tool and its application within the case study. By analysing water consumption patterns across various sectors, including the aquaculture industry, and integrating these with rainfall models specific to Scotland, a clearer picture of the industry's challenges can be drawn. This focus not only highlights the complexities of balancing resource demands but also underscores the need for effective planning tools. These insights are further explored and modelled in Chapter 4, providing a detailed analysis of the results.

Allan et al. (2020) investigate the ramifications of climate change scenarios on water availability for industrial purposes in Scotland. This research identifies potential economic challenges currently faced by industries, within Scotland as the value of water may change over time and calls for the need for developing climate-ready water policies.

Running waters have historically been among the most anthropogenically impacted ecosystems, serving as critical resources for human settlement, providing water, irrigation, electricity, and waste disposal (Malmqvist & Rundle, 2002). Scottish rivers and lochs host a wide range of wildlife, including species of importance to aquaculture, such as Atlantic salmon and rainbow trout, the latter being the primary trout species farmed in Scotland.

The United Nations' Millennium Ecosystem Assessment distinguishes four categories of ecosystem services: provisioning, regulating, supporting and cultural (MA, 2005). There is some critics of the MA (2005) report such as Marzec (2018) who claims that the MA is based on scenarios which arose during the time of the cold war, therefore are no longer valid. While this is the case, the service definitions are widely used and recognised in papers such as Fisher et al. (2009); Martnez-Harms & Balvanera (2012); Raudsepp-Hearne et al. (2010), for more intricate uses other alternatives have been suggested such as Boyd & Banzhaf (2007); Fisher & Kerry Turner (2008).

The MA (2005) defines the four services as provisioning Services are the products obtained from ecosystems. Regulating Services have a role in regulating the local, or wider, environment. Cultural Services are non-material benefits that people obtain from ecosystems which often hold intrinsic value, supporting services help increase the value of other services. Supporting services, which support other ecosystem services.

Groundwater underpins Scotland's private drinking water supplies and provides reliable strategic public water supply to many rural towns, providing 73% of Scotland's private water and 5% of public water supplies. Groundwater contributes 725Ml/d (Mega litres per day) with 240Ml/d being used in

agriculture, 235Ml/d in public water supply, 210Ml/d in industry and 40Ml/d as private water supply (O Dochartaigh et al., 2015). Groundwater sustains the Scottish very profitable whisky industry and is relied upon for irrigation by many farmers (O Dochartaigh et al., 2015). Groundwater also provides many important environmental functions, providing at least 30% of the flow in most Scottish rivers, and maintaining many precious ecosystems (O Dochartaigh et al., 2015). Lochs around Scotland provide cultural services such as recreation, water sports, and hiking and many hotels and villages are based around summer tourism, (Brazier et al., 2017). Another prevalent use of lochs not mentioned within Brazier et al. (2017) is the use of aquaculture pens within lochs. Other cultural services of lochs include symbolic values which are a source of pride for much of Scotland, these include the Loch Ness Monster and Kelpies having great intrinsic value, both contribute to the economy of Scotland through tourism (McKean et al., 2017), although this value is difficult to quantify as a monetary sum. The primary use of Scottish reservoirs falls under 'provisioning services' created for use as a water supply (Reservoirs | Scottish Environment Protection Agency (SEPA), n.d.). The only notable other use of reservoirs is for hydroelectric power, with Cruachan being currently the largest in Scotland (Beer et al., 2018). That said, following the severe floods of December 2015, Scottish Water is now exploring further opportunities for using their reservoirs for flood attenuation as a regulation service (Hurford et al., 2017).

Within the UK, all agencies which monitor the abstraction of water are required to have a water resource management plan (WRNP). The latest WRNP laid out by Scottish Water (Scottish water, 2015) aims to set out a resilience plan that will allow Scottish Water customers to have potable and palatable drinking water until 2040. By balancing the yield from water sources and the abstraction limits it is hoped that the WRNP achieves this goal. The WRNP assesses vulnerability to climate change up to the year 2040, stating that as many as 45% of their customers could be impacted with worst case scenarios. The report notes that due to the high level of uncertainty surrounding scenarios, more information is needed to improve the current levels of understanding of the potential impacts, reinforcing the need for the created decision-support tool to handle uncertainty.

Adaptation to water-related risks and impacts are paramount. For inland flooding, combinations of non-structural measures like early warning systems and structural measures like levees have reduced the loss of lives (IPCC, 2022). Enhancing natural water retention such as by restoring wetlands and rivers, and land use planning such as no-build zones or upstream forest management can further reduce flood risk (IPCC, 2022). On-farm water management, water storage, soil moisture conservation and irrigation are some of the most common adaptation responses and provide economic, institutional, or ecological benefits, reducing vulnerability. Irrigation is effective in reducing drought risk and climate impacts in many regions and has several livelihood benefits

however to avoid potentially adverse outcomes, including accelerated depletion of groundwater and increased soil salinization, appropriate management is needed (IPCC, 2022). Large-scale irrigation can also alter local to regional temperature and precipitation patterns, including both alleviating and exacerbating temperature extremes.

Global and national action will determine the outcome and severity of the impacts of climate change, but when considering the impacts of climate change on aquaculture we must also investigate water use legislation, what determines limits, and the consequences for breaching these laws. Abstraction activities are authorised under the *Water Environment (Controlled Activities) Scotland Regulations 2011*. The regulations include a duty to use water efficiently. SEPA is the main body that controls environmental legislation within Scotland, together with Scottish Water it lays out how blue and green water sources can be used, how they must be monitored, as well as planning for some of the potential impacts of climate change. One of the methods that SEPA uses is a custom drought and flow index, calibrated for use within Scotland created by Gosling et al. (2012). This drought index was tested against other drought indexes and flow indexes to predict potential droughts. Some of the actions also have associated activities such as stop notices and reducing the amount operators can abstract and scheduling, these actions should be considered and planned for within our decision-support system. The drought and flow index was created by SEPA, for use within SEPA to fit their needs, since our study area is Scotland, and we anticipate that it will be a valuable resource. Gosling, (2014) demonstrates a method of combining indices of drought with projections of future climate and hydrology, to produce an indication of the potential change in drought vulnerability in Scotland. Attempts at producing a common definition of drought are fraught with difficulties due to the entanglement between cause (lack of precipitation) and effect (the socioeconomic or environmental impacts). Redmond (2002), for example, defines drought as occurring when there is 'insufficient water to meet needs' whereas the European Commission (2007) makes the distinction between drought – a natural phenomenon resulting in a temporary decrease of the average water availability, and water scarcity – a situation where insufficient water resources are available to satisfy long-term average requirements, in which supply and demand are both relevant. By knowing how SEPA defines and mitigates drought, creating a decision-support system which accommodates these factors is plausible. We must also consider Scotland's National Water Scarcity plan (SEPA, n.d.) gives more detailed guidelines on how the country plans to deal with potential drought. With the actions laid out within the plan anything above "early warning" would potentially involve consideration, with these outcomes becoming more prevalent in future scenarios this should be considered during the planning of an expansion of new business – such as finfish freshwater aquaculture.

2.3 The aquaculture sector and risk management

Freshwater aquaculture is commonly defined as the growing of finfish and shellfish within freshwater. Freshwater finfish aquaculture primarily involves the cultivation of salmon and rainbow trout, which is the dominant trout species farmed (SEPA, 2018).

2.3.1 The aquaculture sector in Scotland

Scottish salmon is the UK's top food export, fetching £581 million in international sales in 2023, despite Brexit challenges. It's also the UK consumers' favourite, generating around £1.2 billion in retail sales yearly. A recent decision (2024) by the Department for Environment, Food and Rural Affairs (Defra) will soon grant "Scottish salmon" a protected geographical indication (PGI) label marking its quality and origin. This move is expected to boost the prestige of Scottish salmon further (Scottish Salmon - GOV.UK, 2024; Scottish Salmon Protected Status Comes into Force, 2024).

 While the global aquaculture industry is dominated by species like tilapia and catfish, Scotland's aquaculture is uniquely focused on salmonids due to its climatic and ecological conditions. This highlights the need to contextualise Scotland's aquaculture within the national framework, as global-scale observations often do not translate effectively to local operations.

Within Scotland there are 47 freshwater aquaculture sites located either directly on lochs in permeable cages, or in facilities which use heavily treated pumped water from local rivers. These facilities can contain hatcheries, tanks, raceways, or ponds. All use large quantities of water, often competing with agriculture for limited water in places which suffer from scarcity, loch cage sites use large quantities of water indirectly, as the lochs themselves provide natural water exchange and dispersal for waste, rather than competing directly with agricultural uses.

The aquaculture industry is expanding; the Scottish Government aims to double the economic contribution of the sector from £1.8 billion in 2016, to £3.6 billion by 2030 and to double the number of jobs to 18,000 by 2030 (Aquaculture - Gov.Scot, 2017). In the context of a changing climate, such expansion emphasises the need for risk management. Whether growth of the sector increases water demand depends on whether the expansion focuses on land-based freshwater facilities or marine-based systems, or whether more water-efficient technologies such as recirculating aquaculture systems (RAS) are adopted. A systematic risk appraisal could inform appropriate development pathways

2.3.2 Water-related risks to aquaculture within Scotland

The potential risks to the aquaculture industry caused by climate change are laid out by FAO (Food and Agriculture Organisation), (a global organisation) and SCCAF (Scotland Climate Change Adaptation Framework). For the in-situ cages this includes:

- Can increase in the risk of flooding may cause an increase the chance of fish escapes, which has been shown to impact wild fish populations (Climate Ready Scotland: Climate Change Adaptation Programme 2019-2024 - Gov.Scot, 2024).

- Potential increase in disease in aquatic animals, although the temperature is known to be a key factor there is a large amount of uncertainty around the exact correlation (*Climate Ready Scotland: Climate Change Adaptation Programme 2019-2024 - Gov.Scot*, n.d.).

- A potential increase in the dilution of microplastics because of rising water temperatures (Duarte et al., 2016).

It is important to note that other freshwater facilities, such as recirculating aquaculture systems (RAS), raceways, and tank-based systems, are also significant contributors to the industry and should not be overlooked. While heavily filtered water may mitigate some climate-related risks, these systems are not entirely immune, as filtration systems can become strained, and biosecurity issues remain a concern. For example, one facility identified uses 190 1m³ tanks and several 4m³ tanks, each requiring a constant supply of clean freshwater (*Scotland's Aquaculture | Site Facilities*, n.d.).

The preceding sections (Sections 2.3.1 and 2.3.2) have highlighted the vulnerability of the aquaculture industry to climate change, particularly with respect to water-related risks such as flooding, temperature increases, and water borne disease outbreaks. As such, there is necessity for a comprehensive DST to assist stakeholders in managing risks and enable informed decision-making in the face of climate uncertainty. The preceding discussions in this Chapter have outlined the parameters of this tool, focusing on its potential to integrate diverse perspectives and foster collaboration among multiple stakeholders, including regulators and industry representatives. To explore this topic further, it is essential to address why such a tool is indispensable in mitigating the water-related vulnerabilities faced by aquaculture. We must also examine its advantages and constraints, as well as the key considerations for its development, ensuring that the tool is both practical and effective in supporting the aquaculture industry's adaptation to climate change. Given the complex regulatory environment and the wide array of stakeholders involved, there is a clear and pressing need for a collaborative and coherent strategy, which will be explored in the forthcoming sections.

2.4 Decision science for climate action and climate resilience

2.4.1 The need for decision-support tools within climate adaptation

Opting out of risk assessment in a high-stakes environment is not a luxury we can afford. A DST empowers stakeholders to make better-informed decisions by offering insights into various factors, outcomes, and potential choices. DSTs vary widely in complexity and scale; even a straightforward flow diagram can serve as a rudimentary yet effective decision-support tool. As the complexity of the issues grows – often turning into wicked problems, so does the complexity of the DSTs required. Although used in a wide variety of sectors, DSTs are prominent within climate adaptation where DSTs are utilised for supporting many types of decisions, such as geospatial modelling (Knight et al., 2015), spatial mapping between hazards (Gudiyangada Nachappa et al., 2020) and vulnerability exposures (Best et al., 2021). Although it has been shown that decision makers prefer more basic tools, there is a need for more complex tools (Wong-Parodi et al., 2020). More complex tools allow for the integration of uncertainty which arises through the complex nature of how the environmental system is interacted with (Wong-Parodi et al., 2020).

While DSTs are often applied to small-scale projects it is not rare for regional, national, and international DSTs to be employed. Czimber & Gálos, (2016) created a DST on a national scale in Hungary to allow stakeholders to analyse the impact of climate change on the forestry and agriculture sector. Torresan et al. (2016) utilised DESYCO, a decision-support system which encourages climate adaptation planning through global information systems at a regional or national scale.

When developing a DST, the main aim is to increase 'decision quality' when compared with a baseline of not using the DST (Perimenis et al., 2011; Ribeiro & Antunes, 2002; Wilby et al., 2002). Therefore, in theory, if a DST increases 'decision quality' it can be deemed as 'successful' (Wilson & Arvai, 2006). In practice, it is a much more complex criterion. Simply defining decision quality is elusive, (Wilson & Arvai, 2006). Wilson & Arvai (2006) p. 1, state *"it is difficult—if not impossible—to identify an ideal course of action before a decision needs to be made and then compare a decision maker's final choice against this benchmark"*. Moreover, with uncertainties, it is possible to make decisions with theoretical good 'decision quality' which produces bad outcomes and vice versa. Although DSTs are widely utilised, they still have limitations such as lack of user support, insufficient training resources, and time to use and access to the DST (Wong-Parodi et al., 2020a).

With so many DSTs available, finding one which suits a projects needs can often be difficult. Walton, (2020) states a limitation of decision-making is the relationship between increased complexity of the understanding of the problem leads to a need for more information, which can lead to a decline in

information quality, and proposes integration with information evolution to circumvent this issue, tying back to the earlier classification of the case study as a wicked problem. Environmental management specific limitations vary with the DST in use, when working on weed management, Kanatas et al. (2020) found; lack of expert knowledge, a refusal to learn new technology and different expectations from the tool, to be the main limitations. Pınarbaşı et al. (2017), reviewed 34 DSTs for usage in marine spatial planning, and concluded that the main limitation of tools was limited functionality, many of the tools assessed could perform one function, such as communication, and assessment of environmental impact or economic analysis. While there are no perfect formulae for a DST the limitations can be softened. Acknowledging the primary limitations when creating a DST leads to a more robust tool. Wong-Parodi et al, (2020) proposed the following six stages to reduce limitations (1) clearly define goals, (2) identify alternatives, (3) obtain relevant information, (4) articulate values, (5) evaluate alternatives, and (6) monitor outcomes. These steps do not however bypass all limitations and effort must be undertaken to limit the subjectivity of experts, making the tool versatile, having clearly defined tool usage, testing expert knowledge, and working with decision-makers to make sure the proposed tool fits their needs and is of a suitable technological level.

Despite limitations, DSTs have seen success in many environmental management projects. (Van de Broek et al., 2019) used a DST to show the climate regulation potential of soils. Using soils for carbon storage reduces atmospheric greenhouse gasses. An important aspect to highlight in this study is the quantifiable effect the DST had. As mentioned previously in section 2.4, assessing the impact of a DST can often be difficult. This experiment compared the results against long-term field experiments, for carbon sequestration, the decision model correctly predicted 11 out of 14 control treatments. Further, Garcia-Gonzalo et al. (2014) proposed a DST to increase the effectiveness of forest management, when faced with climate threats within Portugal. Using the proposed DST to design optimal management techniques the area they concluded that if the DST would have been used in the chosen case study area previously the potential wood supply would have increased to 2.35 from 2.19 million m^3. The land value would have increased to €81.1million from €74.7million and the carbon stock increased by 16 tons (212 to 228). These studies, and more, show that although difficult, it is possible to quantify the 'effectiveness' of a DST when used in environmental management through verification methods. Verification can help determine the effectiveness of a DST for some projects, however with many climate impact-related projects this can often be difficult due to uncertainties surrounding future climate scenarios. Osman et al. (2019) used climate change modelling integrated into a DST for determining water resource-based decisions within Iraq. Using a DST which integrates rainfall, runoff and evapotranspiration to help management strategies. To

verify this data the model used historical data, concluding the DST could provide significant benefits to water management.

It is possible to expand a DST when data isn't available by integrating expert knowledge into DSTs. Tothela et al. (2020) used a mixed approach utilising local farmer knowledge to create a DST to manage sub-Saharan agriculture. Due to the ongoing influences of climate change and desertification, it was found that expert knowledge was semi-reliable. By integrating this indigenous knowledge with a data-based approach a successful DST was created. The Tothela et al. (2020) study also shows a fundamental issue of expert knowledge, which is that knowledge may become redundant as the environment changes, highlighting the need for verifying expert knowledge.

Sufficient DSTs are employed in environmental adaptation, addressing complex challenges often regarded as wicked problems. Leveraging examples from the case study categorised as wicked problems allows us to settle this criterion for the DST, enabling us to shift our focus to the next challenge for DSTs: effectively managing uncertainties.

2.4.2 **Handling uncertainty within decision-support tools**

As problems expand so do their complications, and it becomes increasingly difficult to have all the required information to make an informed decision. This problem is exacerbated further when the problem involves future scenarios, such as climate change impacts. We label these unknowns as uncertainties, which obfuscate both risk management and decision-making (Rowe, 1994). Most risk decisions carry some level of randomness, therefor decision-support tools should be able to account for uncertain judgement (Kjaerulff & Madsen, 2017). Probability theory is the current prevailing theory of assessing uncertainty, with fuzzy theory and belief theory being the two other widely accepted theories. Probability theory uses the concept of probability and assigns a statistical report of the likelihood of a selected event happening. This can be calculated by dividing the change of total events by the change of the desired event. Probability theory, as well as fuzzy and belief theories, can be reported within Bayesian Networks (Kjaerulff & Madsen, 2017).

Bayesian Networks (Box 3, Chapter 1) are a decision-support tool that provides probabilistic relativity for qualitative assertions about likelihood (Mersha & van Laerhoven, 2018)**.** The ability of Bayesian Networks to quantify uncertainty, learn causal effects from observational data and present themselves in a user-friendly interface means its gained traction in many industries (Scutari & Denis, 2018).

Bayesian Networks are comprised of two parts the graphical representation known as the Directed Acyclic graph (DAG) and the Conditional Probability Tables (CPT), figures showing DAGs and

corresponding CPTs will be shown in Chapter 5. A DAG consists of **nodes** and **arcs**, **nodes** are nearly always discrete, but can on occasion be continuous (Zhang & Thai, 2016). Discrete nodes can fall into three categories: Boolean, Ordered or Integral. The values of Boolean nodes are binary, being either 'True' or 'False', the ordered value nodes may take several values, for example, the node 'Water Quality' may take the value of 'high', 'medium', or 'low'. Integral values, in contrast, may take more than a hundred values (Kjaerulff & Madsen, 2008). The other part of DAGs, **arcs**, show dependence, with one node being the 'parent' node and the other the 'child' node, naturally the 'child' node is dependent on the 'parent' node, and one 'parent' node may have multiple child nodes, and vice versa. (Zhang & Thai, 2016). The foundation for DAGs is the CPT. These conditional probabilities could be calculated using statistical, computational methods, known as data mining, or elicited from domain experts (Ben-Gal et al., 2007). Data mining is the process of examining previously constructed large databases for data that outline trends and linkages for processes occurring within the Bayesian Network.

A Bayesian Network can be 'expanded' upon, to form a Casual Influence Diagram (CID), these have the same functionality as a Bayesian Network but allow for incentives of the stakeholder (referred to as agents) to be explored. CIDs achieve this by incorporating two new types of nodes, decision, and utility nodes. Decision nodes allow an agent to set decisions which influence other nodes, these are manually changed, and parent arcs are displayed as a dotted line to represent this. Utility nodes place a quantitative assessment on selected desired outputs, such as cost, space, time, and environmental impact.

The use of Bayesian Networks and CIDs is prevalent in environmental decision-making, as previously discussed, (Laurila-Pant et al., 2019) incorporated stakeholders into their CIDs (although described as BNs the graphs used should be classed as CIDs). The usage of BNs as a DST for water management has also already been established. Phan et al. (2019) perform a critical appraisal of using BNs within water management to soften the impacts of climate and socio-economic issues. Phan et al. (2019) concluded that BNs have a strong potential within decision-making, however, for water management there are limitations. The two primary limitations stated are the depth of expert knowledge and concern over quantitative calibration and validation, both limitations which have been previously acknowledged and will be considered within the construction of the DST. Further, BNs have been used to integrate climate predictions into fish population management. Peterson et al. (2013) acknowledge that dealing with climate projections is becoming increasingly abundant when planning and using fish population decision-support tools, finding the created BN beneficial for management decisions. A DST using BNS or CIDs as its foundation would both excel at dealing with wicked problems and handling uncertainties. Most studies using BNs and CIDs within environmental

management focus on a single stakeholder. In contrast, Laurila-Pant (2019) uses two models to provide a multi-stakeholder perspective. The inclusion of multiple stakeholders within the Laurila-Pant (2019) study was shown to be of benefit to DSTs, further, it was one of the three criteria set out when categorising the case study problem, and therefore there is reason to believe the DST we create would also benefit from multiple stakeholders and a multiple perspective view.

In summary, drawing from current decision-making science, the key considerations for our DST are as follows:

1. Decision-making becomes increasingly complex with uncertainty (Rowe, 1994), particularly for future scenarios like climate change.
2. Probability theory, along with fuzzy and belief theories, can quantify uncertainty, though challenges exist in expert knowledge requirements and calibration (Quigley et al., 2018).
3. Incorporating multiple stakeholder perspectives can improve decision-support tools, making them more effective in handling complex problems (Laurila-Pant et al., 2019).
4. Currently, while decision-support tools such as Bayesian Networks and Causal Influence Diagrams are widely used in topics such as environmental and water management (Laurila-Pant et al., 2019; Peterson et al., 2013) no suitable tool exists for multi-stakeholder decision-making under uncertainty.

2.5 The value of the multi-perspective view

Stakeholders may differ in expectations and interests. Simon (1973) suggests that a key component of problem-solving is to expand the problem, including as many facts and assumptions as is reasonable. Viewing the problem from a different lens, may show that stakeholder priority lies elsewhere. Being able to view the decision from multiple perspectives enhances the decision-maker's ability to make better-informed choices (Hall & Davis, 2007). Discrepancies, however, are likely to occur in the interpretation, particularly in a complex domain where stakeholders may not come from similar backgrounds (Hall & Davis, 2007).

2.5.1 Multi-perspective views in literature

Robertson et al. (2000) discuss the use of multiple perceptions when considering the restoration of ecosystems within Australia. They argued that when considering an environmental issue, such as the potential impacts of climate change, multiple perspectives are needed to integrate biophysical and cultural impacts. By integrating multiple perspectives, a full view of environmental attributes, beliefs, values, and how a sense of loss of these attributes affecting the stakeholders can be achieved. This highlights multi perspectivity as practical means of integrating biophysical and cultural considerations. Unlike the problems faced by climate change, this article only considers the

environment from a purely ecological viewpoint, this may not be possible with the potential economic loss that comes with the degradation of water ecosystem services. As such more inclusive perceptions will be needed to build a holistic decision framework, that can provide solutions to satisfy the full range of perspectives on a valued and shared resource.

When considering modelling multiple stakeholder preferences, it is possible to allow for compensation between alternatives solutions, creating a scenario in which decisions incorporate the values of multiple stakeholders. Whilst this solution can be effective it often can be associated with a providing not the most desirable outcome for the majority of stakeholders (Soltani et al., 2015).

Bohnenblust & Slovic (1998) argue that risks perceived by society and by individuals cannot be captured by simple technical analysis, and decision-making needs to account for both technical analysis and public values.

2.5.2 Incorporating multi-perspective views into decision-support tools

Incorporating multi-stakeholder views into decision-making is becoming increasingly prevalent. Panneer et al. (2021) showed the potential of multi-perspective risk analysis on a large scale by applying a multi-perspective scope to COVID-19 risk management. Thabrew et al. (2009) state that many sustainability targets face problems due to difficulties achieving multi-discipline stakeholder consensus. This ultimately leads to complications and highlights the need for a decision-support tool which can represent the views of multiple disciplines. Hämäläinen et al. (2001) assessed a framework for integrating multi-stakeholder decision-support into water management, this framework shares one of the models from the framework of (Laurila-Pant et al., 2019). It should be noted however that Hämäläinen et al. (2001) lack the usage of BNs, the framework was semi-successful and did not see much widespread use thereafter.

Researchers have continued to attempt to integrate multi-stakeholder perspectives within DSTs. Hettinga et al. (2018) which used a multi-stakeholder approach for theoretical spatial planning of low carbon energy using The Hague as a case study. The authors commented that a facilitator was vital for this approach to be successful, which may be applicable within our own DST creation. Rehr et al. (2012) used a multi-stakeholder approach for coral reef conservation with success within the Florida Keys, which used government agencies, regulated businesses, non-government organisations and other key stakeholders to create a coral reef restoration plan, using outside expert knowledge when required.

Laurila-Pant et al. (2019) aimed to incorporate stakeholder views within a Bayesian Network. The study recognises that decision-making is often a coalition between many parties, and this is hard to

represent within current tools. The study sets out a methodology of using Bayesian Networks with multiple stakeholders using multi-criteria decision analysis. Laurila-Pant et al. (2019) lay out a foundation for incorporating multiple stakeholders into a decision-support tool, which can be improved upon. There is a growing need for multi-perspective DSTs which is being recognised by the influx of literature within the environmental sector. The uncertainty posed by climate change requires a tool that can both integrate multi-perspective judgement, and handle uncertainty. A tool which achieves both these aims would excel within environmental risk management, this is the basis of our decision-support tool, which takes its foundation from multi-agent influence diagrams.

2.6 Multi-agent influence diagrams

Koller & Milch (2003) proposed a new method of representing general multi-plater noncooperative games – multi-agent influence diagrams (MAIDS). Koller & Milch, (2003) states that influence diagrams have been primarily investigated in a primary agent setting. The proposed representation (MAIDs) builds upon the base of existing graphical models - BNS and CIDS. MAIDS extend BNs and CIDs further to a multi-agent decision-theoretic setting. Within Koller & Milch, (2001) MAIDs are set out within the context for use within game theory. Koller & Milch, (2003) further expands upon the use of MAIDs within game theory. MAIDs can be described formally as "*begin with a set A of agents. The world in which the agents act is represented by the set X of chance variables, and a set of decision variables for each agent a $\in$ A. Chance variables correspond to decisions of nature, as in the Bayesian Network formalism*" (Koller & Milch, 2001, p. 11).

Although the idea of MAID was initially proposed in 2001 it has not been deeply investigated outside of the field of information systems (Liu et al., 2010; Zeng et al., 2012, 2016) or game theory (Chan et al., 2016; Hammond et al., 2021; Jiang et al., n.d) and remains a novel front for future research within environmental management and decision making. With BNs and CIDs becoming more prevalent within environmental management, the next logical step would be for MAIDs to be considered, and a framework devised. MAIDs ability to represent multiple stakeholders, something which has shown to be an asset, will allow them to excel within the field. Moreover, MAIDs effectively manage uncertainty, drawing on Bayesian Networks to tackle wicked problems.

In essence, MAIDs provide the foundational elements for constructing a DST applicable to finfish freshwater aquaculture. However, there is currently no established framework for deploying them in this manner. The development of such a framework could enable the versatile application of the DST to address analogous challenges.

Chapter 3 The SEAD method of risk analysis.

This Chapter provides the process of the creation and justification of the SEAD (**S**takeholder identification, **E**licitation, **A**nalysis, **D**ialogue) method. This is achieved through detailing the creation process of the SEAD method which justifies the choices throughout, a detailed description of applying the novel SEAD method for supporting the development of MAIDs (Multi-Agent Influence Diagrams) to perform risk analysis and a discussion which evaluates the SEAD method.

MAIDs were originally proposed within the field of game theory (Koller, 2001). However, their use outside this context has been limited, and they have not yet been applied to real-world risk analysis. Consequently, no framework currently exists for adapting a MAID to real-world scenarios and utilizing the resulting structure for decision-making—a gap that Chapter 4 seeks to address. While the SEAD method is novel, it is grounded in established, peer-reviewed processes such as the Delphi method, Cooke's elicitation, Bayesian Networks, and the Ping-Pong method, all of which are discussed in this Chapter. Rather than introducing entirely new techniques, SEAD integrates these decision-support methods to strengthen its approach. The SEAD method emphasises justifying the recommended methodologies while also providing alternative techniques in cases where the primary recommendations are unfeasible or undesirable.

3.1 Stakeholder roles and identification within the SEAD method.

The ability of MAIDs to quantify stakeholder perceptions through utility nodes positions agents as central to the decision-making process. In this thesis, the term "stakeholder" has been used for familiarity. However, during the development of the SEAD method, it became necessary to refine this terminology. The SEAD method distinguishes between different types of stakeholders based on their roles within the framework, as outlined in Table 3.1. Subsequent Chapters will adopt terminology aligned with this differentiation.

Within the SEAD method, each of the three nodes (Chapter 2) is associated with a specific type of agent responsible for contributing to that node, as detailed in Table 3.1. The term "agent" broadly encompasses all participants, regardless of whether they fulfil one or multiple roles within the process. See Section 2.4.2 for detail on nodes, arcs, and other specific terminology.

Table 3.1 *Terminology of roles within the SEAD methodology.*

Contributes to the node	Chance	Utility	Decision
Expert	X		
Stakeholder		X	
Decision maker			X
Agent	X	X	X

These terminologies will often overlap, as many stakeholders within the model will also be decision-makers, experts, or all three. Identification of differing roles uses differing techniques, and when seeking agents who align with more than one classification, more than one technique may be required.

3.1.1 Expert identification

"What constitutes an expert?" Bolger (2018) offers a methodical approach to identifying experts for elicitation. By first considering the multiple definitions of an "expert", Bolger, (2018) uses a similar method to Alvarado-Valencia et al. (2017) which distinguishes between *a priori* indicators of expertise and on-task measures. Bolger (2018) instead classifies these as "indicators", information that can be accessed about the expert before approaching and "measures" which work as tests of expertise once potential experts have been identified. Bolger (2018) states these as substantive, normative, and social expertise. Substantive expertise is expertise based on knowing about the domain in question, this may include formal qualifications, training courses, job experience and quality of published papers. Normative expertise refers to formal, abstract ways of expressing domain knowledge, although expressed differently when searching for an expert, this may involve similar identifiers as substantive expertise (Bolger, 2018). Finally, there is social expertise which is translated to job titles or positions.

All three expert identification techniques could be suitable for SEAD method depending on the application. Substantive was however chosen to be the technique for SEAD, the indicators for substantive make experts simple to identify. Nonetheless, using either normative or social expertise is not expected to negatively impact the process. It is important to bear in mind that new agents might emerge during the SEAD process, i.e., new experts are required as the structure expands. As such, t the SEAD method allows for adding more agents was included at several key points throughout the process.

3.1.2 Stakeholder identification

Several stakeholder identification techniques were considered, such as formal stakeholder mapping exercises. While these can still be integrated into eliciting of agents it was decided to not include them within the main SEAD method to keep the method streamlined and avoid convolution. In this work we engaged with directly impacted stakeholders - however the SEAD method has the capacity to handle larger stakeholder groups, such as the lay public. A specific methodology for identification and elicitation for these groups will not be included within this work.

3.1.3 Decision maker identification

There are few established methods for identifying decision makers, so the SEAD method instead recommends relying on the judgement of experts and stakeholders already identified. This means that initial identification of decision makers will happen later.

3.1.4 Agent order of contact

The application of SEAD requires bringing in all three participant categories. The order of inviting to participate the participants needed to be considered. Some of the methods for discovery, such as stakeholders, could benefit from expert knowledge. While decision-makers and stakeholders (which often are the same agents) may already be known depending on the application. If, after consulting with agents these roles are not known, then expert knowledge is needed, leading to the recommended order of operations set out below. Therefore, when setting a method for stakeholder identification the SEAD method states:

1. Use prior knowledge and resources to contact stakeholders and decision-makers.
2. Contact experts.
3. Use participating agents' knowledge to elicit other desired stakeholders and decision-makers.
4. Repeat step 3 until agents are satisfied.

3.1.4 Pre-elicitation agent requirements

SEAD involves the elicitation of information from agents, therefore an anonymity plan is highly recommended. This should include the level of anonymity between agents, and circulation of data. This may vary on an individual basis, and looser anonymity between agents may be required if the chosen dialogue is a roundtable.

To accommodate anonymity while allowing SEAD to correctly function we recommend the following:

1. All agents are recorded as a number, and a short description of role/expertise, which cannot be used to identify the agent.

2. In all documentation, except from the final dialogue (Step 4), participants were referred to simply as 'agent' followed by their number.

3. During elicitation and dialogue first names are to be used if desired. If agents request a different level of anonymity this should be discussed and accounted for.

Before elicitation can begin, many suggested methodologies require training (to ensure the agent understands their role) including the classical method (Colson & Cooke, 2017). The training schedule recommend by SEAD can be seen in Appendix B: Full sized images from Chapter 4. In summary, training is split into four major categories: General, Stakeholder, Decision maker and Expert. With some agents satisfying multiple roles, this sets out a template that is easily adaptable to each agent. Thus, allowing agents to receive targeted training and maximising the time-to-effort ratio.

3.2 Methods of structure building

The structure for the decision-support tool is comprised of two main objects: nodes and links, of which there are different types (see Section 3.3). Prior to this study, MAIDs had been applied to problems where the objects were already known (Koller & Milch, 2001). For our research case study, the objects were not already known - therefore we needed to develop a robust approach to build the model structure. The SEAD method depends on agent elicitation to construct the structure.

SEADs capacity to quantify preferences led to the placing utility nodes at the centre of the structure. Therefore, when deciding what order the structure would be completed eliciting utility nodes was the priority, then building the structure from this point. The full methodology will be covered in Section 3.3 – using the SEAD method.

