Institution: University of the Highlands and Islands

Unit of Assessment: 7 Earth Systems and Environmental Science

Title of case study:

Safeguarding human health and sustainable aquaculture through monitoring programmes developed from research into harmful algal bloom (HABs) dynamics

1. **Summary of the impact** (indicative maximum 100 words)

Harmful Algal Blooms (HABs) are a serious risk to human health and the sustainability of the aquaculture industry. Research by Prof. Davidson has improved understanding of temporal and spatial trends in marine HABs and detection of toxins in farmed shellfish. Knowledge gleaned from this research has been adopted by the Food Standards Agency (FSA) in the design of the HAB Monitoring Programme for Scotland. Prof. Davidson leads the FSA HAB Monitoring Programme. The research findings also underpin the Crown Estate's finfish monitoring programmes and are used to advise aquaculture businesses on ways to reduce economic impact of HAB events.

2. Underpinning research (indicative maximum 500 words)

Planktonic algae are microscopic aquatic organisms found in the water-column. Some marine algal species produce biotoxins which can cause damage to, and mass mortality in, fish and other organisms. Human ingestion of shellfish contaminated by algal biotoxins can cause poisoning which may be manifest in illnesses ranging from mild gastrointestinal problems to respiratory and neurological disorders or even death. Toxic algal populations can rapidly increase, forming large naturally occurring accumulations known as harmful algal blooms (HABs).

For >60 years UHI scientists have researched phytoplankton ecology (Drs Marshall & Orr, 1950s), growth theory (Dr Droop 1960s), and the relationship between harmful algal species and finfish mortalities in Scottish sea lochs (Drs Gowen, Jones and Tett).

Since 1998 UHI HAB research has been led by Prof. Davidson and is centred on understanding the environmental interaction of specific HAB species, including the influence of environmental conditions on HAB movement, toxicity levels and risk to the aquaculture industry, producing >60 peer-reviewed publications. This research may be divided into 2 categories:

1. **Algae Harmful to Finfish**

In 2006, Prof. Davidson's group tracked the movement of a large bloom of a HAB genus, deadly to finfish, called *Karenia*. Bloom movement was tracked from the waters of southwest Scotland, northeast to the Shetland Islands and the North Sea. These studies enabled determination of temporal and spatial trends in *Karenia* bloom movement in response to environmental conditions (including temperature, salinity & weather conditions)[1]. The research found that bloom events are influenced by local fluctuations in salinity[1]. In collaboration with Plymouth Marine Laboratory, remote sensing methods were developed to detect and track *Karenia* blooms[2].

2. **Algae Harmful to human health**

In 1999, 49,000km^2 of western Scottish waters were closed to shellfish harvesting due to the risk of Amnesic Shellfish Poisoning (ASP) caused by shellfish contaminated by the HAB species *Pseudo-nitzchia*. Prof. Davidson's team researched this closure and subsequent *Pseudo-nitzchia* bloom events, developing an understanding of the environmental factors influencing temporal and spatial trends in HAB movement and seasonal patterns in growth and toxicity such as temperature and nutrient cycles[3]. It was found that silica limitation, linked to seasonal fluctuations in nitrogen:silica ratios, promoted enhanced toxicity in *Pseudo-nitzchia*[3].

If ingested by humans, toxins from the HAB genus *Alexandrium*, can cause Paralytic Shellfish Poisoning (PSP). Prof. Davidson's studies of *Alexandrium* have revealed the co-occurrence of highly toxic and non-toxic forms of the species *Alexandrium tamarense* which are morphologically identical, but molecularly distinct. The group have developed laboratory and field techniques to aid discrimination of toxic and non-toxic forms[4].

Prof. Davidson's group has discovered much about the influence of environmental conditions on HAB species biology and behaviour. This research led to further collaborative studies to evaluate the likelihood of factors such as climate change, anthropogenic nutrients and ballast water transfer causing the invasion of UK waters by new toxic phytoplankton species, or changing the abundance and toxicity of indigenous species[5,6]. This has allowed us to establish a temporal/spatial understanding of HAB risk that is used by the Food Standards Agency to underpin their shellfish safety policy.

