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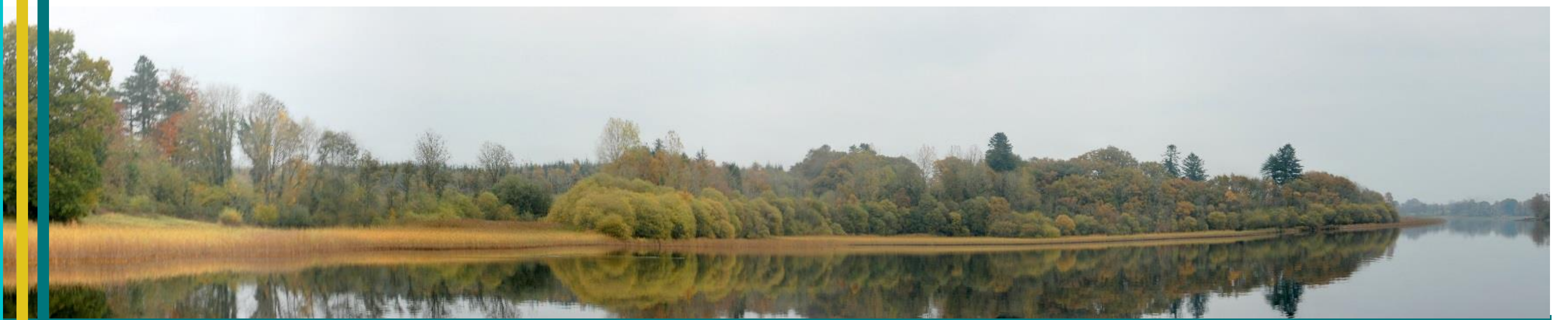

D9.2 Case Study 4 Report

Management and impact of Invasive Alien Species (IAS) in Lough Erne in Ireland

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 642317.

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About AQUACROSS

The project 'Knowledge, Assessment, and Management for AQUAtic Biodiversity and Ecosystem Services aCROSS EU policies' (AQUACROSS) aims to support EU efforts to protect aquatic biodiversity and ensure the provision of aquatic ecosystem services. Funded by Europe's Horizon 2020 research programme, AQUACROSS seeks to advance knowledge and application of ecosystem-based management (EBM) for aquatic ecosystems to support the timely achievement of the EU 2020 Biodiversity Strategy targets.

Aquatic ecosystems are rich in biodiversity and home to a diverse array of species and habitats, providing numerous economic and societal benefits to Europe. Many of these valuable ecosystems are at risk of being irreversibly damaged by human activities and pressures, including pollution, contamination, invasive species, overfishing and climate change. These pressures threaten the sustainability of these ecosystems, their provision of ecosystem services and ultimately human well-being.

AQUACROSS responds to pressing societal and economic needs, tackling policy challenges from an integrated perspective and adding value to the use of available knowledge. Through advancing science and knowledge; connecting science, policy and business; and supporting the achievement of EU and international biodiversity targets, AQUACROSS aims to improve ecosystem-based management of aquatic ecosystems across Europe.

The project consortium is made up of sixteen partners from across Europe and led by Ecologic Institute in Berlin, Germany.

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1 Introduction and Background

1.1 Summary

Invasive Alien Species (IAS) are considered a threat to Lough Erne biodiversity and also negatively affect the society that surrounds it. In this report, we apply the AQUACROSS Assessment Framework to understand this challenge and identify and assess ecosystem-based management solutions to the challenge of the IAS Nutall's pond weed.

The overall goal of this study is to examine the implications of the regulation on invasive alien species for practical management in Lough Erne Co Fermanagh, Northern Ireland, within the context of existing environmental commitments under EU legislation.

To understand context, we assess European and local policies managing biodiversity and related sectoral policies, e.g. agriculture. To understand the complex socio-ecological system of the Lough and its surround society, which affects and is affected by the Lough, we apply the AQUACROSS Linkage Framework and also the semi-quantitative, stakeholder-based Fuzzy Cognitive Mapping (FCM) method.

Relative to the baseline current policy of cutting back pond weed, our research identifies two potential EBM solutions: raising the Lough water level (to decrease the negative social effect of pond weed) and agricultural management of nitrogen pollution. We evaluate the effectiveness, efficiency, and equity of these options.

We conclude that a mixture of efforts to reduce diffuse nutrient inputs to the lake combined with an adaptive approach to the management of the lake levels offer a viable ecosystem-based approach to the management of the impacts of Nutall's pond weed.

1.2 The Science of Invasive Species

Humans have been deliberately translocating plants and animals for as long as human history (Naderi, et al., 2008) and this practice has been fundamental to our development and spread across the globe. The middle of the last century saw the first concerted scientific efforts to understand the phenomenon of biological "invasion", the ecological processes occurring when species are transplanted out of their natural environment (Elton, 1958). Some widespread, costly and high-profile examples of species introductions occurred toward the end of the last century, in particular, the rapid global spread, during the 1980's and 1990's, of the zebra mussel (Dreissena polymorpha) resulted in increased public awareness of the economic costs that can be associated with non-indigenous species, and prompted increased levels of scientific study on the field of "invasion biology". This raised awareness of non-indigenous species occurred in tandem with developing global interest in biodiversity. Figure 1 illustrates how the scientific focus on biodiversity and invasive species has developed together over time. The coining of the word biodiversity (attributed to EO Wilson) and concern about the introduction of non-indigenous species has grown very rapidly over the past 25 years, and invasive species are often cited as the "second greatest threat" to biodiversity after habitat loss

(Wilson, 1992). Note, prior to the convention on biodiversity (1992), the number of papers written about the zebra mussel exceeded the number of papers written about the "invasive species".

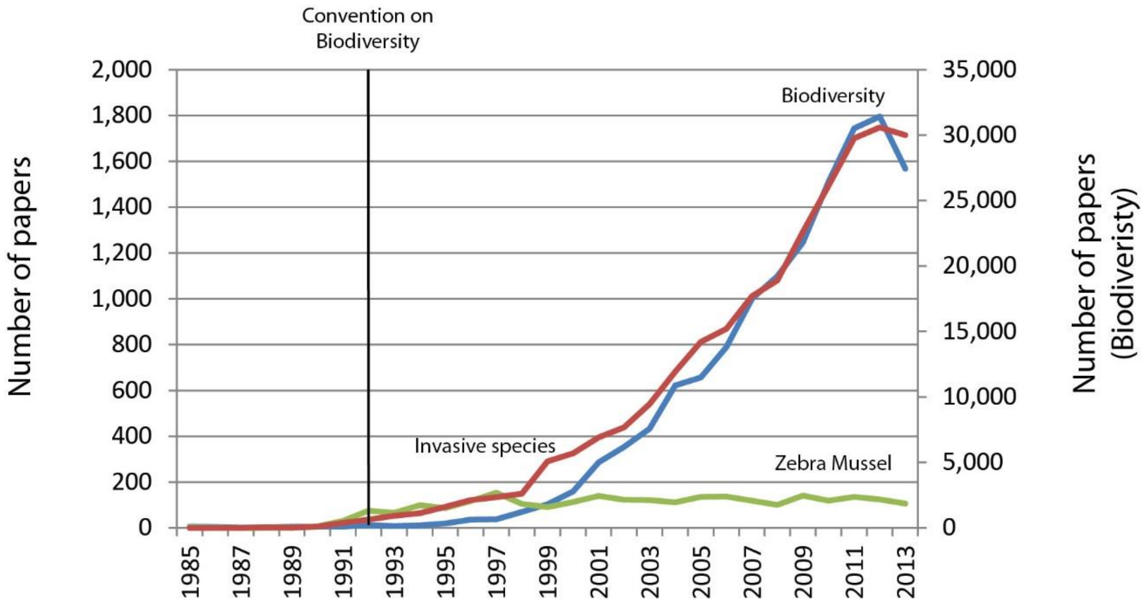


Figure 1: Number of search results for the terms zebra mussel, invasive species and biodiversity in ISI web of science 1985-2013- from O'Higgins (2015).

Yet the field of invasion biology has been criticised on many fronts. Gould (1998), for example, eloquently addresses the xenophobic connotations and social dangers of the narrative of "invasion". Colautti and MacIsaac (2004) argued for a standardised neutral terminology to define "invasive" species. While other authors have adverted to the high levels of subjectivity in determining what constitutes an invasive (e.g. Sagoff, 2005, Davis et al. 2011). Chew (2015) traced the history of the claim that invasive species are the "second greatest threat" illustrating how the idea developed from a speculation about freshwater fish in a popular science book (Wilson, 1992) to an unsubstantiated generalisation which propagated through the literature of invasion biology. Critical quantitative analysis of invasion literature has revealed, that the discipline of invasion biology has lacked consistency and clarity in defining important terms including the term "invasive". In particular, it failed to coherently distinguish between presence and impact of non-indigenous species or sufficiently recognise that measuring impacts necessitates subjective value judgements (Peryera, 2016). Warren et al. (2017) observed that systematic biases have occurred in the invasion biology literature, but these authors found some evidence for recent improvements. There is now a lively (if ignominious) academic back and forth between loyalists to the discipline (Simberloff et al., 2013; Simberloff and Vitule, 2014; Russell and Blackburn, 2017) and those who seek a more nuanced approach (Valéry et al., 2013, Davis and Chew, 2017).

1.3 Invasive Species Policy and Law

Whatever the current status of the scientific debate, concern over loss in biodiversity and its association with the spread of non-indigenous species (legitimate or otherwise) has led to a number of global initiatives aimed at halting the spread of non-native organisms. Aichi target number 9 has as its goal that "By 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment" (CBD, 2010).

At the European scale this international goal is reflected in the EU Biodiversity Strategy (EU 2011). Target 5 of the strategy is to "combat invasive alien species" and its objectives are identical to those of Aichi target 9. Action 16 of the strategy, under target 5, was to "fill policy gaps in combatting IAS by developing a legislative instrument by 2012". This action was achieved through introduction of a Regulation on Alien Invasive Species (EC, 2014).

Under the regulation a list of invasive alien species of union concern has been drawn up (Article 4) and a risk assessment must be produced for each species on the list (Article 5). To date there have been two iterations of the listing process. The listing process itself is an iterative process, candidate species are suggested by member states, these species undergo a transparent (subjective) qualitative review process based on scientific expert judgement. Those species deemed to meet the relevant criteria including the existence of relevant risk assessments and a description of social environmental and economic "impacts" are passed on to a non-expert, non-public, governmental group the Alien Invasive Species Committee for listing.

The regulation forbids the transport or trade of the listed species (Article 7) except under strict conditions set out in Article 8 or "for reasons of compelling public interest". Member states are further required to set out an action plan on the pathways of invasion (Article 13), put in place a surveillance system (Article 14) and for listed species found to be widely spread within a national jurisdiction effective management measures must be put in place (Article 19). Where an ecosystem is deemed to be "degraded, damaged or destroyed" the ecosystem must be restored unless costs of restoration are disproportionately high compared to the benefits of restoration. As such The Invasive Alien Species (IAS) regulation places several new demands on European member states and implementation of the regulation poses a new set of challenges for national and local governments and management agencies.

1.4 Lough Erne- Ecological History

Lough Erne, Co. Fermanagh Northern Ireland is made of two parts, Upper Lough Erne and Lower Lough Erne which are widened channels of the River Erne, the second largest river in Ireland. The former is a shallow, naturally eutrophic lake covering an area of 1,552 ha with a complex shoreline containing many small islands and peninsulas. Lower Lough Erne is a larger deeper lake with an area of 15,303 ha and a maximum depth ca. 60m, the two are joined by a section of the Erne river approximately 10km long. The lakes themselves lie within the jurisdiction of Northern Ireland but a substantial part of the catchment (≈60%, 221km2) is situated within the Republic of Ireland (Figure 2) the international border being delineated between 1922 and 1924 following the declaration of an Irish Free Sate. The Erne is connected to the Shannon river basin (the largest on the island) by the Shannon Erne Waterway (which was constructed in the mid 19th century and re-opened in 1994).The major historical developments in the ecology of Lough Erne are summarised in Figure 3.