The first published elicitation framework is the Delphi technique (G. Rowe & Wright, 1999). Developed for the United States Air Force, the Delphi model is built on the foundational principle that "*two heads are better than one*" (Dalkay, 1969). The Delphi technique has three stages: (1) Anonymous formal questionnaires, (2) iteration using controlled feedback, which may be repeated multiple times, and (3) statistical group response to remove bias of any dominant individual opinions. Various issues are associated with the DELPHI technique (Shields et al., 1987). For example, the Delphi technique relies on a series of iterations, and yet smaller numbers of respondents return questionnaires at each iteration. Rowe & Wright (1999) analyse the use of the Delphi technique for forecasting and conclude that accuracy tends to increase with every iteration, and that Delphi techniques produce more accurate results than forecasts derived from unstructured discussions.

Roundtable discussions were the other structure building option considered. Roundtable discussions offer the advantage of fostering open dialogue and immediate feedback, which can enhance creativity and group cohesion. However, they can also be hindered by dominant personalities, lack

of structure, and scheduling conflicts. In contrast, the structured process provided by the Delphi technique was preferred for its ability to mitigate these issues. Moreover, the structured nature of the Delphi technique enhances the reliability and consistency of the elicitation process, ensuring a more robust and dependable outcome.

3.2.1 Methods for collecting data for conditional probability tables through elicitation

Elicitation to populate Conditional Probability Tables (CPTs; see Section 3.4) and utility nodes already have pre-established methodologies that can be directly substituted within the SEAD method. For CPTs, the prominent methodologies are the classical mode (Cooke, 1991), Shelf (Gosling, 2017) and IDEA (Hemming et al., 2018). Methods for eliciting utility nodes include the Ping-Pong method, and titration up and titration down methods (Attema et al., 2013)**.** Each method has advantages and disadvantages, and the ideal method for different circumstances is a subject of debate (Quigley et al., 2018)**.** We make an informed decision on one to recommend during the SEAD method to keep all cases of the SEAD method application standardised, however if another elicitation method is preferred the SEAD method supports this choice. These justifications for the SEAD method choices are laid out in the following sections.

3.2.2 Elicitation methods for data collection – chance nodes.

When eliciting values from experts the issue of bias arises (Kynn, 2008). There are design elements to elicitation processes that can be used to reduce or minimise bias. In addition, facilitators are typically used within elicitation processes to reduce bias and control the extraction of information (Manzi & Forster, 2019). Facilitators use elicitation frameworks which can be split into two categories: performance-based and behaviour-based.

In terms of process design to reduce bias, De Little et al. (2018) reviewed methods of managing bias within expert elicitation on environmental management issues and identified three stages in elicitation processes where bias must be minimised: pre-elicitation, workshop facilitation and output analysis.

To minimise bias within each stage, De Little et al. (2018) recommend the following:

- **Pre-elicitation:** using a pre-formed CPT based on a literature review to fill any holes in knowledge. While doing so may reduce bias, it also may limit the results by tapering the expert judgement.
- **Workshop facilitation:** encouragement to ask for clarification within the workshop facilitation process and to use the uncertainty intervals set out by Spier-bridge (2010), these principles vary from those used within Cooke's model instead (Further explained within this Chapter) choosing

to give the highest realistic value, the lowest realistic value, the most likely value and the probability this range captures the true value.

- **Output analysis:** use multiple iterations and feedback.

In addition to the approaches recommended by De Little et al. (2018), other ways to remove bias for CPT elicitation include:

- Using well-set out, non-leading questions (Whitehead, 2002)
- Using debiasing strategies that lead people to consider values other than the initial anchor for removed anchoring bias (Box 4) (Mussweiler et al., 2000).

Box 4: Definition: Anchoring Bias

A bias that is resistant to debiasing methods which relies on awareness of the effect (Welsh et al., 2006).

Performance-based frameworks are a structured approach that evaluates and enhances the accuracy and reliability of expert judgments by systematically assessing and utilising their predictive performance and calibration (Quigley et al., 2018). One of the most prominently used within elicitation literature is Cooke's classical model (Quigley et al., 2018). Cooke's classical model instead offers a performance-based approach to elicit judgment from the chosen experts. Performance is analysed by assessing the experts against a set of seed questions, known only to the facilitator (Quigley et al., 2018). Performance when eliciting for the CPTs is then weighted according to each expert's accuracy on the seed questions (Quigley et al., 2018). Cooke's model allows for uncertainty within the expert opinion, the experts are asked to give the 5th, 50th and 95th percentile of each answer, and the 5th and 95th percentile create a range in which the expert is 90% sure the true value falls between (Colson & Cooke, 2018). Cooke's methodology will be shown in greater detail in Section 3.3 - using the SEAD method.

The benefits of Cooke's classical method include:

1) Calibration-Based Weighting -experts are weighted based on their ability to provide accurate and reliable information, using calibration questions with known answers. This improves the overall quality of the elicitation.
2) Combines Expert Judgments - uses a mathematical aggregation method to combine expert opinions, aiming to create a consensus that reflects the best possible estimate.
3) Transparency and Rigor - the process is transparent and based on statistical principles, providing a clear rationale for how expert weights are determined.

4) Validation - the method includes a validation step, assessing the performance of experts against known answers, which enhances credibility and reliability (Colson & Cooke, 2017, 2018; Quigley et al., 2018).

The drawbacks of Cooke's classical method include (Colson & Cooke, 2017, 2018; Quigley et al., 2018):

1) Complexity - the method is mathematically complex and can be challenging to implement without significant expertise in statistical methods.
2) Time-Consuming - requires substantial time and effort to develop calibration questions, conduct the elicitation, and perform the necessary calculations.
3) Data Availability - the need for calibration questions with known answers can be a limitation in some fields where such data are not readily available.
4) Expert Availability - relies heavily on the availability and participation of numerous experts, which can be difficult to coordinate.

Further, getting seed questions for the Cooke's classical method poses its own problems including:

1) Sourcing reliable data – questions must have known verifiable answers.
2) Finding relevant questions to expert domain.
3) Making seed questions the right level of difficult to differentiate varying levels of expert knowledge.
4) Avoiding sensitive or confidential data (Quigley et al., 2018).

There are recommendations to lessen these challenges including using panels to develop seed questions and pilot testing these questions before the elicitation session.

Behaviour-based frameworks allow a panel of experts to co-operate and communicate information to arrive at a consensus (Quigley et al., 2018). Sheffield Elicitation Framework (SHELF) is the most recognised behaviour-based framework (Gosling, 2018). The SHELF framework varies from the Cooke model by allowing feedback to be incorporated for multiple iterations within the same meeting. Within this, all experts' opinions are weighted equally, instead of being based on a seeded question. Once the exercise specification is determined and the experts selected, an expert group meeting occurs. First, the experts are taught the expert knowledge elicitation process, there is then a phase of information sharing, then individual judgements, distribution and then a discussion. Feedback on the distribution is given at this stage, and the group of experts then considers if this distribution is satisfactory, if not further discussions take place, repeating the discussion and

feedback stage until the distribution is deemed satisfactory. SHELF is also supported by documents, software, and templates to ease the use of the framework (Gosling, 2018).

The benefits of the SHELF method include:

1) Flexibility - more flexible in terms of the type of questions and data it can handle, making it adaptable to a wide range of contexts and disciplines.
2) Structured process – SHELF provides a structured process for eliciting and combining expert judgments, including the use of workshops and interactive sessions.
3) Incorporates expert interaction - encourages interaction and discussion among experts, which can lead to more refined and consensus-based estimates.
4) Usability - easier to use and less mathematically intensive compared to Cooke's method, making it more accessible to practitioners without advanced statistical training (Quigley et al., 2018).

The drawbacks of the SHELF method include:

1) Potential for bias - the interaction among experts can introduce groupthink or dominant voices that might bias the results.
2) Less quantitative rigor- SHELF lacks the strict quantitative calibration and weighting process of Cooke's method, which may reduce the objectivity and reliability of the results.
3) Subjectivity - the SHELF method relies more on subjective judgment and consensus-building, which can be influenced by the experts' own biases and perspectives.
4) Validation - does not have a built-in validation mechanism like the calibration questions in Cooke's method, potentially affecting the credibility of the outcomes (Quigley et al., 2018).

Hanea et al. (2017) proposed a novel elicitation framework termed 'the Investigate Discuss Estimate Aggregate (IDEA) method'. The IDEA elicitation protocol encourages discussion between experts before elicitation. The protocol is laid out as follows: 1) Experts investigate background and causal factors behind the posed question – predicting an outcome 2) Experts congregate and discuss their thinking. 3) Privately, make a second anonymous judgement of event probability. 4) Results of elicitation are aggregated mathematically.

Hanea et al. (2017) combined components of behavioural, and mathematical with mixed methods such as the DELPHI method to produce the IDEA protocol. Stating that debating and sharing knowledge improves knowledge, and using weighting judgements based on prior performance, such as those laid out within Cooke's method.

Hemming et al. (2018) published the first practical application of the IDEA method, sharing all but the primary author with Hanea et al. (2017). Hemming et al. (2018) show that IDEA can be used in a

range of scenarios such as conservation and geopolitical forecasting. While IDEA is a novel elicitation framework, we decided to move ahead with other more established options for inclusion within the SEAD method, due to the lack of primary literature applying the IDEA method. However, as the SEAD method evolves the use of IDEA may be revisited.

When eliciting information, the data elicited can be measured against three criteria: calibration. Accuracy and informativeness (Hanea et al., 2018). Calibration and accuracy are often not chosen as measures of performance together. A low information but high calibration as an example, may occur from performance-based methods, with experts not wishing to state false information, they may instead "cast the net" too wide, incorporating a wide range of values. While this would have high calibration, it would be largely uninformative for practical purposes. On the other end of the spectrum, for the behaviour-based methods, experts may agree on a certain value, which may be false. This would be informative, with low calibration. When considering which framework to use, one must consider what results are desired.

In line with the recommendations of the National Academies of Science, Engineering, and Medicine (NASEM, 2017), we employ Cooke's classical method to elicit chance nodes in the SEAD framework. Cooke's method is widely regarded as a gold standard for expert elicitation due to its robust quantitative rigor, which ensures that subjective judgments are systematically incorporated into the decision-making process. While the method can be more challenging to implement due to its reliance on structured scoring and calibration of expert opinions, its ability to enhance reliability and reduce bias makes it a superior choice for this application. The additional effort required for implementation is justified by the resulting increase in transparency, reproducibility, and overall robustness of the elicited data, aligning with the SEAD method's emphasis on methodological soundness and stakeholder trust.

3.2.3 Elicitation methods for data collection – utility nodes.

When deciding the most suitable elicitation technique for utility nodes the options are limited. Elicitation strategies considered include titration-up and titration-down and the Ping-Pong method (Mohammad & Nakadai, 2019). Titration-up, titration-down and the Ping-Pong method are known as standard gamble techniques (Dolan et al., 1996) the other utility elicitation method is known as the time trade-off method, although as time trade-off utility elicitation is primarily used within the medical field is not well suited for the SEAD methodology. Note that time trade-off would also use a variance of Ping-Pong methodology (Dolan et al., 1996). Mohammad & Nakadai, (2019) assessed the standard gamble Ping-Pong, titration up and titration down method, finding that Ping-Pong on average produced the lowest utility and that all three methods are viable. Wanting to keep a simple

approach that both stakeholder and facilitator could easily use the Ping-Pong method was chosen for use within the SEAD methodology, however, if the facilitator prefers an alternative method they are laid out as options. Due to the average utility difference laid out by Mohammad & Nakadai, (2019), the methodology should remain consistent throughout the SEAD methodology. Full methodology on how to perform the 'Ping-Pong' method will be laid out within Section 3.3 – using the SEAD method.

Utility nodes can either be 'local' scale or 'global' scale. Local scale describes a scale in which the best possible outcome within the options given is the highest value (Braziunas & Boutilier, 2008). By contrast, within a global scale the highest utility is the best possible outcome, though often that outcome is not actually possible (Braziunas & Boutilier, 2008). After consideration of both local and global options for the SEAD method, we decide to recommend a local scale because a global scale would not easily allow evaluation across multiple utilities (Braziunas & Boutilier, 2008).

Utility nodes require weighting, although the scales presented range from 0-1, an agent will prefer one or more utilities. In most applications of utility nodes, a variety of weightings are done (Blavatskyy, 2006). While this was considered, a more elegant solution was proposed. Instead, it was chosen for utility weightings to be built into the SEAD interface, which is provided with the SEAD method, being able to be adjusted within live time. There is an option within SEAD to elicit basic weightings in the form of a ratio, to start the final dialogue with this available.

3.2.4 Summary of chosen elicitation techniques and rationale

Given the complexity and uncertainty involved in many decision-making processes, SEAD was designed to ensure a balance between accuracy, usability, and efficiency. Key methodological choices were made based on their ability to mitigate bias, enhance consensus, and streamline the elicitation process. This summary section outlines the rationale behind selecting specific approaches for specific SEAD components (structure elicitation, CPT elicitation, utility elicitation, and weightings) including why alternative methods were considered but ultimately not chosen.

Structure elicitation: We choose the Delphi method (Benarie, 1988) because it provides a structured, iterative approach to expert consensus, thus reducing the risk of groupthink and dominant voices influencing outcomes. The DELPHI method allows for anonymous feedback, ensuring that all expert opinions are given equal weight. In contrast, the alternative method, group discussion, while valuable for brainstorming, is prone to bias from louder participants, lacks structured iteration, and may not reach a clear consensus as effectively (Krueger & Casey, 2015; Timmermans & Vlek, 1996).

CPT elicitation: We choose Cooke's Method (Cooke, 1991) due to its rigorous approach to aggregating expert judgment and weighting of expert opinions based on their performance in related tasks. Cooke's Method ensures a more reliable and mathematically sound probability assessment. The alternative approaches considered, Sheffield (Quigley et al., 2018) and IDEA methods (Hemming et al., 2018) place more emphasis on expert calibration and group dynamics, which may introduce unnecessary complexity or reduce individual accountability in probability elicitation.

Utility elicitation: We choose the Ping-Pong method (Braziunas & Boutilier, 2008) because it efficiently narrows down utility preferences through a structured back-and-forth process, allowing for rapid convergence on a decision. The Ping-Pong method is intuitive and balances trade-offs effectively. Alternative methods considered include Titration Up (Braziunas & Boutilier, 2008) and Titration Down (Braziunas & Boutilier, 2008). These methods were not chosen because they require a stepwise approach that can be time-consuming and may lead to inconsistencies in user responses, making them less efficient.

Weightings: We choose to integrate weightings directly into the SEAD interface to allow for a streamlined and user-friendly approach, reduce cognitive load on users and ensure consistency in the decision-making process. The alternative - eliciting multiple weightings - would add further complexity by requiring users to assess different weight scenarios, which could in turn introduce inconsistencies and reduce usability (Blavatskyy, 2006).

These choices are summarised in Table 3.2.

Table 3.2: Summary of major decisions for constructing and eliciting the MAID within the SEAD method, including methods chosen and methods disregarded.

	Considered and chosen	**Considered but not chosen**
Structure elicitation	DELPHI (Benarie, 1988).	Group discussion (Nicholson et al., 2022).
CPT elicitation	Cooke's Method (Cooke, 1991).	Sheffield (Quigley et al., 2018), IDEA (Hemming et al., 2018).
Utility elicitation	Ping-Pong (Braziunas & Boutillier, 2008).	Titration up (Braziunas & Boutillier, 2008)., titration down (Braziunas & Boutillier, 2008).
Weightings	Built into SEAD interface.	Elicit multiple weightings (Bavatskyy, 2006).

3.2.5 Methodology Construction of Analysis

Raw, elicited data should not be presented to decision-makers (Watkins, 1983). Data must be processed, sanitised, and presented graphically or pictorially to allow decision-makers to make more informed decisions (IPCC, 2022). SEAD places reliance on decision-maker and stakeholder needs by including their utilities, as each stakeholder and decision maker needs are different as such, we decided to recommend a minimum analysis to fit the SEAD method, with optional other techniques based on stakeholder and decision-maker requests. Section 3.2.5 outlines and justifies the methods used to *construct* the analysis – the A of SEAD. The various methods for subsequent data analysis are detailed in Section 3.3, though the elicitation method for chance nodes and utility nodes both incorporate data analysis and so is included in this section (Section 3.2.5). For detail on converting raw elicited data into a conditional probability table, see Cooke (1991) which lays out this process.

The SEAD method recommends using Microsoft Excel ("Excel") as the primary database for produced conditional probability tables. While there is other database software, Excel is easily integrated into Python (in which the SEAD interface is coded) and easily accessible to the widest audience.

A few different programs were considered and tested for use to create the MAID, including Genie (GeNIe User's Manual, 2019), R (R Core Team, 2021) and Python (Van Rossum, & Drake Jr, 1995). Genie is a Bayesian Network software, however, at the time of SEAD's creation did not suitably fill the needs of a MAID. R, while being versatile and able to create Bayesian Networks and resources available for doing so, could not accommodate multiple stakeholders (Scutari, 2017). Python had a MAID package available, which had seen use within game theory and AI applications (Carey & Everitt, 2023; Fox et al., 2021).

We used the MAID Python package as a foundation for a trial, which we designed to test the capabilities of the package. Although the package worked as intended, and suitably fit the needs of game theory, we found that it was not suitable for stakeholder and decision-maker use as a standalone. An interface was needed, as the package relied on performing 'queries' within the console, each taking significant time. The trial highlighted which components would be important for an interface, including options to change all chance nodes, and decision nodes and choose the weightings of utilities. Further, to encourage stakeholder discussion a button was included to create a pop-out visual of the structure of the MAID. The interface shows the utilities (accounting for weightings) in both numerical and graphical form, allowing for visual comparison between two decision paths. The interface will be included within the SEAD GitHub deposit as it was decided to be an integral part of the SEAD method and can be seen in Figure 4 within Section 3.4.

The data prepared for stakeholder and decision-maker dialogue will depend on the agent's preferences. Therefore, a minimum of dominated decision paths is recommended, non-dominated decision paths should emerge from discussions with agents at the dialogue stage of the method.". Dominated decision paths eliminate all paths that are objectively worse than another decision path for every utility. In the case of complex MAIDs, the amount of decision paths could exceed numbers which makes it hard to perform this function manually, therefore, a script has been included within the GitHub repository which automates this function.

3.2.6 Methodology for construction of dialogue

Dialogue is the final stage of the SEAD method, allowing agents – primarily decision-makers and stakeholders, to participate in knowledge exchange with the decision-support tool present. Like the analysis stage of SEAD, a minimum dialogue is recommended within the SEAD method, which is based on agent availability and desired application. The decision to make the dialogue stage versatile was to allow it to be suitable to as many agents as possible. The two main forms of dialogue within SEAD are individual meetings and roundtables. While not necessary, it is advised, when possible, to use individual meetings for application one (one primary decision maker) and roundtables for application two (multiple primary decision makers). It is not always possible to perform the preferred dialogue of the application; availability may make a roundtable more difficult, or a single primary decision maker may prefer a roundtable. Justification for minimum criteria will be discussed below. The method for performing dialogue will be shown in Section 4.3 and is implemented in the chosen case study within Chapter 5.

Literature around the desired dialogue options was sparse. Porthin et al. (2021) present a structured dialogue for risk assessment through group elicitation with four main categories 1) Introduction 2) Hazard identification 3) Risk estimation 4) Risk control ideas. This needed to be adapted for SEAD, and hazard identification and risk estimation could be edited. Thus, the four stages of dialogue for SEAD are 1) Introduction 2) Risk discussion 3) Decision discussion 4) Adaptation ideas. All categories have criteria which is determined by dialogue choice and application choice which will be shown within Section 3.3. Further, prior to the dialogue the decision to provide all attending agents with the completed MAID, to explore pathways and allow for more insightful discussion during dialogue.

3.2.7 Methodology for verification

Elicitation from experts is hard to verify (Fenton & Neil, 2019). The primary reason to use experts is because there is much uncertainty – therefore little novel data within the subject. Validation was therefore not chosen to be an integral part of the SEAD method, which aligns with other uses of BNS and CIDs within literature (Castelletti & Soncini-Sessa, 2007; Laurila-Pant et al., 2019; Pérez-Miñana,

2016). Verification methods such as scoring rule systems i.e. Briers score were researched and considered. However, Brier scores require data to be compared and can make the process longer. Instead, a simpler verification method is suggested, during the dialogue process agents can express issues with the models and outputs. Further, by using peer-reviewed methods throughout the SEAD process, using multiple experts, and utilising bias reduction methods, the results of the SEAD method should be reliable for the decision-making process.

3.3 Using the SEAD method.

Section 3.3 presents the SEAD methodology in flow diagram form (figure 3.1), with an accompanying guide. Where more detail is needed than can be presented within the flow diagram, a number indicates what section of the guide should be checked. Further, the SEAD method assumes the use of an independent facilitator.

3.3.1 Results from designing the tool (Figure 3.1).
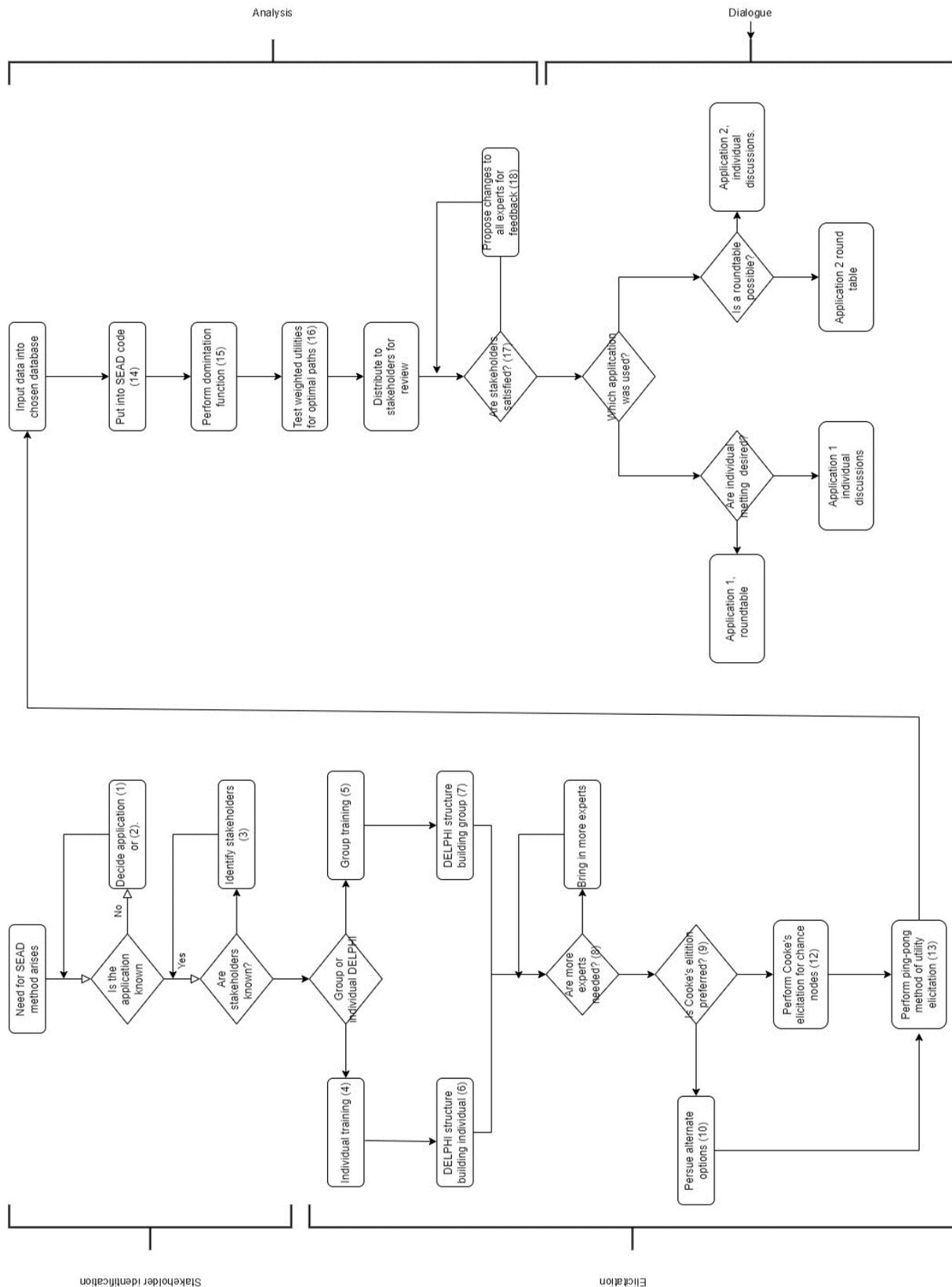
Figure 3.1: The SEAD methodology presented as a flow diagram. Each number has a corresponding information section seen below.

1) SEAD Application 1

Application 1 assumes that there is one primary decision maker, although other decisions may be mapped within the application. This application of SEAD works to test the primary decision makers' decisions on selected stakeholders' decisions and utilities, under variable conditions set by the chance nodes – while performing risk analysis.

2) SEAD Application 2

Application 2 assumes multiple primary decision-makers. Under this application, it is assumed that decision-makers are willing to be cooperative to an extent. Under this application, the primary objective is to maximise utilities, under variable conditions, set by chance nodes - while performing risk analysis.

3) Identify agents.

Identification of the agents happens in three stages: 1) Decision makers 2) Experts 3) Stakeholders. Depending on the application, often decision-makers will be known. Using application 2, decision-makers may not be as obvious, under these circumstances it is advised to wait until experts have been contacted.

It is recommended to discover experts using substantive indicators, such as those set out by Bolger (2018), these include formal qualifications and publications.

Once experts have been identified, work with experts and decision-makers to map potential stakeholders. Depending on the pre-established scope of the project, not all stakeholders may be needed. This process can be iterative and discussed with all agents to make sure all agents are satisfied, there will be opportunities throughout the SEAD process to add more agents.

4) Individual training

Training is split into four categories: 1) general 2) decision-makers 3) stakeholders 4) experts. All agents should participate in general training + their roles. The training should cover the entire SEAD process, with examples and practice questions throughout the process. Therefore, it is recommended a full scan through the SEAD methodology to determine which techniques will be used throughout. An example training plan has been included in appendix 4 which covers all four categories.

5) Group training

Depending on circumstance and availability the elicitation for the structure may be done as a singular workshop, in these circumstances it may be easier to do the training as part of the workshop.

As with the individual training, the group training should cover the entire SEAD method, with examples and practice questions throughout the process. Therefore, it is recommended a full scan through the SEAD method to determine which techniques will be used throughout. An example training plan has been included in Appendix C.

6) Delphi structure building individual

The Delphi technique can be deployed while meeting agents individually if it not feasible or desirable to get agents together. However, multiple meetings with agents can be time-consuming.

The SEAD method begins by asking stakeholders about the utilities that they are aiming to evaluate; alongside what factors and decisions may influence these utilities. When asking for factors, states (see accompanying terminology in Chapter 2) should be elicited.

There should be 2-5 states per node, and each state should include a brief description of their variables and an in-depth explanation, ideally linked to an indicator. An example state layout can be found in Appendix C. Further, agents should provide notes and reasonings to be passed along in iterations to other agents, justifying their decisions. The SEAD method relies on states, while it is possible to use continuous variables within Bayesian Networks – it is not currently explored within the SEAD method.

Once all stakeholders have completed the first iteration, they should then be mapped by the facilitator, assigning colours to each stakeholder and decision maker (sharing a colour if the same agent). At this stage the mapping is not functional and does not have to accompany CPT, a clear way to show the structure back to agents is desired, it is recommended to use the MACID plug-in for LATEX which can be found within the bibliography.

The new structures should then be redistributed to stakeholders for evaluation, following the same process as before. At this stage, it is recommended to remind agents of the scope of the project.

Iterations should be repeated in this manner until all agents are happy with the structure. If any disagreements arise, the designated facilitator should review with agents in disagreement and come to a solution.

7) Delphi structure building group

The group structure-building method should be used if it's possible to get all participants together, either online or in person, for several hours. It follows the same progression as the individual method. However, participants should have time to discuss the structure between iterations. In the group stakeholders express the utilities that they would like to explore, from here all agents give input into decisions and factors, deciding together states and indicators.

The structure is then built up over several iterations and rounds of discussion until all participants are satisfied with the structure. If any disagreements arise, the designated facilitator should review with participants in disagreement and come to a solution.

8) Are more experts needed?

The facilitator should launch the discussion of the scope of the project, and ask agents "Are all areas of the structure covered by experts involved"? If not, more experts should be brought in, using the previously outlined (Point 3) expert identification methods. All experts brought in should go through the required training.

9) Is Cooke's elicitation preferred?

Cooke's method is the SEAD methods recommended elicitation method (Section 3.2.4), however, facilitators, businesses or experts may prefer another method, such as Shelf or IDEA, which should be discussed at this point.

10) Pursue alternate options.

Research and perform alternate elicitation methodologies such as the Shelf or IDEA. The methodology for Shelf is shown in Gosling, (2018) and IDEA can be seen in Hemming et al. (2018)).

11) Perform Cooke's elicitation for chance nodes.

Colson & Cooke (2018) method is done by first assessing the experts against a set of seed questions, known only to the facilitator. Performance when eliciting for the CPTs is then weighted according to each expert's accuracy on the seed questions (Quigley, Colson, Aspinall, & Cooke, 2018). The expert judgements are then combined, using seed questions as weightings. An in-depth walkthrough of Cooke's methodology is seen in Quigley et al. (2018) and Colson & Cooke (2018). Further, Chapter 6 shows the full SEAD method applied to a case study.

12) Perform Ping-Pong method for utility nodes.

a) The facilitator should start by laying out all available options for a utility node (each decision and chance node possibility), this should be prepared ahead of time. The SEAD method uses a local scale, therefore, ask the stakeholder to rate the best possible outcome as 1 and the lowest as a 0.

b) Go through every outcome, first ask 'Would you rather have a 100% chance of [outcome eliciting] or a 50% chance of [best possible outcome]. Depending on which option is stated change the next question accordingly. Choosing a 100% chance of [outcome eliciting] places its utility as >0.5.

c) Repeat by changing the chance of the best possible outcome to higher, Ping-Ponging back and forth until a 2dp number is reached.

d) Repeat for every utility outcome.

The stakeholder often grasps the concept quickly and can give a number from 0-1 without needing the Ping-Pong method, although encourage the use of the method for as long as possible. The Ping-Pong method can be seen in more detail within Mohammad & Nakadai, (2019). Further, Chapter 6 shows the use of the Ping-Pong method within the case study.

13) Put into SEAD code (provided).

The facilitator should compile the CPTs and input them into the SEAD method Python code. A link to the code will be provided with the accompanying GitHub. The code assumes the chosen database to be Excel, however, this can be changed. The code lays out full instructions on how to build a custom MAID with templates for different size nodes provided. Further, the code includes instructions on package installation and customisation of the interactive interface. Within the GitHub repository, there are also instructions to turn the code into a .exe file for distribution to stakeholders and details on using the Pycid LaTeX package, for non-functional, but visually appealing structures.

14) Perform the domination function.

Within the accompanying GitHub, there is also a Python Script which performs domination on data sets. Domination filters out pathways that are equal to or less in every utility, removing non-optimal decision paths, and allowing decision-makers to focus efforts on discussion of viable decision pathways. This should be performed by the facilitator prior to the discussion phase of SEAD.

15) Test weighted utilities for optimal paths

Although utility weights are integrated into the SEAD display interface. Eliciting and testing estimated utility weights before allows for the facilitator to analyse multiple scenarios, providing more succinct dialogue.

16) Are stakeholders satisfied?

The facilitator should use this time to perform a final check, is everything okay? Did agents find any inconsistencies, this would be the time to raise them.

17) Propose changes to all experts for feedback.

Make sure all experts agree with the feedback, with reasoning, with a majority after a discussion between experts. Without a majority then changes should not be implemented. The facilitator should oversee these discussions.

18) Dialogue options

Each of the four suggested dialogue options will have nuance within them. However, they should all follow the rough plan below, whether that be individually or as a group. The facilitator should record or make notes during the dialogue and re-distribute these after the dialogue.

Task 0: Introduction

- Goals and scope of the workshop.
- Short description of MACID.
- Description of the work method.

Task 1: Risk discussion

- Explore risks within the model.
- Explore likely scenarios.
- Explore extreme scenarios.

Task 2: Decision discussion

- Discuss best decision pathways.
- Test under likely scenarios.
- Test under extreme scenarios.
- Conclude on potential decision pathways.

Task 3: Adaptation of pathway ideas

- Discussion about potential adaptation pathways for scenarios.

- Discuss viability with potential decision pathways.

3.4 Discussion: SEAD method creation

Section 3.4 outlines the importance, relevance, implications and further uses of the SEAD method. We achieve this by evaluating the method and exploring potential issues that arise by combining methodologies and bias reduction strategies. Then we compare the method to previous studies, to show how the method fills a clear gap that will benefit the environmental decision-making landscape.

3.4.1 Evaluating the SEAD method.

There is a need to be critical when creating a method, there is no tool that is suitable for all occasions with no downsides. By assessing the niche that a tool fills, and verifying its effectiveness the tool can effectively be utilised. The SEAD method combines existing methodologies, giving the tool credibility - using tried and tested methodologies, however, it is not known how these methodologies may affect each other. Further, as with all expert elicitation bias is seen as an issue (Manzi & Forster, 2019). The SEAD method uses bias reduction strategies throughout, such as; the use of a facilitator and training and validation within the classical model (Cooke, 1991).

As discussed, the interactions between methodologies are considered a potential weak point for the SEAD method. The main methodologies used (Cooke's, Delphi and Ping-Pong) have no literature about how they interact. Although all three have literature and evidence used within applicable context. Each methodology was shown to be accurate within its domain, and when performed together no issues arose with compatibility. Alongside bias this was the main cause for concern, however, each of the methodologies has built-in bias reduction methods, which alongside further implemented bias reduction methods we believe to be sufficient. The Delphi technique uses multiple agents which has been shown to reduce individual bias (Benarie, 1988). Cooke's methodology reduces bias by using seed questions and asking the expert for their 5th, 95th then 50th percentile and validation being part of the methodology. Furthermore, the SEAD method uses bias reduction methods alongside Cooke's methodology recommended by De Little et al. (2018) and Whitehead, (2002) 1) using well-set-out non-leading questions 2) Encouraging clarification if experts do not fully understand the question 3) the inclusion of an independent facilitator, which has been shown to reduce multiple biases (Manzi & Forster, 2019). Verification of the SEAD method was not possible within its construction, however during the case study verification was performed (Chapter 5), showing that the tool gives accurate results in line with what experts would expect.