3. References to the research (indicative maximum of six references)

1. **Davidson K**, Miller PI, **Wilding T,** Shutler J, Bresnan E, Kennington K, **Swan S** (2009) A large and prolonged bloom of *Karenia mikimotoi* in Scottish waters in 2006. Harmful Algae 8:349-361 (Journal Impact factor 4.3)
2. Shutler, JD, **Davidson K**, Miller PI, Swan SC, Grant MG, Bresnan E (2012) An adaptive approach to detect high biomass algal blooms from EO chlorophyll-*a* data in support of harmful algal bloom monitoring. Remote Sensing Letters 3: 101-110 (Journal impact factor: new)
3. Fehling J., **Davidson** K., Bolch C.J., Bates S.S. (2004) Growth and domoic acid production of *Pseudo-nitzschia seriata* (P.T. Cleve) H. Peragallo (Bacillariophyceae) under Phosphate and Silicate limitation. J. Phycology 40: 674-683 (Journal impact factor: 2.239)
4. Touzet N., **Davidson K.,** Pete R., Flanagan K., McCoy GR., Amzil Z., Maher M., Chapelle A. & Raine R (2010) Co-occurrence of the West European (Gr. III) and North American (Gr. I) ribotypes of *Alexandrium tamarense* (Dinophyceae) in Shetland, Scotland. Protist 161: 370-384 (Journal Impact factor 3.3)
5. **Davidson K,** Gowen R, **Tett P**, Bresnan E, Harrison PJ, McKinney A, Milligan S, Mills DK, Silke J, Crooks (2012). Harmful algal blooms: How strong is the evidence that nutrient ratios and forms influence their occurrence? Estuarine, Coastal and Shelf Science 115, 399-413. (Journal Impact factor: 2.6)
6. Gowen RJ, **Tett P**, Bresnan E, **Davidson K**, McKinney A, Milligan S, Mills DK, Silke J, Gordon A, Crooks AM (2012). Anthropogenic Nutrient Enrichment and Blooms of Harmful Micro-algae. Oceanography and Marine Biology: An annual review. 50: 65-126. (Journal Impact factor 8.5)

Key grants:

- Food Standards Agency: Research to support a monitoring programme for new or emerging biotoxins in shellfish in UK waters (2005-2012)
- EU FP7: Applied Simulations and Integrated Modelling for the Understanding of Toxic and Harmful Algal Blooms (€300K, 2009)
- NERC: The competitive dynamics of toxic and non-toxic ribotypes of the harmful dinoflagellate *Alexandrium tamarense* (£70K, 2009)
- EU Interreg: Warning of Algal Toxin Events to support Aquaculture in the NPP coastal zone Region "WATER" (€250K, 2009)
- DEFRA: Harmful algae, nuisance blooms and anthropogenic nutrient enrichment (£75K, 2008)
- Crown Estate: Analysis of the exceptional 2006 *Karenia mikimotoi* bloom in Scottish waters (£58K, 2007)

- EU interreg: Forecasting the INitiation of harmful ALgal blooms "FINAL" (€420K, 2006)

Evidence of quality of research:
The research of Prof. Davidson and his team has been cited >3800 times since 2008.

4. Details of the impact (indicative maximum 750 words)

Harmful algal blooms (HABs) generate natural biotoxins that are harmful to humans who ingest shellfish that have concentrated the toxins in their flesh. Examples include paralytic shellfish poisoning (PSP) of which there are ~2000 recorded cases annually worldwide, with 15% mortality. HAB events can have a catastrophic effect on the sustainable development of the aquaculture industry worldwide due to economic loss resulting from regulatory closures of shellfish farms and farmed fish mortalities.

HAB research by Prof. Davidson's team underpins monitoring programmes and advice to the Crown Estate, Food Standards Agency (FSA), aquaculture businesses and industry bodies such as Seafood Shetland to ensure UK shellfish safety, human health and economically sustainable aquaculture[1].

Research by Prof. Davidson's team to track and study the 2006 *Kareina* bloom led to the development and implementation in 2008 of a monitoring programme to protect finfish aquaculture on the Scottish west coast. As blooms of this organism move around the coast, monitoring provides early warning to allow the industry to plan finfish husbandry operations and the routing of fish transport by well boat. Operating since 2008, the programme has been successful in providing early warning of elevated *Karenia* densities and hence preventing significant losses/costs to industry. This monitoring programme is on-going, commissioned by the Crown Estate and Scottish Salmon Producers Organisation. Prof. Davidson's team also developed, on behalf of the Crown Estate, a report which provides a series of recommendations on predicting the progression of *Karenia* along the Scottish coastline and the potential impact for fish farming[2]. Published in 2009, the report provides finfish aquaculture businesses with advice on how to reduce the impact of *Karenia* blooms through operational changes such as cessation of feeding and reduction in fishfarm husbandry during bloom events.