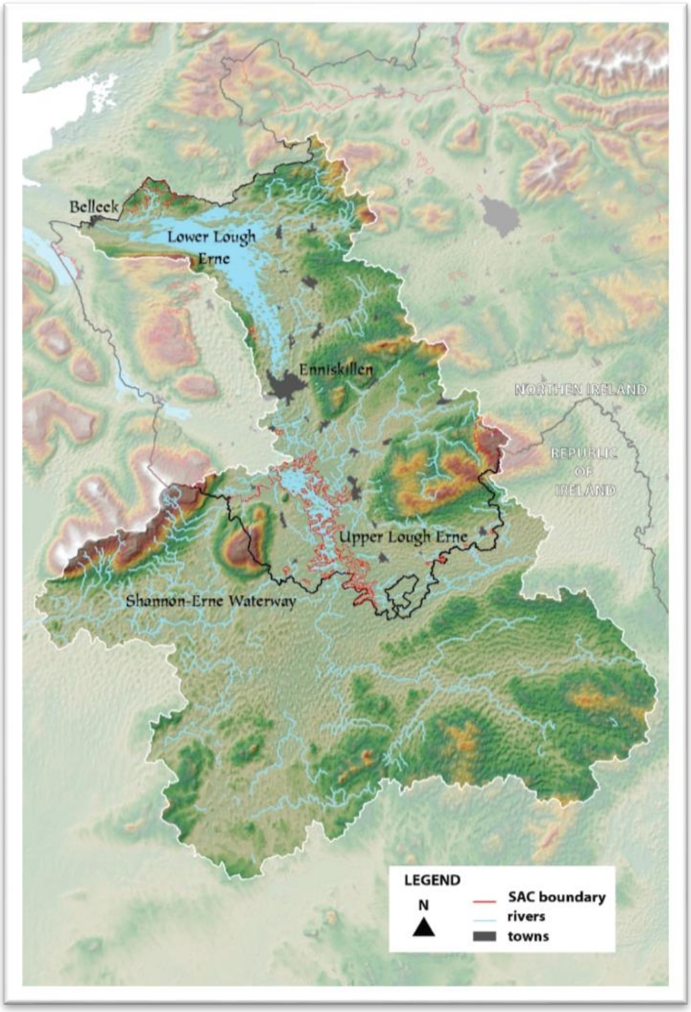
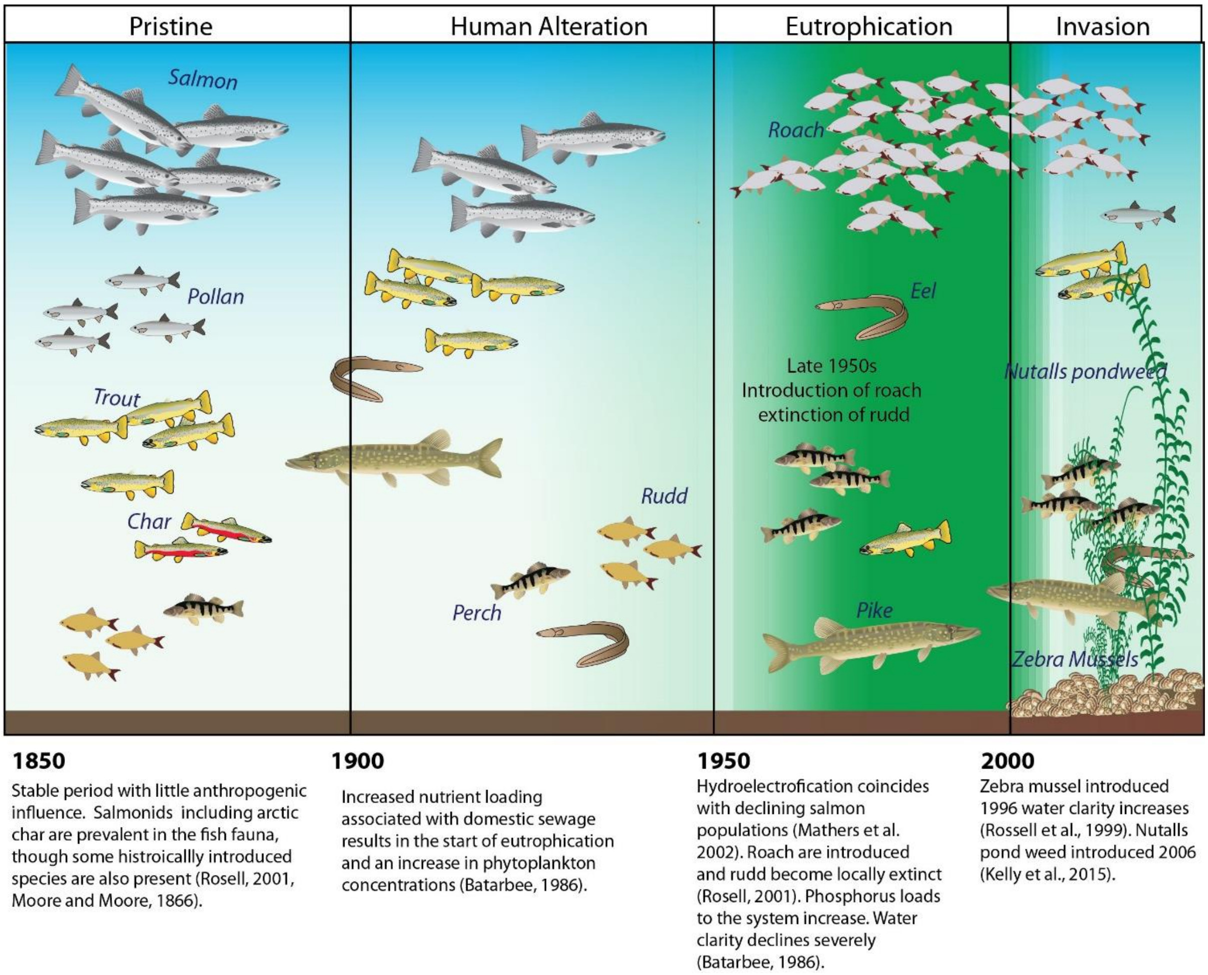


Figure 2: Map of the study area, showing Upper Lough Erne SAC and international border

The Lough Erne system has been settled since neolithic times and the ecological conditions in the lake have been shaped by human society for millennia (Lafferty et al., 2006). References to the Erne fisheries date back to mythology and the oral tradition of early Christian times (Went, 1945). In so far as a natural state can be determined for the Erne system, the fish fauna of the lake (as in the rest of the island of Ireland) is a naturally depauperate one, comprised of post-glacial relic species (Salmon, trout, arctic char, pollan and eel) supplemented by historically introduced species, including, bream, perch and pike (Rosell, 2001). Pike are known in the Irish language as “Gall Iasc” which translates as “French” or “Foreign Fish” which may suggest a Norman origin in the island’s waters. Scientific records of non-native species date back as early as 1884 when Canadian pond weed (*Elodea canadenis*) was recorded to be “*not plentiful but decreasing fast*”, (Moore and More, 1884). Based on the analysis of lake sediments Batarbee (1986) reconstructed a trophic history of the lake from 1850 to the present. His analysis indicated a relatively undisturbed trophic status prior to the 20th century, increasing loads of organic matter between 1900 and the 1950s were followed by a rapid phase of change, with increasing eutrophication.

Figure 3: Overview of the major changes in the ecology of Lough Erne since 1850.



At this time (1950s) construction of a hydroelectric power station in Belleek altered the hydrological regime of the lake. The construction of the Kathleen's falls and Cliff power stations was enabled by international cooperation between the UK and the Republic of Ireland resulting in the Erne Drainage and Development Act (1950). Such international cooperation was uncharacteristic of the relationship between the two nations at the time, but the agreement was mutually beneficial to both governments, providing increased electrical capacity for the republic while alleviating some of the long-standing flooding pressures (Cunningham, 1992) within Fermanagh[1] (Kennedy, 2006).

The mid 20th century marked a shift in hydrological regime of the lake as well as gradual decline in the historically significant Erne salmon fisheries despite considerable salmon restoration

[1] Locally it is said that in Summer Lough Erne is in county Fermanagh, but in winter Co. Fermanagh is in Lough Erne.

efforts (Mathers et al., 2002). During the same period roach (*Rutilus rutilus*) were intentionally introduced to the system rapidly replacing the long established (though not native) rudd populations (Rosell, 2001). The period from the 1970s to the 1990s was characterised by eutrophication (Battarbee, 1986; Hayward et al., 1993; Foy et al., 1993), and the declining water quality was associated with a shift in fish composition toward a less sensitive fauna and the decline in the native pollan (Rossell, 2001).

The most significant recent ecological development in the lake has been the arrival of the invasive zebra mussel (*Dreisenna polymorpha*) (Rossell et al., 1999, Maguire et al., 2006). The mussel, first observed in 1996 has had profound effects on the trophic status of the lake, resulting in dramatic reductions in phytoplankton biomass (by about 10mg.chl m^3 less than prior to invasion), and enhanced water clarity. Since that time, the non-native species nutall's pond weed (*Elodea nutallii)* has been introduced and has spread rapidly in subsequent years, being able to colonise deeper areas due to the increased water clarity caused by the Zebra mussel (Kelly et al., 2015). More recent non-native arrivals include the Blood red shrimp (*Hemimysis anomala*) (Gallagher et al. 2015) and the Freshwater jellyfish (*Caspedacusta sowerbyi)* (Minchin et al., 2016).

Upper Lough Erne is particularly prized for its flora and fauna having several national (Site of Special Scientific Interest) and international environmental designations (Specially Protected Area, Ramsar wetland and a Special Area of Conservation). While the Lough is designated as a "heavily modified water body" under the Water Framework Directive, its supports a wide range of recreational activities and is a major contributor to the local tourist industry. Agriculture is also vitally important in the surrounding catchment. The recent proliferation of Nutall's pond weed is of particular concern to local tourist interests as it interferes with recreational boating and fishing and has considerable economic costs, in 2010, €91,000 was spent in removal of the weed to facilitate recreation (Kelly et al., 2013).

2 Establishing Objectives

2.1 Policy Objectives.

In the Lough Erne catchment, European directives and regulations set the basis for common approaches to environmental protection and management across the international boundary between Ireland and Northern Ireland, with directives being transcribed into national laws and having the same objectives either side of the border. However, while the objectives and reporting obligations for specific directives are the same in both Ireland and Northern Ireland, the ways in which various laws are implemented vary between the different institutions of the member states. O'Higgins (2017) describes the range of competing values and objectives surrounding European environmental policies distinguishing "Pure", "Practical" and "Popular" norms. The Pure perspective is encapsulated by the slogan adopted by the US environmental movement of the early 1970s "we have met the enemy and he is us". This viewpoint considers human activities as inimical to ecosystem functions, juxtaposing man against nature. The norms associated with this narrative of purity seeks a return to pre-anthropogenic disturbance.

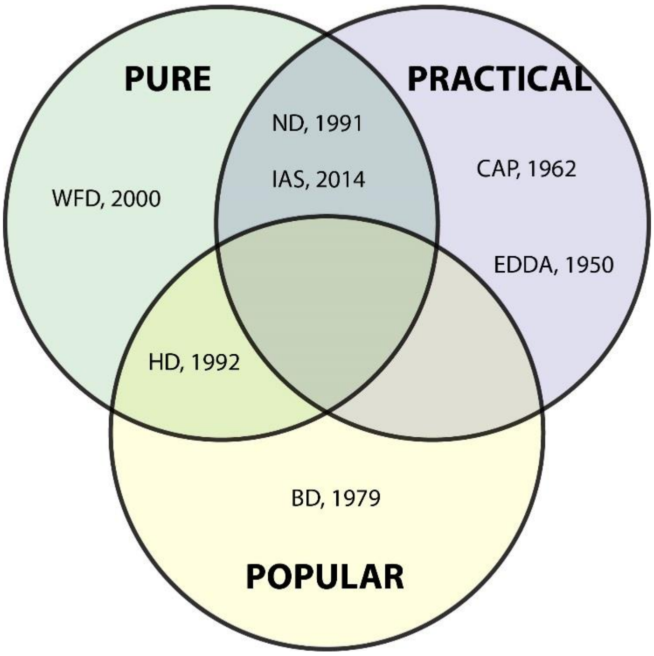


Figure 4: EU and selected national environmental laws and directives relevant to the Lough Erne case study, classified according to their underlying norms. Adapted from O'Higgins (2017). CAP= Common Agricultural Policy. ND= Nitrates Directive. IAS=Regulation on Invasive Alien Species. WFD=Water Framework Directive. HD= Habitats Directive. BD= Birds Directive. EDDA- Erne Drainage and Development Act.

Environmental policies with an anthropocentric focus may be considered "Practical". "Practical" norms are largely aligned with natural resource management concepts, for example, management of stocks to meet human ends, through the exploitation or stewardship of the natural environment. These may be loosely aligned with the concept of economic well-being, where individuals or firms seek to maximize their own profits or production. Practical policies often relate to the systematic use of provisioning ecosystem services. In this analysis policies are considered to fall into this category if their primary focus is on natural resource extraction and management.

Popular norms are defined by their focus on cultural ecosystem services. The impact of these policies may be associated with non-use cultural ecosystem services for example with species that are highly visible, the "warm glow" (Kahneman and Knetsch, 1992) of protecting charismatic species, such as the giant panda, the polar bear or cetaceans, which elicit strong responses toward conservation. Similarly, sustainability policies which have clear impacts on direct use cultural services where, public goods are directly used by individuals without the intermediary of a specific economic sector (e.g. recreational fishing, swimming), may be considered popular as they relate to the public good rather than economic development of any specific sector. The values or cultural ecosystem services associated with these conservation norms may not necessarily be aligned with scientific justification (e.g. Potts et al. 2016).

Regulations and policies, which implicitly focus principally on cultural ecosystem services or components of ecosystems, which supply these services, are categorised in this analysis as Popular. Figure 4 illustrates the norms behind the European environmental directives applying in the Lough Erne case study.