How the SEAD method is presented went through multiple iterations. Having the method presented clearly and concisely, while still allowing users to follow with enough detail that it was easily repeatable was paramount. To achieve this a flow diagram with accompanying text was used, allowing for a clear overview of progress made, while giving users the option to read in-depth about the process below. Other considered options included an online interactive resource or a booklet to explain each step. However, we felt that although both these methods of presenting the methodology had benefits, they were resource-heavy, so time was focussed elsewhere within the project.
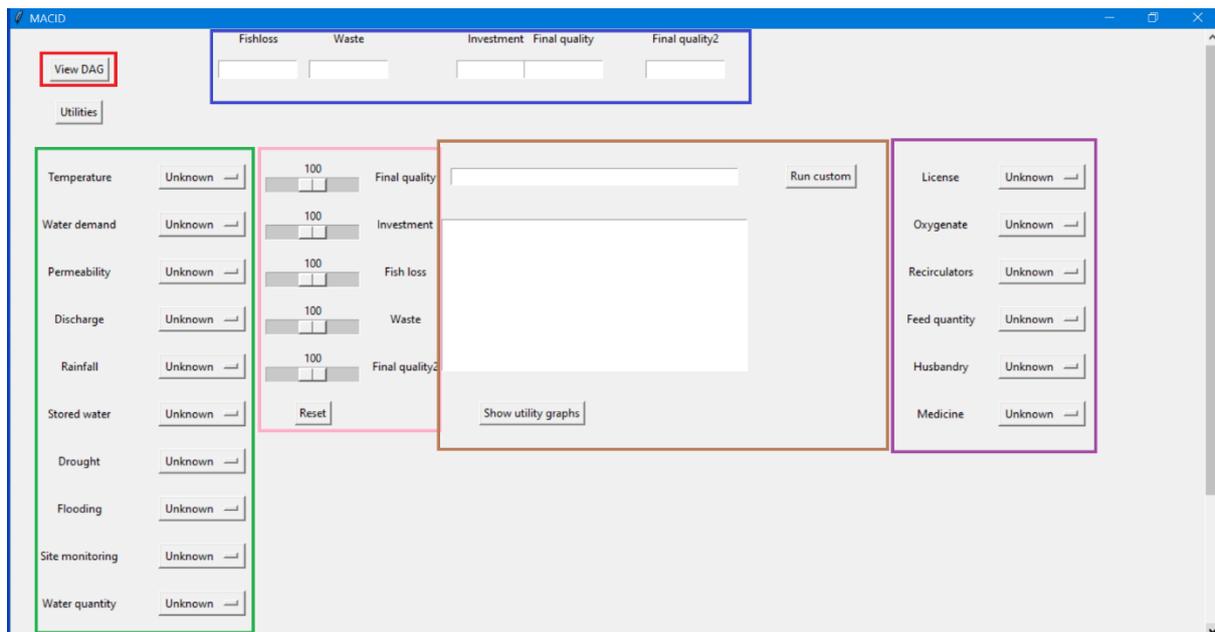
Figure 3.2: The SEAD interface, customisable within the provided Python Git Hub. Boxes are drawn over the top to identify different sections – these are not within the actual interface. The different colours represent different parts of the SEAD interface. 1) The green box shows chance nodes 2) The red shows the button which displays the DAG 3) The pink shows weightings 4) Blue shows utilities 5) Brown shows CPTs and 6) Purple shows decisions.

The SEAD method interface was designed with a similar philosophy, to be easily accessible for users who were not familiar with Bayesian Networks or MAIDs. Figure 3.3 shows the interface (Taken from the case study). Chance nodes can be changed on the left, seen by the green-coloured rectangle, and are listed as discrete variables, these are quantified in an accompanying document. Decisions can be seen on the right within the purple rectangle. The expected utility can be seen at the top (Blue rectangle), from 0-1. Further risk assessment is possible within the brown box if the agents wish to explore risks under decision scenarios. Further, Weighted utilities can be changed within the pink box and the structure can be viewed at the red box. The interface is designed to be simple, and feedback from the case study showed overwhelming positivity for the usability and layout. The

negative feedback about the initial design was taken onboard and improved upon, the interface had no help feature, multiple question marks buttons were added which gave handy hints when using the interface. Further, users felt it difficult to remember the states of the chance nodes and their quantitative counterparts, a button was added which now displays this information in a pop-up window.

3.4.2 Suitable applications for SEAD

The SEAD method shares a similar structure, due to being heavily influenced by, Bayesian Networks as such many of the aspects which make Bayesian Networks viable also carry over. There are still applications in which a normal Bayesian Network would be a better option, for example: looking at risk without perception or single decision-maker scenarios.

Many areas such as: ecosystem services (Pérez-Miñana, 2016) logistics (Zhang & Thai, 2016) and project management (Rodrigues & Williams, 2017) amongst others would benefit from the SEAD method, Bayesian Networks are prominent decision-support tools within these disciplines, therefor the effort required to transform these using the SEAD methodology is minimal - when compared to sectors which currently do not use BNs.

Further, as discussed, the scope of the SEAD method is flexible. Although the case study (Chapter 5) looks at the Scottish salmon aquaculture industry, the scope could have been zoomed in, looking at a single farm or zoomed out, looking at more than just the salmon aquaculture, and the independencies between different aquaculture industries.

3.4.3 Importance of results

The severity of the climate crisis means that mitigation of climatic impacts will be insufficient, therefore businesses, governments and policymakers are looking to adapt (Abbass et al., 2022). Adaptations are often made using a decision-support tool, decision-support tools present data in an informative, accurate, and strategic way (Wagener et al., 2022). The need for such a decision-support tool becomes more apparent when you consider wide-scale climate impacts. COP26, held in Glasgow in 2021 was a meeting of UN members that aimed to discuss and implement climate change strategies. Forbes (Forbes, 2022) classes COP26 as a failure, failing to produce anything of little impact, with many reasons being given, lack of resources, lack of commitment and communication, all areas in which a tool such as SEAD would be beneficial. We are not expecting the SEAD methodology to be used by the IPCC, but it does show a need for such a tool, and although this is the most prominent case of a need for clearer climate risk and decision making, there are an instance of examples, such as those laid out within Section 4.4.2 in which the tool would excel, one such example is the case study presented in the coming Chapters.

We show that the SEAD method fills this niche, achieved by laying out criteria for a climate decision-support tool that needs to be successful, then relying on established methodologies and widely used tools to build a tool which fits all the laid-out criteria. While we see the SEAD method as a success, this does not mean the project will be ending. The method has been applied to an industry-scale case study, explored in Chapter 5 onward, and there are plans to apply it to more local-scale industries, further cementing its place as a viable tool.

Chapter 4 Aquaculture and climate change.

Chapter 4 outlines how climate change impacts to the Scottish finfish freshwater aquaculture industry presents an example complex decision-making problem to be used as a case study for a decision-support tool. First, the rationale for a case study is provided, followed by the criteria required to identify a suitable case study for the decision-support tool to be applied to. The remainder of the Chapter then presents research that examines the vulnerability of the freshwater finfish aquaculture industry in Scotland to climate change impacts, and how the sector meets the criteria to be an appropriate case study.

Note: Visser-Quinn et al. (2021) provides an in-depth analysis of changing water availability on Scotland's major industries, identifying aquaculture as a major at-risk sector. The research presented in this Chapter presents a similar analysis which was conducted prior to the publication of Visser-Quinn et al. (2021). The scope of the work in this Chapter is narrower in scope, focussing only on aquaculture, and ultimately the findings corroborate those of Visser-Quin et al. (2021).

4.1 Justification for the case study

Yin (1994) defines a case study as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident." Understanding this definition is crucial when choosing a case study, as it emphasizes the importance of analysing events within their contexts rather than in isolation (Rowley, 2002). This contextual analysis is a key feature of case studies, allowing for the assessment of specific technologies (Kitchenham, 1995).

Due to their ability to test scenarios in real-life contexts, case studies are often employed by emerging decision-support tools to improve and calibrate their effectiveness (Breuer et al., 2008; Dey, 2004; Leskinen et al., 2006; Rose et al., 2016; Vinodh et al., 2014).

To identify a suitable industry for the case study the criteria outlined in Table 4.1 were considered

Table 4.1: Criteria and reasoning for potential case study industries.

	Criterion	Rationale
1	Multiple stakeholders must have a vested interest.	There are already decision-support tools available which occupy a similar niche with single stakeholder environments, such as Bayesian Networks and Causal influence diagrams. Therefore, the case study should be able to test the tools capacity to accommodate multiple stakeholders.
2	Must be vulnerable to climate change impacts.	Anthropogenic climate change has, and will continue to, exacerbate the intensification within Scotland's hydrological cycle (*IPCC,* 2022), resulting in a larger disparity between dry and wet periods. Exploring this interaction tests one of the desired features of the proposed tool – dealing with uncertainties. Further, the complexity caused by climate change impacts would lead the problem to be a wicked problem – allowing the third and final case study categorisation to be addressed.
3	Must have a considerable economic output within Scotland.	One commonly cited limitation for novel risk analysis is stakeholder engagement (Akermann el., 2007; Hansen, 2013). Using a high stakes environment, with established risks and economic consequences, that stakeholders will be more willing to engage. This enables the application of the Decision-support Tool to the case study while effectively addressing a prominent limitation.

Potential case study sectors that met these criteria include whisky production, forestry, hydro-power generation, agriculture, and aquaculture (Allan et al., 2020; Gosling et al., 2012; Werritty & Sugden, 2012). Each of these sectors aligns with the established criteria in distinct ways, making any of them suitable for the study. Whisky production, for example, has a significant economic footprint and involves multiple stakeholders across its supply chain, from raw material suppliers to manufacturers and distributors. Forestry addresses climate vulnerability and stakeholder complexity, particularly in balancing conservation goals with economic outputs. Hydro-power generation exemplifies high-stakes decision-making with clear climate dependencies, particularly in managing water resources amid shifting precipitation patterns. Agriculture similarly integrates economic importance, climate sensitivity, and diverse stakeholder involvement, such as farmers, policymakers, and supply chains. Ultimately, aquaculture was selected due to its strong alignment across all criteria, particularly its pronounced vulnerability to climate change impacts, multi-stakeholder engagement challenges, and

its critical role in Scotland's economy. While any of these sectors would have been appropriate for testing a decision-support tool, aquaculture offered unique opportunities for exploring the tool's capacity to address uncertainties in a dynamic and high-stakes environment. Aquaculture was chosen for two reasons:

1. **The anticipated growth trajectory of the aquaculture sector**: the aquaculture industry's motivation to continue to expand currently accounting 40% of Scotland's food exports, and the sector is anticipated double its economic output from 2016 levels to £3.6 billion by 2030 (Scot.gov, 2016).
2. **The sector is potentially very vulnerability to climate change impacts**, in particular changes to water availability (Visser-Quinn et al., 2021), and yet there was very little in the academic or grey literature about managing or mitigating these impacts.

4.2 The location and distribution of freshwater aquacultures in Scotland.

Figures 4.1 & 4.2 show the spatial distribution of finfish freshwater aquaculture sites in Scotland. Showing a geographic bias towards the west coast.

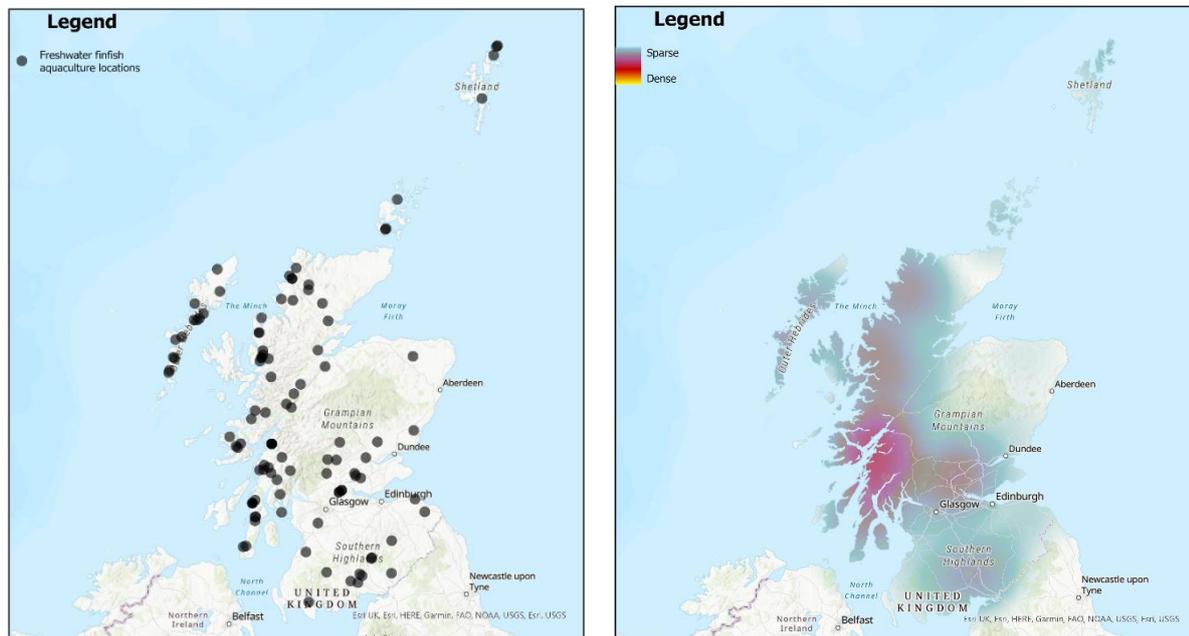*Figure 4.3 (left) & 4.2 (right): Spatial distribution of all freshwater, finfish aquaculture sites within Scotland. Figure 4.2 is a heat map showing areas of higher density of aquaculture sites. (for full sized image, see Appendix C2). Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx. Figure 4.2 is a heat map of the same data. Both figures can be seen in Appendix A.*

Some site locations have multiple sites registered to the same location. Eliminating duplicates (n=10) gives 97 remaining individual site locations (hereby refrerred to as just "sites"). 19 are located on islands, 88 on the Scottish mainland. The most abundant islands are the Outer Hebrides (Innse Gal) (N=12), with Shetland (Sealtainn) following (N=4). 38 sites are located in mainland Scotland, on or within 1km of the western coast (inshore). Other areas with significant proportion of sites include the Highlands, Loch Lomond and surrounding areas, Southern Highlands and, Stirling and surrounding areas. Figure 4.2 shows a distribution heatmap of the sites.

Water availability, water quality, climate, and soil type are each factors that are considered when deciding on a location for freshwater finfish facilities (*FAO*, 2020). These factors all present potential vulnerabilities to climate change.

4.3 Water abstraction quantities for aquaculture

Depending on water resources in the region surrounding an aquaculture site, water may be abstracted to keep a continuous supply of high quality water (Benejam et al., 2010). A decrease in abstraction rate could render the fish with not enough water, or low-quality water (Benejam et al., 2010). The abstracted water may be used for one or all of the following facilities within an aquaculture site:

- **Hatcheries**: Enclosed space, designed to nature small eggs until large enough to be placed into tanks.
- **Tanks**: Tanks for raising fish within a closed environment.
- **Raceways**: Artificial riverbeds, designed to simulate rivers.
- **Ponds**: Large man-made ponds which some farms prefer to use rather than tanks.

Alternatively, cages can be placed within large bodies of freshwater such as lochs. Use of cages means that there is no requirement for water to be abstracted (Boyd & Gross, 2000; Engle et al., 2020; Lebel et al., 2018; Lekang, 2013).

Abstraction data for freshwater aquaculture from 2019 is shown in Figure 4.3. Within the provided dataset there was 67 'missing' points, which are sites that do not abstract (i.e the sites that use cages within lochs).
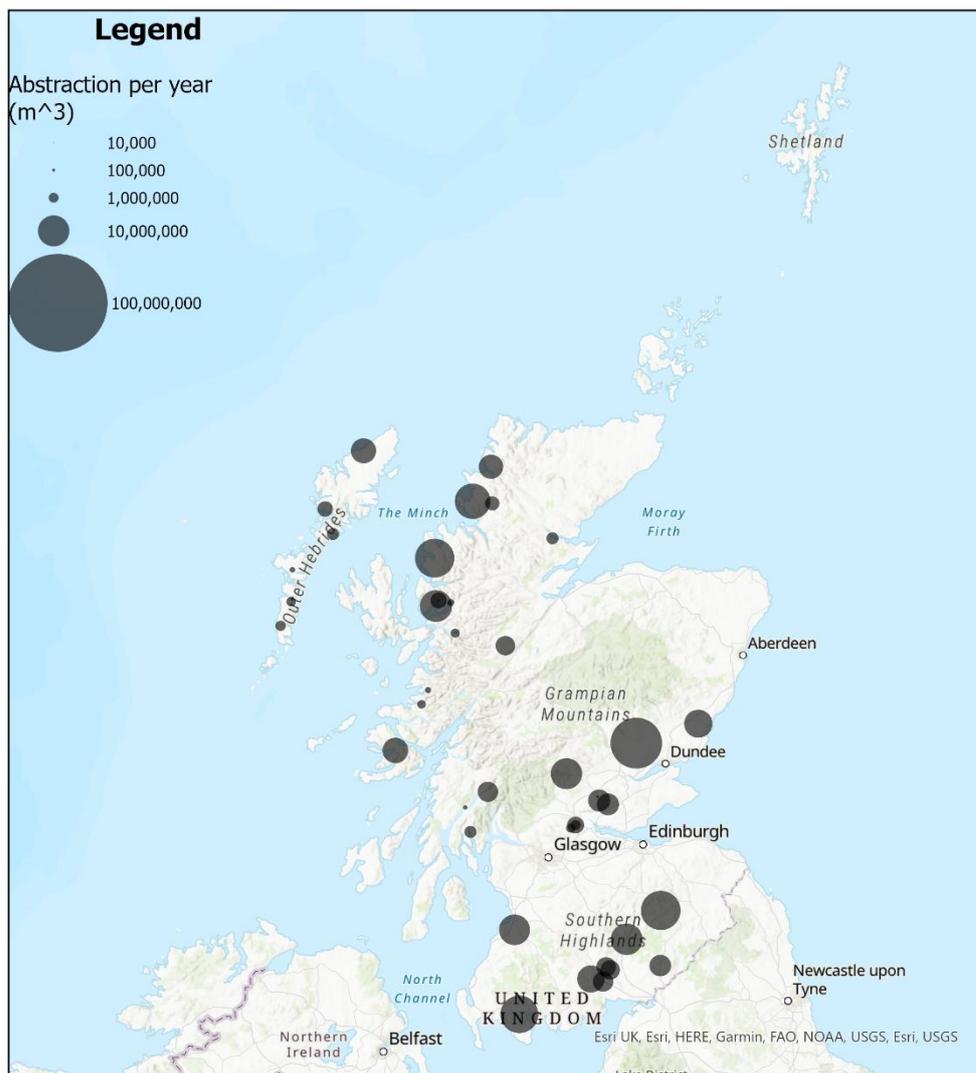
Figure 4.3: Freshwater, finfish aquaculture abstraction(m³/y) at permitted sites in Scotland. (Full sized image found within appendices A). Map compiled using data provided by SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.

The total water abstracted by freshwater aquaculture sector is 219,098,264 m³/y, and this varies with meteorological season, as shown in Table 4.2. Meteorological seasons divide the year into four fixed three-month periods. Spring runs from March 1 to May 31, summer from June 1 to August 31, autumn from September 1 to November 30, and winter from December 1 to February 28 (or 29 in a leap year).

Table 4.2: Seasonal variation in abstraction(m^3/y) for freshwater aquaculture sector.

Season	Water abstracted (m^3/y)	Proportion of total
Total	219,098,264	n/a
Winter	53,636,949	24.5%
Spring	49,946,900	22.8%
Summer	56,330,114	25.7%
Autumn	59,184,301	27.0%

Over the 39 abstraction sites the mean yearly abstraction is 5,216,625m^3, with a range from 33,545m^3 to 27,009,486m^3. Figure 3.4 shows a heat map of abstraction for aquaculture. Regions with greatest water abstraction include northwest coast of Scotland, Dundee and the Southern Highlands (Figure 3.4). Sites which use less water could still face consequences of shifting precipitation patterns, as could areas which there are no available data for.
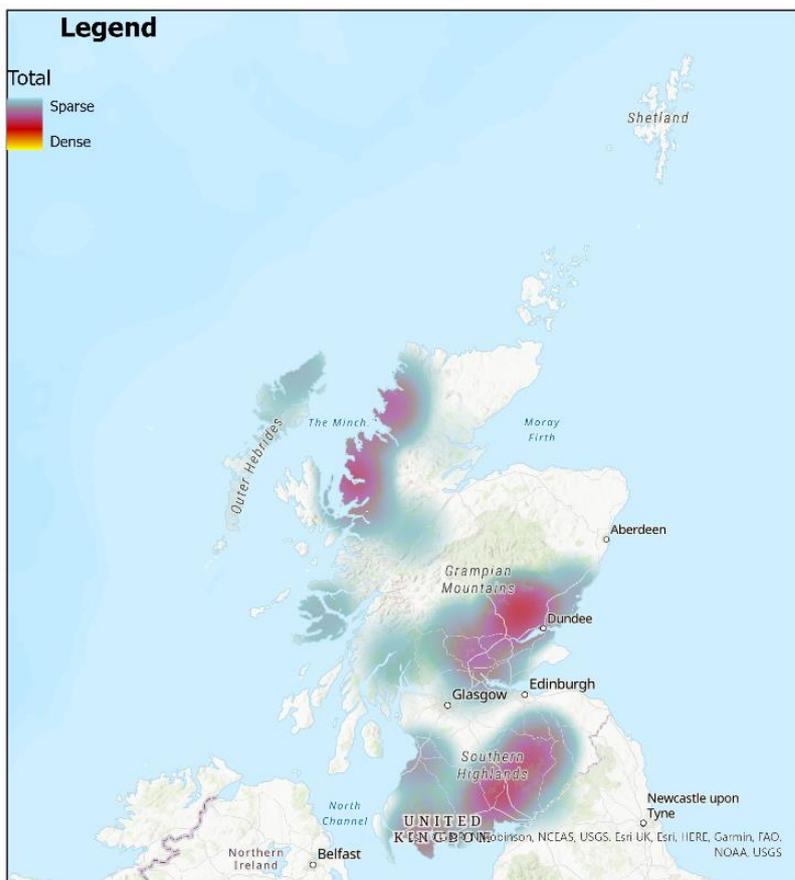
Figure 4.4: A heat map showing available data of water abstraction. (Full sized image found within appendices A. Map compiled using data provided by SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.

4.4 Assessing the vulnerability of the aquaculture sector to climate change impacts.

4.4.1 Climate change scenarios

The IPCC adopted four main Representative Concentration Pathways (RCPs) which are climate projections based on concentrations of greenhouse gasses within the atmosphere. RCP2.6, RCP4.5, RCP6 and RCP8.5. The number refers to the possible range of radiative forcing values in the year 2100 (Met Office, 2018) and directly correlate to worsened effects of climate change. RCP8.5 was chosen to use as the projections for the testing of the viability of the case study for two reasons:

1) it is the RCP with the most easily accessible data, often used in climate modelling such as (Li et al., 2015; Mukherjee, 2021; Yasarer et al., 2017 and therefor has the most comparable data sets

2) RCP8.5 is the worst of the 'feasible' pathways, and using worst case scenarios is a common form of strategic planning, to minimise unforeseen contingencies (Gopalakrishnan & Okada, 2013; Kunreuther et al., 2013).

4.4.2: Climate impact on freshwater fin fish

The aquaculture industry is sensitive to changes within the hydrological cycle (Finfish and aquaculture, 2021). Climate change is expected to continue to influence, both spatially and temporally, precipitation rate within Scotland (see Chapter 2). Here, we investigate the vulnerability of freshwater aquaculture sector to changes in the hydrological cycle both to understand impacts and sensitivities, and to understand the scope of a proposed decision-support tool. To achieve this, we mapped high resolution climate projections (UKCP18, 2019) at 5km spatial resolution, driven by the regional climate model projections of RCP8.5 from the years 2031-2040 and compared them to aquaculture abstraction amounts.

Figure 4.5 shows the rainfall in Scotland(mm/d) average over a 10 year span from 2011-2020. We chose to only map rainfall amounts in summer and winter, as these seasons according to the IPCC will have the most extreme effects, with extremes expected to fall within these seasons. The summer and winter projections have been mapped alongside abstraction data (SEPA, 2019), of their respective seasons. Projected abstraction data is not available, so 2019 data has been used for all time periods. Abstraction is anticipated to increase until 2030, likely in correlation with the proposed aquaculture expansion, although this projection is based on extrapolated data and involves a degree of uncertainty. Abstraction is anticipated to increase until 2030, likely in correlation with the proposed aquaculture expansion, as the two are inherently connected; increased aquaculture activity would, in theory, necessitate greater water usage. However, while this assumption aligns with the logical relationship between sector growth and resource demand, the precise scale of this

increase remains uncertain and would benefit from further detailed analysis (Salmon Scotland, 2020).

Figure 4.5: Summer (2011-2020) precipitation (mm/day) for Scotland, plotted alongside aquaculture water abstraction for correlating season (Full sized image found within appendices C2). Showing how expected temporal shifts in precipitation caused by climate change could impact water availability within the industry. Precipitation data sourced from CEDA, abstraction data sourced from SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.

Figure 4.6: Winter (2011-2020) precipitation (mm/day) for Scotland, plotted alongside aquaculture water abstraction for correlating season (Full sized image found within appendices C2). Showing how expected temporal shifts in precipitation caused by climate change could impact water availability within the industry. Precipitation data sourced from CEDA, abstraction data sourced from SEPA and Aquaculture co-ordinates sourced from *http://aquaculture.scotland.gov.uk/map.aspx.*

Figures 4.5 and 4.6 vividly illustrate the stark contrast between Scotland's dry summers and wetter winters. Throughout the year, the west coast consistently experiences higher levels of precipitation, in contrast to the east, which is often characterized by extended dry spells. Among these regions, the Highlands stand out as the wettest, regardless of the season.

A closer look at the three primary areas of intensive water extraction, as identified in Figure 4.4, reveals their notable alignment with regions of substantial winter rainfall. However, during the summer months, only one of these extraction hotspots—the Southern Highlands—falls within a relatively dry zone.

By comparing Figures 4.5, 4.6, and 4.3, a strong correlation emerges between the key aquaculture sites and the consistently wetter conditions along the west coast. This relationship highlights the strategic importance of precipitation patterns in supporting aquaculture activities.