The FSA, the regulatory body responsible for monitoring food safety, monitor biotoxin producing phytoplankton for aquaculture safety. Prof. Davidson's research on understanding the ecology and environmental interaction of key shellfish poisoning causative genera (*Pseudo-nitzchia* and *Alexandrium*) has been used to inform FSA shellfish monitoring policy, and since 2005 Prof. Davidson has led the operation of the FSA Official Control Biotoxin Producing Phytoplankton Monitoring Programme[3,4,8]. This programme is on-going and in compliance with the EU shellfish hygiene directive that requires all shellfish harvesting countries to monitor the abundance of potential biotoxin producing phytoplankton to ensure shellfish safety and safeguard human health. Knowledge of the temporal and spatial trends of important harmful algal species gained from Prof. Davidson's research was used to developed a network of inshore representative monitoring points (RMPs) that are currently monitored on a weekly basis to give optimal country-wide spatial and temporal coverage of HAB events in shellfish harvesting areas. Weekly water samples from 36 monitoring sites are tested for a number of biotoxic phytoplankton. This data is reported against regulatory thresholds and used by the FSA to determine whether shellfish are safe to be marketed in the UK or abroad[3,4,8].

<u>**Additional Impacts:**</u>

- **Provision of advice to the aquaculture industry:** Since 2006 Prof. Davidson's team has worked closely with European aquaculture businesses, most notably Seafood Shetland[5], to develop and evaluate methods of HAB early warning and of detecting shellfish toxicity. This included the evaluation of commercially available, Enzyme-Linked Immunosorbent Assay (ELISA) kits for the determination of Diarrheic Shellfish Poisoning (DSP). This evaluation, as part of an EU consortium, recommended commercial use of DSP-ELISA to be replaced by a protein phosphatase based method due to erroneously high toxin readings in the former method. Recommendations were presented at a project meeting in Shetland (2011) to aquaculture regulators and operators from Scotland, Norway, Ireland and Faroe Islands[5].

- **Informing standards:** Commissioned by the UK National Reference Laboratory (UKNRL) for Biotoxins, UHI in collaboration with the Agri-Food Biosciences Institute (AFBI) reviewed monitoring of the algae thought to produce azisporacid shellfish toxins. This review paper was presented to the UKNRL for Biotoxins and was used as a template for the regulatory monitoring of these organisms[6]. Prof. Davidson's team was subsequently commissioned by the FSA to develop a molecularly based method of identification and numeration of *Azadinium.* This method was completed in April 2013 and its implementation is currently being reviewed.

- **Advice to the International Council for the Exploration of the Sea (ICES):** ICES, an intergovernmental organisation, provides scientific advice to governments on the use and management of the marine environment. Since 2007 Prof. Davidson has been a member of the ICES Working Group on Harmful Algal Bloom Dynamics[7]. UHI hosted the 2012 annual ICES Working Group Meeting which reported fish-killing algal events in ICES regions[7]. This report is used by ICES to advise member states on HAB issues and management.

5. Sources to corroborate the impact (indicative maximum of 10 references)

1. Details of UHI research activities relating to HABs and FSA monitoring Programmes can be found on the UHI website at http://www.UHI.ac.uk/keith-davidson/toxic-plankton-monitoring/?searchterm=FSA. Details of the Crown Estate funded project can be found at http://www.UHI.ac.uk/keith-davidson/karenia-mikimotoi-hab

2. The Crown Estate Report, authored by Prof. Davidson on predicting the progression of *Karenia* along the Scottish coastline and the potential impact for fish farming: http://www.thecrownestate.co.uk/media/211054/karenia.pdf

3. Food Standards Agency Official Control Biotoxin Monitoring Programme: UHI operate this monitoring programme on behalf of the FSA and developed the representative monitoring points for the programme. Up to date monitoring data is published on the web: http://www.food.gov.uk/business-industry/farmingfood/shellfish/algaltoxin/

4. Prof. Davidson's Report on behalf of the FSA on the Monitoring Programme for the Presence of Toxin Producing Plankton in Shellfish Production Areas in Scotland http://www.food.gov.uk/multimedia/pdfs/monitoring-planton-rep2011.pdf

5. Seafood Shetland is a Scottish Industry body which can provide corroboration of the use of outputs of Prof. Davidson's research and FSA Monitoring data by the shellfish industry to plan their harvesting activities and of the industry uptake of the recommendations related to the use of DSP ELISA.