Regulation on Invasive Alien Species

The primary focus of the Lough Erne case study is on implementation of the regulation on IAS. The list of Invasive Alien Species (IAS) and its update (EC, 2016, EC, 2017)) drawn up under the regulation on IAS (EC, 2014) contains a total of 49 species. The Biodiversity Ireland invasive species database lists 18 non-native species in the Lough Erne catchment with seven of these species being on the list of European Concern Table 1. For those species listed, the regulation on Invasive Alien Species mandates that effective management measures be put in place.

Of the listed aquatic species shown in Table 1, Nutall's pond weed as well as *Crangonyx pseudogracilis* (an amphipod native to North America) have well described impacts in Lough Erne. For Nutall's pond weed the impacts relate to its proliferation and interference with recreational activities (Kelly et al., 2013). For Crangonyx, the main impact appears to be in its ability to outcompete (though not eradicate completely) native amphipod species (Minchin et al., 2013). The third listed aquatic species is the Ruddy duck (introduced to the U.K. as an ornamental species), which, while established in nearby Lough Neagh, is an occasional visitor to Lough Erne. The major impact attributed to Ruddy ducks, and the reason for their listing, is "genetic introgression" with the white headed duck (*Oxyura leucocephala*), a species, native to southern Spain, protected under the Birds Directive.

European efforts at population control of ruddy duck are aimed at mitigation of impacts in southern countries associated with the genetic purity of the white headed duck (Henderson, 2009, Robertson et al., 2015. See Annex 1). In terms of the normative classification presented above, much of the criticism of "invasion biology" has been on its focus on biological purity. The example of the ruddy duck illustrates how dilution of genetic purity (or "genetic introgression") is considered an environmental impact, the risk-assessments supporting the listing of the ruddy duck describes the impact on European biodiversity as "MASSIVE" [2] (EC, 2018). As such, the norms ascribed to the regulation on IAS may be considered to be "Pure". However, the regulation also contains a number of exceptions to enable loopholes for certain aquaculture (EC, 2007) species which are based on "Practical" considerations. Accordingly, the regulation may itself be considered a hybrid of "Practical" and "Pure".

[2] Here the concept of biodiversity seems to be the opposite of the concept of diversity in human society.

Table 1: Non-indigenous species listed on biodiversity Ireland invasive species database and those also contained the list if IAS of Union Concern.

	Species	Common Name	Realm	Status
Plants	*Elodea canadensis*	Canadian pond weed	Aquatic	
	Elodea nuttalli	Nutall's pond weed*	Aquatic	Listed
	Fallopia japonica	Japanese knotweed	Terrestrial	
	Gunnera tinctoria	Chilean rhubarb	Terrestrial	Listed
	Heracleum mantegazzianum	Giant Hogweed	Terrestrial	Listed
	Impatiens glandulifera	Indian balsam	Terrestrial	Listed
	Lemna minuta	Least duckweed	Aquatic	
	Lysichiton americanus	American Skunk Cabbage	Marsh	Listed
	Nyphoides peltata	Fringed water lily	Aquatic	
	Rhododendrum ponticum	Rhododendron	Terrestrial	
	Symphoricarpos albus	Common snowberry	Terrestrial	
Animals	*Crangonyx pseudogracilis*	Northern River Crangonyctid*	Aquatic	Listed
	Dreissena polymopha	zebra mussel	Aquatic	
	Gammarus pulex	-	Aquatic	
	Gammarus tigrinus	-	Aquatic	
	Mustela vison	Mink	Terrestrial	
	Oxyura jamaicensis	Ruddy duck*	Aquatic	Listed
	Tamias sibiricus	Siberian chipmunk	Terrestrial	

Of the three aquatic species listed occurring within the case study area, only Nuttall's pond weed has demonstrated economic impacts within the area. Following consultation with stakeholders at a meeting of the Lough Erne Invasive species working group (Nov 2015) and through a follow-up meeting with Waterways Ireland (Feb 2016).

Water Framework Directive

Under the Water Framework Directive (WFD), Lough Erne is designated as a "heavily modified water body"[3]. Lough Erne is currently considered to have "Moderate Ecological Potential" with the target for both upper and lower Loughs under WFD being Good Ecological Potential (GEP). Agricultural land is the major source of nutrients to the Loughs (NIEA, 2016).

The WFD established River Basin Districts (RBDs) as a management unit and sets River Basin Management Plans (RMBP). The Northwestern RBD that includes Lough Erne is transboundary and shared between Northern Ireland and the Republic of Ireland. The implementation of the River Basin Management Plan is therefore supposed to be coordinated between the two jurisdictions. In practice, however, the WFD cycles in Northern Ireland and in the Republic

[3] Due to the presence of the hydro-power schemes.

operate at different timescales and are not fully harmonised, resulting in limited coordination across the two jurisdictions.

The objective of the WFD is to reach Good Ecological Status (or in the case of heavily modified water bodies, GEP) which is set by reference to pristine conditions, in terms of nutrients, as well as fish and insect assemblages. As such the norms underling in the WFD are considered "Pure" in that they seek a return to pre-anthropogenic conditions.

Eutrophication has been a long standing phenomenon in Lough Erne (Batarbee, 1986), and the trophic status of the lake has both affected, and been affected by, the presence of invasive species. The proliferation of the zebra mussel was supported by high levels of plankton biomass in the lake, which provided a supply of food for the non-indigenous mussel. The establishment of zebra mussels in the lough has been associated with a reduction in phosphorus concentration (Maguire and Gibson, 2005), despite nutrient loading from agriculture. *Elodea* populations are increased by higher nutrient concentrations, and are further enhanced by the greater water clarity that results from the presence of zebra mussels (LELP, 2017).

Common Agricultural Policy (CAP)

The CAP drives and subsidises land use in the Lough Erne catchment, the majority of which is used for pasture (LELP, 2017; NIEA, 2015b, c). This agricultural land is the major source of nutrient loading to the lough (NIEA, 2016). The CAP is a quintessentially "Practical" policy, designed to enable farming and to ensure food security at the European level, but recent reforms have recognised the need to integrate protection of biodiversity and increased environmental responsibility within the CAP through a series of "greening measures" (Pe'er et al., 2014). These measures have the potential to contribute to the goals of the WFD and of the Birds, Habitats and Nitrates Directives.

However, the greening measures are only required for arable farms above 15ha, meaning that pasture lands, the majority of the land use in the Lough Erne catchment, are not required to have Ecological Focus Areas (which include buffer strips) (LELP, 2017; NIEA, 2015b, c; Pe'er et al., 2014). Funding for some voluntary agri-environmental schemes is set to decline in absolute terms between in the period to 2020 (Pe'er et al., 2014). Therefore, there are fewer policy incentives for farmers in the Erne catchment to convert productive land to buffer strips or seek other improvements that could reduce nutrient loading.

The CAP, by contrast to the WFD, is typically implemented at Member State level, although in the UK the responsibility is devolved to regional (Northern Ireland) level. The implementation of the CAP in the Republic of Ireland affects nutrient loading from agriculture to tributaries in upstream parts of the catchment, which then has the potential to affect the state (i.e. nutrient concentrations) and status (i.e. ecological potential) of Lough Erne. While the RBMP seeks to improve the state and status of the loughs through transboundary coordination, the driver (farming) and pressure (nutrient release) are affected by separate policy implementation (in the Republic of Ireland and Northern Ireland.

Nature Directives (Habitats Directive and Birds Directive)

The directive is concerned with the development of a network of Special Areas of Conservation (SAC) for specific habitat types and species in which biodiversity is prioritised. The Natura 2000 network, which is comprised of Habitats Directive SACs and Birds Directive Specially Protected Areas (SPA), is the largest network of reserves in the world, and its development was seen as a major achievement of the EU Biodiversity Action Plan. Sites are designated according to the presence of particular target habitats or species listed in the Annexes of the Directives. Though the Habitats Directive arose from the CBD, and was published in the same year, it may be considered as a hybrid of Pure and Popular in terms of its norms because it includes a mix of obscure and popularly unrecognised species (e.g. *Dytiscus latissimus* a diving aquatic beetle) which provides neither cultural nor provisioning services, as well as charismatic species (for example all species of whales are protected under the directive) and the process of designation of species for inclusion within the Annexes of the directive, through expert judgement included value based as well as ecologically based decisions (Bryan, 2012).

In Northern Ireland, the Conservation (Natural Habitats, etc.) Regulations (Northern Ireland) 1995 as amended gives effect to the Birds and Habitats Directives of the European Union. The specific targets are to achieve favourable conservation status of listed habitats and species. Designation of Upper Lough Erne as a SAC is due to the presence of habitats contained within Annex I of the Habitats Directive (EEC, 1992), these include the aquatic habitats “Natural eutrophic lakes with *Magnopotamion* or *Hydrocharition*-type vegetation”, as well as terrestrial habitats namely “Old sessile oak woods with Ilex and Blechnum in the British Isles” and Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (*Alno-Padion*, *Alnion incanae*, *Salicion albae*)”, the primary reason for the designation of the site is the presence of the Annex II species, the otter (*Lutra lutra*). Upper Lough Erne is also designated as a RAMSAR site, qualifying in part because it supports an appreciable assemblage of rare, vulnerable or endangered species, these include -clawed crayfish, Lunar hornet moth, a pondskater *Limnoporus rufoscutellatus*, the water beetles, *Donacia aquatica*, *Donacia bicolora*, *Gyrinus distinctus*, *Gyrinus natator*, *Hydroporus glabriusculus* and the carabid beetle *Lebia cruxminor*.

In the Upper Lough Erne Local Management Area, five water-dependent SACs are in unfavourable: unclassified condition and one is in unfavourable: recovering condition (NIEA, 2009b). In Lower Lough Erne LMA, one water-dependent SAC is in favourable: unclassified condition and one is in unfavourable: unclassified condition (NIEA, 2009b). Of relevant listed species (freshwater/wetland species found in Lough Erne), two are at favorable status and three less than favourable (JNCC, 2013).

Erne Drainage and Development Act (1950).

The 1950 Agreement enacted by the Dail in Ireland and the Houses of Parliament in the UK controls water level regulation in Lough Erne, and therefore interacts with the implementation or on-the-ground impacts of several environmental policies. The act was an historic example of cross-border cooperation that received support from both sides of the border due to its potential to deliver mutual benefits. For the Republic of Ireland, in its post "emergency"[4] state the agreement enabled the construction of the Kathleen's falls and Cliff hydro-power plants at Belleek. For Northern Ireland the construction of the dam alleviated flood pressure in the county. The international agreement between the UK and the Republic of Ireland assigned control of the water levels to the Electricity Supply Board (ESB) in the Republic of Ireland and the Rivers Agency in Northern Ireland. The agreement requires that levels are maintained in the Upper Lough between 150ft and 154ft (April - September) / 155ft (October - March), and in the Lower Lough between 147ft and 152ft. These levels relate to the base reference at Poolbeg for imperial (i.e. feet and inches) measurements. The focus of the EDDA on flood alleviation and hydro-power development places it firmly in the category of "Practical" in terms of its underlying norms.

2.2 Stakeholder Objectives.

Stakeholder objectives for the system were explicitly considered at a workshop (July 2017). A summary of stakeholder objectives as stated by workshop participants is given in Table 2. Participants in the workshop were also given a comprehensive list of activities which take place in the Lough Erne catchment and asked to rank the influence of these activities on their own specific objectives (Figure 5)

Table 2: Biodiversity related and sectoral goals and the number of workshop participants holding these goals identified as part of the 1st Aquacross Lough Erne workshop. Adapted from Blincow (2017).

Stakeholder Goals	No
To protect and restore biodiversity of Lough Erne	3
To manage and reduce the spread of invasive species in Lough Erne	2
To create and increase hydropower in Lough Erne	1
To create and increase outdoor recreational activity in Lough Erne	1
Increase community engagement and protection of heritage	2
Mitigation of pesticides in Lough Erne	1
Provide and increase drainage functions to the rivers in the Lough Erne Catchment	1
Manage commercial development	1

Boating and water sports with engines, hydroelectric power, flood management agricultural, forestry, turf cutting and mining were all perceived to have the strongest negative influences on objectives, while scientific research boating without engines and conservation and restoration were all perceived to have the strongest positive effects.

[4] Official recognition of World War II in the Republic of Ireland came in the form of the Emergency Power Act (1939) which was designed to enable the government to keep its neutral stance while maintaining order in the country.