Finally, the juxtaposition of historical data (Figures 4.5 and 4.6) with future projections (Figures 4.7 and 4.8) provides valuable insights into the temporal and spatial evolution of precipitation across Scotland. These comparisons shed light on potential shifts in climate dynamics, offering a clearer understanding of how changing rainfall patterns may impact water resource management and ecological systems in the years to come.
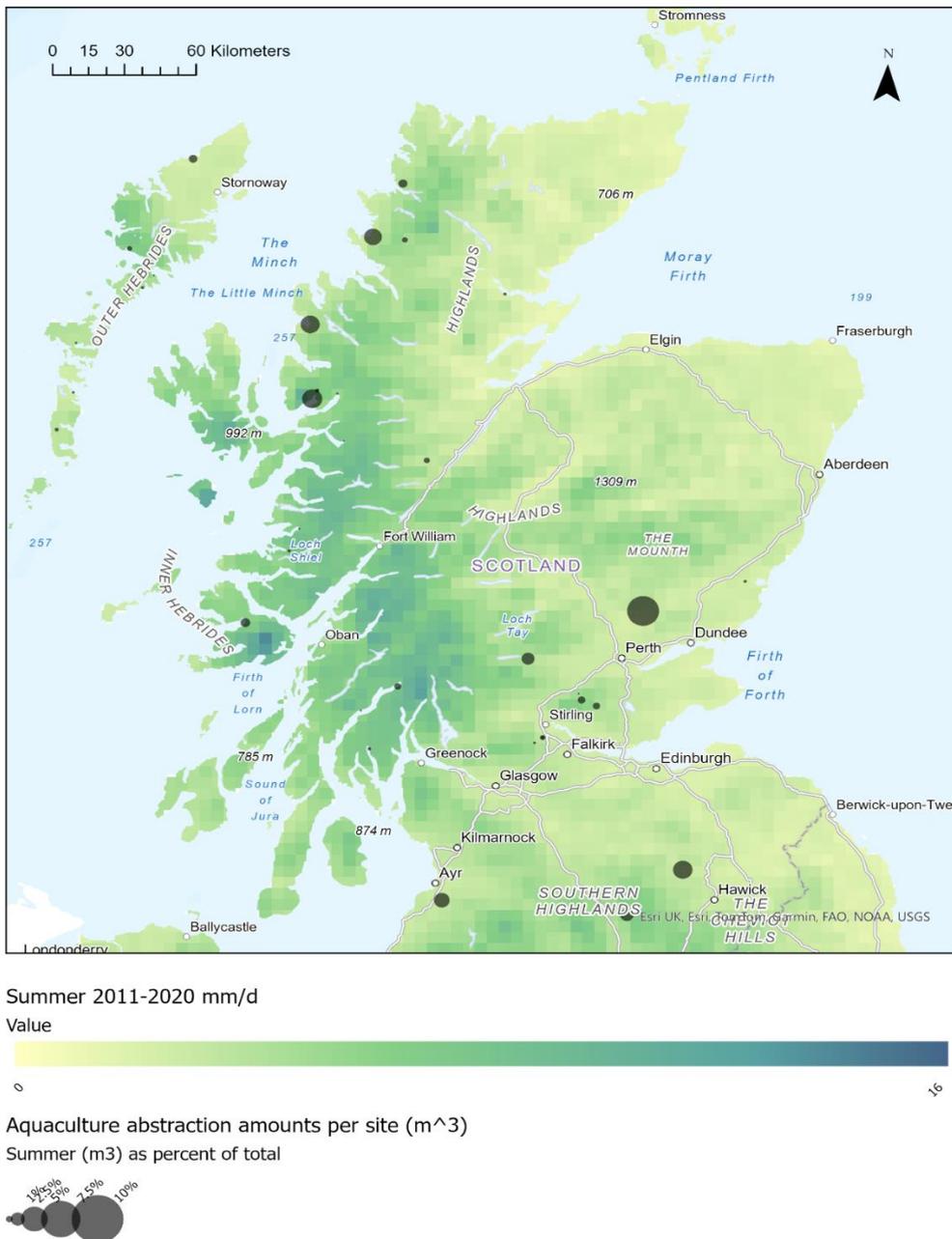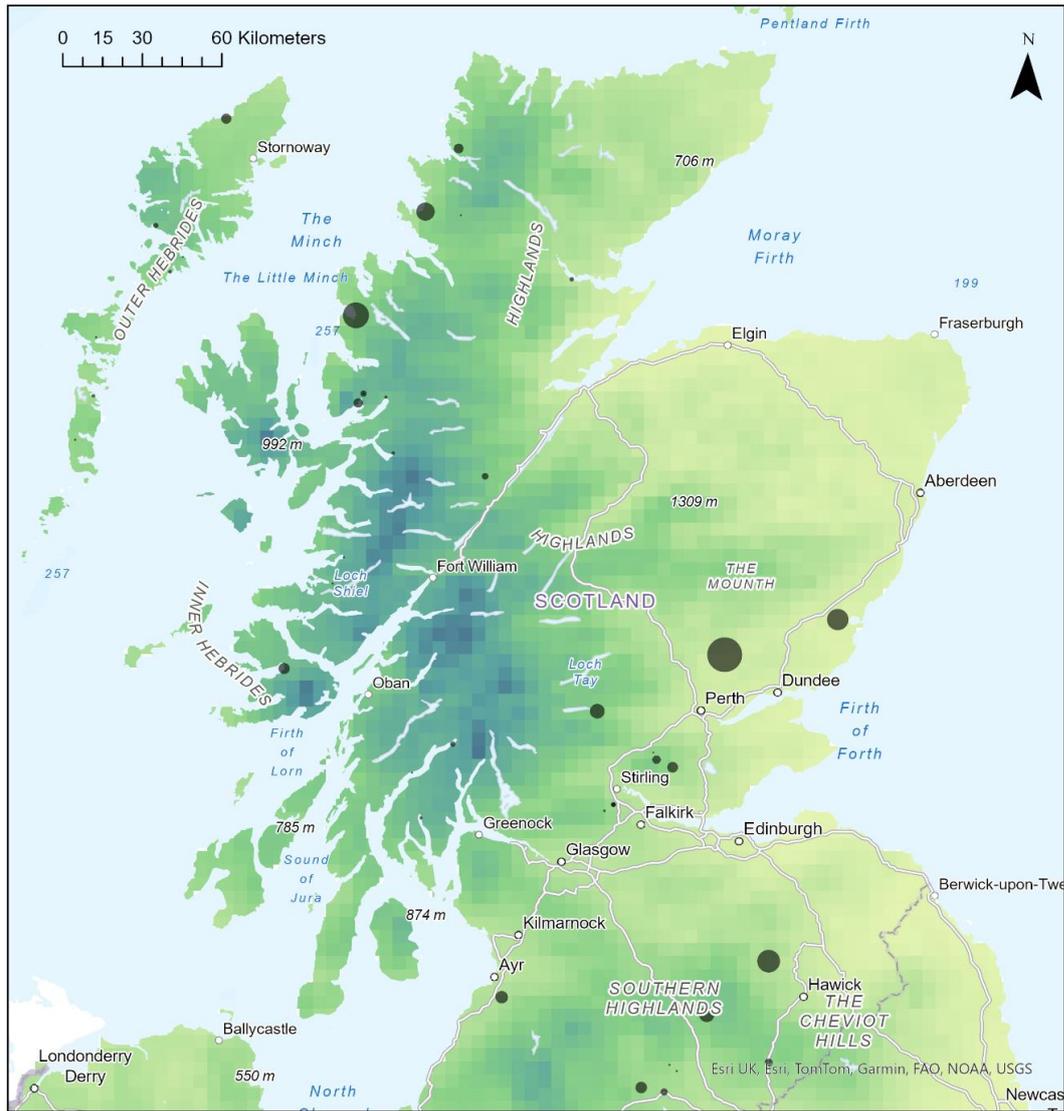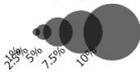
Figure 4.7: Summer 2031-2040 precipitation (mm/day) for Scotland, plotted alongside aquaculture water abstraction for correlating season (Full sized image found within appendices C2). Precipitation data sourced from CEDA, abstraction data sourced from SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.
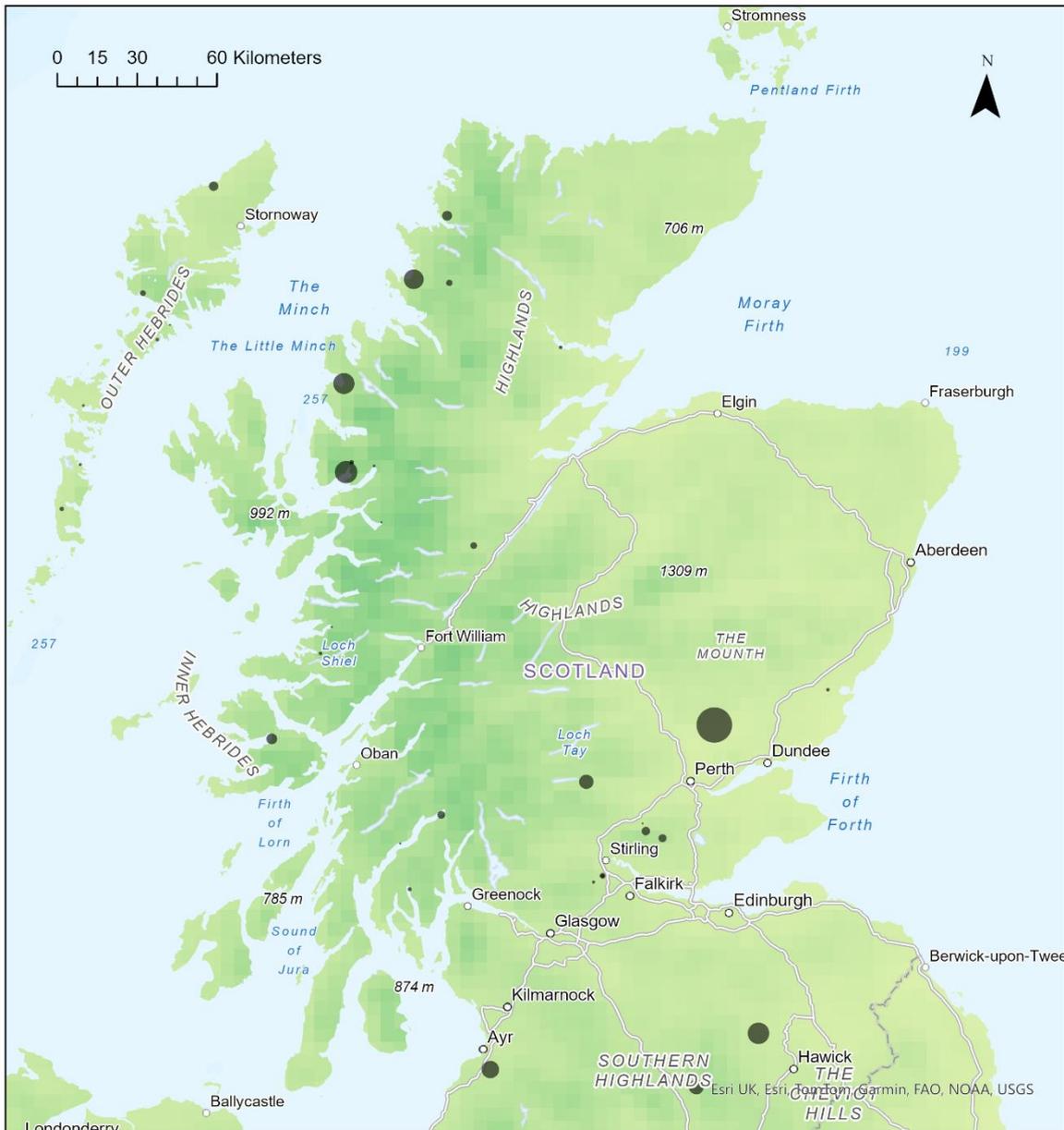
Figure 4.8: Winter 2031-2040 precipitation (mm/day) for Scotland, plotted alongside aquaculture water abstraction for correlating season (Full sized image found within appendices C2). Precipitation data sourced from CEDA, abstraction data sourced from SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.
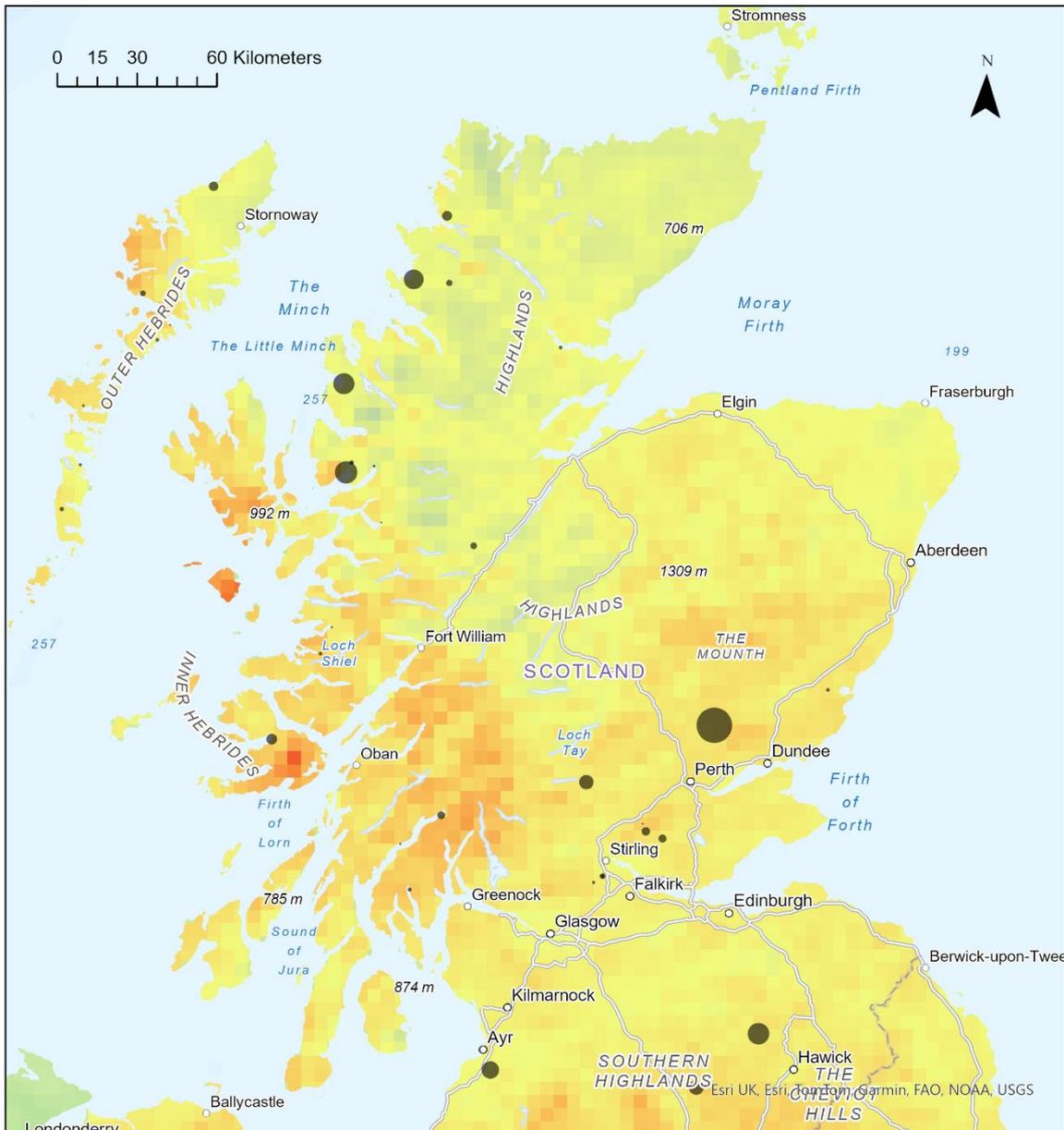
Difference between past summer rainfall (2011-2020) to predicted rainfall (2031-2040) mm/d
Value

Aquaculture abstraction amounts per site (m^3)
Summer (m3) as percent of total
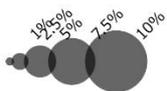
Figure 4.9: Projected precipitation difference under RCP8.5 during summer 2031-2040 (Full sized image found within appendices C2). Precipitation data sourced from CEDA, abstraction data sourced from SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.
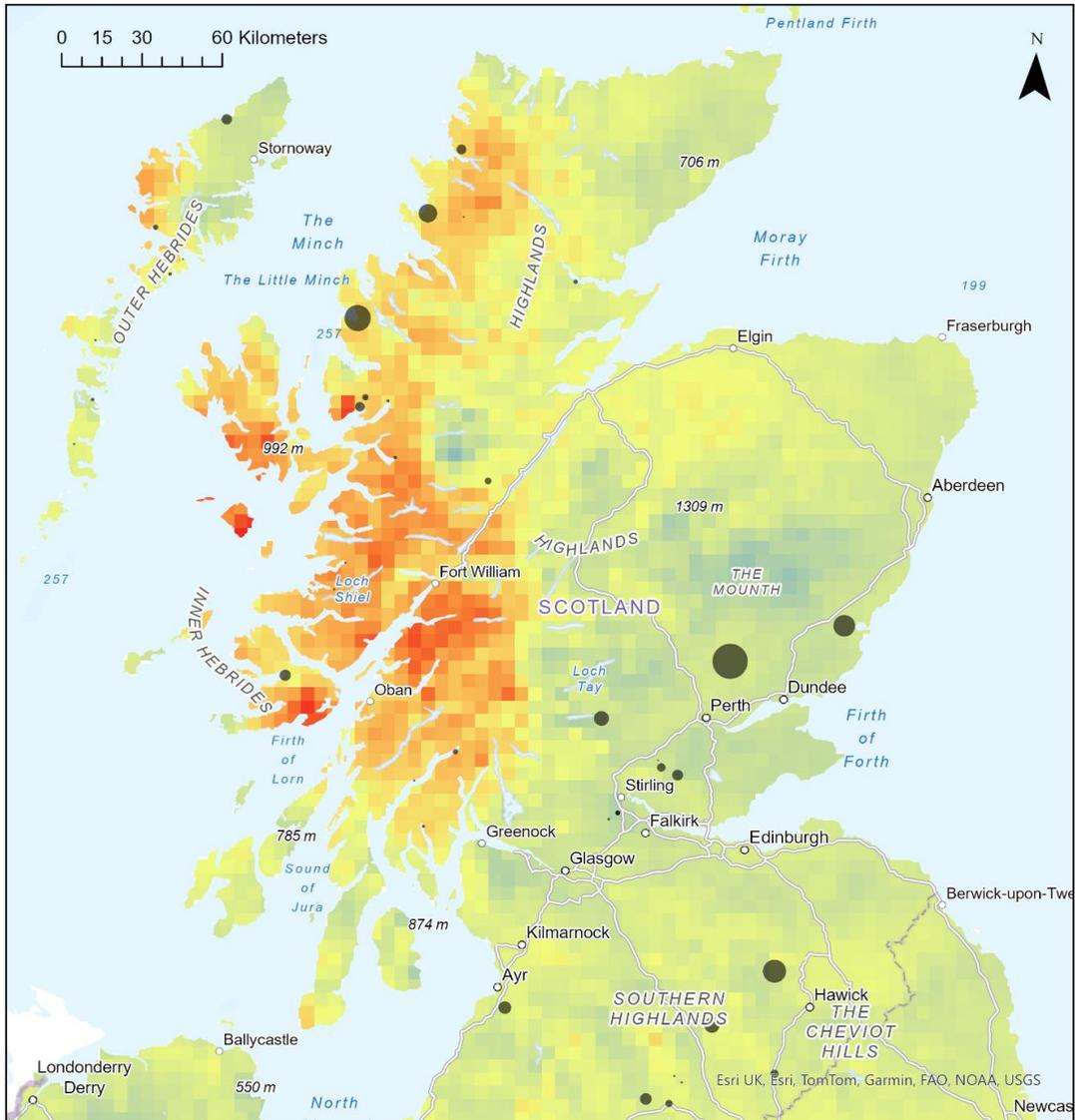
Difference between past summer rainfall (2011-2020) to predicted rainfall (2031-2040) mm/d
Value

Aquaculture abstraction amounts per site (m^3)
Winter (m3) as percent of total
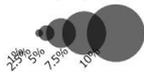
Figure 4.10: Projected precipitation difference under RCP8.5 during winter 2041 (left) and 2061 (right) (Full sized image found within appendices C2). Precipitation data sourced from UKCP18, abstraction data sourced from SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.

Further, we then subtracted the past data (2011-2020) from the projected data (2031-2040) for the two chosen seasons to give two spatial projected difference maps (Figures 4.9 & 4.10). In projected future summer scenarios, the Southern Highlands and areas around Dundee will be drier, with many aquaculture facilities there using high levels of abstraction, and it being two of the hot spots identified by the heat map, this could pose an issue. The expected most affected abstraction hotspot is the Inner Hebrides, with between 2-4mm/day less of rainfall expected by 2041. Comparing Figure 4.6 with Figure 4.3, the areas which previously had the most precipitation, and therefor correlates with aquaculture site locations, are the areas with the largest reduction in precipitation. Further, while some areas are projected to have an increase in summer rainfall, this is due to two of the wettest years on record (2016 & 2020) being included within the present data set, these two years. The average seasonal rainfall range (across Scotland) from 2011-2020 was 132.9mm/season to 971.517mm/season (summer). However, the range of the wettest areas within summer over this ranged from 751 (2013) – 1,441 (2020). With 2020 being close to twice as wet in some areas than other years the present data set may appear to be wetter, comparatively this makes projected data then appear like it may be drier due to these outliers. This will cause an increase of risks to the aquaculture industry associated with lower water quality and water shortage.

These outliers are unavoidable with the impacts of climate change worsening – using an average 10 yearly data set is used to minimise these issues, but they still prevail.

Figure 4.10 shows some areas within the Highlands and Inner Hebrides may be drier in projected scenarios – while much of the rest of the Scotland will see an increase in rainfall. One explanation can be attributed to the two outlying years (2016-2020), the range of the wettest areas over this ranged from 1050mm/season (2011) to 2326mm/season (2016), with all other years except 2020 & 2016 falling below 1600mm/season. While these two years saw over 2.2x more seasonal rainfall within the highlands than other years. These years skew the average of the present day (2011-2020) rainfall, making them appear wetter. Further, this leads to comparatively future projections appearing drier than expected (Section 4.4). Understanding these outliers are important for making climate predictions. Despite the two outlying years some aquaculture abstraction hotspot areas such as Perth, Ayr and the Southern Highlands still see an increase in rainfall during the winter seasons, if the outliers were to be removed much of the Highlands would see the same.

4.4.3 Data verification with literature

In 2021, Adaptation Scotland produced a report for Scotland detailing long term climate projections for Scotland, using both low and high emission scenarios; RCP2.6 and RCP8.5 respectively (Adaptation Scotland, 2021). The Adaptation Scotland report shows that over the past few decades Scotland has been increasingly wetter, with the period 2010-2019 experiencing a yearly average of 9% more rainfall than 1961-1990.

4.4.3.1 Summer

Summer rainfall is projected to decrease overall, although extreme heavy rainfall events will become more extreme i.e. larger quantity of rainfall within these events (Adaptation Scotland, 2021). Under low emission scenarios (RCP2.6) the rainfall is predicted t be less, however in these scenarios there is still projected to be over 10% less rainfall by 2061. Under high emission scenarios (RCP8.5) rainfall increases considerably, with many years projected to be over 15% less rainfall. By 2050, extreme years are projected to have as low as 36% (RCP2.6) and 38% (RCP8.5) less rainfall when compared with current rainfall levels. Adaptation Scotland (2021) backs up the findings found within Chapter 4.

4.4.3.2 Winter

In Winter high emission (RCP8.5) and low emission (RCP2.6) scenarios are both predicted to have wetter winters (Adaptation Scotland, 2021). This contradicts the findings found in Section 4.3, which showed some areas of the Highlands having less rainfall during winter, the reasoning for this difference has been explored within Section 4.3. By 2050, Adaptation Scotland predict, for RCP2.6 on average winters to receive 8% more rainfall, RCP8.5 having 12% more rainfall. However, there is a large variance, under low emission scenarios this ranges from 19% less rainfall to 36% more rainfall, showing a spatial change within the country, more closely aligning with the data produced in Section 4.3. While high emission scenarios the range is from -17% to 42%. Adaptation Scotland (2021) also states that during winter the intensity of the wettest days will increase. Although the adaptation Scotland data in some areas goes against the data produced in Section 4.3, both pose their own unique threats to the aquaculture industry, and resilience measures should be taken.

4.5 Implications for the aquaculture sector

Sections 4.3 and 4.4 illustrate that the Scottish aquaculture industry is subject to a wide array of potential impacts from climate change, many of which are directly linked to alterations in the hydrological cycle. For freshwater salmon farming, these impacts include increased water temperatures, reduced summer water flows, and heightened risks of algal blooms—all of which can stress fish populations, compromise water quality, and exacerbate disease outbreaks. Changes in precipitation patterns may also lead to more frequent flooding or drought events, further

challenging the stability of water resources critical for salmon farming. The full extent of these implications, along with their nuanced interdependencies, is thoroughly explored during the application of the SEAD method, which offers valuable insights into managing and mitigating these climate-driven risks. These risks, alongside other factors discussed in Chapter 4, underscore and contribute to why aquaculture emerges as a particularly suitable candidate for a case study in the development of the proposed decision-support tool.

Within Chapter 2 general risks to aquaculture were set out, including water related risks (Section 2.3.2). Using data (Sections 4.3 & 4.4) we can investigate vulnerability to these risks for different sites. SEPA (2021) includes freshwater quality and availability, escapes of fish stock due to storm damage and disease outbreaks as potential risks to aquaculture from climate change. These risks are made more prominent by lack of water (freshwater availability), increased heavy rainfall events (storm damages) and a loss in water quality (disease outbreaks).

Abstraction hotspot areas (Figure 4.4), such as Southern Highlands and west Dundee will see competition from other industries for abstraction, exacerbated by an increase in population within these areas. The national records of Scotland (2016), project the population of Scotland to increase by a further 5% by 2040, focused primarily within the lower regions, which includes two of the abstraction hotspots, placing more strain on these areas and leading to more resource competition.

While population growth may contribute to changes in water demand, the combined effects of shifting population dynamics and alterations in the hydrological cycle introduce too many variables to definitively predict their impact on Scotland's water distribution and potential water management conflicts. The complex interplay of these factors makes it challenging to reliably forecast the extent of disruption in water resources. However, population increase coupled with shifts in the hydrological cycle is anticipated to disrupt Scotland's water distribution and increase water management conflict (national records of Scotland, 2016; Betts et al. 2018).

The SEPA finfish aquaculture sector plan (2021) page 24 stresses the importance that sites have "*water in the right place, in the right amount and of the right quality*". With clearly highlighted scenarios creating uncertainty, many risks causing a wicked problem, and multiple stakeholders sharing the burden of risk, the finfish freshwater aquaculture industry fits all the criteria set out within Chapter 1.

Chapter 5 Application of SEAD method climate change and its impacts on Scottish finfish aquaculture

In Chapter 5, the SEAD method is applied first to a pilot study and then to the case study (climate change and its impacts on Scottish finfish aquaculture). Chapter 5 refers to Figure 3.1 "flow diagram of SEAD methodology "(Found in Chapter 3 and Appendix B) throughout. Where the SEAD method presents multiple options we will give justification and reasoning for the option chosen. No results or outcomes are presented within Chapter 5 and are instead presented in Chapter 6.

5.1 Applying the decision-support tool to a pilot study.

5.1.1 Summary of pilot study

To ensure the DST (decision-support tool) worked as intended and to find potential flaws an early iteration of the SEAD method (note: a name had not been applied to the DST at this point) was piloted. The pilot used project members role-playing as experts and stakeholders (Note: the terminology laid out in Section 4.1 had not been established yet). The pilot study was named "Creating a MAID to see how drought and flood risks to Glasgow caused by climate change."

The pilot had three "stakeholders" and two "experts" with an overlap of one expert also being a stakeholder. The three stakeholders were 1) lay public 2) city planners 3) A Glasgow council representative, the two experts were 1) water and flooding 2) city infrastructure and planning.

Each stakeholder was given a prompt:

Lay public:

Prompt: Your job is to roleplay the average concerned citizen of Glasgow. Think of what you value most within the city, is it clean water, working sewage or it could be broader aspects – cheap council tax etc.

City planners:

The city planners are tasked with the design and development of urban areas, such as towns and cities. As a city planner, you would ensure there is balance between demands on the land being developed and the needs of the community. For this roleplaying exercise you will also have control over planning basic amenity services such as pipelines and sewage treatment.

Glasgow City Council representee:

As the Glasgow City Council representee you manage a budget, which provides for schools, roads, libraries, museums, parks, planning and other such. You have been giving a short brief on the

potential impacts of climate change and water resources but are also aware that there are more pressing issues within the city that the budget could be allocated right now. You are the primary decision maker in this context and are the one who has initiated the use of the MAID.

The pilot study proceeded with the following steps, unless stated, steps were the same as the final SEAD method.

1) Identified as application 1 (one primary decision maker).
2) Stakeholder and expert training.
3) Delphi individual elicitation.
4) Cooke's method of expert elicitation.
5) Ping-Pong method of utility elicitation.
6) Put into Python code.
7) Discuss outcomes with stakeholders.

5.1.2 Changes made to the SEAD method through implementation of pilot study.

The pilot study was useful for identifying issues within the DST, Table 5.1 contains changes made to the final version, and the reasoning for their change.

Table 5.1: Changes implemented and their justification from use within the pilot test of the DST.

Changes implemented	Justification
Added agent terminology.	Confusion arose during elicitation as to what a stakeholder and expert were.
Streamlined training to be based off roles, previously all agents underwent general training which covered all roles.	Feedback was that training was too long and convoluted.
Included Pareto domination to analysis step.	Too many decision paths to discuss, a way to eliminate non-optimal decisions was needed.
Added a dialogue stage.	Results of analysis were passed to agents but no formal dialogue stage limited co-operative decision-making.

The changes presented in Table 5.1, along with the experience gained at each stage of the newly named SEAD method, enabled us to confidently apply it to our case study on the impacts of climate change on Scottish freshwater finfish aquaculture.

5.2 Stakeholder identification during the case study.

Justification for the case study selection is provided in Chapter 3. This satisfies Step 1 of the SEAD method. Step 2 asks "Is the application known?". For this case study we approached the aquaculture industry stakeholders with intent of applying the tool – therefore the application was already known to be application 2. Application 2 is that all stakeholders have mutual interest in this application - climate resilience and adaptation of finfish aquaculture in Scotland. When applying the SEAD method organically one of the applications highlighted within the SEAD method would be chosen.

To identify agents, we adhered to the process outlined in Step 3, leveraging the recommendations provided by Bolger (2018). Initially, we engaged two experts in discussions to identify additional agents. Through this collaborative process, three agents were identified. Each agent was both a decision-maker and a stakeholder, collectively bearing the responsibility for addressing the risks posed by climate change to Scottish finfish aquaculture. For definitions of these roles, please refer to Table 4.2.

The selected agents represented distinct yet complementary perspectives: one was from a regulatory body, another from an insurance firm, and the third was a representative of a trade body for the sector. These individuals were chosen for their unique roles and their collective capacity to provide a comprehensive understanding of the challenges and risks faced by the industry.

Additionally, three subject-matter experts were contacted based on areas identified by the initial experts as requiring specialised judgment. These areas included climate change, water systems, and aquaculture systems. While the exact scope of expertise required was initially uncertain, all three experts were ultimately involved throughout the application of the SEAD method.

5.3 Elicitation Step 1: Structure building within the case study

The first step of the elicitation stage of the SEAD method was to decide on elicitation methods (Figure 4.1). Without deciding methods, the training would be too broad. This part of the elicitation was during the COVID19 pandemic and was forced to be online, for this reason, individual training was chosen over group training. At this stage of the SEAD method, the classical method (Cooke, 1991) was chosen for the elicitation of data. The classical method (Cooke, 1991) is the method recommended by the SEAD method and there was no cause to deviate from it. Choosing the conditional probability table (CPT) elicitation method at this time meant training sessions could be combined, streamlining the process.

The three primary agents and three experts were trained. While the SEAD method gives guidance on using multiple agents working together for each body, for testing the method it was not necessary

(discussed in Chapter 7). If required the SEAD method shows how to combine expert judgements using techniques from Charisse Farr et al. (2020). Experts were brought in to provide expert judgment throughout the process on areas outside the domain of the three primary agents. The training followed the guidelines set out by the SEAD method (Figure 4.1); Table 5.2 shows which training was done by which agents.

Table 5.2 Table showing training done by different agents.

Agent	General	Decision maker	Stakeholder	Expert
Primary agents (x3)	x	x	x	X
Experts (x3)	x			x

Training for the three primary agents took between 2-4 hours per agent, the training covered 1) An introduction to the project 2) Learning about MAIDs 3) Structure elicitation 4) chance node elicitation 5) utility elicitation 6) Worked examples 7) trial elicitation and practise. The experts did not do 5) utility elicitation and had reduced 6) worked examples and 7) trial elicitation and practice.

Following training moved to step 2 of the elicitation phase to build the structure (Figure 4.1), which comprises of chance nodes (and their complementary states), decision nodes (and the possible decisions), utility nodes, links, and information links (see Chapter 2).

Structure building was completed using the Delphi method and through individual exchange (rather than as a group such as via a round table discussion) via email exchange and online meetings for each agent. As sessions were often several weeks between each session, sessions started with a training summary, a brief reminder of the scope and application and how to complete their task.

The first contact with the three primary agents within the structure elicitation consisted of the following questions:

1) Which variable may influence the above scenario? (*note: The scenario had been laid out within the scope and introduction at the start of the email*).
2) What states are realistic for this variable?
3) Provide a quick description for each of these states.
4) What other variables may influence this variable?

Next the agents were asked to repeat this with multiple nodes. The elicited nodes were then compiled into a basic Bayesian Network structure, with no utilities, decisions or CPTs. These "structures" were then redistributed to the agents, with the following questions added:

5) What decisions could you or the body you represent make to affect any of the above nodes?

6) Which utilities that you or your body represent could any of the nodes affect?

The structure was expanded to include the newly elicited data. The structures were then redistributed to stakeholders for feedback. The structures underwent three additional iterations until all agents were satisfied that their decisions, utilities and all applicable uncertain variables were represented.

The completed structure had 14 chance nodes variables which agents agreed were outside of the three primary agents' expertise (surrounding climate and water change), therefore the stand-by experts (Section 5.2) were contacted and received training in preparation for the conditional probability table elicitation. The completed structure can be seen in figure 6.3 in Chapter 6.

5.4 Elicitation Step 2: Conditional probabilities

5.4.1 Elicitation of chance nodes

Following the SEAD method we chose to use the classical method of elicitation (Cooke, 1991). There were 14 chance nodes and five utility nodes in the final structure, and each of required data to populate the conditional probability tables (CPTs).

The 14 chance nodes which needed data were categorised into the following three themes:

1) Environmental (four nodes): rainfall, temperature, flooding, and drought.

2) Water management (five nodes): permeability, water demand, discharge, water quality and water quantity.

3) Aquaculture (four nodes): monitoring, smolt quality, abstraction, smolt amount.

The desired areas of expertise were each given to one expert. The SEAD method suggests more than one expert should be assigned to a node, with expert judgement then aggregated in the methodology highlighted by the SEAD method (Figure 4.1). Due to limitations with expert engagement, this was not possible, instead all nodes had exactly one expert. This deviates from the standard application of the Classical method, which aims to aggregate expert judgement based off seed question answers.

The classical model performance is based on "seed questions", the method for choosing seed questions has been discussed within Chapter 4. In summary, seed questions should be unknown to the expert being elicited and ideally not publicly available (Quigley et al., 2018). It was not possible to use unpublished papers as seed questions as suggested by Quigley et al (2018) and a mix of recently published data and publicly available upon-request data was used. Seed questions included information from the latest IPCC report for environmental nodes, latest SEPA and Scottish reports

for water questions and a mix of recently published journals. All experts scored a high average for the seed questions. While the seed questions would ideally be used to determine how best to aggregate the expert weightings, with only one expert node they were instead used to determine if the expert knowledge was adequate. The seed questions however still give a rough representation of the statistical accuracy of these experts, answers from the seed questions are not discussed as all experts fell within the satisfactory range.

Data mining as an approach to populate conditional probabilities was explored for each change node. However, this was not possible for any of the nodes, and therefore the conditional probabilities for all 14 chance nodes needed to be elicited through expert judgement. Over four sessions, the 5th 95th and 50th quantiles were elicited through the relevant expert (allocated based on the three main categories) for each of the nodes and their dependencies – in accordance with the Cooke's classical method.

5.4.2 Elicitation of utility nodes

In the final step of elicitation stage within the SEAD method utility nodes are elicited through the Ping-Pong method (Chapter 4). Five utility nodes needed elicitation: 1) investment, 2) fish loss, 3) waste, 4) final quality 1, and 5) final quality 2. Note that "final quality" has two nodes, this is because a node can only be owned by a single agent, and since two agents stated final quality as a utility there must be two separate nodes; one for each agent.

To elicit the utility nodes, each stakeholder provided a number from 0-1, 0 being the worst outcome from available decisions, 1 being the best. Every possible decision path for each utility node was elicited over one 2-3 hour session per stakeholder, taking place three months after elicitation of the chance nodes. Utility nodes are kept as a 0-1 figure for two reasons. Firstly, to allow easy comparison between multiple nodes (and even multiple MAIDs). Secondly, it obscures potentially sensitive or private data, such as the investment node, thereby encouraging a more transparent dialogue between agents.

5.5 Data analysis within case study

5.5.1 Analysis of elicited conditional probability tables.

Elicitation through the Classical model (Cooke, 1991) produces results formatted as percent likelihood within a range. These numbers are then aggregated (if using multiple experts) using data collected through seed questions, the main benefit of using seed questions is the ability to aggregate and validate multiple experts into one number.

In this study, all of the chance nodes were populated by a single expert, rather than multiple experts. The option of using multiple experts is shown within Chapter 4. To convert these quantiles into the conditional probability tables: every possible state is listed – i.e. if there are 3 dependent nodes each with 3 states all 9 combinations are listed, with the states of the node the CPD is being built for placed down the left, each column then must add up to 1 (100%) with the chance for each state in each row.

A simple CPT for the *Water storage* chance node can be seen in Table 5.3. *Water storage* only has one interdependency so is relatively simple consisting of only 9 cells. A chance node with more interdependencies is more complex; for example, *Smolt quality* has five interdependencies and upwards of 1500 cells.

Table 5.3: *The CPT of the chance node "Water storage" as elicited by the water management expert. The*

Rainfall	Increase	No change	Decrease
High	0.6	0.2	0.1
Medium	0.35	0.7	0.6
Low	0.05	0.1	0.3

Table 5.3 shows the CPT for water storage available in relation to a historic 5 year average (2018-2022). The first column shows that an increase in rainfall would lead to a 60% chance of high amounts of water storage, 35% chance of normal levels of water storage levels (medium) and a 5% chance of water storage levels being low.

The CPTs were all stored within an Excel file, meaning the CPDs can be easily opened, and easily imported into the SEAD Python code. The SEAD Python code (available through github) is a building block code which has pre-set segments for different node sizes. The user must change the import file for the CPDs to the relevant file location and edit all links within the MAID. Running this produces a pop-out window of the interactive program, labelled the "SEAD interface". The SEAD interface is used for the dialogue section of the SEAD method.

5.5.2 Generating future climate scenarios to facilitate dialogue

Following the SEAD method (figure 3.1), primary agents were contacted for potential scenarios to be used to facilitate dialogue. A future summer and a future winter scenario or ~2040 were requested by agents to examine potential climate vulnerabilities within the industry. Table 5.4 shows how the chance nodes were set to achieve these scenarios, based off findings from Chapter 3. All other nodes were set to "unknown".

Table 5.4: Scenarios achieved through setting chance nodes, requested by agents for the dialogue stage.

Chance Node	Summer	Winter
Temperature	*Slightly hotter*	*Slightly colder*
Water demand	*High*	*Low*
Rain	*Decrease*	*Significant increase*

5.5.3 Streamlining decision pathways: Pareto domination

Within wicked problem decision-making processes (and therefor most applications of the SEAD method) there are hundreds of decision paths available for agents to explore within the dialogue stage. For this reason, the SEAD method recommends using Pareto domination (Willig, 1978). Pareto domination removes non optimal decision paths, comparing the utilities of a decision path against all other decision paths, any path which does equal or worse in every utility is removed. Pareto domination can be done for any "future scenario" or, in a future application of the SEAD method any configuration of chance nodes.

The code to run this can be seen within the SEAD Python code package, to do this the user uploads a database of each utility, for each decision path, under the chosen scenario and runs the model.

Applying the Pareto domination function to the case studies decision path (no scenario selected) eliminated ~110 pathways (n=324) for all three scenarios (present day, future [10 year] summer and future [10 year] winter). The number of Pareto-dominated pathways identified was low. This may be due to the direct trade-off between the investment utility and other utilities: the cheapest produces a lower investment utility, while high quality is reversely proportional. This means that often decision pathways are better than either one or the other, leading to fewer dominated pathways.

During the elicitation stage basic utility weights were elicited in the form of a ratio, these weightings were run through the SEAD interface before the Dialogue stage of the SEAD method (figure 4.1). The weightings were then applied to the scenarios. These weights provided a starting point for dialogue. By then removing Pareto dominated decision paths, the highest 10 (10 was chosen due to it being possible for discussion within a single session) of these pathways were presented to the three primary agents before the Dialogue stag. Further, prior to the dialogue stage (four weeks) the agents were sent a copy of the completed SEAD program – and were encouraged to explore decision paths under varying scenarios.