6. The minutes of the UK National Reference Laboratory Meeting 21st July 2011 confirm that the *Azadinium* review paper produced by UHI & AFIB has led the Food Standards Agency to commission a research project to develop testing methods for *Azadinium* species. This development project is commissioned by the Food Standards Agency. Contact *Food Safety Monitoring and Policy, Food Standards Agency. Tel: 01224 285111*

7. International Council for the Exploration of the Sea, working group on Harmful Algal Bloom Dynamics Meeting Report: http://www.ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/SSGHIE/2012/WGHABD12.pdf

8. The Food Standards Agency, Shellfish Monitoring and Policy Advisor can corroborate the contribution of the Prof. Davidson's research to regulatory monitoring and policy.

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In 2006, Prof. Davidson's group tracked the movement of a large bloom of a HAB genus, deadly to finfish, called *Karenia*. Bloom movement was tracked from the waters of southwest Scotland, northeast to the Shetland Islands and the North Sea. These studies enabled determination of temporal and spatial trends in *Karenia* bloom movement in response to environmental conditions (including temperature, salinity & weather conditions)[1]. The research found that bloom events are influenced by local fluctuations in salinity[1]. In collaboration with Plymouth Marine Laboratory, remote sensing methods were developed to detect and track *Karenia* blooms[2].

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- **Provision of advice to the aquaculture industry:** Since 2006 Prof. Davidson’s team has worked closely with European aquaculture businesses, most notably Seafood Shetland[5], to develop and evaluate methods of HAB early warning and of detecting shellfish toxicity. This included the evaluation of commercially available, Enzyme-Linked Immunosorbent Assay (ELISA) kits for the determination of Diarrheic Shellfish Poisoning (DSP). This evaluation, as part of an EU consortium, recommended commercial use of DSP-ELISA to be replaced by a protein phosphatase based method due to erroneously high toxin readings in the former method. Recommendations were presented at a project meeting in Shetland (2011) to aquaculture regulators and operators from Scotland, Norway, Ireland and Faroe Islands[5].

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- **Advice to the International Council for the Exploration of the Sea (ICES):** ICES, an intergovernmental organisation, provides scientific advice to governments on the use and management of the marine environment. Since 2007 Prof. Davidson has been a member of the ICES Working Group on Harmful Algal Bloom Dynamics[7]. UHI hosted the 2012 annual ICES Working Group Meeting which reported fish-killing algal events in ICES regions[7]. This report is used by ICES to advise member states on HAB issues and management.

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2. The Crown Estate Report, authored by Prof. Davidson on predicting the progression of *Karenia* along the Scottish coastline and the potential impact for fish farming: http://www.thecrownestate.co.uk/media/211054/karenia.pdf

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8. The Food Standards Agency, Shellfish Monitoring and Policy Advisor can corroborate the contribution of the Prof. Davidson's research to regulatory monitoring and policy.

Institution: University of the Highlands and Islands

Unit of Assessment: 7 - Earth Systems and Environmental Science

Title of case study:

DEPOMOD & AutoDEPOMOD: Models changing aquaculture planning practices in Scotland and worldwide

1. Summary of the impact (indicative maximum 100 words)

DEPOMOD, and AutoDEPOMOD, are models, developed by Prof. Black's research team, which predict the impact of fish-farm discharges on the seabed in order to optimise the operation of aquaculture sites to match the environmental capacity. Since being adopted by the Scottish Environment Protection Agency, AutoDEPOMOD now forms a compulsory stage in the aquaculture planning consent process in Scotland, and has been used in the development of all presently operational salmon sites in Scotland. DEPOMOD and AutoDEPOMOD software have 122 licences in 25 countries worldwide.