Figure 5: Primary activities, pressures and ecosystem components in Lough Erne. Policies acting on specific components are shown in red. Stakeholders with interest in specific components are shown in blue, acronyms are contained in the text. Activities

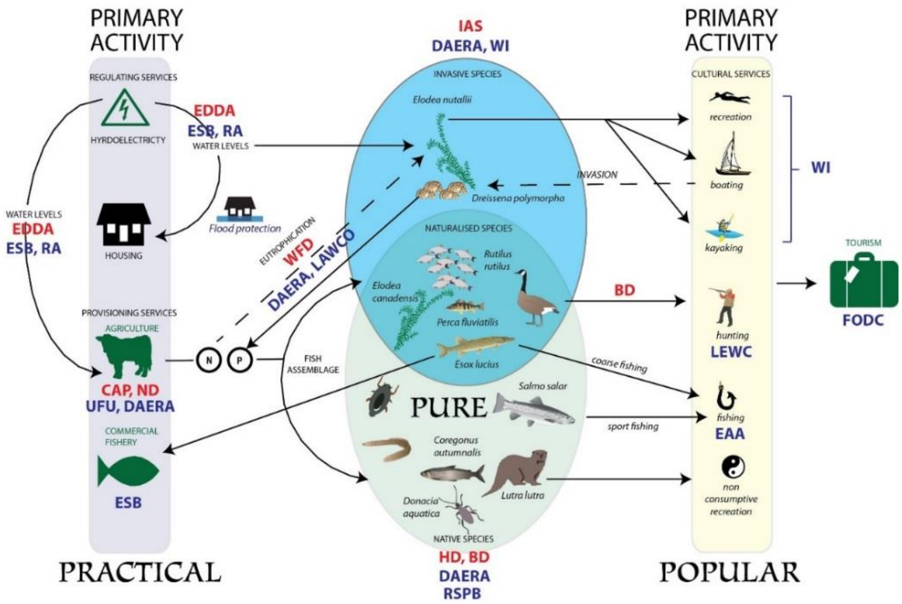


Figure 5 illustrates some of the interrelationships between individual sectors (also called primary activities), the pressures these activities place on components of the ecosystem, and the relationship between these components and other primary activities. The major directives and laws and stakeholder groups with interests in specific components are also shown. For many activities, specific governmental or organisations have responsibility for management. For example, statutory responsibility for implementation of CAP as well as the Habitats (HD) and Birds (BD) and Nitrates (ND) directives as well as the WFD falls to Department of Agriculture Environment and Rural Affairs, this is supported by the Local Authority Water and Communities Offices (LAWCO) in the Republic. The Electricity Supply Board (ESB) is a private organisation which operates the hydro-power plants in Lough Erne and has statutory responsibility for management of salmon and eels and, along with the Rivers Agency (RA), for maintenance of the Lough Levels under the Erne Drainage and Development Act (EDDA). Waterways Ireland (WI) is an all-island agency with statutory responsibility for management of Ireland's inland waterways and with a mission to maintain the waterways (including protecting them from non-indigenous species) was well as to promote their use. Fermanagh Omagh District Council (FODC) is the local government and has responsibility for general economic development in the area including the promotion of tourism.

There are also a number of charities and voluntary organisations which represent various recreational and commercial sectors in the area, these include the Ulster Farmers Union (UNU), the Erne Anglers Association (EEA), the Lough Erne Wildfowlers Council (an umbrella group for the local gun clubs), as well as larger charitable organisation with local subgroups, such as the Royal Society for Protection of Birds (RSPB).

With respect to the management of Nutall's pond weed, Figure 5 illustrates how it lies at the intersection of implementation of the regulation on IAS, the EDDA, and the WFD, CAP and ND and that several stakeholders have direct interests including, the ESB, DAERA, WI, UFU. Based on initial stakeholder consultation one possible response to the proliferation of pond weed which may be favourable to recreational stakeholders is to raise the water levels of the Lough by altering the rate of water out-flow at the ESB hydro-electrical stations in the Lower Lough. Increasing water levels in summer could facilitate recreational activities by increasing the clearance between recreational boats and stands of pond weed thereby reducing the risk of entanglement of boat engines in the weed. A potential additional outcome would be the reduced availability of light to pond weed stands (due to increased water depth) which could reduce the proliferation of the species (Figure 7). This Response would place a new Pressure (raised water levels) on the system and will affect not only the recreational users of the lake, but also cause other changes in the system. In particular, the raised water levels may cause inundation of surrounding agricultural land thus affecting the livelihoods of local farmers and therefore generating the potential for conflict.

The analysis of policies and stakeholder objectives indicates a wide variety of conflicting objectives interacting in a range of complex ways. Potential avenues for the control of Nutall's pond weed, or mitigation of its negative impacts could focus on the implementation of the CAP and the WFD or on the EDDA, all of which involve complex interactions. Understanding these interactions and finding solutions which are amenable to all stakeholders and incorporating the trade-offs between different options is a critical step to developing ecosystem-based management solutions for Lough Erne.

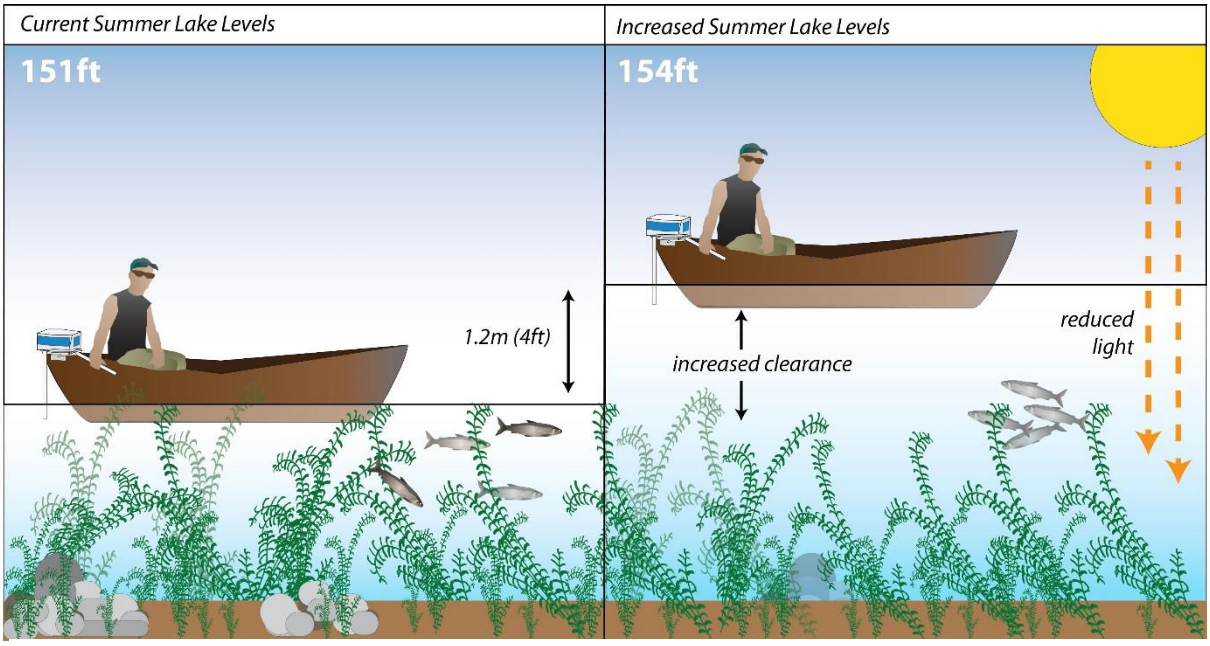


Figure 6: Illustration of how raising water levels within the constraints of the EDDA might affect recreational boating activities and the light availability to the non-indigenous species.

3 Assessing the current state of the Social Ecological System

3.1 Social Ecological Systems

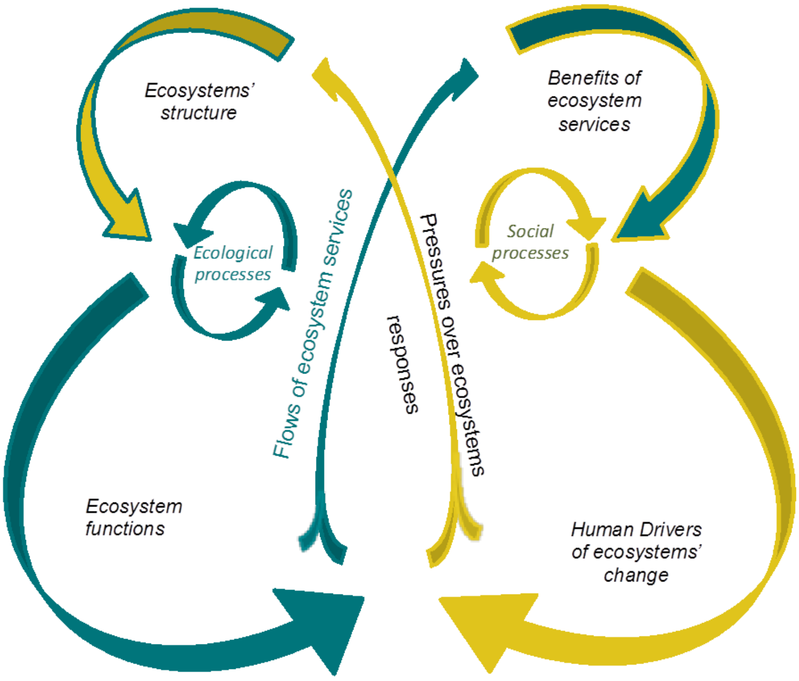


Figure 7. The AQUACROSS Architecture for Social-Ecological Systems analysis. (Source: Deliverable 3.2)

To help identify potential solutions to the challenge of IAS and ways to achieve the identified policy and stakeholder objectives, we assess the current state of the socio-ecological system of Lough Erne. We apply two methods: firstly, the semi-quantitative AQUACROSS linkage framework method and secondly, stakeholder-assisted semi-quantitative Fuzzy Cognitive Mapping.

All human activities are contained within and are completely dependent on the ecosystems which surround them (Boumans et al., 2002). Effectively managing human activities within the bounds of the ecosystems that support them requires understanding the connections between the social and ecological components of what are known as "Social-Ecological System" (SES). Understanding the dynamics of such complex and dynamic SES requires transdisciplinary approaches incorporating many different types of information, from many different sources, about the behaviour and interactions between different system components as well as analytical tools to connect these different types of information. While economists and social scientists traditionally seek to understand the social elements of SES, ecologists traditionally focus on the bio-physical components and each group typically works with different types of tools and analysis.

Ecosystem-Based Management (EBM) is an approach to management which integrates the connections between land air water and all living things, including human beings and their institutions (Mee et al., 2015). In order to put EBM into practice, conceptual and analytical tools are required to structure and integrate different types of social and ecological knowledge, and these may be tailored to the specific requirements of a particular analysis, or be more generally applicable. For example, Ostrom (2009) proposed a general framework for analysing sustainability of SES, this framework considered interactions between a resource system, resource units, users and a governance system, and was applied to the sustainable exploitation of specific resources. For individual environmental problems the Driver Pressure State Impact Response (DPSIR) conceptual frame has been widely used and modified, to emphasise different aspects of SES. Elliott (2017) traces the development and evolution of the DPSIR framework as it has been adapted over time. Gomez. et al., (2016a,b) present a conceptual frame, the AQUACROSS Assessment Framework (Figure 8) where the DPSIR component of environmental "State" is expanded to include ecosystem structure, ecosystem function and ecosystem services, the benefits of which flow in to the social system mediated by social processes (Figure 8) recognising two distinct but interconnected systems, which form the supply and demand side for ecosystem services (the benefits obtained by humans from nature).

One critical challenge in combining the social and ecological sides of the SES is in identifying units of measurement and relationships between these units. For example a change in a Driver (Fig 8 bottom right) might be measured in economic output (e.g. € of fish production) while a Pressure indicator may have a physical component (e.g. number of hectares of seabed trawled) which might cause a loss in ecosystem structure (e.g. tonnes of molluscs- Figure 8 top left) with a resulting loss in ecosystem function (eg. m^3 of water filtered- Figure 8 bottom left) and the benefits of this filtration can (in theory) be converted back to an economic value of the benefits foregone (Figure 8 top right) from lost ecosystem structure and function. In most cases, however, quantitative information on one or all of the links between the different components are missing or poorly understood. In addition the example above deals with a single activity pressure combination while real world SES contain many interacting activities, with multiple, cumulative pressures simultaneously acting on multiple ecosystem structures, functions and services which may respond in non-linear or unpredictable ways. Where the nature of the multiple linkages is not known, simply recognising that the linkages exist may be a useful first step around this problem.

By compiling information on habitat types, with comprehensive lists of activities and pressures along with lists of ecosystem functions and services Teixeira et al. (2018) and Borgwardt et al. (2018) developed linkage matrices based on the AQUACROSS Assessment Framework to enable assessment of risk to ecosystem service supply. By identifying (but not quantifying) the links or relationships between the various system components, their analysis identifies ecosystem components exposed to the highest numbers of pressures and further identifies which ecosystem services are associated with each ecosystem component. Such approaches are potentially useful in comparing SES and the role of ecosystem components across different SES, as well as prioritising which activities and ecosystem components should be addressed to minimise environmental risk.

Figure 8 shows the linkage matrix for Lough Erne illustrating the complexity of interactions between different system components in the Lough. Of all Drivers identified, mining is associated with the highest number of pressures. Introduction of non-synthetic compounds is the most common pressure (and is introduced by multiple drivers). Surface running waters are exposed to the highest number of pressures while recreational and intellectual services are provided by the highest number of habitats. Overall, highest numbers of regulation and maintenance services were identified. While these linkage frameworks clearly provide a holistic and comprehensive overview, they provide only a limited representation of the overall complexity of the systems and therefore omit important feedbacks, and therefore may not apply adequate weight to individual components of the system. As regards to the management of non-indigenous species in Lough Erne, pertinent information from the linkage framework above includes the fact that they are associated with 8 individual activities (motorised and non-motorised boating, stocking, angling, collecting, research, hunting and mining) and that they potentially affect all 13 habitats and biotic groups identified in the case study.