5.5.3 Dialogue

The final stage of the SEAD method is the Dialogue stage. The SEAD method offers multiple dialogue options to fit the circumstance.

Due to very limited availability of the agents, scheduling a discussion as a group was not possible, and therefore we conducted an interview with each agent (see Section 7.5)**.** Prior discussion had taken place - with all agents, as to what data they would like before the meeting, this included desired scenarios. One agent could no longer participate in the research, and they were replaced by a new agent with a similar background who will now be known as agent 4 to differentiate from the previous agent.

Each dialogue was conducted online, and lasted between 60 and 90 minutes. The dialogues followed the recommended format of SEAD method under one of two possible final steps: Individual dialogue (rather than group dialogue), the questions asked to each agent are in Appendix 5. The meeting had three sections:

- **Section A:** Dialogue: The dialogue consisted of four parts 1) Introduction (recap and purpose of this stage) 2) Risk discussion 3) Decision discussion 4) Adaptation pathway discussion.
- **Section B:** Discussion on the method.
- **Section C:** Verification.

Within Section A-4 (adaptation pathway discussion) adaptation pathways were elicited by encouraging discussion about vulnerable areas within the risk system of aquaculture. The facilitator and agents configured chance and decision nodes to explore various risks and consequences to the salmon freshwater aquaculture industry in Scotland. As all applicated of the SEAD method vary, the SEAD method gives guidance on how to elicit adaptation pathway ideas, however for this PhD research after identifying vulnerable areas through the SEAD interface we discussed climate change adaptation and vulnerability.

Although not part of the SEAD method, since this PhD research aims to test and improve the method, we discussed the experience of participating in this research with the agents, and ideas of how to improve the approach, including for example how to reduce burden and maximise benefit to study participants. This feedback can be seen in Chapter 7 with further changes made to the methodology based on agent feedback.

After the dialogue, verification was performed, this was to help strengthen the model, although it is not required by the SEAD method (due to the complexity of verifying an uncertainty (Olivier et al., 2008). To verify the model, the facilitator led the agent through an assessment of an assortment of

five nodes that aligned with the expertise of that agent, the randomised node's dependencies set to random states and agents verified they were accurate and fell between agent belief bounds.

Chapter 6 Case study results: climate resilience of freshwater finfish aquaculture

In this Chapter, we present and discuss the results and outcomes of the SEAD method when applied to the freshwater aquaculture industry in Scotland. This Chapter will cover results from 1) structure building 2) state elicitation 3) conditional probability table elicitation 4) investigating different scenarios 5) feedback of the SEAD methodology. Further, no surveys, recordings will be shown– however anonymised statements can be used as per the ethics and privacy agreement signed with all agents and experts. Blank survey sheets are provided within Appendix 5.

6.1 The model structure created through the Delphi method.

6.1.1 Model iterations

The first (out of four) iteration of the model structure, having elicited only chance nodes, is shown in Figure 6.1. The models are built using the Delphi method (Chapter 4), in which multiple iterations are done building up the structure until all agents are satisfied. The three primary agents chose to focus on water quality as a starting point, and build up to factors that may influence water quality.

Figure 6.2 shows iteration three out of four, which was the first model structure to contain decision nodes, shown as rectangles. The survey used can be seen in "Iteration for decisions survey" (Appendix 5). Between iterations one and three, Water quantity, Smolt quality and Abstraction were added as chance nodes. Further, Husbandry, Medicine, Oxygenate, Recirculatory aquaculture systems and Licensing were added as decision nodes, with relevant information links (knowledge of the outcomes of these nodes) added to inform the decisions.

Figure 6.2: Iteration three (of four) - the structure when applying the SEAD method to a case study: Scottish aquaculture risks through water management. Showing an expansion on the initial chance nodes to include decision nodes and agent colours including adding of chance nodes water quantity, smolt quality, abstraction .

6.1.2 Final model

Figure 6.3 shows the finished structure (iteration four out of four), between iteration three and the completed structure five utility nodes (Investment, Fish loss, Waste, Final quality 1, Final quality 2) were added. Further, a chance node Monitoring was added, "monitoring" was discussed amongst two agents as to whether it should be classed as a decision, being informed by flooding, or a chance node (Discussed further in Section 7.4). Iteration 4 was done via a structured online interview rather than through a survey, the questions asked can be seen in Utility structure interview questions (Appendix 5), this adaptation was to suit the needs of agents. Due to the successful transition, the SEAD method now recommends using structured online interviews for structure building.
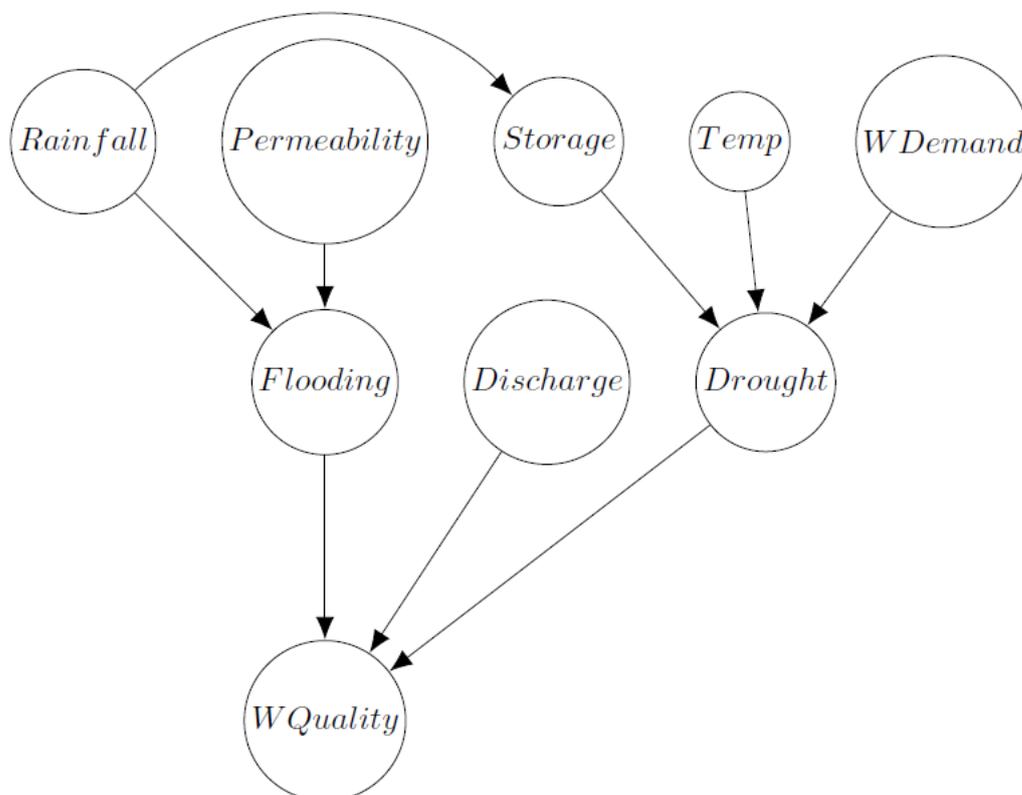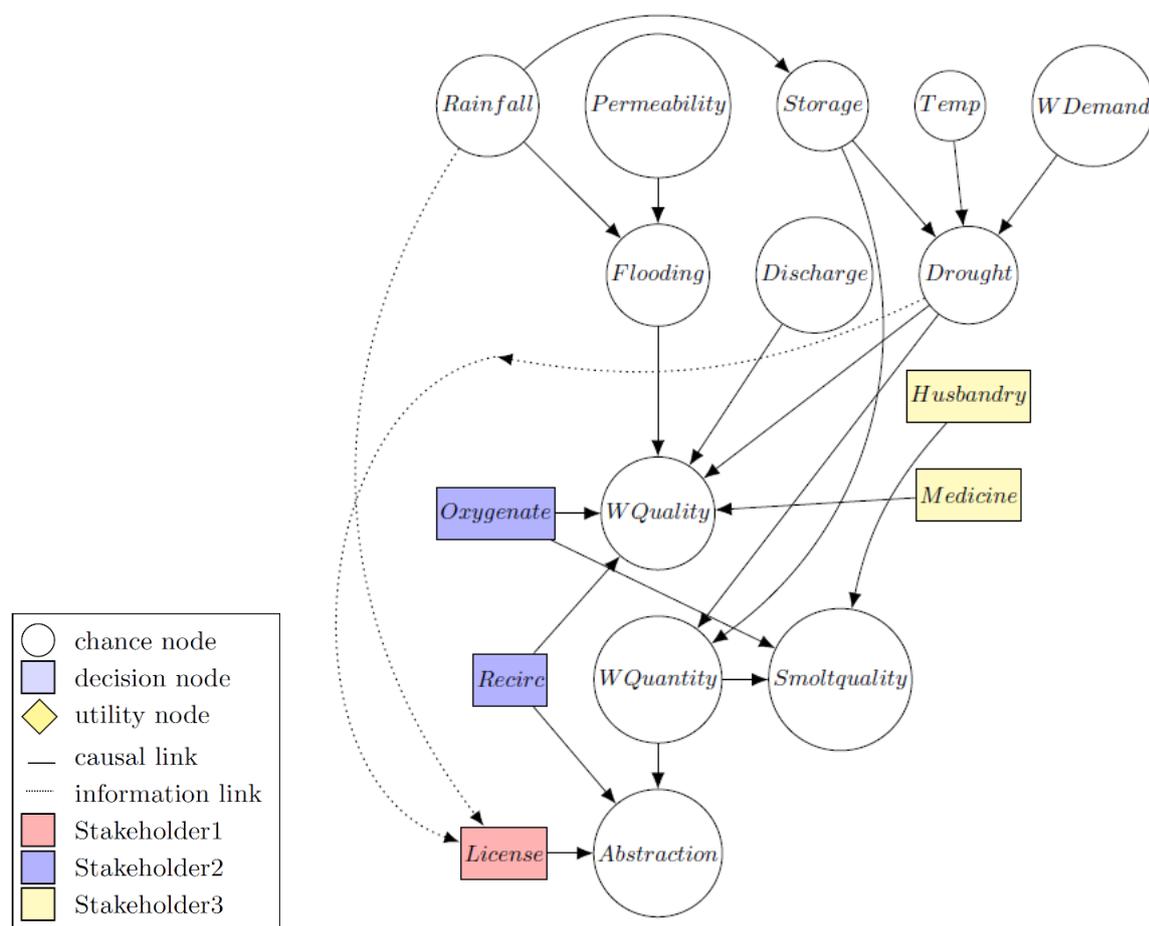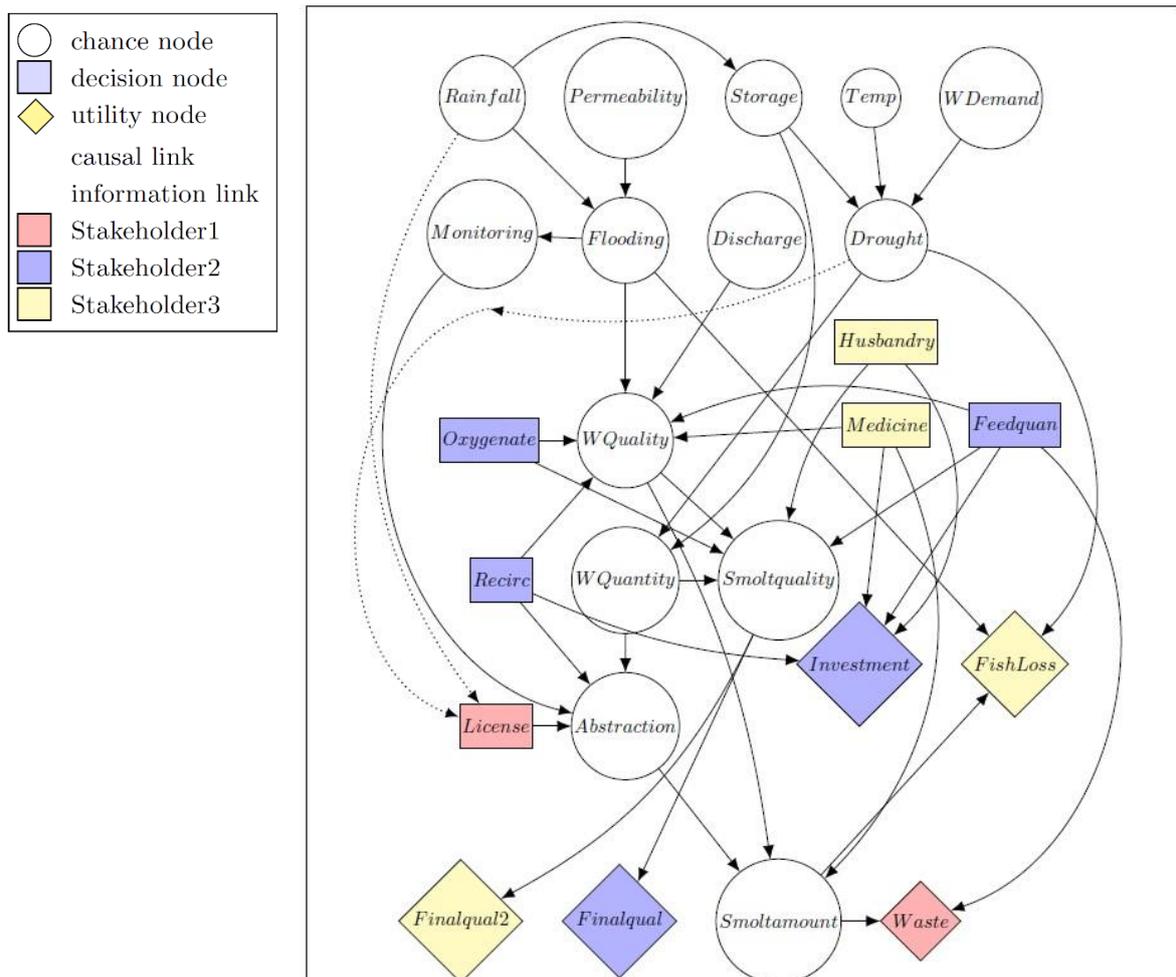

Figure 6.3: Iteration four (final) of the structure when applying the SEAD method to a case study: Scottish aquaculture risks through water management. The final version is expanded to now all include all node types.

Accompanying resource 1 Aquaculture states.xlsx provides states and descriptions for each of the nodes of the completed structure. The states were elicited at the same time as the nodes - although agents were given time to research suitable indicators. Each node and state have a name (the label shown in the model) and a descriptor (the technical classification). All nodes have between two and five states, which are elicited by experts in line with the SEAD method (Chapter 3). As an example, the water demand node and associated states are shown in Box 5.

Box 5: The name and descriptor of the water demand node and its three states, all elicited from experts.

Box 5.

Node name: Water demand.

Node descriptor: Water demand within the catchment area, both commercial and household.

States for the water demand node:

- High: Average demand over a season is more than 2% higher when compared with a 10-year average.
- Medium: Average demand over a season is between -2% and 2% when compared with a 10-year average
- Low: Average demand over a season is more than 2% lower when compared with a 10-year average.

6.2 Conditional probability tables

The 19 (with two to four states each) conditional probability tables (CPTs) (elicited through the Ping-Pong method, see <u>Section 5.4.2</u>) can be viewed in accompanying resource 2, "Conditional probability tables.xlsx" note: decision nodes do not have CPTS. The daw data elicited in the surveys and seed questions cannot be included due to signed privacy agreements with agents, a blank survey sheet can be seen in Appendix 6.

Each node within "Conditional probability tables.xlsx" has it's own sheet. Nodes which contain CPTs can be split into three categories: (1) independent chance nodes (2) dependent chance nodes, and (3) utility nodes. *Temperature* is an example of an independent chance node; within the final model structure (Figure 6.3) no other nodes influence *Temperature* (shown as *Temp* in Figure 6.3),

therefore the probabilities are simply the probabilities of each state under normal circumstances, see Table 6.1 .

Table 6.1: The CPT for the independent chance node "temperature", information detailing full node and state descriptions can be seen at the accompanying resource 1 "aquaculture states.xlsx".

Chance node: Temperature	Conditional probability
Significantly hotter	0.3
Slightly hotter.	0.6
No change	0.1

Dependent chance nodes are influenced by other nodes. In this case study, dependent nodes vary from having only one node influencing it and therefore relatively few states and modest CPT (for example, *Stored Water*, see Table 6.2), to complex dependent nodes such as Smolt quality which has five influencing nodes with 188 total states and a CPT with 564 cells (see accompanying resource 1 "aquaculture states.xlsx – tab Smolt quality").

Table 6.2: The CPT for the dependent chance node "stored water", which is influenced by only one other node: rainfall. Information detailing full node and state descriptions can be seen at the accompanying resource "aquaculture states.xlsx".

Chance node: Stored Water	Conditional probability		
Rainfall	Increase	No change	Decrease
High	0.6	0.2	0.1
Medium	0.35	0.7	0.6
Low	0.05	0.1	0.3

Table 6.3 shows the CPT for the *Waste* utility node, which is influenced by two nodes: *Feed quantity* (decision node, two states) and *Smolt amount* (chance node, three states). The best outcome for waste is medium *Feed quantity* and low *Smolt amount* because these conditions produce the least waste, and this combination therefore has a utility value of 1.

Table 6.3: The CPT for the utility node Waste, information detailing full node and state descriptions can be seen at the accompanying resource "aquaculture states.xlsx". Utility nodes don't have states. For utility nodes, every possible outcome is ranked from 0 (lowest) to 1 (highest).

Feed quantity	high	high	high	medium	medium	medium
Smolt amount	high	medium	low	high	medium	low
Utility	0	0.5	0.9	0.55	0.95	1

6.3 Optimal decision pathways

There are three decisions and 324 potential decision pathways (setting every decision node to a decision) in the final SEAD model (Figure 6.3) when applied to climate impacts on freshwater finfish aquaculture. The Pareto domination process (a process to remove non optimal pathways – Section 5.5) removed 109 potential pathways. Decisions and decision pathways are shown in Table 6.4, which also shows the number of decisions removed through Pareto domination (in brackets).

Table 6.4: All decision nodes and their potential decision information detailing full node and state descriptions can be seen at the accompanying resource "aquaculture states.xlsx". The numbers in brackets next to each decision show how many of the 109 removed decision paths contained that decision.

Node	Decision 1	Decision 2	Decision 3
License (Agent 2)	Suspend (38)	Limit (35)	No change (36)
Oxygenate (Agent 1)	Oxygenate (14)	Do not oxygenate (95)	N/A
RAS (Agent 1)	Significantly increase (48)	Slightly increase (48)	No change (13)
Feed quantity (Agent 1)	High quantity (69)	Normal quantity (40)	N/A
Husbandry (Agent 3)	Meets criteria (38)	Does not meet criteria (41)	No husbandry (30)
Medicine (Agent 3)	Satisfactory (40)	Does not meet (35)	Does not use (34)

It should be noted that just because a decision had more removed through domination, it is not always the worst decision (this is covered more within Chapter 8).

Pareto domination for this was done with all chance nodes set to *Uncertain*. The decision path with the highest overall utility under these conditions were; *Suspend (License), Oxygenate (Oxygenate), Significantly increase (RAS), Normal quantity (Feed quantity), No husbandry (Husbandry) Satisfactory (Medicine).* Note that Significantly increasing*, RAS* is within the optimal decision path - despite being

removed the joint highest within its decision (alongside slightly increase), showing that *Significantly increasing RAS* is a viable decision when other decisions are aligned with the choice, however choosing non optimal other decisions significantly decreases the value of this choice. Essentially there are less viable pathways with increasing RAS, however those that are viable are more optimal and produce higher all-round utility.

6.4 Climate scenarios

Two scenarios were tested, within the Dialogue section of the SEAD method before the individual meetings took place. The two scenarios were future (20 years - within the life span of a new aquaculture facility, as chosen by agents as suggested by the SEAD method) summer and winters. The SEAD interface shown in Figure 6.4 shows the configuration for *Summer*, for a full breakdown of sections within the SEAD interface see Chapter 5. This configuration had *Temperature* set to *Slightly hotter*, *Rainfall* to *Decrease* and *Stored water* as *Low*.
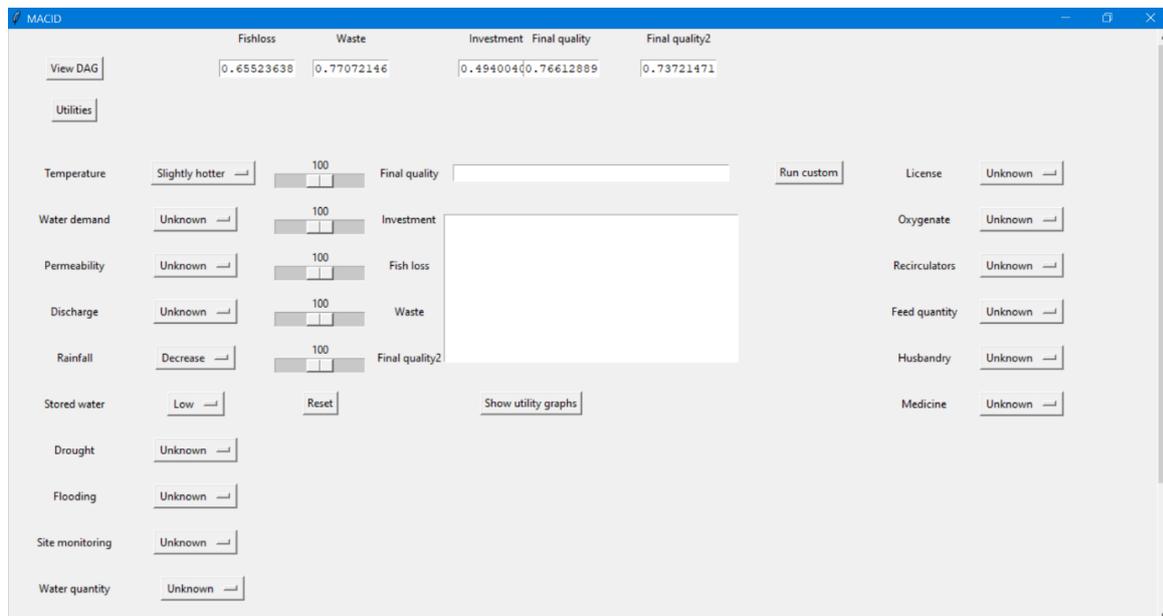
Figure 6.4: The SEAD interface set to simulate a future summer for 20 years within a theoretical area within Scotland.

As shown through the models produced in Chapter 3, future summers pose a threat to the aquaculture industry in Scotland. By changing variables, we saw an overall total utility decrease within the optimal pathways, on average reducing the fish loss utility by 5% and reducing the final quality utility by 3%. Further, each of the posed scenarios had different optimal pathways, however often there was one decision which was consistent. For example, in summer scenarios medicine *Does not use* was always dominated. This is likely linked to the increase in pathogens (which thrive in warmer waters which decrease water quality (Vezzulli et al., 2013).

6.5 Adaption and mitigation pathways for climate resilience

Adaptation pathways are potential pathways which emerge directly through the SEAD interface or through dialogue surrounding the SEAD method, some options agents may feel are not suitable, despite in theory being optimal solutions, which agents may discuss during the dialogue stage. Adaptation pathways were elicited through the methodology laid out within Chapter 4. Within the final portion of the Dialogue stage of the SEAD method, agents discussed various utilities compared with future scenarios. The facilitator and agents configured chance and decision nodes to explore various risks (through altering chance nodes such as rainfall to stimulate flooding) and consequences to the Scottish salmon aquaculture industry.

Four adaptation pathways were identified. These were primarily focused on water storage strategies, RAS and climate mitigation. Moreover, there was some discussion of reduced carbon methods. A point of discussion between all agents was the use of RAS, while they reduced impacts posed by the threat of climate change, they were multitudes of times more expensive than other facilities and had high CO_2e emissions associated with their construction, maintenance and operation, which weren't captured within the SEAD method. Climate mitigation strategies were also discussed, these included adapted building techniques and potentially thinking of ways to introduce healthy algae/macroalgae (seaweed) into the facilities, these adaptation pathways.

6.6 Expanding on Adaptation Pathways

In Section 6.5, potential adaptation and mitigation pathways were elicited and discussed with agents, while the dialogue was only meant to present innovative pathways (which did not need to be viable), this section (Section 6.6) explores these pathways further. The four ideas are split into mitigation (Box 6) and adaptation (Box 6), as shown in Table 6.5.

Table 6.5 Describing if elicited pathways are mitigation or adaptation.

Pathway	Adaptation or mitigation
Reduced CO_2 concrete buildings	Mitigation
Algae inclusion within raceways or other freshwater systems.	Mitigation
Increased RAS	Adaptation
Water storage strategies	Adaptation

Box 6: Defining terms: Mitigation and Adaptation

Climate Change Mitigation: Mitigation means making the impacts of climate change less severe by preventing or reducing the emission of greenhouse gases (GHG) into the atmosphere (European Environment Agency, 2024).

Climate Change Adaptation: Adaptation means anticipating the adverse effects of climate change and taking appropriate action to prevent or minimise the damage they can cause, or taking advantage of opportunities that may arise (European Environment Agency, 2024).

6.6.1 Reduced carbon methods in building

The first potential mitigation pathway was to reduce the CO_2 output of the concrete-based infrastructure within aquaculture. The aim of this mitigation plan was to increase the sustainability within the construction process and lifespan of the site. The suggestion was originally to decrease the carbon footprint of the manufacturing process, working towards making the system carbon neutral. Loannidou et al. (2020) state that "The sharply increasing solid waste generation has raised the environmental concerns worldwide which currently have been escalated to a worrying level.", highlighting that more sustainable construction methods are needed. Following this, Hossain et al. (2020) highlight the need for a more circular economy within construction to circumvent these issues. While no specific methods were mentioned during the dialogue stage, the topic of more sustainable construction has been prominent for many years. The book "sustainable construction" 2008 (Halliday, 2008), provides a foundation, although more innovative techniques have been developed since. Although not stated during elicitation - corresponding literature Kennedy et al. (2014) often includes energy waste reduction within building methods.

Methods for more sustainable construction include the implementation of a circular economy (Hossain et al., 2020) and the use of less carbon-intensive material such as sand (Loannidouet al., 2020)although there are limitations around the implementation, such as sand stock limits and transportation (Lannidou et al., 2020).

While investigating this mitigation pathway, we could not find any publicly available data on what building practices are currently used within Scottish aquaculture, these practices would not be industry-specific and instead company-specific. The Scottish Government (*Building standards technical handbook 2022: non-domestic*, - 2022) framework for non-domestic construction within

Scotland, claimed it was designed with sustainable construction in mind, therefore all new builds will have a reasonable level of sustainability. Further, the handbook states that "Scottish Ministers consider that it is not practicable currently to require every building to incorporate higher performance standards or further sustainability measures. However, developers may wish to gain recognition for building to higher standards." The aquaculture industry may wish to go above and beyond to implement mitigation measures, especially if choosing to integrate high-energy systems such as RAS (covered in Section 6.6.3, a later adaptation pathway).

6.6.2 Algae inclusion within pens

The second mitigation pathway suggest during the dialogue phase was the inclusion of algae within aquaculture systems, such as raceways. Like reduced carbon within construction, this mitigation aimed to reduce the industry's total CO2 output, by reabsorbing this within macroalgae (suggested as seaweed). The idea is that, like trees, macroalgae efficiently absorb carbon therefore, reducing the carbon output of the salmon aquaculture life cycle (Sondak et al., 2017).

Gao & Beardall (2021) page 1 states that "*among efforts to explore ways to achieve carbon neutrality globally or regionally, photosynthetic carbon sequestration by algae has been identified as having immense potential*". Further, research from Froehlich et al. (2019) investigates using seaweed for carbon sequestration, for offsetting finfish emissions, showing Scotland within the native range for seaweed. Froehlich et al. (2019) highlight Scotland as a country which does not have seaweed aquaculture, showing a potential pathway for cultivation in an unused market. This opens the pathway of farming macroalgae in areas not used by aquaculture, to offset CO_2 emissions of the industry.

Limitations of this mitigation pathway address how to restrict the type of algae. Many algae have been shown to be harmful and reduce water quality, leading to loss of stock. This could be exacerbated by algal blooms in the summer heat, which are forecast to become more prevalent with the impacts of climate change. Further, if choosing to offset carbon through seaweed, enforcement and legislation would need to be considered, as well as impacts to ecosystem services (Chapter 2).

6.6.3 Increased implementation of RAS

Another suggested adaptation pathway was to explore the decision *Increased RAS* within the MAID produced by the SEAD method. RAS allow for an entirely enclosed system, significantly reducing the environmental impacts of climate change, while containing any outbreaks of diseases or parasites. RAS are also in a controlled environment and therefore are resilient against increased temperatures, flooding, and drought (Ahmed & Turchini, 2021).

RAS come with many limitations, which is one of the main reasons they are not widely used despite the above factors. Firstly, they are expensive - a recirculation facility is often its own new site. Once built, the operation costs are vastly more expensive than a normal facility, in part due to the increased energy consumption (Badiola et al., 2018). Badiola et al. (2018) state the final limitation as greenhouse gas emissions, which directly conflicts with other proposed mitigation strategies. Although the mitigation strategies would no longer be as impactful, they increase the burden on other industries. Badiola et al. (2018) present a design for a more efficient and less energy-dependent recirculatory, which integrates renewable energy resources hoping to alleviate some of the presented limitations.

6.6.4 Water Storage Strategies

The final adaptation pathway was looking at water storage strategies, this idea looks at storing water through the disparity within the seasons and using this to supplement water in times of drought. Alexander et al. (2019) show that storage structures can significantly absorb more intense rainfall events, which Scotland is expected to see due to the impacts of climate change (Chapter 3). Boelee et ale. (2013) use areas with high variability of rainfall (east and west Africa) to show that temporary water storage tanks can be successful.

Limitations of these tanks are that a variety of storage options are often needed to increase resilience and the increased availability of open water surface may increase the transmission of water-related diseases (Boelee et a., 2013). Further limitations include the amount of high-quality water needed for aquaculture, discussed in Chapter 3. These tanks would not be feasible to fully run a system and would only be able to supplement water. However, when paired with recirculation systems (which have a much less water demand and remove diseases) could be a viable adaptation pathway, perhaps even integrating the suggested mitigation methods to offset the carbon output of the recirculation systems.

6.7 Method reflections and changes.

Section 6.7 covers results from applying the tool to the case study, primarily feedback to improve the SEAD method. The feedback was elicited during the meetings of the final Dialogue stage, in a section not part of the normal SEAD method.

The general feedback given from agents was that the process was lengthy, with it being a complicated method, each meeting would start with a recap of methods and aims, this was addressed during the construction of the final method, which now recommends online calls rather than surveys and is set out in a way that allows the process to be completed within three sessions or

workshops. Agent 1 acknowledged that this was exacerbated by 1) The method happening during a pandemic 2) the method being a pilot study.

Further, the agents could not compare the application to an alternate method such as Bayesian Networks, as they had no previous experience with them. Despite also being a lengthy process Bayesian Networks are still a popular decision-support tool across the environmental industry.

All Agents also stated that although the SEAD interface was easy to use after explanation, as a standalone software there was little instruction, as such guidance and tips have been placed around the interface, clicking any of the question mark boxes produces a pop-up which gives guidance to users.

Section 7.4 further discusses the feedback received from this stage and expands on the changes made.

Chapter 7 Discussion of SEAD method application.

Chapter 7 discusses the results and outcomes of the SEAD method applied to climate change impacts on the Scottish freshwater aquaculture industry. Chapter 7 covers 1) a discussion of the completed structure 2) a discussion of elicited states 3) a discussion of conditional probability table elicitation 4) a discussion from investigating different scenarios 5) A discussion of feedback of the SEAD method.

7.1 Model structure

7.1.1 The scope of the final iteration

The finished structure and accompanying legend (figure 6.3 –Chapter 6, appendix B) were created using a modified Delphi method (Chapter 5). Within the iterative method, a few points of discussion emerged. Once the structure was completed there was a discussion with agents to make sure the model fit within the scope laid out at the start of the structuring process "The current model only aims to look at 'risks posed to Scottish aquaculture through climate change'. Further, this model will be considering a 20-year period (2021-2041)." The agents and facilitator were content that this scope aligned with the finished structure (Figure 6.3).

The facilitator conversed with the three primary agents about some of the more nodes which could be considered outside of the scope, for example, *Discharge*, but agents raised points that this linked to *Water quality*, *Water quality* was deemed potentially at risk through *Flooding*, so including other factors which would pose risk to this node made sense within the context. Therefore, the agents agreed all utilities and decisions would be affected, or affect risks posed climate change. The scope for this PhD research was limited to focus on refining the SEAD method, after using the SEAD method there was agreement that scaling up would be easily achieved and all climate change risks or with more resources – all risks, could have been achieved.

7.1.2 managing subjectivity between different agents

Despite efforts to minimise subjectivity within the SEAD method, eliminating all bias is not always possible. An example of subjectivity between different agents was then node *Monitoring*, *the* node was listed in two separate surveys received from the agents during the structure building part of the SEAD method (accompanying resource 2). One agent placed *Monitoring* as a decision node and another agents as a chance node. Although there is no correct answer for the nodes category the two agents discussed (as per the SEAD method recommendation) and placed it as a chance node. Both agents made compelling points – the choice to monitor a site on any given day is a decision that an agent would make. However, the decision is not always possible, often timetable and weather meant monitoring can only be done some of the time, leading to an element of uncertainty

within the node. Having multiple experts and agents was the solution for many of these subjective debates, with more resources more experts could have been brought into this pilot project.

Most areas of the structure are objective, except utility nodes – these by nature are subjective, and are brought into the SEAD method to allow stakeholder perception to be evaluated alongside risks. Our agents produced utilities which they felt were important to their organisation or body, however, it is very possible that different agents from the same body would produce a different set of utilities.

An example of utility difference is the omission of any climate mitigation utilities, which two of the agents' bodies had recorded as a potential development target, such as reducing the environmental footprint of future facilities– note: adaptation pathways were discussed within the final dialogue which encouraged climate mitigation strategies. The reason for this omission is unknown, this could be due to several reasons – it was not seen as a major issue, they may have been working more on climate resilience rather than focus on climate mitigation or it may have been seen as a utility that none of the agents wanted to take responsibility for i.e., the bystander effect a phenomenon in which participants collectively ignore a problem, assuming another person nearby will help (Hall, 2003). This raises a potential problem within the SEAD method, ownership of responsibility over utilities.