2. Underpinning research (indicative maximum 500 words)

Fish-farms discharge waste (fish faeces, food waste and chemical treatments) accumulates on the seabed causing organic enrichment which can lead to conditions toxic to marine life. The Scottish Environment Protection Agency (SEPA) monitors and regulates aquaculture discharges and specifies Environmental Quality Standards (EQS) for sea-floor sediments which are enforced for all aquaculture sites in Scotland.

Predicting how discharge levels will impact seabed environmental quality in order to plan new, or for expansion to existing, aquaculture operations is difficult due to the complex site-specific predictive modelling required.

For >20 years UHI researchers (Black, Nickell, Cromey) have studied the aquaculture - marine environment interaction, investigating aquaculture pollution, disease and parasite management and recovery processes in fish-farm sediments. In 1998, Prof. Black's research team began a 2 year project to model how fish-farm waste settles on the seabed. The project developed a model, named DEPOMOD, which took into account site specific conditions such as current speed, water depth, fish biomass and feed volume to predict discharge amount and deposition area. DEPOMOD was the first aquaculture discharge model which could be accurately adapted for individual sites. The project steering committee comprised SEPA and representatives from the aquaculture industry including the Scottish Salmon Growers Association (now SSPO). SEPA recognised the development of the model as a means to accurately predict effects on the seabed below fish-farms. In 2001 SEPA supported further development of the model by the research team to examine the discharge of sea-lice medicine from fish-farm sites in order to derive appropriate limiting license conditions for discharge.

DEPOMOD has since been adapted to aquaculture practices in other parts of the world: from 1999-2003 the UHI research team led an EU consortium to develop MERAMOD for Mediterranean fish-farms to model the predicted deposition of particulate waste faeces and feed from sea bass and bream farms. Prof. Black (UHI) also led the development of TROPOMOD (2006-2008) to analyse the environmental impact of aquaculture in the Philippines. The model assesses the impact of milkfish and tilapia, the two most important fish cultured in the Philippines.

DEPOMOD provided accurate prediction of fish-farm waste deposition and impact to the seabed, however the functionality of the model was limited as any changes to specific parameters meant all parameters had to be re-set. Since 2001 work has been on-going to enable the user to change individual parameters within a live model. This development, named AUTODEPOMOD, increased the use of the model to enable it to be used in optimising fish-farm capacity. AUTODEPOMOD allows individual parameters (such as biomass) to be changed until the modelled discharge level reaches the EQS set by SEPA, thereby advising the optimum fish farm capacity within environmental limits.

In 2005 AUTODEPOMOD was adopted by SEPA as a compulsory step in the planning process for new and expanding aquaculture sites. Prof. Black and his team continue to work to improve the model and are currently integrating sulphur chemistry into AutoDEPOMOD and have been commissioned by the Scottish Government to re-parameterize and recode AutoDEPOMOD.

3. References to the research (indicative maximum of six references)

1. Cromey, C.J., **Black, K.D.,** Edwards, A. and Jack I.A. (1998) Modelling the deposition and biological effects of organic carbon from marine sewage discharges. Estuarine Coastal and Shelf Science, 47, 295-308 (IF 2.247, 5IF 2.622,19 citations)
2. Cromey, C. J., **Nickell, T. D. & Black, K. D.** (2002). DEPOMOD - modelling the deposition and biological effects of waste solids from marine cage farms. Aquaculture 214, 211-239. (IF 2.041, 5IF 2.696, 111 citations)
3. Cromey, C. J., **Nickell, T. D., Black, K. D.,** Provost, P. G. & Griffiths, C. R. (2002). Validation of a fish farm waste resuspension model by use of a particulate tracer discharged from a point source in a coastal environment. Estuaries 25, 916-929 (IF 2.109, 35 citations)
4. Cromey, C.J., **Nickell, T.D.,** Treasurer, J., **Black, K.D., Inall, M.,** (2009). Modelling the impact of cod (Gadus morhua L) farming in the marine environment-CODMOD. Aquaculture 289, 42-53. (IF 2.041, 5IF 2.696, 7 citations)
5. Dean, R. J., **Shimmield, T. M. and Black, K. D.** (2007). Copper, zinc and cadmium in marine cage fish farm sediments: an extensive survey. Environmental Pollution 145, 84-95. (IF 3.746, 5IF 3.987, 30 citations)
6. Cromey, C.J., Thetmeyer, H., Lampadariou, N., **Black, K.D**., Kögeler, J., Karakassis, I., (2012). MERAMOD - predicting the deposition and benthic impact of aquaculture in the Eastern Mediterranean. Aquaculture Environment Interactions. 2, 157-176 (IF 2.2 , 0 citations)