A range of techniques for the analysis of SES in the face of the uncertainty resulting from limited information are available and have been applied to the analysis of aquatic ecosystems. These include the use of Bayesian Belief Network methodologies (e.g. Langmead et al. 2008 Brandt et al., 2012) and soft systems methodologies (Varjapuro et al., 2015, Potts et al., 2015, Cinnirella et al., 2015). One such technique is Fuzzy Cognitive Mapping.

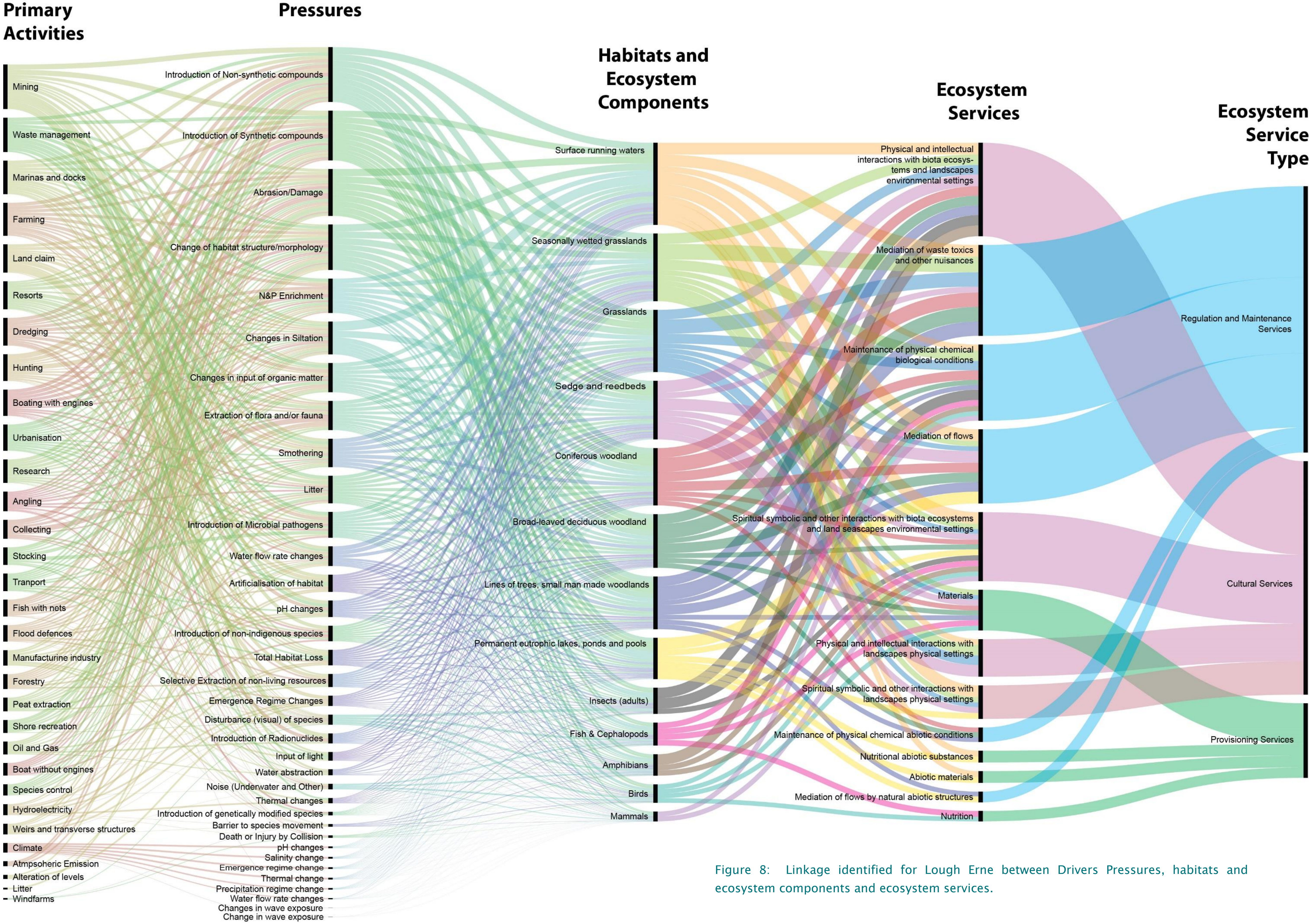


Figure 8: Linkage identified for Lough Erne between Drivers Pressures, habitats and ecosystem components and ecosystem services.

3.2 Fuzzy Cognitive Mapping

Fuzzy Cognitive Maps (FCM) are qualitative models of system operation. An FCM is a diagraph or directed graph made up of variables (points, nodes or concepts), and relationships between these concepts (links or edges) (Figure 9). Diagraphs have been used for over 40 years to incorporate expert opinions into models of system functioning (Azelrod, 1976) FCM that includes fuzzy causal functions assigned to values (between -1 and 1) has been used since the 1980s (Kosko, 1986). Since this time, FCM has been widely applied to a range of situations and can be used to build consensus amongst stakeholders as well as to develop predictions for system function based on scenarios. Özesmi and Özesmi (2004) describe the mathematical aspects as well as a range of different approaches to developing FCMs.

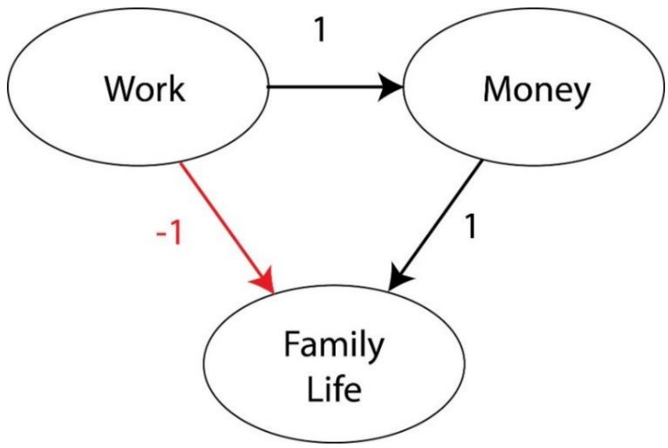


Figure 9: An autobiographical FCM. Positive causal relationships (black edges) are illustrated between the concepts of work and money, and money and family life, while there is a negative relationship (red edge) between work and family life. Full knowledge of the shape of the relationships would enable optimisation. While clear units might be identified for work (hours) and money (€), obvious units are less apparent for the third concept.

Data to generate FCMs for the Lough Erne system were collected during a stakeholder workshop held at Castle Archdale Country Park in Lough Erne County Fermanagh on the 20th of July 2017. Table 3 lists the organisational affiliation of the stakeholders who attended the meeting. In total, 22 stakeholders took part in the FCM exercise.

Five separate groups produced FCMs. Each FCM was generated by starting with a particular element of the SES which interfered with the objectives of specific groups (see Blincow, 2017), the specific components were agreed by the groups and acted as a starting point for the FCMs and the DPSIR was used as an organisational frame to elicit connections from participants. Each FCM was written on a whiteboard and all links between all concepts identified were considered and assigned a positive or negative weight.

Following the workshop, the maps for each table were re-drawn using Mental Modeller software which resulted in a matrix file for analysis. The matrices from each table were combined to develop a joint matrix representing the overall FCM of the whole group (called the JOINT FCM) and the open source software GEPHI (https://gephi.org/) was used to visualise the data (Figure 10)

Table 3: Participants in the FCM workshop

Organisation	Sector	Jurisdiction
Agri-Food and Biosciences Institute	State Agency	NI
Department of the Environment and Rural Affairs	Government	NI
Erne Rivers Trust	NGO	NI
Electricity Supply Board	Private Company	ROI
Fermanagh Omagh District Council	Local Government	NI
Infrastructure-NI	Government	NI
Local Authorities Water and Community Office	Local Government	ROI
Lough Erne Wildfowlers Council	NGO	NI
NI Water	Rebecca Allen	NI
RSPB	NGO	UK
Waterways Ireland	State Agency	Cross border

Since each group (or table) was free to use whatever concepts they wanted (the method did not proscribe the use of particular concepts) each table had different perspectives and slightly different concepts emerged in different maps. In order to develop a consensus map, it was necessary to harmonise concepts within the maps. For example, concepts such as "*fish stock salmonids*" and "*game fish*" were amalgamated as were "*fish stock cyprinids*" and "*coarse fish*". Figure 11 illustrates how the concepts were aggregated to develop a consensus map. For the final consensus map, the weight of each connection was determined by adding the weights of all connections from each contributing map. Only consensus connections from one or more table contributed to the overall map. Full details of the methodology are given in Costea et al. (2018).

The simplified final consensus model is shown in Figure 12. The following chapter uses this model to examine trends in the baseline functioning of the system and to develop some simple scenarios.

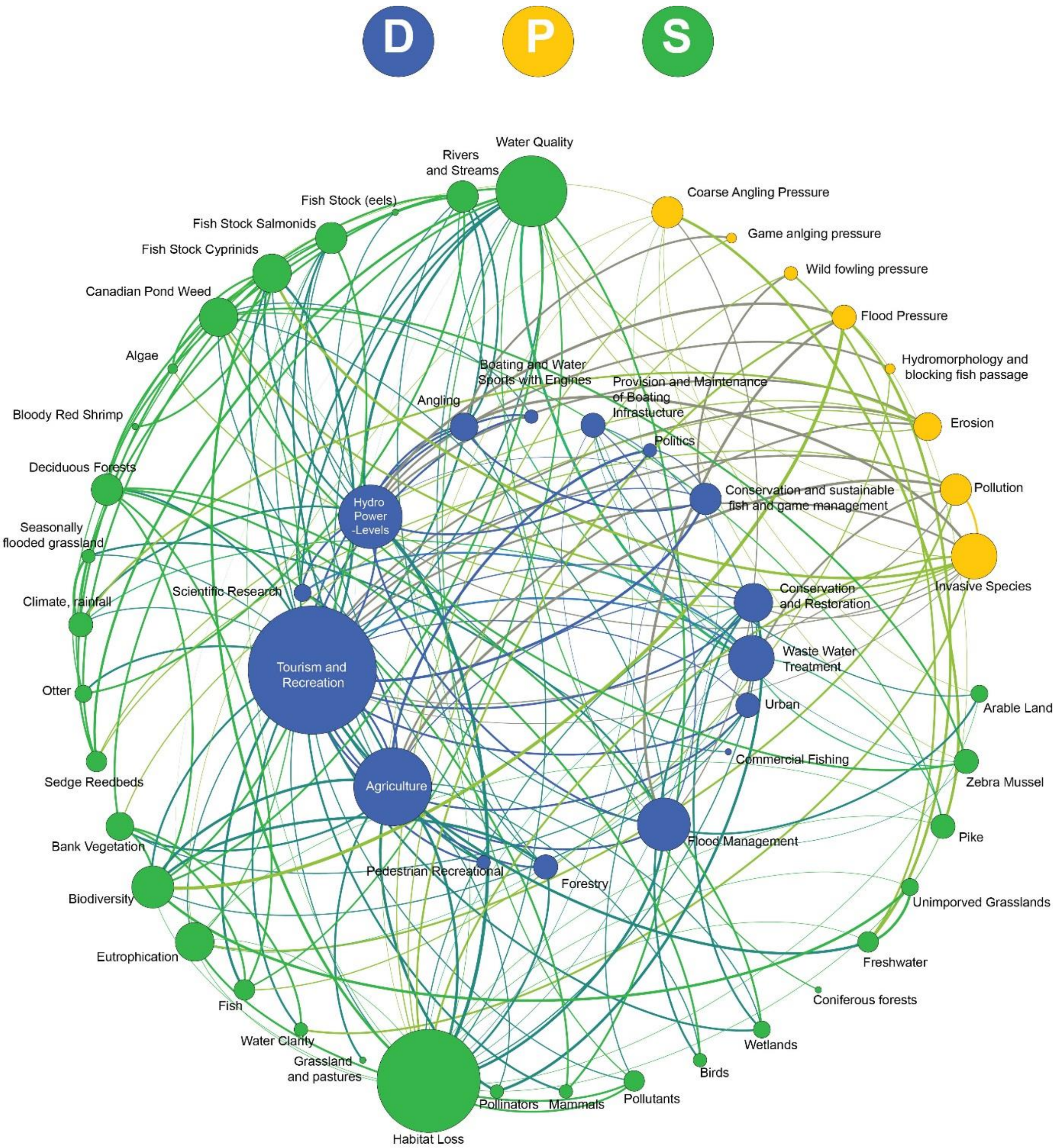


Figure 10: Joint FCM model containing all concepts and interconnections between all tables.