7.1.3 Model states

The node states (see accompanying resource "Aquaculture states.xlsx") were elicited alongside the structure-building process. Experts spent time researching the states independently, aligning them with measurable indicators to ensure the results were actionable and quantifiable.

Feedback from two agents (Agents 1 & 3) highlighted that linking states to real-world indicators made the process more accessible. They reported that having clear, measurable indicators corresponding to simpler state names "made it easier to visualise" the model and "improved accuracy." Based on this feedback, the SEAD method now recommends linking states to real-world indicators or measures whenever feasible, as this approach enhances clarity and usability.

Despite this positive feedback, challenges were identified that complicate the practical application of this method. Experts noted that finding suitable scales and indicators for some chance nodes was particularly difficult. One agent specifically mentioned that translating qualitative scales into precise numerical values required additional context, making it challenging to apply consistently. In cases where indicators had to cover a broad range of interactions, the resulting scales risked becoming too generalised, potentially reducing the accuracy and specificity of the data captured.

Additionally, experts highlighted the cognitive demands of the elicitation process. During the sessions, having the states and their corresponding terms readily available was necessary to ensure clarity and consistency. However, this requirement slowed the process and increased the cognitive load on participants, as they frequently required clarification or needed to revisit definitions. This issue suggests a need to streamline the elicitation process to reduce cognitive burden while maintaining accuracy.

Participant feedback reveals two distinct priorities: enhancing usability and ensuring accuracy. Feedback about the benefits of linking states to indicators (from Agents 1 & 3) emphasised usability, suggesting this step should remain a core recommendation of the SEAD method. Conversely, challenges around finding suitable indicators, translating scales, and reducing cognitive load point to areas where improvements are necessary to maintain accuracy without overburdening participants. To address these competing priorities, the following steps are recommended:

1. **Prioritise Linking States to Indicators:** This approach improves accessibility and accuracy, as noted by multiple agents, and should be retained as a core practice.

2. **Develop Scalable Indicator Frameworks:** Create flexible frameworks or guidance for identifying and applying indicators, especially for chance nodes, to standardise the process and minimise confusion.

3. **Simplify Elicitation Processes:** Streamline the process by providing pre-defined examples, glossaries, or automated tools to reduce the cognitive burden on agents and improve efficiency.

4. **Integrate Feedback Loops:** Establish regular review points during the elicitation process, allowing experts to refine scales and indicators iteratively, ensuring both clarity and precision.

By addressing these points the SEAD method can balance the need for clarity, usability, and accuracy in future applications.

7.2 Decision Pathways

Section 7.2 will discuss decision pathways, how decisions impacted different utilities and using supporting literature to determine why this may be. Throughout this discussion, unless stated otherwise all chance nodes are set to *Uncertain*.

7.2.1 Exploring the impact of decisions and chance nodes.

The decision which impacted utility the most was the implementation of more RAS units, four decisions contributed to the utility node *Investment,* these were 1) *Medicine*, 2) F*eed quantity,* 3) *Husbandry* and 4) *Recirculators*. *Recirculators* accounted for magnitudes more than the other

decisions put together, completely dictating the investment utility node, the *Recirculator* node also reduced *Waste* utility significantly (~80%), decreased *Fish loss* (~30%) and increased *Final quality* (~10%). The decision which had the least impact was *Feed quantity* the node had negligible impact on *Investment* and only a small (~2%) increase in *Smolt quality*.

These decision path results are when all chance nodes are set to the state *Uncertain*, however, the node states can be changed to be appropriate to conditions at a site and the wider environmental context, such as scenarios 1-3 which were requested by agents following the SEAD method (Chapter 2). Changing the node state will mean that decisions have different impacts. A series of conditions and implications for decisions are explored as follows:

- *Scenario 1*: For a new site being planned in an area with lower permeability and higher rainfall than the base case (which are the conditions in some areas in the Scottish highlands, (Holness, 1998).
  This site will be more prone to flooding compared to the base case and therefore husbandry is more desirable at this site to ensure smolt quality stays high.

- *Scenario 2*: For a new site being planned in an area which has comparatively less rainfall than the base case (such as areas shown in Chapter 3) or in an area with high water stress.
  To avoid vulnerability to drought, abstraction should be reduced as much as possible or avoided. As a result, a recirculation becomes more desirable (Elalouf et al., 2017).

- *Scenario 3*: For a new site being planned in an area with higher increase in temperatures than compared to base case. Water quality issues are more likely due to increased pathogens associated with warmer water temperatures (Vezzulli et al., 2022). In a scenario with increased pathogens a RAS would keep water quality at acceptable levels (Ngo et al., 2017). Further, Elalouf et al. (2017) state that the use of a RAS would potentially "increase profits 10 fold".

7.2.2 Weightings

The initial utility weightings proposed by agents were 90% *Final quality* and 10% *Investment* for agent 1, stating that "The aquaculture companies who are currently doing the best are those not afraid to spend", agent 2 said that *Fish loss* and *Fish quality* were seen as similar although a slight preference to reducing *Fish loss*, placing the weightings at 60% *Fish loss* and 40% *Fish quality*. Agent 3 only had one weighting (*Waste*) and therefore it accounted for 100% of their preference.

The initial weightings were used to gather data to discuss during the dialogue, the weightings could be changed using sliders within the SEAD interface (Figure 6.4) during the dialogue session. The SEAD interface allows for customisable weightings during the dialogue phase, this was done to encourage cooperative decision-making. Agent 1 having a strong preference to *Fish quality* aligned

with the Scottish Salmon brand being high quality (*Salmon Scotland,* 2022). Agent 1 (industry representative) stated *Fish quality* was integral to its place as a world-leading fish export, a reduction in this quality could potentially see a decline in profit (*Scottish Salmon: The Economic Facts -* 2021).

7.2.3 Restrictions on decisions

The SEAD method is limited in capturing restrictions, as it struggles to represent them effectively. These restrictions may manifest as decisions that lack realistic viability and could only be executed under extreme circumstances. An example from this case study is *Licensing*.

The decision to allow aquaculture to have more lenient licensing restrictions was presented by agent 3. While this option is technically possible, it could only be considered under theoretical circumstances, agent 3 states the reason for restriction would then need to be considered for all other industries, which agent 3 stated was not a realistic possibility.

These restrictions may lead to wider impacts of decision-making, the SEAD method and other decision-support methods should provide data for decision-makers to make more informed decisions however, context should be applied. Although reducing licensing is often the best decision path (see accompanying resource 2), it is not often viable.

7.3 Current vs future climate scenarios

It's important for decisions to be considered not just for now but for the entire lifecycle of the facility, in this case study we limited the scope to 20 years. It is also important for decision makers to plan for seasonal weather variance, this is why summer and winter scenarios in the year 2041 were simulated. The criteria set out within Chapter 1 (being able to handle wicked problems and deal with uncertainty) mean that the SEAD method excels at future climate scenarios.

Although the simulations (Chapter 6) achieved through using the SEAD method show winter poses less risk to the aquaculture industry, if the trends modelled in Chapter 3 and the literature (Bickle, 2022.; *Climate Change (Scotland) Act 2009*, 2009; *Climate Ready Scotland: Climate Change Adaptation Programme 2019-2024 - Gov.Scot*, 2014) continue the winter season could also pose a significant threat - an increased flooding chance and increased frequency and severity of storms. This poses further risk to aquaculture as in recent years storms have caused damage to Scottish aquaculture pens, one such storm killing 200,000 salmon (Scottish Penned Salmon Escape after Fish Farm Storm, 2022).

7.4 Evaluating the application of the SEAD method to the case study.

The SEAD method was applied to climate change impacts on the freshwater finfish aquaculture industry to integrate stakeholder perception into a climate vulnerable industry. The SEAD method is more time consuming and resource-intensive than a standard Bayesian Network –the question arises, did the SEAD method add value over a Bayesian network? And is that value worthwhile when considering the added time and resources? These questions could not be directly answered by the participating agents, although during dialogue all agents expressed that the SEAD method did positively impact their decision-making capabilities, they could not compare it to a Bayesian Network, as none of the agents had used one.

Instead, we must assess the value added, defined here as the additional benefits and functionality provided by the SEAD method compared to a standard Bayesian network, specifically through the inclusion of multiple stakeholders, decision nodes, and utility nodes, which enhance its capacity for collaborative and decision-focused analysis. The decision nodes allowed agents to see the direct impact of the choices they made; one agent is quoted as saying this "was greatly beneficial to see the direct impact of our decisions". The utilities allowed agents to directly see their outcome preferences change, even on a small scale, participating agents gave positive feedback to this inclusion to risk analysis. Agent 3 expressed that the SEAD method had great potential as a decision-support tool to accompany decision making, but reaffirmed it was not a decision-making tool, but was a "catalyst for discussion".

Moreover, although it didn't occur within the case study, there is potential that by including multiple stakeholders a mutually beneficial cooperative decision could be made, a popular example of this within game theory (in which MAIDs stem from (Koller & Milch, 2001)) is the two generals problem, where multiple stakeholders choosing a non-optimal decision, leads to an optimal outcome. In the context of the SEAD method, an optimal decision refers to a choice that results in the highest weighted utility based on the decision-making framework, indicating the most favourable balance of outcomes according to the predefined criteria. Conversely, a non-optimal decision occurs when the weighted utilities are lower, reflecting a less favourable outcome or a deviation from the best possible choice as calculated by the tool's utility evaluation process. This distinction helps guide decision-makers toward options that maximise overall benefits. A close example of this within our case study is that agent 3 choosing to lower licensing restrictions would usually decrease the "waste" utility by increasing abstraction and potential smolt amount, however, if coordinated with agent 2s decision to increase RAS which would then decrease waste this becomes an optimal decision.

As established, the SEAD method was beneficial as a decision-support tool for climate change impacts on Scottish salmon aquaculture industry. To establish itself as a prominent decision tool the SEAD methods benefits need to be transferable to other disciplines. While not currently performed this is planned as the next stage of the project. From testing the SEAD method and making changes discussed throughout Chapters 6 and 7, there is indication that the SEAD method would be beneficial to any industry which fit the laid out criteria, (a wicked problem, high uncertainty, multiple stakeholders).

7.5 Research limitations and suggestions for improvement

The SEAD method is a "systemic" approach to risk (Schwarcz, 2008), and with this approach, certain systemic challenges are inherent. These include:

1. **Difficulty in gathering data** (compared to isolated risk assessments).
2. **Stakeholder understanding and willingness to participate** (stakeholders often find systemic approaches harder to grasp and may be resistant to change).
3. **Increased time and resource investment** (relative to isolated risk assessment).
4. **Uncertainty in defining links between risks** and determining the extent of their relationships.
5. **Scoping challenges**, as systemic approaches can lead to model expansion beyond manageable limits. Knowing when to stop adding to the model is crucial and should be established early to avoid cyclic risks (Ackermann et al., 2007).

While not all of these challenges were encountered during the case study, they remain relevant for future applications. General limitations of the entire project will be discussed in Chapter 8.

This PhD research was the first substantive application of the SEAD method beyond its pilot phase, making it a learning experience that informed the refinements outlined in Chapter 4. During the method's development, trade-offs between ideal design and practical constraints were necessary. For instance, the inclusion of more experts during expert elicitation, as recommended by the SEAD method, was unfeasible due to resource and time limitations. Similarly, seed questions for chance node elicitation were not derived from unpublished papers, a limitation stemming from the same constraints.

The inclusion of the public as a fourth stakeholder group was also intended, and the SEAD method outlines the process for incorporating such agents (typically associated with utility nodes rather than decision nodes). However, resource limitations prevented their integration within this case study. While the public's involvement would have provided valuable perspectives and enhanced the

systemic approach, this shortcoming was acknowledged and will be prioritised in future applications of the method.

A debated topic around Bayesian Networks, and similar structures, is whether to populate data using mined or artificial intelligence-generated data versus eliciting data from experts. Both approaches have pros and cons, which were addressed in Section 2.4. For this application, all chance nodes were populated via expert elicitation, except for easily accessible and independent data such as temperature. This approach was chosen due to the lack of suitable mined data for creating conditional probability tables. Future iterations of the SEAD method will recommend incorporating AI-driven or data-mined information when feasible, aligning with modern practices in Bayesian Networks (Korb & Nicholson, 2012).

Finally, limitations in testing the tool's reliability and accuracy in identifying strategic pathways emerged. While a roundtable discussion was initially proposed as the preferred method of dialogue, it was not feasible due to resource and scheduling constraints. Furthermore, limitations in the technical knowledge of agents required adaptations to the process. This issue could be mitigated in future iterations by including a final group workshop involving experts not previously engaged with the SEAD method to evaluate and discuss adaptation pathways. While not currently part of the SEAD method, this enhancement could further improve its applicability and outcomes.

Chapter 8 Synthetic data case study

The SEAD method is an adaptable framework designed to investigate complex systems where multiple stakeholders interact under dynamic environmental, social, and economic influences. By facilitating structured interactions, eliciting stakeholder priorities, analysing systemic relationships, and fostering dialogue, SEAD seeks to enable informed decision-making and the development of innovative, collaborative solutions. To further reinforce this after the application of the SEAD method to finfish aquaculture (Chapters 5-7) the SEAD method was applied to a synthetic case study. This was done to test the tools capability without access to agents and show versatility of application to the tool. It was chosen to use one of the previously considered case studies from Chapter 1.

This study applies the method within the context of Scotland's whisky industry to explore the impacts of climate change on water availability and its ripple effects. The study focuses on key interrelated factors, such as whisky quality, ecosystem health, and cultural heritage, while considering the roles and concerns of three stakeholders. By extending SEAD beyond its prior application in aquaculture, this exercise demonstrates the method's versatility across multiple sectors.

8.1 Limitations and strengths of the theoretical approach

This application highlights the adaptability of the SEAD method but also acknowledges the limitations inherent in a theoretical exercise. A key advantage of this approach lies in its ability to demonstrate the method's potential for cross-sectoral relevance. By using a hypothetical scenario, it illustrates how SEAD can be tailored to explore systems as diverse as aquaculture and whisky production. This breadth underscores the method's value as a versatile tool for examining complex, stakeholder-driven systems.

However, as this is a theoretical exercise, certain critical stages of the SEAD process, such as the dialogue phase, cannot take place. The dialogue phase is a cornerstone of the method, fostering innovation and generating actionable solutions through stakeholder engagement. Without real-world interactions, this phase cannot be meaningfully replicated, and the exercise remains confined to highlighting potential issues rather than resolving them.

Furthermore, without the involvement of experts, the elicitation of reliable data for the nodes in the structure is unattainable. This absence restricts the ability to perform detailed analysis or quantify relationships within the system. Consequently, no diagram is formed, instead potential nodes are discussed.

Despite these limitations, the exercise has notable benefits. Illustrating how SEAD can be applied to identify stakeholder concerns and systemic relationships in industries beyond aquaculture.

By providing a structured visualisation of climate change impacts on the whisky industry, this approach highlights potential pathways for future dialogue, even in its theoretical form. Additionally, it demonstrates the method's capacity to integrate diverse stakeholder perspectives, making it a valuable starting point for interdisciplinary collaboration and system-wide innovation.

To illustrate its applicability, this methodology is tested through examining climate change impacts on water availability and its cascading effects on Scotland's whisky industry. This industry is deeply interwoven with economic, environmental, and cultural considerations, making it an ideal context for stakeholder engagement. Further, it highlights key nodes, such as water availability, whisky quality, ecosystem health, and cultural heritage, alongside the causal pathways linking them.

8.2 Agents within the synthetic case study

Stakeholders for the synthetic study were identified through a review of the literature. Additionally, the lay public was included as a stakeholder group to demonstrate the potential capability of SEAD to engage effectively with non-expert audiences. The three chosen agents and they're priorities are laid out below.

- **Distillery Owners**: Concerned with water availability (Visser-Quinn et al., 2021), production continuity (Roberts & Maslin, 2021) , and quality of whisky (Roberts & Maslin, 2021).
- **Environmental Regulators**: Responsible for maintaining sustainable water use , ecosystem health , and compliance with climate adaptation strategies (SEPA Scotch Whisky Sector Plan, Accessed 2024).
- **Lay Public**: Focused on cultural heritage, employment, and environmental impacts (Carmen & Waylen, 2023; Christou et al., 2024; Duffy et al., 2023; Roberts & Maslin, 2021).

8.3 Nodes and States

As the synthetic case study has no elicitation, building the structure for the SEAD method isn't possible, however it's possible to speculate on what some potential chance, decision and utility nodes may be.

Table 8.1: Potential <u>chance</u> nodes if applying the SEAD method to climate change impacts on water affecting the Scottish whisky industry. Nodes were discovered using a mix of primary literature – and where overlap (such as extreme events and water quality) sourced from previous application of the SEAD method (Carmen & Waylen, 2023; Christou et al., 2024; Duffy et al., 2023; Malanca, 2022, Roberts & Maslin, 2021; Scotch Whisky Sector Plan, Accessed 2024).

Nodes	Description
Climate Change	Represents the overarching influence, driving temperature increases, rainfall variability, and extreme weather events.
Water Availability	Reflects how water may be affected by climate change, directly impacting whisky production.
Water Quality	Affected by rainfall patterns, pollution, and temperature, influencing the taste and quality of whisky.
Production Costs	Driven by changes in resource availability and regulatory compliance.
Whisky Quality	Influenced by water quality and production conditions, affecting brand reputation.
Consumer Demand	Reflects the public's response to changes in whisky availability, price, or perceived quality.
Ecosystem Health	Represents the condition of natural environments supporting water sources.
Policy and Regulation	Environmental policies and their stringency affect water usage and conservation efforts.
Cultural Heritage	Represents the cultural significance of whisky production for Scotland and its lay public.
Employment	Indicates job availability in the whisky industry, affecting the public's socio-economic well-being.
Extreme Weather Events	Affects infrastructure, water cycles, and operational resilience.
Public Perception of Sustainability	Reflects how the lay public views industry efforts to mitigate climate impacts.
Export Market Competitiveness	Represents the industry's ability to compete globally based on product quality, pricing, and sustainability image.

8.4 Key Pathways:

The key pathways identified represent critical relationships within the whisky industry system, such as the impact of climate change on water availability, the subsequent effects on whisky quality, and the interplay between ecosystem health and policy decisions. These pathways are explored to understand how interconnected factors shape stakeholder decisions and highlight potential vulnerabilities. However, without empirical data or stakeholder input, this analysis is limited to theoretical speculation. While the pathways provide valuable insights into possible dynamics, the absence of real-world validation means the findings remain conceptual rather than definitive, serving primarily as a framework for future investigation.

Climate Change → Water Availability → Whisky Quality: Direct impacts on resource availability influence production and product quality.

Water Availability → Ecosystem Health → Policy and Regulation: Water scarcity can harm ecosystems, prompting stricter regulations.

Policy and Regulation → Production Costs → Consumer Demand: Policies may increase costs, potentially reducing demand if prices rise.

8.5 Stakeholder decisions and utilities:

In the context of the SEAD method, potential utility and decision nodes represent critical points where stakeholders can influence or benefit from the system's dynamics. Utility nodes capture outcomes valued by stakeholders, such as whisky quality, cultural heritage preservation, and ecosystem health, while decision nodes highlight actionable areas like water management strategies, technological investment, and policy interventions. These nodes provide a foundation for identifying where decisions might yield the greatest impact or address key vulnerabilities. By structuring these elements, the SEAD method facilitates a better understanding of how stakeholder priorities and actions intersect, even though the absence of empirical data limits this exercise to conceptual exploration.

Distillery owners

- **Decisions**: Investment in water-saving technologies, sourcing alternative water supplies, and adjusting production processes to maintain whisky quality.
- **Utilities**: Preserving product quality, ensuring cost efficiency, and sustaining market competitiveness.

Environmental Regulators and Policy Makers

- **Decisions**: Implementing water use restrictions, setting sustainability standards for the industry, and safeguarding ecosystems linked to water sources.
- **Utilities**: Protecting water resources, ensuring compliance with climate adaptation policies, and balancing economic and environmental goals.

Lay Public

- **Decisions**: Advocacy for cultural heritage preservation, support or opposition to industry practices, and participation in community-led sustainability initiatives.
- **Interests**: Maintaining employment opportunities, protecting local environments, and preserving the cultural significance of whisky production.

8.6 Synthetic application outputs

The synthetic data approach provides an alternate means of applying the SEAD method, revealing key relationships and pathways within the whisky industry's socio-environmental system. By simulating stakeholder engagement—including distillery owners, regulators, and the lay public—the method highlights how diverse perspectives can inform decision-making. Utility and decision nodes serve as focal points for understanding where stakeholders' priorities converge and how targeted actions may influence outcomes such as whisky quality, cultural heritage preservation, and sustainability.

However, this synthetic approach is inherently limited by the absence of empirical data, a challenge prevalent in environments like this where systems are complex and data is often sparse or fragmented, as discussed in Chapter 2. This limitation underlines the critical importance of elicitation, which is central to the SEAD method. Elicitation bridges knowledge gaps by drawing on the insights of domain experts and stakeholders, providing richer, context-specific data to inform utility and decision nodes. While the theoretical exercise offers a conceptual framework, the lack of real-world validation restricts its practical application.

In environments with greater access to empirical data, this application could potentially reveal more precise dynamics and actionable insights, this is explored further in Section 9.4.5. However, in its current form, the synthetic approach does not achieve its intended function, as it lacks the grounded perspective that only actual stakeholders can provide. Rather than undermining the SEAD method, this reinforces its strength: the ability to incorporate authentic data and foster meaningful dialogue among real agents. The synthetic applications' shortcomings highlight the necessity of direct

stakeholder engagement to fully realise the method's potential for delivering collaborative, sustainable solutions.

Chapter 9 Discussion

This thesis aimed to complete four objectives 1) Investigate decision-making methods and identify gaps in existing decision-making tools [Chapter 2] 2) Develop a generalisable decision-support tool and associated methodology [achieved in Chapter 3] 3) Identify a suitable case study to apply, test and refine the decision-support tool, with particular focus on climate change vulnerability. [achieved Chapter 4] 4) Apply, test and refine the decision-support tool using the chosen case study (freshwater finfish aquaculture industry in Scotland) to explore emerging climate change adaptation and mitigation pathways [achieved in Chapters 5-8]. The outcomes from each objective collectively tell a complete story, starting by showing a vulnerability within an industry, creating a decision-support tool, and then applying the decision-support tool to the chosen industry, leading to ways the industry can adapt and mitigate the vulnerability. Chapter 9 provides an overarching discussion of the overarching story that the research in this thesis presents. First, the relevance and integrity of the work is discussed, and the research limitations assessed before further avenues of research are proposed.

9.1 Relevance of the research and results

Since this PhD research started in October 2019 many of the environmental threats identified in this thesis have become more apparent, and, with this, the need for concise 'whole systems' decision-making has become increasingly and more urgently needed. The salmon industry's climate vulnerability is becoming more prominent within the UK and in mainstream media. The BBC (Farmed Salmon Production Drops by a Fifth in Scotland - BBC News, 2022) reported that 2022 saw an 18% drop in Scottish salmon- the largest food export, compared to 2021 (down 36,200 tonnes). The loss of 36,200 tonnes was pinned to a bloom in micro-jellyfish due to, the article states, rising sea temperatures. Highlighting the interconnected nature of risks and challenges within the industry and increased attention to these issues in the public eye. This specific example (increased temperature leads to increased jellyfish, leading to decreased water quality, leading to increased fish loss) is exactly the kind of risk that the SEAD method excels at explicating to inform and optimise decision-making to reduce that risk.

The identification of vulnerability which led to the creation and application of the SEAD method in the industry, may lead to a higher quality of decisions if applied to a wider scope. This highlights the increasing need for decision-support tools such as SEAD within environmental management.

9.2 Verification, value added and use of the SEAD method

Verification ensures that the built system—in this case, the SEAD method—achieves its intended goals. As stated in Chapter 1, "accurate data" is essential for driving decision support. However, in

Chapter 6, we acknowledged that the SEAD method does not include model verification due to the complexities associated with verifying uncertainties. This raises the question: how can we be confident that the SEAD method provides accurate data?

The data elicitation processes used throughout the SEAD method have been proven reliable and verified in near future applications (applications in which verification could take place shortly after the research), particularly for Bayesian Networks (Quigley et al., 2018). Bayesian Networks are known for providing valuable decision-support and risk analysis. So, why should we opt for the SEAD method, and are its additional features worth the investment of time?

The SEAD method offers two main advantages over Bayesian Networks: the involvement of multiple agents and the use of utility functions. Section 2.5 demonstrates the value of incorporating multiple agents. Utility functions add significant insight to the tool, enabling more informed decision-making. They allow stakeholders, who may not have control over decisions but are heavily impacted by them, to have their perceptions quantified. This information can be invaluable to decision-makers.

When compared to Bayesian Networks, the SEAD method requires only a modest additional effort. Utility functions, the shortest time to elicit node, often take less than an hour per node to complete. While the SEAD method may not always be preferable over Bayesian Networks (particularly if the main focus is on just risk analysis), in many cases, it offers substantial benefits that justify its use.

9.3 Research Limitations

The PhD research relied on multiple stakeholder participants, whose availability and capacity to engage were significantly impacted by external factors, including a major national security breach and the COVID-19 pandemic. These events caused a cascade of long-lasting challenges, disrupting schedules, slowing research progress, and hindering sustained stakeholder engagement. The impact of these disruptions was exacerbated by difficulties in accessing agents. Many of those contacted did not respond or were unable to participate, while some potential participants requested compensation or remuneration for their time. While such requests are both reasonable and important to reduce barriers to participation, the financial resources required were beyond the scope of this PhD research.

These limitations meant fewer experts were involved throughout the project. For example, during the conditional probability table elicitation, having multiple stakeholders would have significantly strengthened the elicitation protocol testing. Ideally, best practices for the SEAD method involve several agents per node, with the classical method (detailed in Chapter 4) used to combine elicited data. However, resource constraints limited the project to one agent per node. Nonetheless, all

experts involved scored well on the seed question segment of the classical method (Chapter 6), which justified the decision to proceed with the minimal number of participants.

Bias stemming from agent availability influenced the research in other ways as well. For instance, due to limited stakeholder engagement, the dialogue stage of the SEAD method was conducted solely between the agent and facilitator, rather than within a group dialogue setting as originally envisioned. This deviation from the ideal methodology potentially restricted the opportunity for cooperative decision-making and the incorporation of diverse perspectives, which may have influenced the depth and robustness of the insights generated.

Additionally, the challenges related to agent responsiveness introduce potential biases, particularly concerning the representativeness of the data collected. Participants who responded may reflect a subset of stakeholders with specific capacities or perspectives, rather than a full representation of the stakeholder pool. This limitation underscores the need for future iterations of the SEAD method to address these issues, possibly by exploring alternate elicitation systems, such as the IDEA method (discussed in Chapter 6), which might reduce the reliance on a large number of agents while maintaining methodological rigor.

By acknowledging these limitations and their influence on the research outcomes, this study highlights the importance of adaptable methodologies and the need to balance practical constraints with theoretical best practices in stakeholder-driven research.

9.4 Expanding the SEAD method.

Several branching projects were envisioned during the creation of the SEAD method, which look to apply the method to other environments or alter the method to fit other niches.

9.4.1 Applying the SEAD method to other industries.

Currently, avenues are being explored to apply the SEAD method to individual aquaculture sites within Scotland. Doing so would involve working to find stakeholders of the site, customising the pre-existing structure to fit the site (adding more agents if needed), customising node states within the SEAD interface to fit the site, and then eliciting optimal decision pathways (and adaptation pathways).

While aquaculture was chosen for a case study through which to develop and apply the SEAD method, multiple suitable industries were highlighted in Chapter 3, including Scottish whisky industry. In the time since making this selection the climate vulnerability of Scotch whisky has become more apparent (Roberts & Maslin, 2022), potentially increasing the relevance of this industry for applying the SEAD method. By Scottish law (Legal Protection in the UK, 2022) whisky

distillation can only use water, cereals, and yeast. An increase in droughts and heatwaves (discussed in <u>Chapter 2</u> and <u>Chapter 3</u>) can cause cereal loss and water shortage. Like Scottish aquaculture, Scotch whisky has multiple stages (malting, fermentation, distillation, and maturation), so applying a broader-scoped SEAD method to the whisky industry (rather than simply a synthetic approach) within Scotland would be a natural next step.

9.4.2 Open source conditional probability tables.

As the SEAD method gets applied to new and different contexts, a shareable database of previously used conditional probability tables could be made available, reducing time to implement the SEAD method. This technique has seen some use such as by (Howick et al., 2006), which created a database of risks. This progression would rely on probability conditional probability tables being added to a publicly accessible database.

However, there could be limitations to such an approach: previously used tables may be out of date, and furthermore, the tables would struggle to encapsulate the complexities within individual MAIDs such as location and other chance nodes. Implementation of the idea would also face limitations, including hosting and data privacy issues, as such the idea was not pursued in this thesis.

Finally, while not currently an established and verified approach, there is potential that progress in AI-generated Bayesian Networks may allow for databases of AI generated conditional probabilities to be populated and shared.

9.4.4 A qualitative SEAD method for decision making.

Not all decision-support tools rely on quantitative data. The primary purpose of the SEAD method is to assist decision-makers relying on qualitative approaches to also be able to optimise decision-making on complex issues in a resource efficient and transparent way. In a similar way to how the SEAD method is built upon the foundation of a Bayesian Network, a qualitative SEAD method would be built upon causal maps, such as those used by (Ackermann et al., 2014; Dawid, 2002) which excel at mapping strategic thought and gives a systems view of risks. A qualitative SEAD method would then work on a structured methodology to elicit a MAID, then promote discussions of risks, decisions, and adaptation pathways, a qualitative SEAD method could be done within one workshop creating a resource and time-reduced method.

9.4.5 A synthetic approach with AI

Advancements in artificial intelligence (AI) offer the potential to bridge the gap between synthetic and real-world scenarios, particularly in frameworks like the SEAD method. AI models can simulate stakeholder behaviours, preferences, and decisions by integrating large datasets, creating synthetic

agents that mirror real-world dynamics. This could allow for the representation of utility and decision nodes with greater precision and flexibility, even in data-scarce environments. AI-driven simulations could identify pathways, explore potential outcomes, and generate insights that would otherwise require extensive stakeholder engagement. Such tools may complement real-world processes, offering a scalable and efficient means to test hypotheses or visualise complex interactions.

However, the implications of using AI to represent human utilities and preferences are profound, both ethically and practically. While AI can analyse historical data and patterns, it cannot fully encapsulate the nuanced, evolving nature of human values, emotions, and context-specific preferences. Attempting to replicate these with AI risks oversimplifying or misrepresenting stakeholder priorities, potentially leading to decisions that do not align with real-world needs. Moreover, there are moral considerations surrounding the use of synthetic agents in decision-making. For instance, if AI models are treated as proxies for real stakeholders, whose values and interests might they unintentionally prioritise or exclude? Without transparency and accountability, such systems could inadvertently perpetuate biases or undermine trust in stakeholder engagement processes.

Another critical question is whether AI can ever fully represent a person's utilities and wants. Human decision-making is influenced by subjective experiences, social dynamics, and ethical considerations that are often difficult to quantify or predict. While AI can approximate preferences based on behavioural data, it cannot replicate the deeper layers of human identity, such as personal motivations or moral frameworks. This limitation raises concerns about the validity of using AI as a stand-in for human engagement, particularly in collaborative processes where empathy and dialogue play central roles.

Ultimately, while AI advancements hold promise for augmenting synthetic approaches, they should not replace real-world stakeholder involvement. Instead, AI tools could serve as a complementary layer, providing preliminary insights or testing scenarios before engaging with actual stakeholders. Balancing the strengths of AI with the irreplaceable richness of human input will be essential for ensuring that methodologies like SEAD remain inclusive, ethical, and effective.

Chapter 10 Conclusions

This PhD aimed to enhance decision-making processes within complex environments characterised by wicked problems, multiple stakeholders, and high levels of uncertainty. Central to this aim was developing and refining an innovative decision-support tool that could handle such conditions including different stakeholder values. In this Chapter, research progress, findings and contributions will be mapped against each of the four objectives (Section 1.3) and highlight the key research points stemming from each.

10.1 Investigating decision-making methods to identify suitable decision-support tools.

Objective 1 was to investigate decision-making methods to identify suitable decision-support tools which would fit our laid-out criteria. In the absence of an appropriate existing tool, we developed a new method, called the SEAD (Stakeholder interaction, Elicitation, Analysis, Dialogue) method. The development of the method is laid out in Chapter 4 which details the SEAD method and justifies the choices made throughout. We provided a comprehensive explanation of how the SEAD method was applied to support the development of Multi-Agent Influence Diagrams (MAIDs) for performing risk analysis.

The conclusions from Objective 1 are

1) **We need a DST for climate adaption.** Climate adaptation is a complex, multi-faceted challenge that requires informed decision-making to mitigate risks and enhance resilience. A dedicated DST is needed to support policymakers, researchers, and practitioners in making evidence-based decisions regarding climate adaptation strategies

2) **No such tool exists.** Despite the growing need for climate adaptation strategies, no comprehensive decision-support tool currently exists that effectively integrates multi-stakeholder perspective and can handle uncertainties.

3) **We define the criteria needed for such a tool.** To develop a functional and impactful DST, clear criteria must be established based on best practices from decision science, risk assessment, and stakeholder engagement methodologies.

10.2 Develop a generalisable decision-support tool and associated methodology

Objective 2 was to develop a generalisable decision-support tool and associated methodology. This was the creation of the SEAD method and the foundation for this thesis. This was achieved throughout Chapter 3.

The contributions and key research points of Objective 2 are:

1) **Creation and Justification of SEAD Method:** <u>Section 3.2 </u>outlines the process of developing the SEAD (Stakeholder identification, Elicitation, Analysis, Dialogue) method. Justification for methodological choices is provided throughout the creation process.

2) **Expansion of MAIDs**: The SEAD method expands on the application of Multi-Agent Influence Diagrams for risk analysis. This represents an innovative application of MAIDs beyond their original game-theoretic context.