Key grant-funded projects:

- **DEPOMOD**, the original modelling project, supported also by SEPA and Marine Harvest: NERC LINK (1997), £127,647
- **Meramed** provided the opportunity to develop MERAMOD at Greek fish farms: EU FP5 (1999), £177,300
- **DEPOMOD** developed the model to predict medicine residues in sediments: SEPA (1999), £9,703
- **ECASA** tested the model at a range of European sites (www.ecasatoolbox.org.uk): EU FP6 (2004), £1,657,504
- **Depobiomass** developed a new front-end to allow iterative operation: AutoDEPOMOD: SEPA (2004), £12,268
- **Cod Environment** developed the model for application at cod farms: SEAFISH/CEC/HIE (2005), £178,909
- **Philmanaq** developed the model for operation in the Philippines: EU FP6 (2005), £92,478
- **Benthic recovery** added a diagenetic model based on sulphur cycling to predict seabed recovery: SARF (2007), £149,498
- **Large Sites** developed code to allow model-derived spatially varying currents at large sites: SSPO (2008), £88,015
- **Sulphides** extended the Benthic recovery project to further develop carbon diagenesis and predict sulphide concentrations in sediments: SARF (2012), £99,922
- **New AutoDEPOMOD** addresses perceived weaknesses in the model's resuspension processes and recodes the model in Java and ensures platform and third party software independence: Scottish Govt EFF (2012), £576,400

4. Details of the impact (indicative maximum 750 words)

Scottish aquaculture is a major industry with an estimated value of £584.7 million (2011). Scotland is also the largest producer of farmed salmon in the EU. Where adequate regulation is absent, aquaculture can have a detrimental environmental impact, affecting not only the marine environment but the overall sustainability and performance of a site. Discharges are a primary environmental concern when it comes to planning or expanding sites. Determining appropriate limits for discharges has been a difficult task for environmental regulators, because they lacked a reliable model to accurately predict the impact on the local ecosystem. In Scotland, SEPA are responsible for the monitoring and regulation of aquaculture sites, enforcing environmental quality standards for sea-floor sediment at all aquaculture sites.

Prior to the work of Prof. Black's team in the development of DEPOMOD, SEPA used a simple empirical matrix as the main planning tool for consent. This matrix could not optimize farms to their environmental surroundings, creating a 'trial and error' approach to finding the optimum farm size, leading many farms to close due to pollution problems[4,5]. Research by Prof. Black's team (1998-2000) saw the development of DEPOMOD. As part of the original steering committee, SEPA realized this model could provide a means to apply scientific rigor to their aquaculture planning process and enable plans to be optimized to the site-specific conditions. SEPA supported the work of Black and his team to further develop and streamline DEPOMOD leading to the development in 2005 of AutoDEPOMOD[4,5]. AutoDEPOMOD has the capability to automatically iterate towards a solution which will optimise productivity whilst remaining within Environmental Quality Standards.

In 2005 AutoDEPOMOD was adopted by SEPA as a compulsory stage in the planning process. Since 2005 (and continuing), any operator wanting to develop a new aquaculture site or expand an existing one must use AutoDEPOMOD to identify the sustainable size for a proposed farm[4,5]. All presently operational salmon sites in Scotland have used AutoDEPOMOD, enabling site developers to accurately match farm size to the capacity of the environment providing the industry with a streamlined process to enable farm optimisation from the outset whilst ensuring environmental standards are maintained.

AutoDEPOMOD continues to be a compulsory stage in the aquaculture planning process and Prof. Black and his team continue to work with SEPA and aquaculture industry representatives, including the Scottish Salmon Company[6] and Marine Harvest[7] to update the model to support future industry developments. The research team have been awarded a grant of £576,400 from the Scottish Government (2012-2014) to recode AutoDEPOMOD and to improve the modelling of resuspension processes.

International Impact

- The DEPOMOD model developed by Black and his team has international presence within the aquaculture arena. At present, 122 DEPOMOD licence holders exist in 25 countries, 26 of which have been issued in the period 2008-2013, including 21 commercial licences and 5 non-commercial licences[1]. In 2012 the Canadian Department of Fisheries and Oceans requested DEPOMOD to regulate the aquaculture industry and was used to predict benthic impacts at new and proposed Salmon farms in Southwestern New Brunswick (2009, 2012)[8].