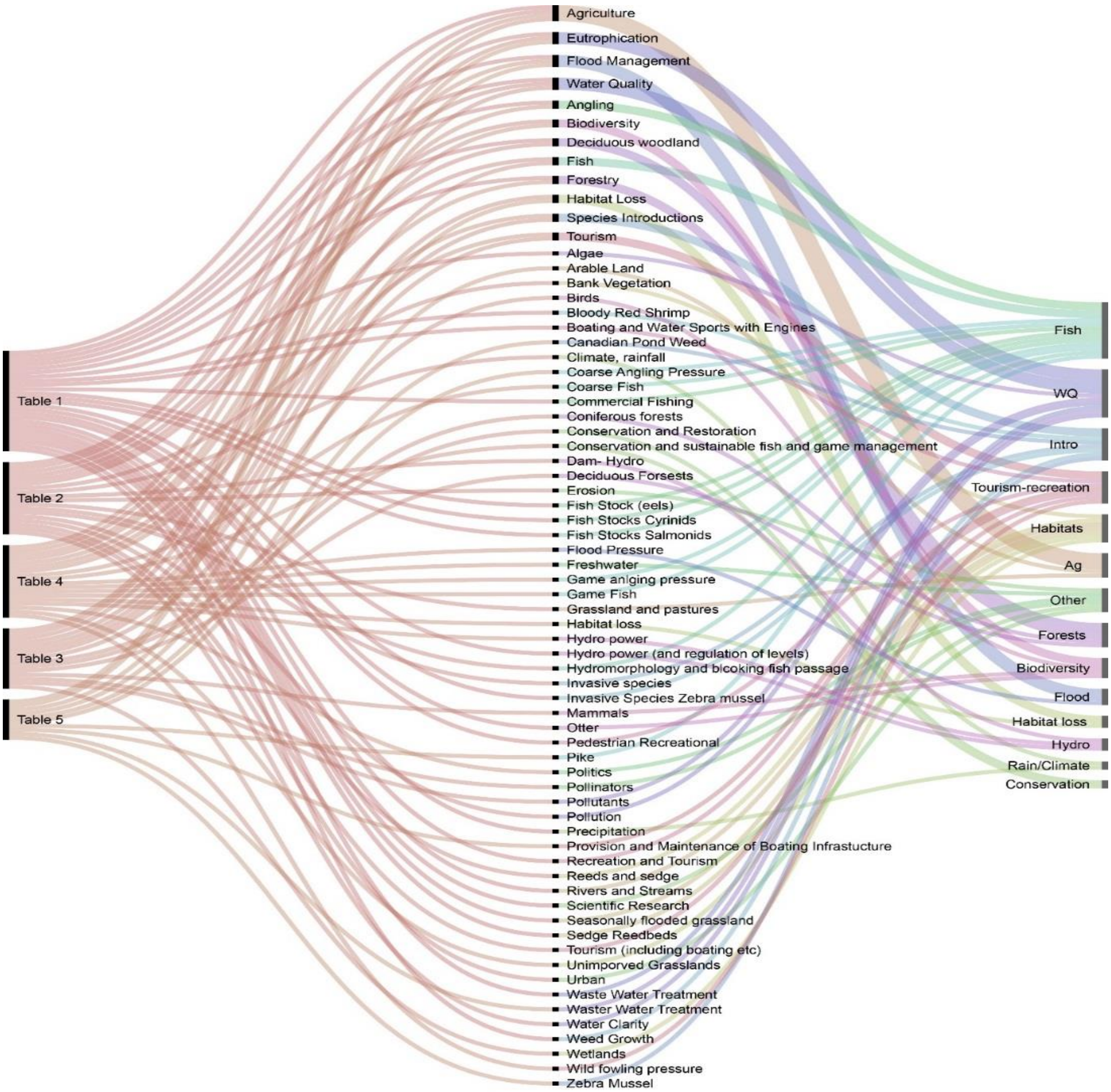


Figure 11: Links between FCM concepts and combined concepts.

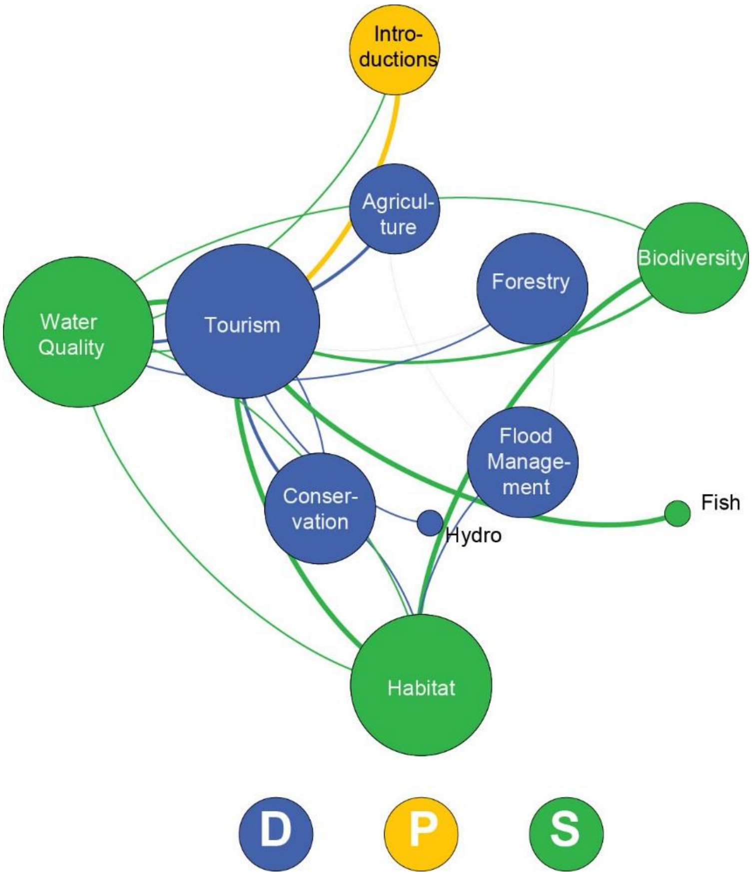


Figure 12: Final consensus model used for assessment of the baseline and development of scenarios.

4 The Baseline and Future Scenarios

4.1 Modelling the Whole Social Ecological System with Fuzzy Cognitive Mapping

FCMs describe system functioning as a set of weighted relationships (edges) between concepts (nodes) and these relationships define a matrix of interrelationships between concepts. Figure 13 illustrates how a matrix is developed from an FCM. Since the matrix defines a set of

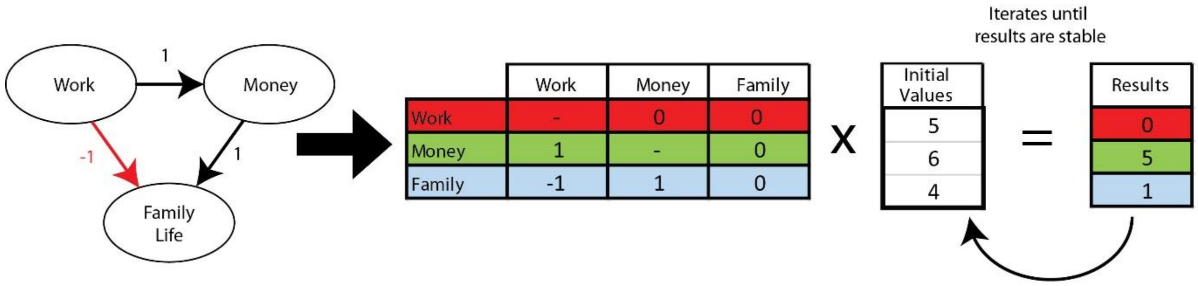


Figure 13: Schematic diagram of simulation using Fuzzy Cognitive Mapping.

interrelationships, multiplying a (vector) set of initial conditions by this matrix enables us to observe how values change over time based on our understanding of the system. While figure 13 shows a much simplified model many FCMs contain multiple feedback loops and therefore take several iterations to stabilize. In order to keep the system within the bounds of −1 to 1 a "squashing function" is also used to transform the results from each iteration (Özesmi and Özesmi, 2004).

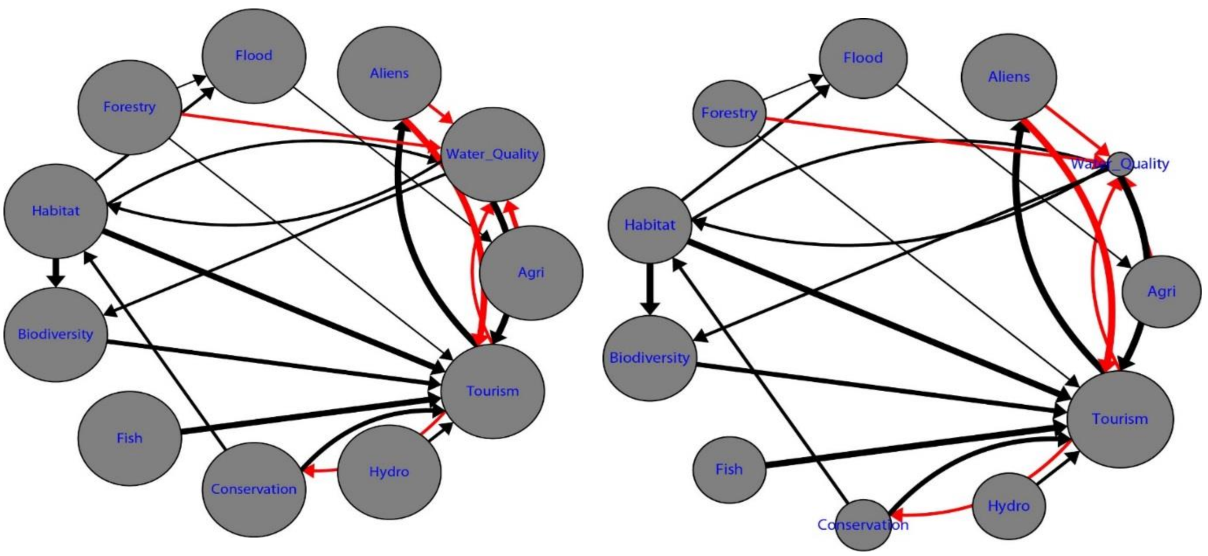


Figure 14: Graphical output of FCM analysis in R showing initial and final state for each of the 11 concepts. Black arrows indicate positive relationships, red arrows show negative relationships.

The consensus FCM (explained in the previous chapter) was used to understand the likely trends in system components based on the stabilisation of the dynamic FCM model. The model was run dynamically by importing the matrix to R and using the R library "FCM Mapper" to determine the likely future state based on the agreed relationships between concepts of the stakeholder group as well as to explore the influence of various system components on other components. The baseline conditions were determined by allowing the model to run to stability (Figure 14). Subsequently 11 different model runs were performed. For each, one of the eleven model component was set to its initial state of 1 and the effects on all other components were examined (Table 4). For example the first column "Ag" describes the results of a model run where the agriculture was kept at a value of 1, this resulted in negative consequences for the water quality (on the second last row).

Table 4: Percent change (rows) from baseline scenario for each of 11 scenarios (columns) fixing individual model concepts to an initial value of 1. Shading from green to red indicates strongest positive or strongest negative effects on individual model components summed vertically for each run

	Ag	Tour	Hydro	Cons	Fish	Bio	Hab	Forest	Flood	AIS	WQ
Agriculture		0	0	0.04	0	0	0.2	0.14	1.84	0	0.06
Tourism	-0.17		0.47	1.06	0.87	0.32	0.77	0.12	-0.01	-1.41	1.72
Hydro	0	0		0	0	0	0	0	0	0	0
Conservation	0.06	-0.97	-0.15		-0.28	-0.1	-0.25	-0.04	0	0.45	-0.55
Fish	0	0	0	0		0	0	0	0	0	0
Biodiversity	-0.51	-0.05	-0.01	0.89	-0.01		3.91	-0.41	-0.02	-0.39	6.18
Habitat	-0.71	-0.13	-0.02	6.71	-0.04	-0.01		-0.59	-0.03	-0.52	9.42
Forestry	0	0	0	0	0	0	0		0	0	0
Flood Management	-0.07	-0.01	0	0.63	0	0	2.87	2		-0.05	0.88
AIS	0	0	0	0	0	0	0	0	0		0
Water.Quality (WQ)	-18.29	-1.38	-0.22	1.85	-0.4	-0.15	11.09	-14.92	-0.91	-14.24	
OVERALL	-19.69	-2.54	0.07	11.18	0.14	0.06	18.59	-13.7	0.87	-16.16	17.71

A further scenario was run by fixing the value of invasive species to 0 reflecting the stakeholder and policy goals of eliminating invasive species. This resulted in positive changes to Tourism (2%), biodiversity (1%), habitats (1.5%) and water quality (46%).

In order to further examine the relationship between agriculture and water quality a series of 10 model runs was performed where agriculture was fixed at specific values from between 1 and 0 at increments of 0.1. Figure 16 illustrates the results of these model runs.

Overall the baseline FCM model suggests that further declines in water quality are likely in the future and also indicates declining conservation status. These findings are broadly in line with assessments under the Water Framework and Habitats Directives.