3) **SEAD method evaluation:** <u>Section 3.4</u> evaluates the SEAD method, discusses other suitable applications of the SEAD method and highlights the importance of the results.

10.3 Demonstrating the vulnerabilities that climate change posed to the freshwater finfish aquaculture industry.

Objective three was to demonstrate the vulnerabilities that climate change posed to the freshwater finfish aquaculture industry. How this objective was approached and achieved is laid out in <u>Chapter 4</u>, where we justified why decision-making to reduce climate change impacts on the Scottish freshwater finfish aquaculture industry was used a case study for our research.

The contributions and key research points of Objective 3 are:

1) **Risk Analysis**. <u>Section 3.2</u> investigates vulnerabilities to various climate-induced risks, such as freshwater quality and availability, fish escapes due to storm damage, and disease outbreaks. Importantly, we find that these risks are exacerbated by factors like increased heavy rainfall and population growth. Overall, a comprehensive risk inventory is presented.

2) **Geographic and temporal considerations.** <u>Section 3.4</u> presents spatial analyses showing how abstraction hotspots (e.g., Southern Highlands and West Dundee) interact with projected climate changes, and anticipates increased resource competition. The geographic and temporal insight emphasizes the complex interplay between human activity and environmental change.

3) **Policy and management implications.** <u>Section 3.5</u> underscores the importance of adequate water management, as highlighted by the Scottish Environmental Protection Agency's (SEPA) finfish aquaculture sector plan. By addressing the need for water in the right place, quantity, and quality, the research contributes to policy and management discussions, emphasising the need for strategic planning and stakeholder collaboration.

4) **Validation of Case Study**. The Scottish finfish freshwater aquaculture industry is validated as a suitable case study for the proposed decision-support tool, demonstrating its relevance and practical implications. This is shown through meeting the criteria laid out in Chapter 1. Further, we show that a synthetic case study in <u>Chapter 8</u>, and show the need for stakeholder dialogue.

In conclusion, the research contribution from objective one offers a thorough analysis of climate change impacts on aquaculture in Scotland.

10.4 Applying the tool to the case study sector identified in Objective 1.

Objective 4 was to "Apply, test and refine the decision-support tool ". This objective was achieved in Chapters 5-8.

In Chapter 5, the SEAD method was first applied to a pilot study and then to the case study on climate change and its impacts on Scottish finfish aquaculture.

In Chapter 6, we view the results of applying the SEAD method when applied to the Scottish freshwater aquaculture industry. This Chapter covered results from 1) structure building, 2) state elicitation, 3) conditional probability table elicitation, 4) investigating different scenarios, and 5) feedback on the SEAD methodology.

Chapter 7 discussed the results and outcomes of the SEAD method applied to the case study. This Chapter included 1) a discussion of the completed structure, 2) a discussion of elicited states, 3) a discussion of conditional probability table elicitation, 4) a discussion of different scenarios investigated, and 5) a discussion of feedback on the SEAD method.

Chapter 8 applied the tool to a synthetic case study to see how the SEAD method would fare with no stakeholder input.

The contributions and key research points of the research that stemmed from Objective 4 are:

1) **Testing through pilot study**. In Chapter 5, the SEAD method was tested through a pilot study before its application to the case study on climate change impacts on Scottish finfish aquaculture. This step demonstrated the method's feasibility and reliability in a controlled environment, establishing a foundation for its broader application.

2) **Application to real-world case study.** The application of the SEAD method to the Scottish freshwater aquaculture industry, detailed in Chapter 6, provided concrete evidence of its effectiveness in addressing real-world issues.

3) **Detailed methodological insights**. By detailing the processes of structure building, state elicitation, and conditional probability table elicitation, the research offered in-depth methodological insights. These insights are crucial for understanding how the SEAD method can be effectively implemented in various contexts.

4) **Scenario analysis.** investigating different scenarios using the SEAD method provided a comprehensive understanding of potential outcomes and risks. This analysis is vital for stakeholders in the aquaculture industry to make informed decisions regarding climate change adaptation and risk management.

5) **Feedback integration**. Incorporating feedback on the SEAD method highlighted its strengths and areas for improvement.

6) **Contribution to Decision-support Tools.** The research significantly contributed to the field of decision-support tools, particularly in the context of climate change and aquaculture. By presenting a novel method and demonstrating its practical applications, the study filled a critical gap in the literature and provided a valuable resource for future research and industry practices.

7) **Real stakeholders are still needed.** Testing the synthetic case study in Chapter 8 shows the need for real stakeholders, although this may change with advancing technologies such as artificial intelligence.

In conclusion, the research within Objective 3 successfully developed and validated the SEAD method - a novel decision-support tool, through a pilot study and a case study on climate change impacts on Scottish freshwater aquaculture. This method demonstrated its effectiveness in structure building, state elicitation, conditional probability table elicitation, scenario analysis, and incorporating feedback, providing a robust framework for informed decision-making and climate adaptation strategies in the aquaculture industry.

10.5 Investigating emerging adaptation and mitigation pathways.

The second part of objective 4 was to investigate emerging adaptation and mitigation pathways. This was initially addressed in Section 5.5 and further expanded upon in Sections 6.4 through 6.6. In Section 6.5, potential adaptation and mitigation pathways were elicited and discussed with agents. While the dialogue was intended to present innovative pathways without needing to ensure their viability, Section 6.6 explores these pathways.

The contributions and key research points from Objective 4 offer several innovative adaptation and mitigation pathways for the Scottish finfish aquaculture industry in response to climate change. Key contributions include:

1) **Identification and exploration of pathways**. The study identified and explored four key pathways, distinguishing between mitigation and adaptation strategies as shown in Table 6.1. This differentiation provides clarity on how each pathway contributes to either reducing carbon emissions or adapting to climate impacts.

2) **Real-world applicability and Industry relevance.** By applying these pathways to the Scottish finfish aquaculture industry, the research provides practical insights and actionable recommendations for industry stakeholders. This real-world applicability ensures that the contributions are not only theoretical but also relevant and useful for addressing current and future climate challenges in aquaculture.

In conclusion, the research advances the field by offering innovative, practical, and theoretically grounded pathways for mitigating and adapting to the impacts of climate change in the aquaculture industry, supported by detailed exploration and discussion of each proposed pathway.

10.5 Further work

10.5.1 Testing expert limits.

Further work on the SEAD method would include testing limits of experts needed. By reducing resources needed within the SEAD method it will make it more widely accessible. With the tool excelling at climate change risk adaptation, making the tool as widely accessible is paramount to tackle the issues highlighted in Chapter 2 and Chapter 3.

10.5.2 Longevity of results

The SEAD method captures agents' perceptions at the time of elicitation – for uncertain scenarios. As time passes these perceptions may change. While these changes would be easy to update within the model (by performing the elicitation again and updating the CPTs), further work would include a structured approach to this. This may include an approach to understand 1) optimal intervals between updates and 2) how to handle new experts (which would be inevitable over such time frames) 3) verifying past uncertainties.

10.5.3 Linear approach of the SEAD method

In its current state the SEAD method is presented as a purely linear approach. However, often real-world scenarios (especially those involving wicked problems) are not linear. New information is discovered during the process, experts may decide to contribute once elicitation has been completed, new agents may emerge (Or current agents may no longer be relevant). Further work would be exploring this flexibility.

10.5.4 Future projects

Emerging projects are already demonstrating how the SEAD method could be applied to new contexts. For instance, one such future project involves a baseline study investigating the effects of tides and freshwater discharge on estuaries and open coastal habitats. By analysing species composition and abundance in relation to spatial–temporal fluid density variations, this study aims

to enhance climate change scenario modelling for marine ecosystems. It is intended the SEAD method could provide a structured framework for integrating diverse stakeholder perspectives, managing uncertainties, and synthesizing data from ecological, hydrological, and climate models.

Other applications which have emerged through discussion while presenting the SEAD method include urban planning to address climate resilience in densely populated regions, agricultural adaptations in response to shifting climatic conditions, or even broader international collaborations focusing on cross-border environmental challenges. The methodology's adaptability positions it as a valuable tool for climate research fields, ranging from renewable energy planning to biodiversity conservation, where decisions must reconcile competing priorities and navigate significant uncertainties.

10.6 Concluding remarks.

This thesis aimed to address a niche within decision-support tools by creating a structured method which incorporated risk analysis, stakeholder perceptions, and decisions.

The tool had to:

1. Highlight uncertainty—to deal with multiple scenarios and unknowns.

2. Incorporate multiple stakeholder inputs—alleviating problems caused by multiple stakeholder priorities.

3. Handle wicked problems—to allow for use within complex scenarios, such as climate change.

The research in this thesis showed that the created tool, known as the SEAD method, met the required criteria. This was achieved by identifying an industry which was vulnerable to the impacts of climate change within Scotland, Scottish finfish aquaculture, creating a decision-support tool which fits the above criteria, and applying the SEAD decision-support tool to the Scottish finfish aquaculture industry.

The research presented in this thesis highlights the SEAD method's potential to be adapted for use beyond the Scottish finfish aquaculture sector. The methodology is industry-agnostic and could address complex decision-making scenarios across a wide range of sectors, communities, and geographic regions.

The research presented in this thesis suggests that there is a need for and value in the SEAD method for the case study industry for which it was applied: the Scottish Finfish sector, which must both decarbonise and adapt if it is to continue, let alone grow as anticipated in future decades.

Appendix A: Full size figures from Chapter 3

Figure 3.1a Spatial distribution of all freshwater, finfish aquaculture sites within Scotland. Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.
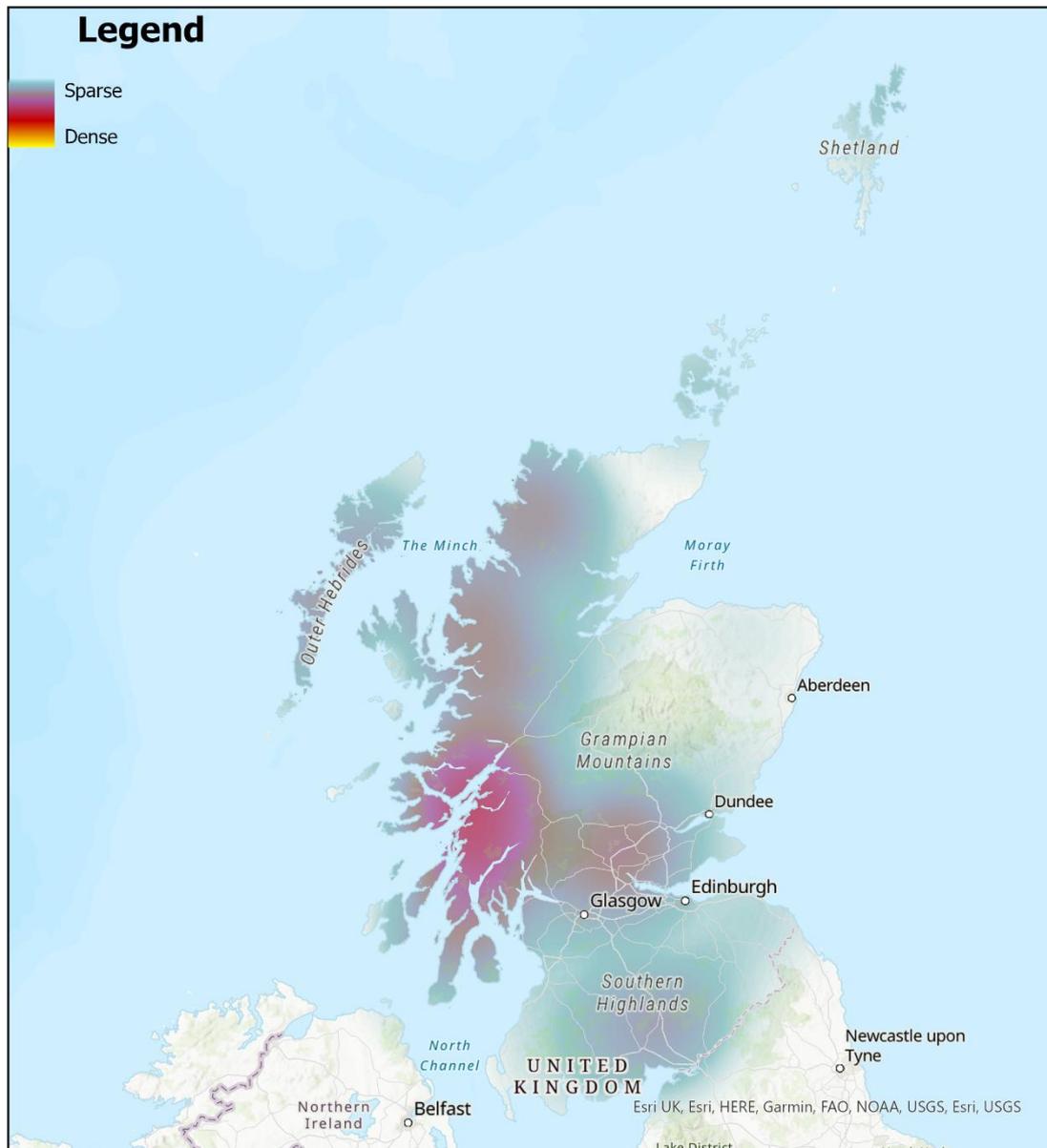
Figure 3.1b: Heat map showing spatial distribution of freshwater, finfish aquaculture sites, within Scotland. Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.
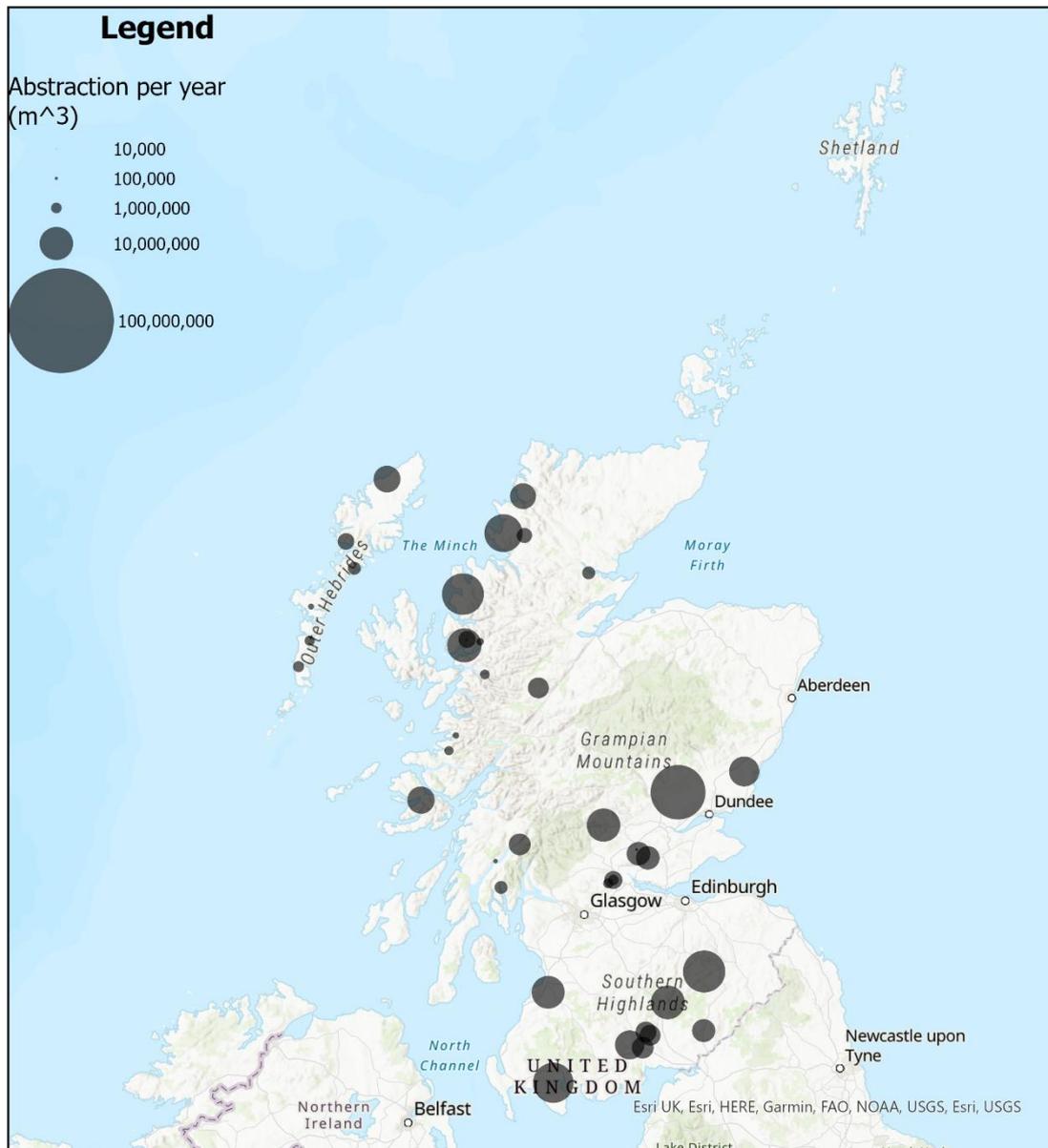
Figure 3.3: Freshwater, finfish aquaculture abstraction(m^3/y) around Scotland. Map compiled using data provided by SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.
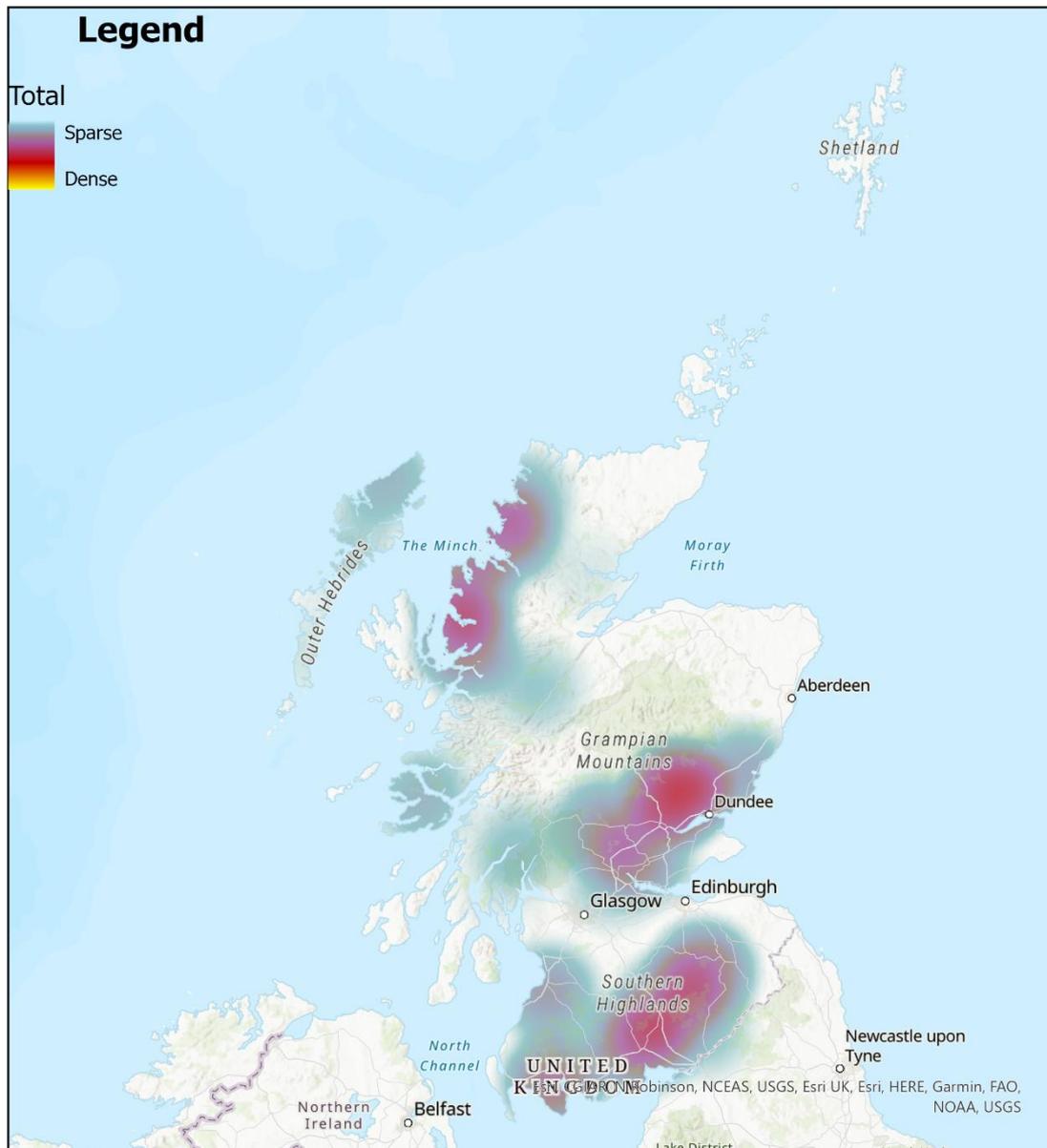
Figure 3.4: A heat map showing available data of water abstraction. (Full sized image found within appendices C2). Map compiled using data provided by SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.
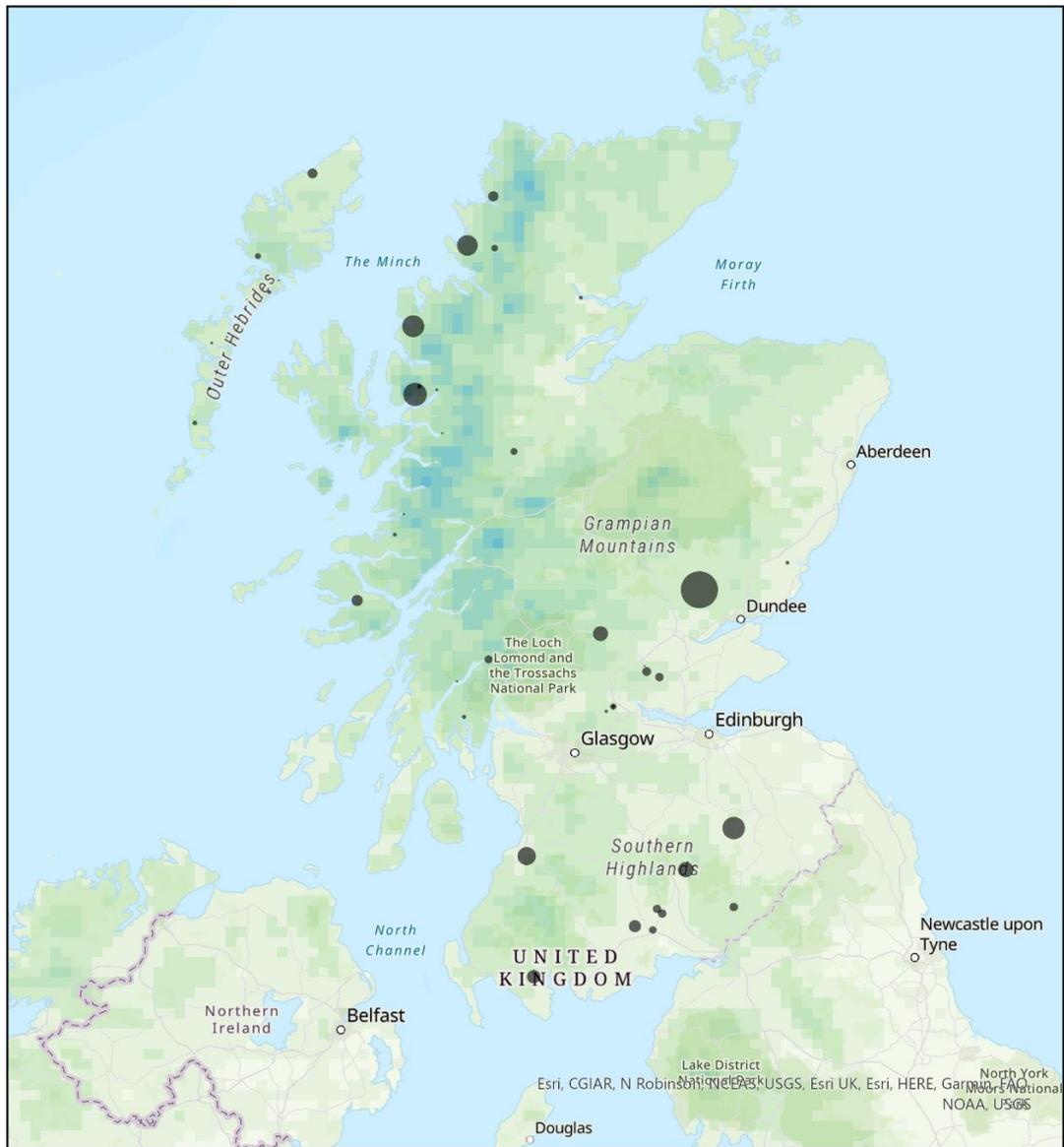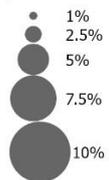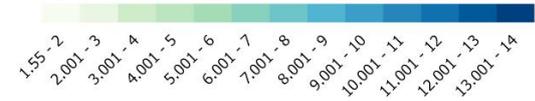
Figure 3.5a: Summer 2021 precipitation (mm/day) for Scotland, plotted alongside aquaculture water abstraction for correlating season. Precipitation data sourced from UKCP18, abstraction data sourced from SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.
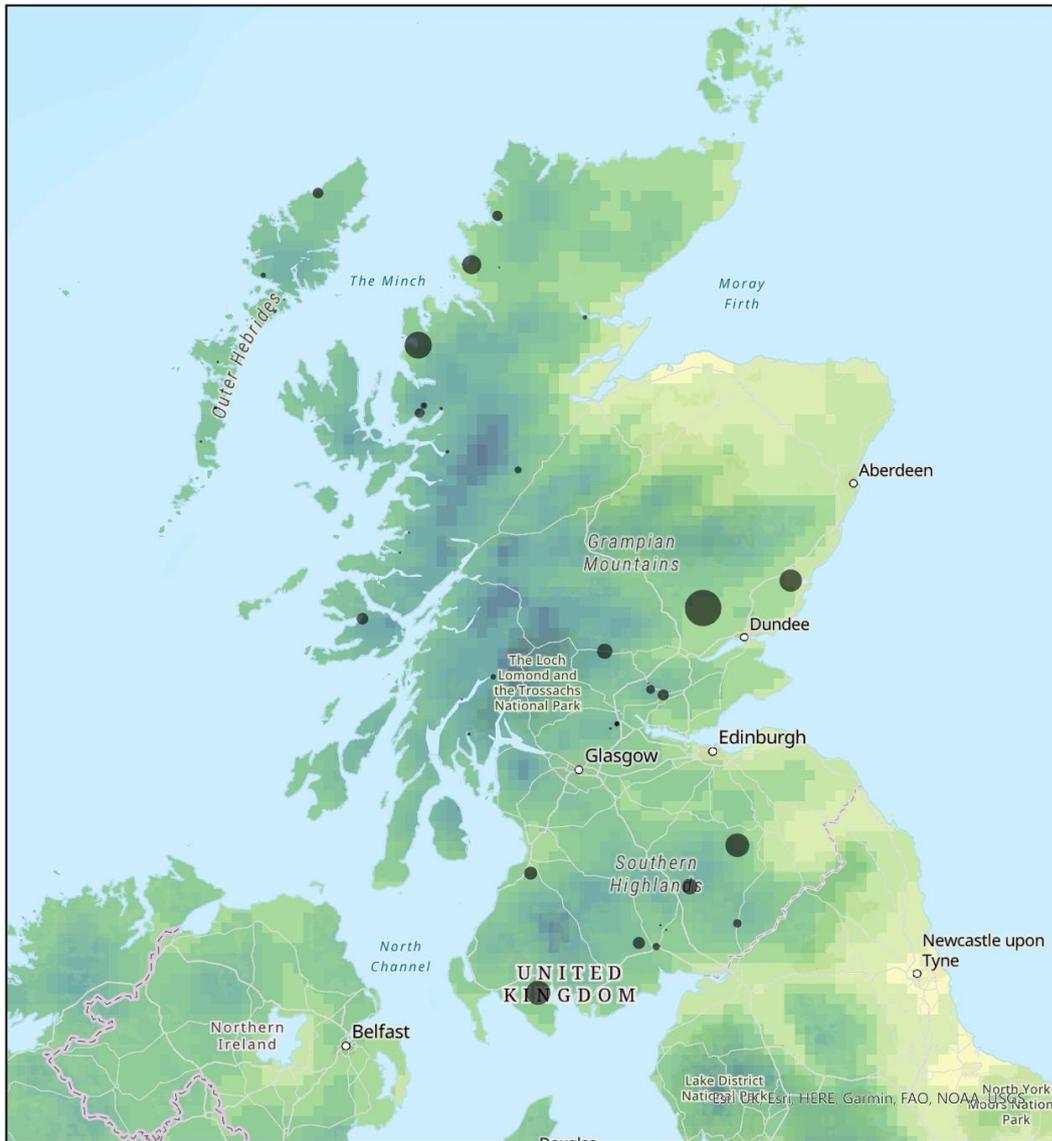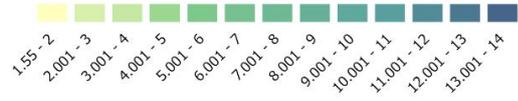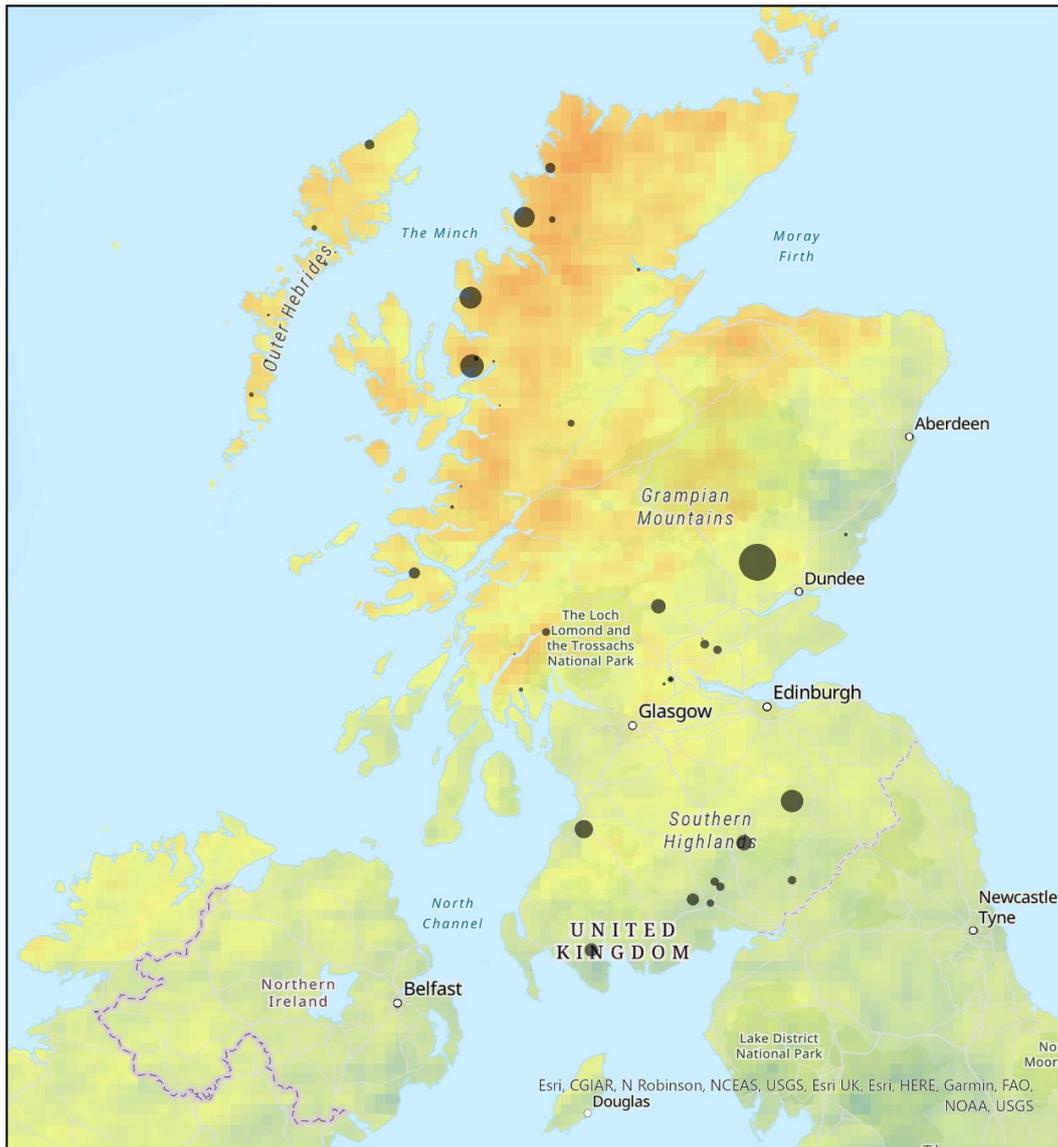
Figure 3.5b: Winter 2021 precipitation (mm/day) for Scotland, plotted alongside aquaculture water abstraction for correlating season. Precipitation data sourced from UKCP18, abstraction data sourced from SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.