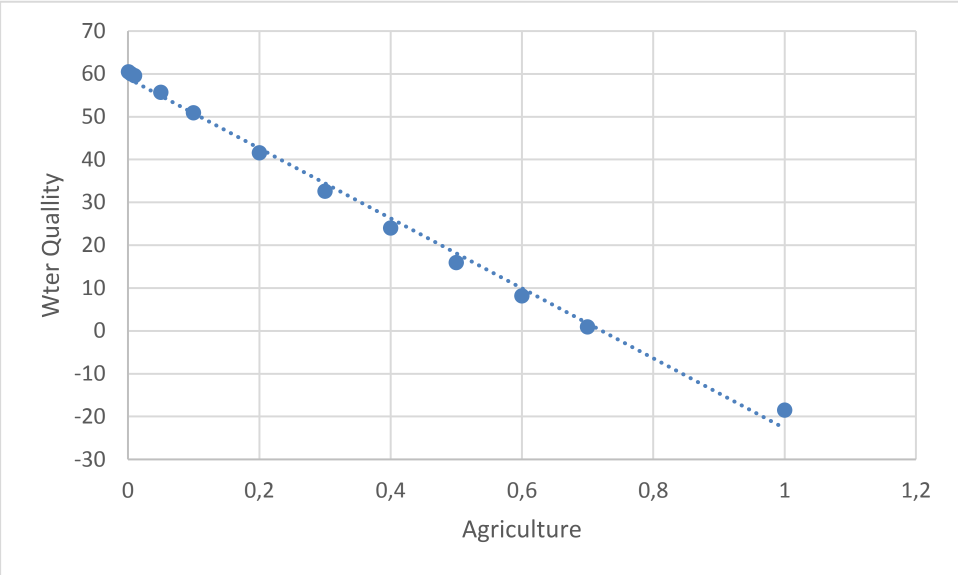


Figure 15: Modelled relationship between agriculture and Water Quality based on FCM each point on the line represents a single model run where the level of agriculture was kept steady in the model while all other components of the model were allowed to run dynamically. WQ=-81.699x(Agriculture)+58.962. The results are expressed as % of the initial starting value. Non-negative results for WQ occur at levels of agriculture of 0.7 (approximately representing a reduction of 30%).

Though qualitative in nature, the FCM model developed as part of the case study indicates that reductions in agricultural pressures to about 70% of current values may result in gradual improvements to Water Quality (Figure 15).

The modelled scenarios indicate the importance of agriculture and forestry in controlling water quality and the positive associations between habitats and water quality. Strongest positive modelled changes occurred in the scenario where water quality was kept constant and these were mainly associated with habitats and biodiversity.

Given the qualitative nature of the information in the FCM, the values generated by scenarios should be considered to indicate the relative strength and direction of likely future changes rather than quantitative estimates of the likely changes. Nevertheless, the modelled results clearly suggest that targeting of water quality and the sectors that negatively affect it (particularly agriculture) are likely to produce the most positive results in terms of habitats, biodiversity and conservation. While not explicit in the FCM model, the proliferation of Nutall's pond weed is also associated with reduced water quality and measures to improve water quality are likely to have positive effects in the reduction of pond weed.

4.2 Modelling Lake Levels

While the consensus FCM gives a general picture of the likely future outcomes of the status quo and makes some general predictions about future system behaviour, it is not sufficiently detailed to address the specific question of managing the impacts of Nutall's pond weed in Lough Erne. In order to address the proposal of raising lake levels to manage the impact of the pond weed on recreational activities, a modelling approach to analyse the potential affect on the physical environment was required.

The Erne Drainage and Development Act (1950) stipulates strict limits for the lake levels during the summer season (between 150ft and 154ft) above sea level. In order to estimate the horizontal extent of flooding at different lake levels the European Digital Elevation Model (EURODEM, horizontal resolution 25m), was used. GIS was used to identify cells within a 5km distance of the Lough with elevations marginally greater than the Lough Level, the location and extent of potentially flooded lands was simulated at 5 increments from 0.2m to a level of 1.2m above the lake levels of the Digital Elevation Model[5]. Figure 16 shows the cumulative area of land flooded over the range of 4ft (approximately 1.2m). Figure 17 represents the spatial distribution of simulated inundation.

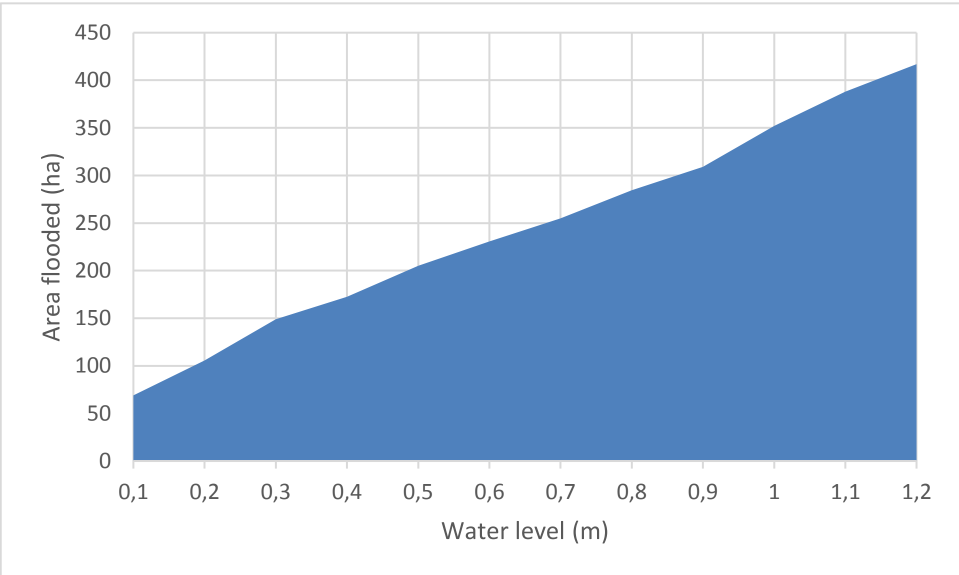


Figure 16: Cumulative inundation of land with 1.2m rise in water levels, based on EURODEM data.

[5] An elevation of 40m was assumed to be equivalent to the base summer elevation of 150ft stipulated within the agreement.

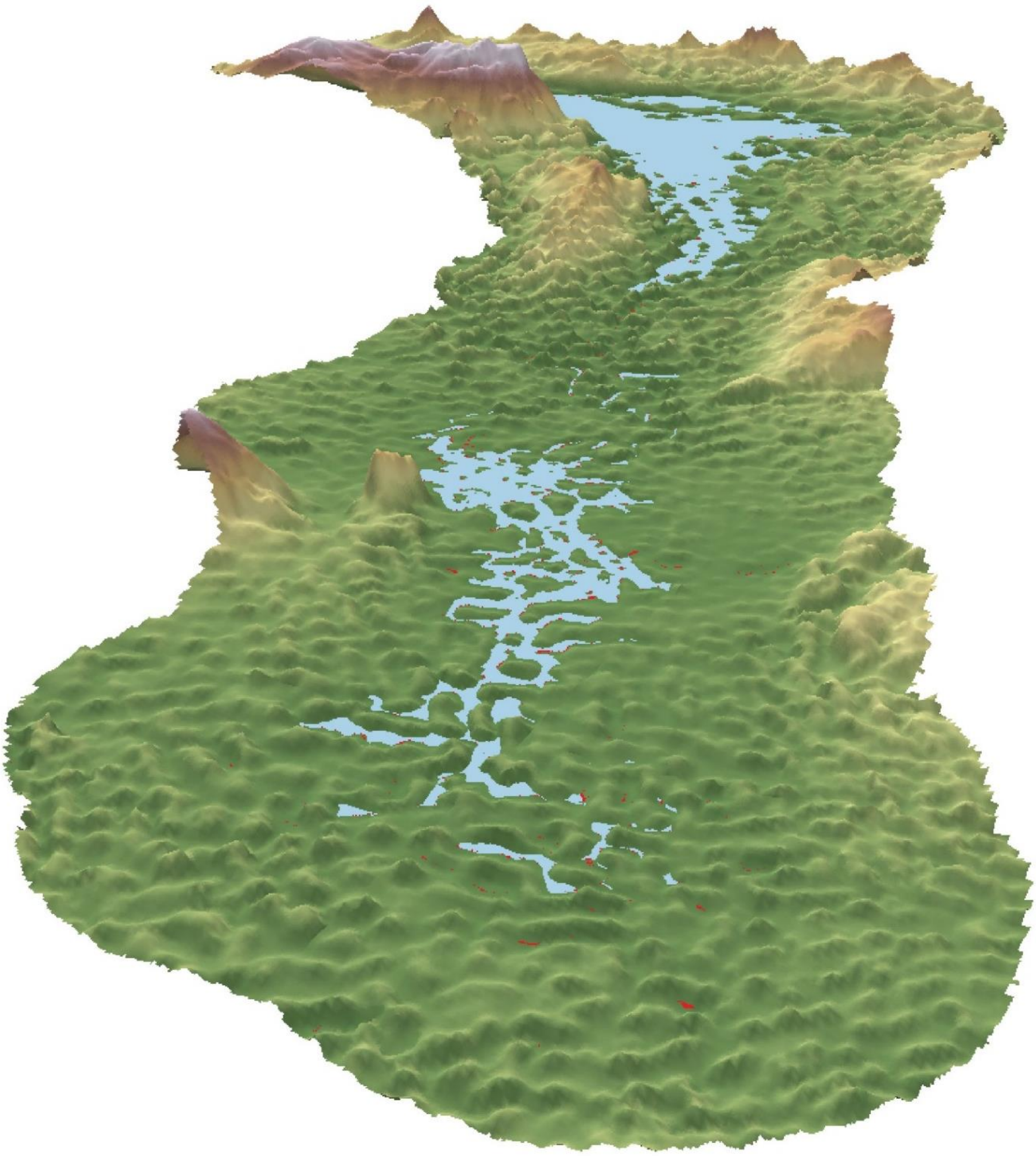


Figure 17: Digital elevation model of land surrounding Lough Erne. Lough Erne is shown in light blue, lands flooded by raising the elevation of the lake are shown in red.

5 Evaluation

Following the assessment framework, against this baseline scenario, we evaluate two ecosystem-based management measures in terms of effectiveness, efficiency, and equity: decreasing agricultural nutrients and increasing water levels.

Current practices for management of Elodea involves physical removal in major navigational channels to enable passage of recreational vessels. In 2010, €91,000 was spent in removal of the weed to facilitate recreation, however this strategy is considered costly and ineffective (Kelly, 2013) and does not take into account the ecosystem processes contributing to the problem, nor does it incorporate consideration of the full range of human activities occurring in the lake.

The models described in the previous chapter address two different mechanisms for the management of pond weed in the Lough Erne system. The FCM identified water quality as a problem and clearly links this to the system component of agriculture, and was used to identify an approximate relationship between reductions in agricultural and water quality but does not prescribe specific mechanisms for how to de-couple the agricultural activity from the problem of water quality. The modelling of lake levels indicates that raising water levels would involve inundation of significant areas around the Lough. In order to examine and compare these two approaches for the management of pond weed in the Lough, a clearer picture of the costs and benefits of the two options is required.

The baseline information for water quality in the Lough Erne catchment, which straddles the border of (the Republic of) Ireland and Northern Ireland, comes from the Water Framework

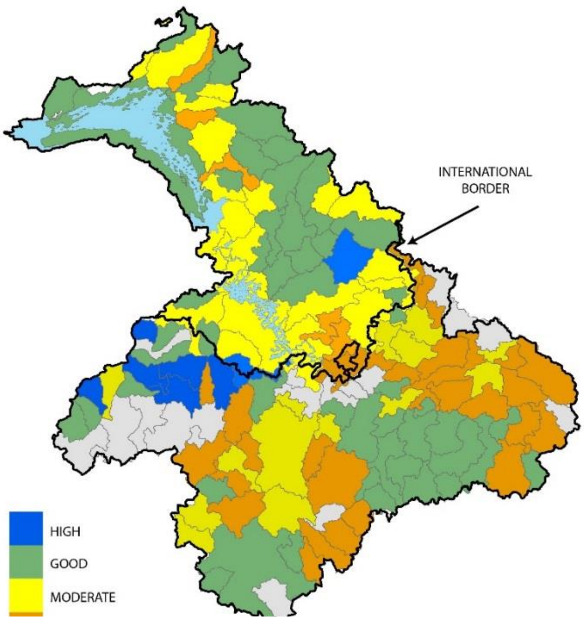


Figure 18: Ecological Status of sub basin surface waters in the Lough Erne catchment

Directive. Approximately 59% of the Erne catchment is in the Republic of Ireland with the remainder in Northern Ireland. WFD data for the North are collected by the Department of Agriculture Environment and Rural Affairs (DAERA) in the North and by the Environmental Protection Agency in the South. Figure 18 illustrates the baseline situation for Ecological Status of surface waters in the Lough Erne Catchment, while Table 5 indicates the areas for each WFD category within the Lough Erne catchment and within the two national jurisdictions of the catchment.

		NI		ROI	Combined	
	Area(km^2)	%	Area(km^2)	%	Area(km^2)	%
High	61	4	122	6	182	5
Good	638	41	649	29	1286	34
Moderate	603	39	364	16	967	26
Poor	83	5	711	32	794	21
Heavily Modified	176	11			540	14
	No Assessment		364	16		
Total	**1560**	**41**	**2209**	**59**	**3769**	**100**

Table 5: Agricultural area of Lough Erne Catchment sub-basins and WFD ecological status broken out by jurisdiction (NI-Northern Ireland, ROI=Republic of Ireland).