Legend

Summer (m3) as percent of total
- · 1%
- • 2.5%
- ● 5%
- ● 7.5%
- ● 10%

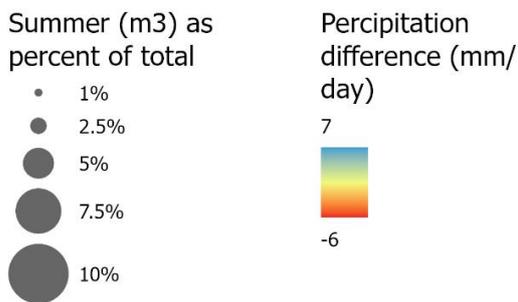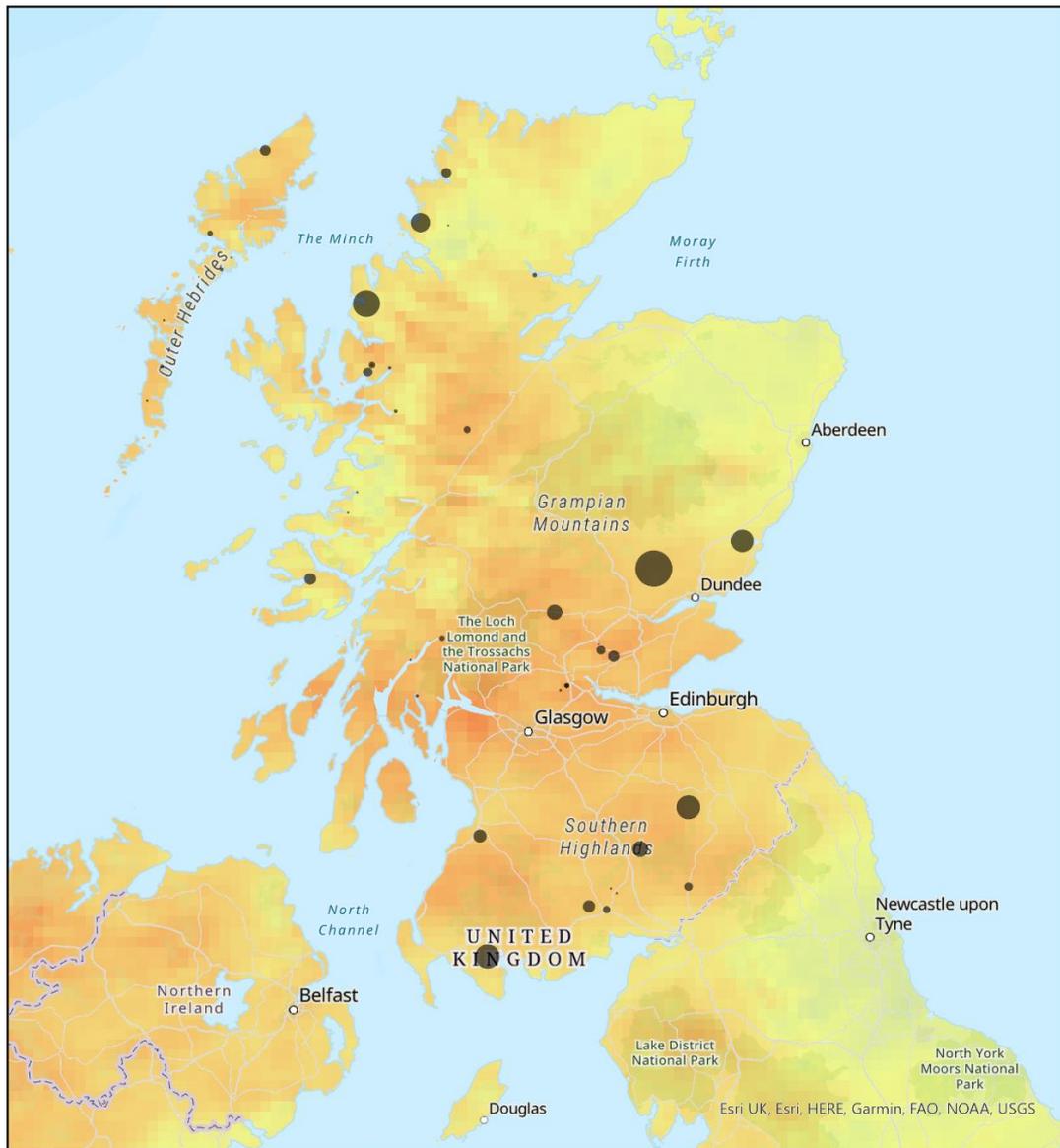Percipitation difference (mm/day)

7

-6
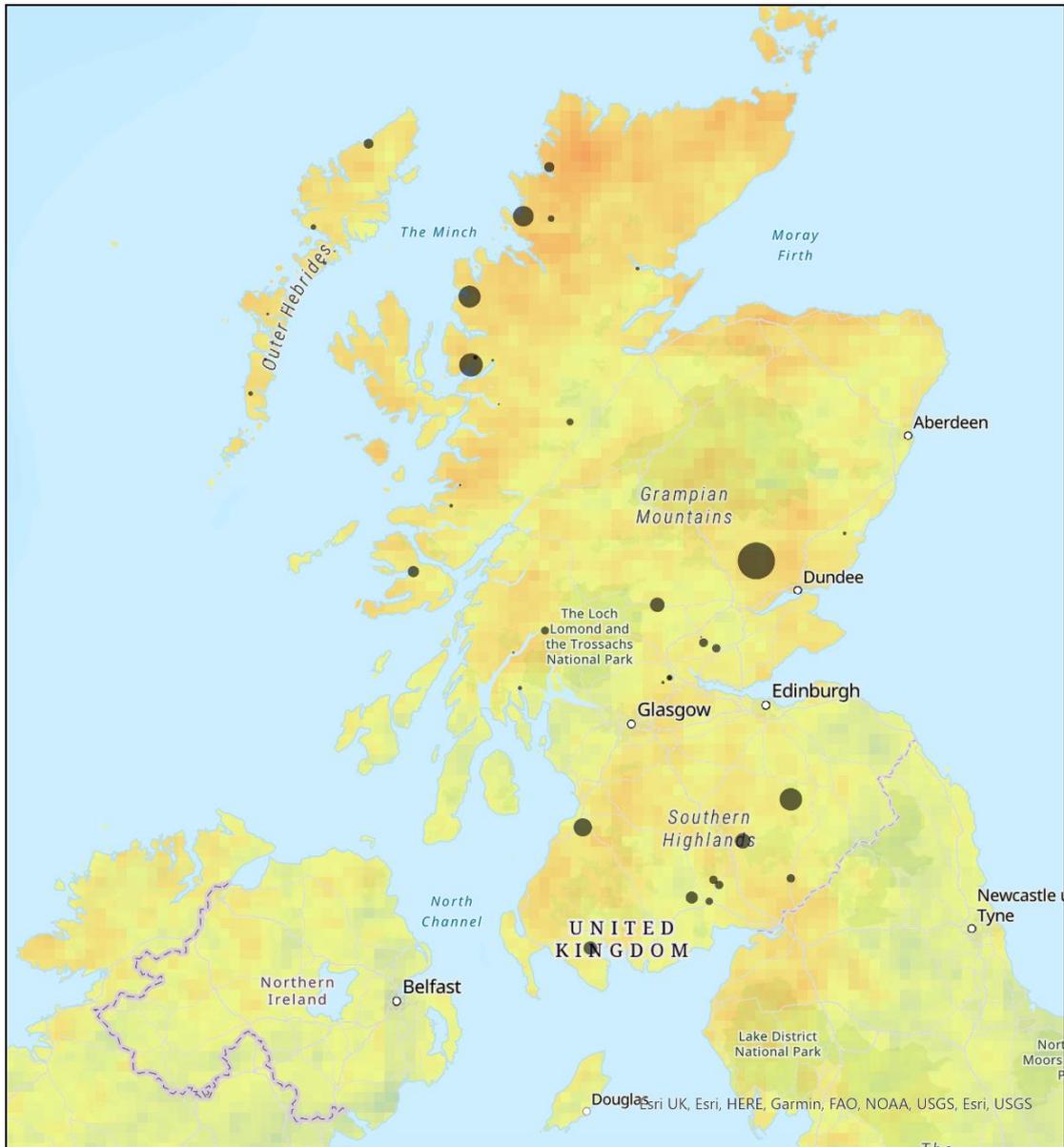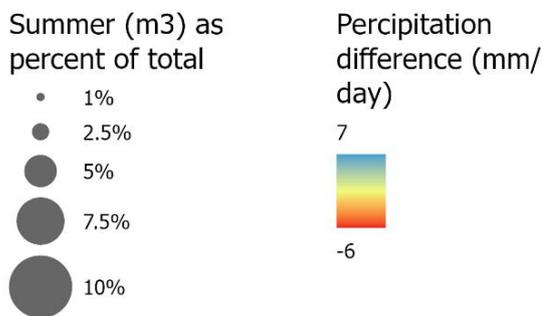
Figure 3.6a: Projected precipitation difference under RCP8.5 during summer 2041. Precipitation data sourced from UKCP18, abstraction data sourced from SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.

Legend

Summer (m3) as percent of total
- · 1%
- ● 2.5%
- ● 5%
- ● 7.5%
- ● 10%

Percipitation difference (mm/day)

7

-6

Figure 3.6b: Projected precipitation difference under RCP8.5 during summer 2061. Precipitation data sourced from UKCP18, abstraction data sourced from SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.
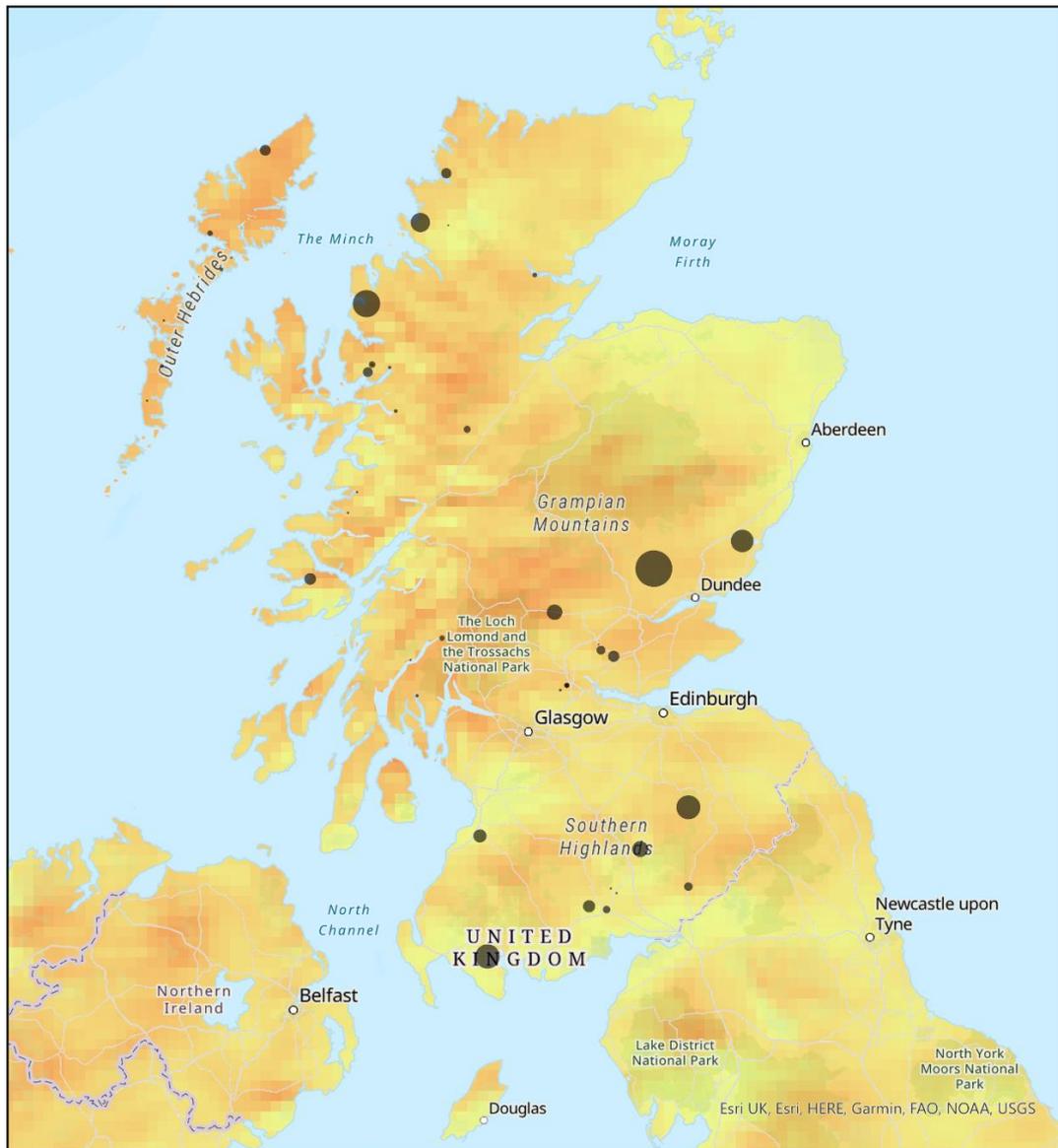
Legend

Winter (m3) as
percent of total

· 1%

● 2.5%

● 5%

● 7.5%

● 10%

Percipitation
difference (mm/d)

7

-6

Figure 3.7a: Projected precipitation difference under RCP8.5 during winter 2041. Precipitation data sourced from UKCP18, abstraction data sourced from SEPA and Aquaculture co-ordinates sourced from http://aquaculture.scotland.gov.uk/map.aspx.

Legend

Winter (m3) as percent of total
- · 1%
- • 2.5%
- ● 5%
- ● 7.5%
- ● 10%

Percipitation difference (mm/d)
- 7
- -6

Figure 3.7b: Projected precipitation difference under RCP8.5 during winter 2061. Precipitation data sourced from UKCP18, abstraction data sourced from SEPA and Aquaculture co-ordinates sourced from *http://aquaculture.scotland.gov.uk/map.aspx*.

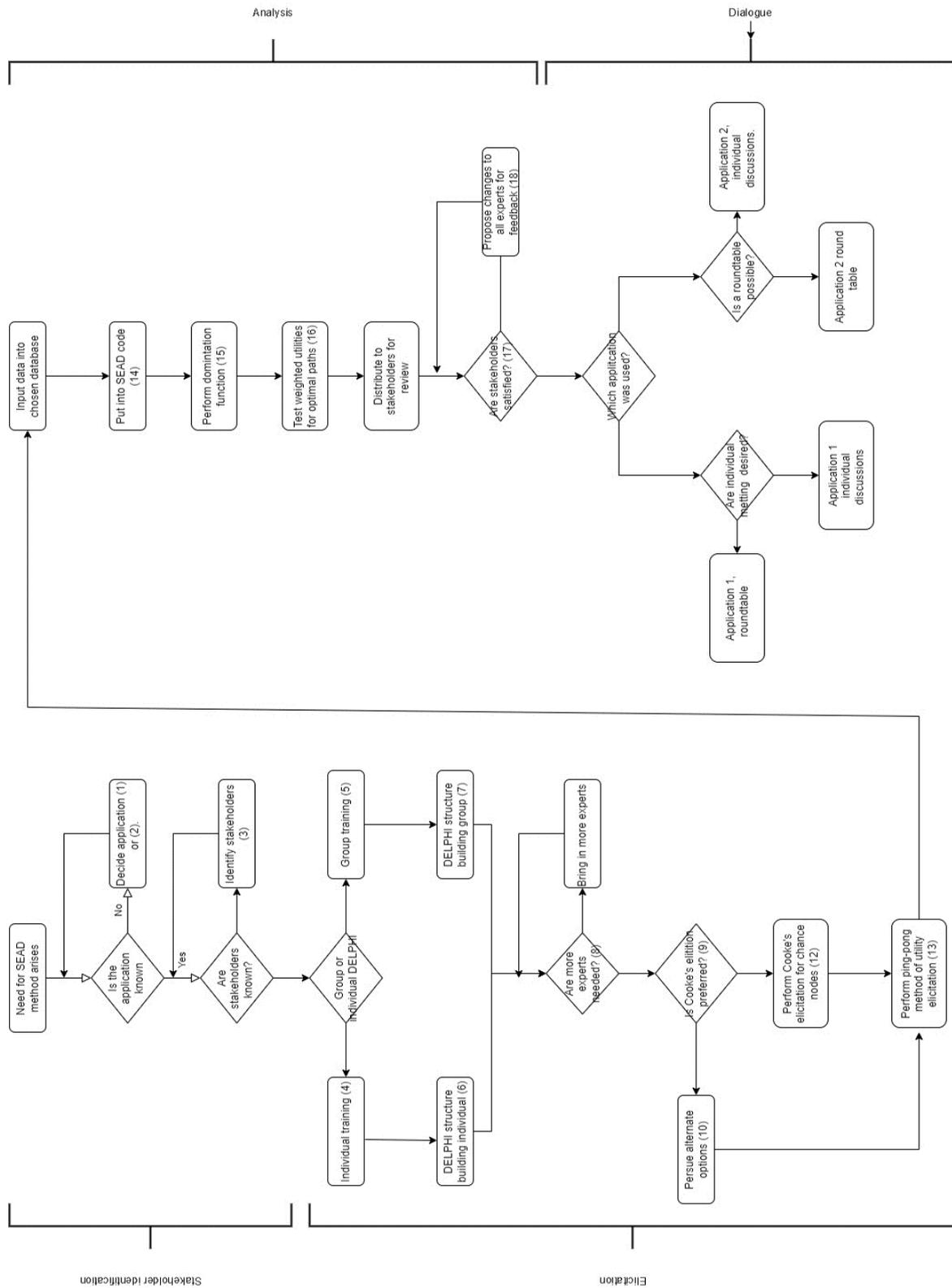# Appendix B: Full sized images from Chapter 4

Figure 4.1: The SEAD methodology presented as a flow diagram. Each number has a corresponding information section seen below.
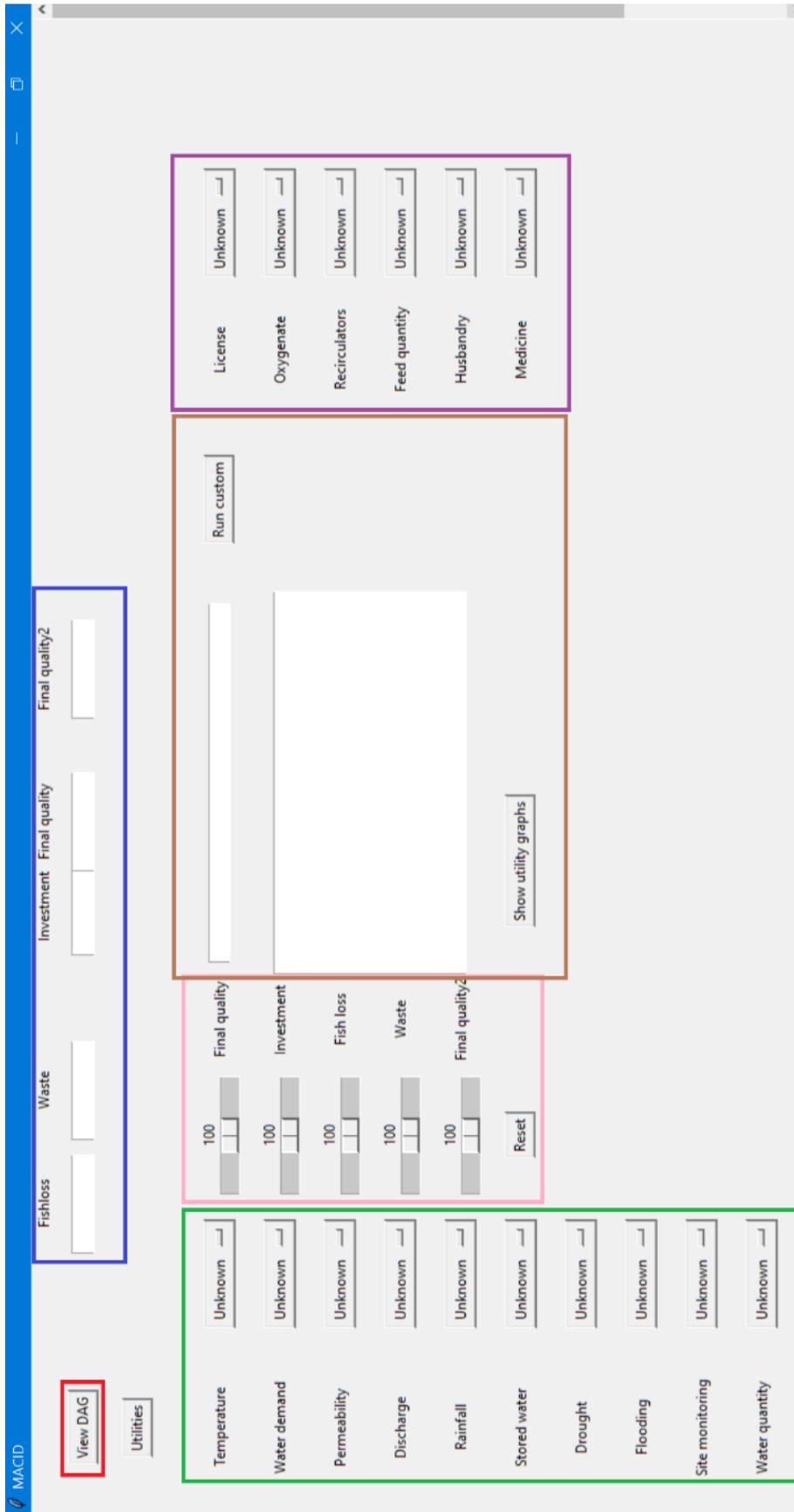
Figure 4.5: The SEAD interface, customisable within the provided Python Git Hub.

Appendix C: Full sized images from Chapter 6

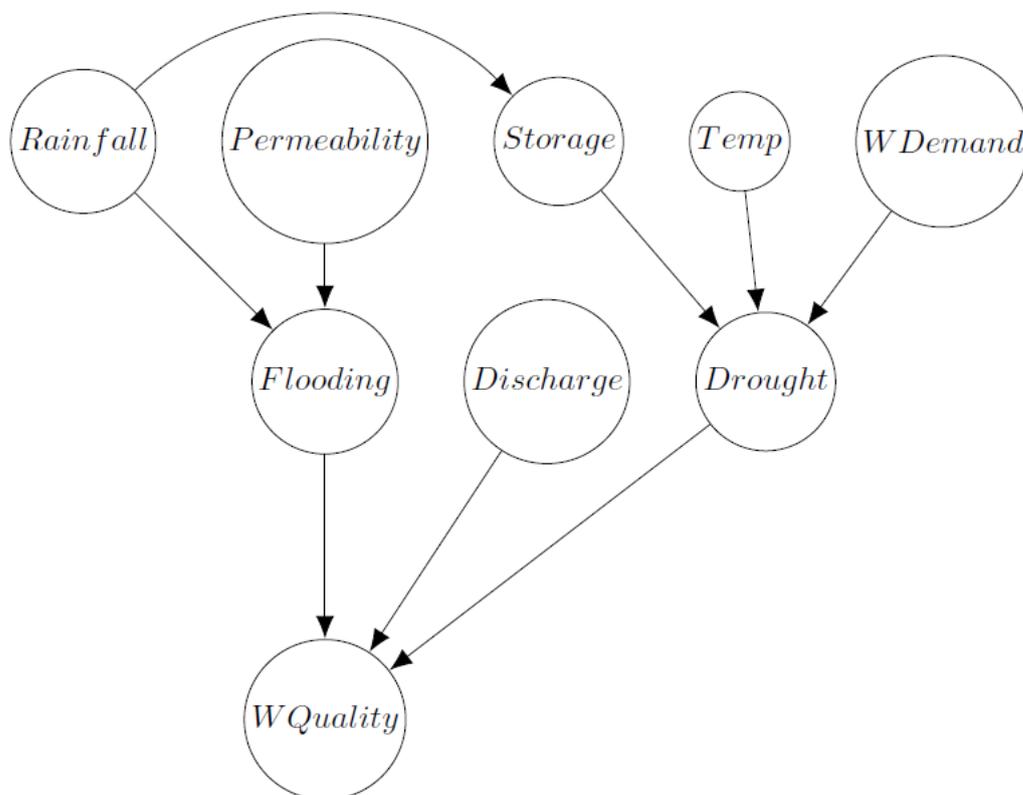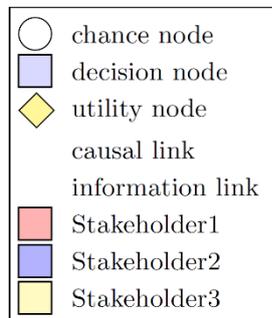*Figure 6.1: Iteration one of the structure for applying the SEAD methodology to a case study: Scottish aquaculture risks through water management.*

Legend:
- ○ chance node
- □ decision node
- ◇ utility node
- causal link
- information link
- ■ Stakeholder1
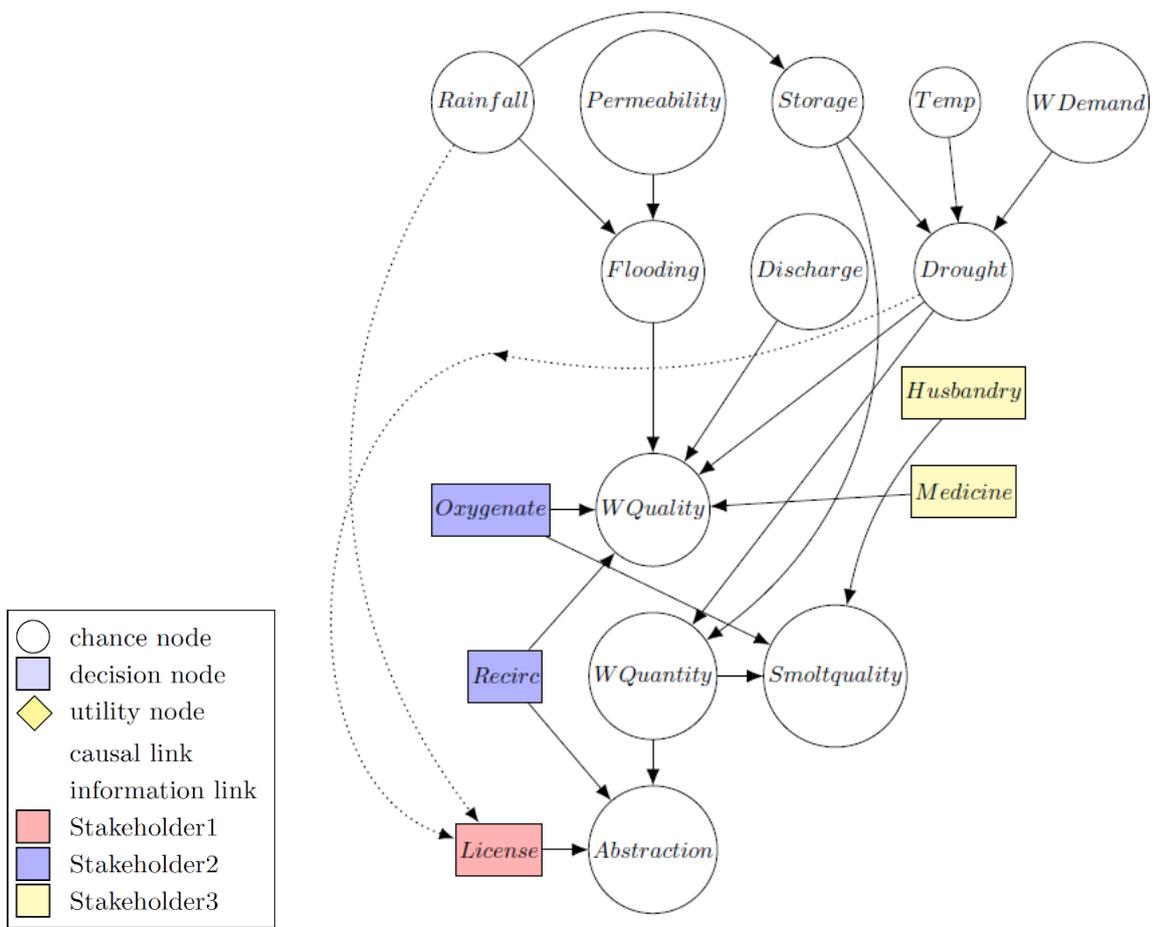- ■ Stakeholder2
- ■ Stakeholder3

Figure 6.2: Iteration three of the structure for applying the SEAD methodology to a case study: Scottish aquaculture risks through water management.
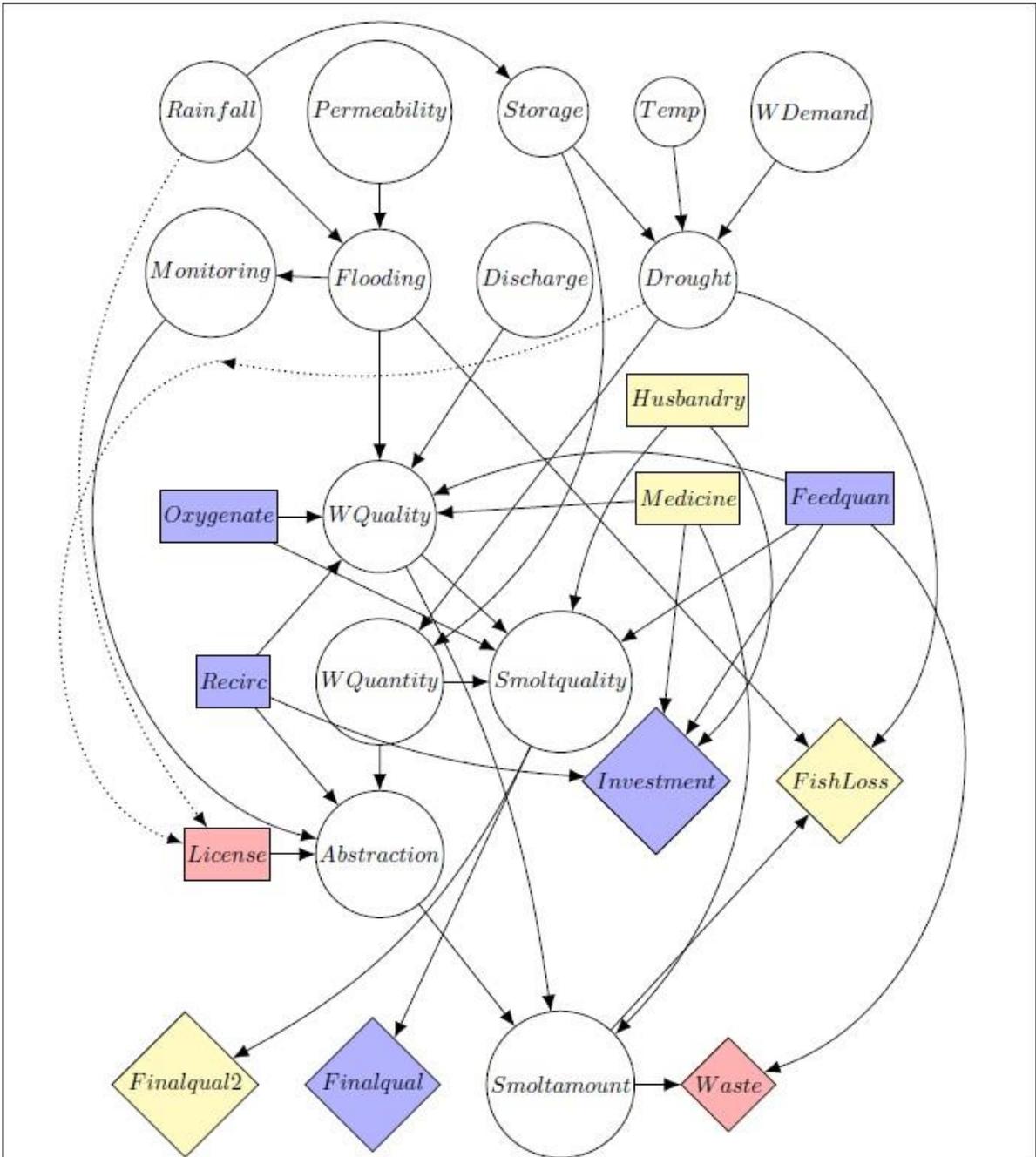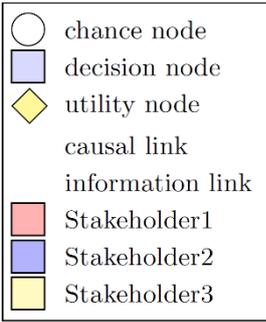
126

Figure 6.3: Iteration four (final) of the structure for applying the SEAD methodology to a case study: Scottish aquaculture risks through water management.
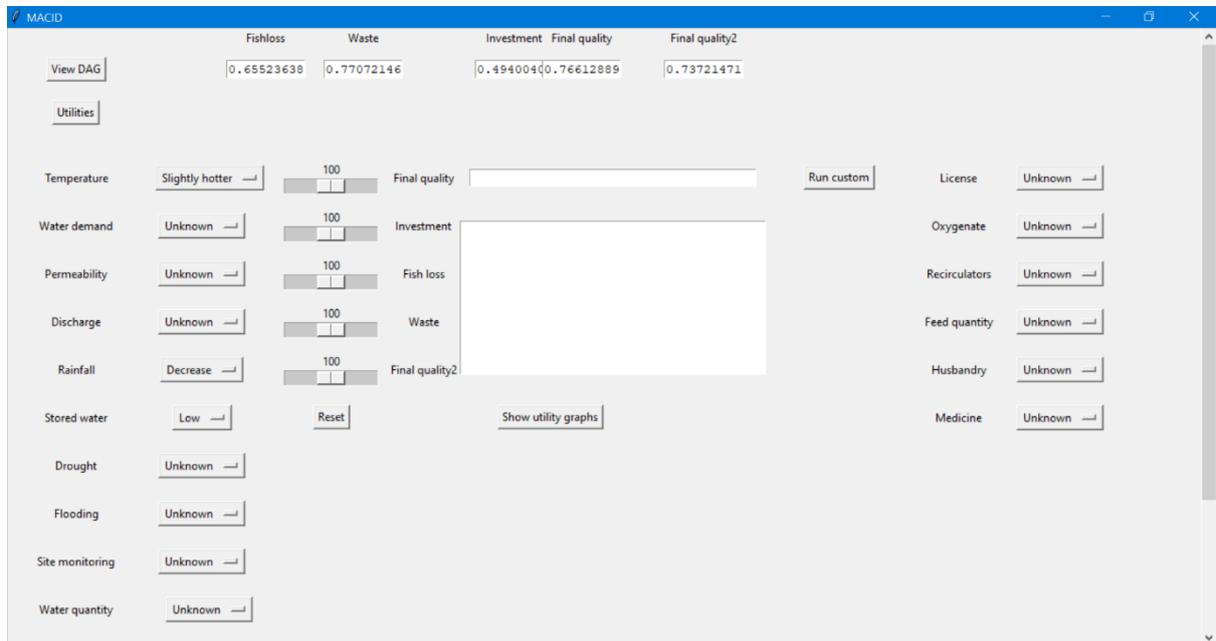
Figure 6.4: The SEAD interface set to simulate a future summer.

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