There are many potential mechanisms to decouple agricultural activity from water quality impacts. Cuttle et al. (2007) reviewed a range of farm Best Management Practices (BMPs) to reduce diffuse water pollution from agriculture, describing in detail the costs and technical effectiveness of each measure. Table 6 provides a list of BMPs considered for Lough Erne ranked by their cost effectiveness ratios. Using the Cost Effectiveness Analysis (CEA) method, we identify those BMPs that can be implemented at least cost for the farmer while maximising potential P losses reductions. The cost curve method was subsequently applied (Lago, 2009) to estimate levels of abatement that could be potentially achieved as we sequentially implement these BMPs at farm level while considering their financial costs. The costs were calculated for two targets, 30% reduction in nutrient concentrations (based on the FCM model outputs, see Figure 16) and 70% reduction in nutrients at the farm level under the assumption that the reductions would translate proportionally into improvements in water quality.

The economic analysis summarised in Figure 19 illustrates how a number of cost saving BMPs (negative costs) can save money to individual farms while also contributing to reduced nutrient loading. The target of 30% reduction can be met by implementing the first 6 measures sequentially with an overall cost of £15m for the whole catchment.

Overall we identified two possible approaches to the management of the proliferation of Nutall's pond weed in Lough Erne. The first approach is in line with more effective implementation of a well-established environmental directive the WFD and relates to decoupling the driver of agriculture from the pressure of nutrient pollution. A range of potential mechanisms to implement this decoupling were considered. In all cases the costs are borne by farmers and the benefits are expressed in terms of water quality. As such these measures are not specifically focussed on Nutall's pond weed but it is likely that their implementation would have effects on the proliferation of the weed, as well as more generally improving lake water quality in line with the obligations under the WFD. The FCM modelling also identified co-benefits of improving water quality in terms of habitats and conservation of biodiversity (which are not quantified or valued here).

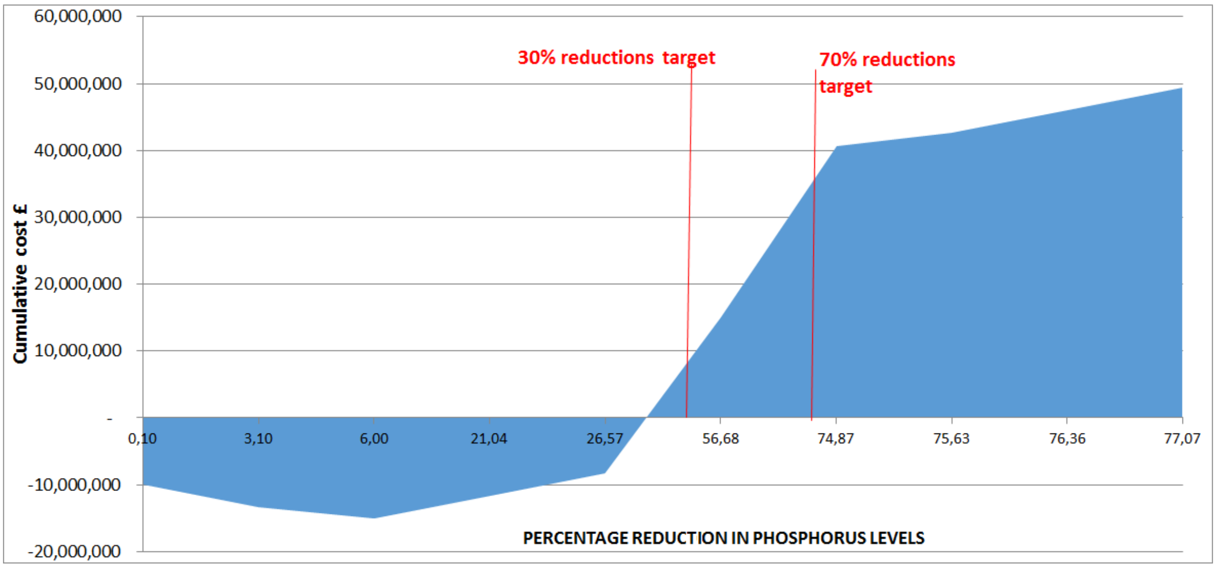
Table 6: Farm Best Practice Measures identified (from Cuttle et al., 2007 and Lago, 2009) to reduce nutrient loading to Lough Erne

		CE ratio*	P Loss**	N Loss**	FIO Loss**
	Clay loam soil				
1	Integrate fertiliser and manure nutrient supply	-472,44	0,10	2,50	0,00
2	Reduce fertiliser application rates; 20% Reduction P	-5,25	3,10	2,50	0,00
3	Do not apply P fertilisers to high P index soils	-2,62	6,00	2,50	0,00
4	Do not spread farmyard manure to fields at high-risk times	0,98	21,04	3,31	0,00
5	Do not apply manure to high-risk areas	2,25	26,57	4,12	0,00
6	Transport manure to neighbouring farms 5km	2,69	56,68	12,11	0,00
7	Establish and maintain artificial (constructed) wetlands	2,86	74,87	85,35	20,00
8	Re-site gateways away from high-risk areas	3,17	75,63	85,35	20,00
9	Use a fertiliser recommendation system	5,25	76,36	85,72	20,00
10	Site solid manure heaps away from watercourses and field drains	5,25	77,07	85,84	28,00
11	Transport manure to neighbouring farms 20km	5,57	86,47	87,02	28,00
12	Move feed and water troughs at regular intervals	5,85	88,36	87,23	35,20
13	Do not apply fertiliser to high risk areas	7,87	88,83	87,34	35,20
14	Site solid manure heaps on concrete and collect the effluent	22,87	89,16	87,45	41,68
15	Avoid spreading fertiliser to fields at high-risk times	27,36	89,38	87,55	41,68
16	Reduce field stocking rates when soils are wet	28,43	90,34	88,79	47,51
17	Fence off rivers and streams from livestock	38,40	90,53	88,98	52,76
18	Establish riparian buffer strips	38,40	90,72	89,17	57,48
19	Reduce overall stocking rates on livestock farms	54,05	94,15	90,97	78,74
20	Loosen compacted soil layers in grassland fields	85,04	94,21	90,97	78,74
21	Allow field drainage systems to deteriorate	177,85	94,27	91,35	78,74
22	Reduce the length of the grazing day or grazing season	255,90	94,33	91,71	80,87

* £/% Reduction in P loss/ha, NPV/ha over an 8-year period. Discount rate 3.5%

**Farm level per ha

Figure 19 The cumulative costs and nutrient reductions for the 10 most effective measures.



The second management measures considered was the adjustment of lake levels, which would result again in costs to farmers due to the inundation of productive agricultural lands. This measure does not address the water quality of the Lough specifically but is designed to manage the impact of pond weed proliferation on recreational activities within the Lough. Inundation of agricultural land may also produce co-benefits in terms of biodiversity by increasing the area of semi natural riparian habitats. Maintaining the Lough at higher levels during summer may also result in benefits to the hydro-production sector enabling increased generation capacity. Figure 20 shows the costs to agriculture of raising lake levels estimated in terms of annual standard output (blue) and in terms of land value (red) based on compulsory purchase price.

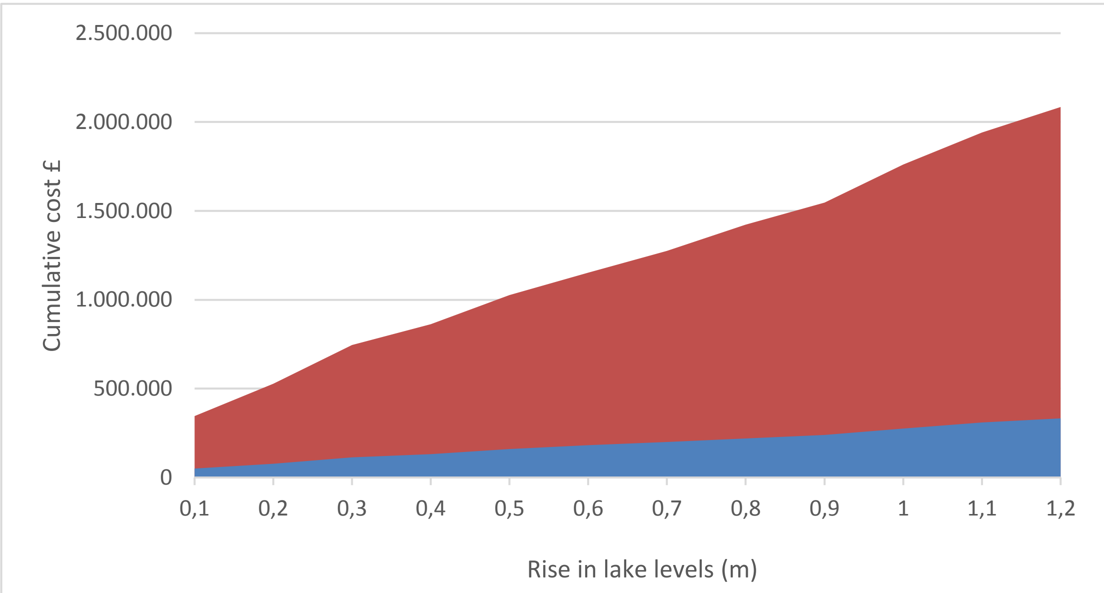


Figure 20: Costs to agriculture of raising lake levels expressed as lost farm standard output (blue) and compulsory purchase price (red).

The results of the analysis shown above were presented to a group of stakeholders at the second AQUACROSS Lough Erne workshop on the 1st of August 2018[6]. The fact that cost estimates were provided to allow comparison between the different ecosystem based management measures was seen as a very practical and useful output from the case study.

While reduction in diffuse nutrient emissions was considered a useful exercise to prevent eutrophication in the lake, some stakeholders suggested that the considerable existing nutrient pools in the lake and the interaction between Nutall's pond weed and the zebra mussels provide an efficient mechanism for the continual cycling of existing nutrient pools. They suggest this may effectively extend the time period over which reductions of nutrients might be expected to result in reductions in the levels of eutrophication in the lake. With regards to the proposal to manage lake levels, some stakeholders expressed concern over maintaining the lake levels at the end of the Elodea growing season, as this can coincide with periods of heavy rainfall and result in increased flood risk. Others suggested that the Elodea, which currently reaches, and extends beyond, the lake surface, may simply float to the surface and that the benefits of increased water levels may not be experienced by recreational boaters. By contrast it was suggested that altering lake levels earlier in the season to prevent annual establishment of the weed might be a useful strategy. There was consensus that the effects of altering lake levels on the proliferation of the weed remains unknown and that any strategies would be experimental exercises in adaptive management or "learning by doing", which should be combined with nutrient abatement measures in the long term.

6 Discussion and conclusions

The current state of the Lough Erne Social Ecological System results from a very long history of human use and alteration dating back for millennia. The modern Lough is a highly valued ecosystem which provides multiple benefits to humans yet also suffers from a range of chronic and acute environmental problems. European environmental legislative requirements for the Lough are not fully integrated into the management practices of the Lough, and the recent regulation on Invasive Alien Species adds an additional burden of management. Of the aquatic species listed in the regulation and found in the Lough Erne catchment, only one, Elodea nutalli (Nutall's pond weed) has had significant economic impacts to date.

A range of techniques were employed to understand the Lough Erne SES, these included linkage frameworks, to connect human activities to pressures and ecosystem services, fuzzy cognitive mapping to incorporate stakeholder perceptions into a dynamic model of system behaviour, and more mechanistic GIS-based modelling approach to understand the effects of specific management measures on other activities within the catchment. In combination, these methods revealed a system which is overwhelmingly complex and where incomplete knowledge is the rule. Nevertheless, the techniques enabled identification of a range of potential measures for

[6] More information on the workshop available online.

management of pond weed in the system. Ultimately the potential measures were reduced to a single metric of cost effectiveness to enable stakeholders in Lough Erne to consider the relative merits of the measures identified. Stakeholder workshops provided model input and evaluation, and valuable insight on how any policies should be practically implemented.

While currently EU environmental regulation provides a common cross border framework for environmental management in the Lough Erne catchment across an international boundary, the future basis for such cooperation is unclear. The UK is currently in the process of leaving the European Union and the current political and economic basis for environmental regulation as well as for enabling and subsidising agricultural production is unlikely to remain as it is, while the potential future alternatives are largely unknown. Major changes in the social system comprising primary activities as well as the norms and values enshrined in environmental laws and regulations may be on the way. The effects of these changes on a social ecological system already characterised by overwhelming complexity cannot be foretold.

Overall, integrated, ecosystem-based management approaches to the management of Lough Erne enable consideration of multiple primary activities and their pressures and provide a basis to meet multiple environmental as well as social and economic objectives. The transboundary nature of the Lough Erne catchment is a barrier to truly integrated management of the catchment and the political boundaries between the two jurisdictions appear to be becoming more pronounced as the UK is set to leave the European Union.

The Erne Drainage and Development Act (1950) was an early example of cross-border cooperation and succeeded because there were mutual benefits to be gained in the two jurisdictions. Changes to the management regime of the lake levels (within the legal limits of the EDDA) offer one opportunity for the management of the system which could continue to provide benefits to user of the Lough Erne SES on both sides of the border and could act as a focus for continued cross border cooperation.

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Annex

All annexes are available on the AQUACROSS website Case Studies page.

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