- Black led the development of DEPOMOD for specific regions including the Mediterranean (MERAMOD) and Philippines (TREPOMOD). At present, 25 licence holders of MERAMOD and TREPOMOD exist, 11 of which have been issued since 2008[1].

Additional Impacts

- The development of AutoDEPOMOD means that a greater level of confidence can be applied to measuring the sustainability of a fish-farm at any given site. In 2010 SEPA Aquaculture Specialist commented to NERC (funders of the original DEPOMOD project 1998-2000): "*The development of DEPOMOD and subsequently AutoDEPOMOD as tools to be used in the regulatory process has significantly improved the means by which SEPA* *assesses the size of fish farm which can be sustained at any given site and has provided an increased level of scientific rigour in defining local environmental capacity'*[2,5].

- In recognition of his international reputation in aquaculture environment impact research and development of DEPOMOD, Prof. Black (UHI) became a member of the Scottish Government Working Group on Aquaculture[8] as an expert in aquaculture environment impacts (2002-2013).

- AutoDEPOMOD has facilitated a positive impact to the natural environment by placing environmental health at the centre of aquaculture planning. Since AutoDEPOMOD has been implemented in Scottish aquaculture planning, farms have been re-scaled to match local environmental capacity and many former polluted sites are no longer used. Overall, Scottish aquaculture now has, and continues to have, a relatively lower seabed impact than pre-2005 due to better planning through AutoDEPOMOD[4,5,6,7].

5. Sources to corroborate the impact (indicative maximum of 10 references)

1. The Head of IT at SAMS, controls licence distribution for DEPOMOD and AutoDEPOMOD and provides support to licence holders. Steve can corroborate licence distribution figures and provide further details where possible.
2. In 2010, the Natural Environment Research Council (NERC) published an Impact Statement detailing the research and impact of DEPOMOD. This case study provides an overview of the scientific research, the funding inputs, research partners, industry collaborations and the resulting socio-economic impacts. The case study also provides comment from an Aquaculture Specialist at SEPA. http://www.nerc.ac.uk/business/casestudies/documents/scottish-ing.pdf
3. PHILMINAQ: mitigating impact from aquaculture in the Philippines. This project developed Depomod for the Philippines. Here is an independent account of that project: http://www.gefcoral.org/LinkClick.aspx?fileticket=T79qyZpH-cs%3D&tabid=3260
4. Head of Operations (North), SEPA – a key figure representing Scottish Government in terms of the Ministerial Working Group on Aquaculture and driving the SEPA approach to fish farm regulation.
5. Aquaculture Specialist, SEPA – the key fish farm regulator in Scotland who is intimately associated with the application and development of DEPOMOD to the Scottish fish farming industry.
6. Environmental Manager, Scottish Salmon Company – can provide insight into the direct impact that DEPOMOD makes on the business environment in the fish farming sector, from the point of view of a large enterprise.
7. Representative of Marine Harvest – This individual will be able to give an insight into the direct impact that DEPOMOD makes on the business environment in the fish farming sector from the point of view of a multi-national company, Scotland's largest fish farmer.
8. DEPOMOD is used by the Department for Fisheries and Oceans of Canada to regulate aquaculture activities in the region. Evidence of the use of DEPOMOD by the Canadian Authorities can be found: http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2012/2012_035-eng.pdf
9. More information about DEPOMOD and DEPOMOD projects can be found on the UHI webpages at http://www.sams.ac.uk/kenny-black

Institution: University of the Highlands and Islands

Unit of Assessment: 7 Earth Systems and Environmental Science

Title of case study:

The CSTT model underpinning the UK defence in European Court of Justice

1. Summary of the impact (indicative maximum 100 words)

Eutrophication results from excessive nutrient discharge to a water-body, reducing water quality. Eutrophication status must comply with the Urban Waste Water Treatment Directive (UWWTD). As part of a consortium, UHI developed, validated and researched a model (CSTT) capable of screening a water-body for eutrophication. The model was used to defend the UK in the European Court of Justice (2009), against proceedings brought by the European Commission alleging infraction of UK obligations under the UWWTD. The model proved that British waters were not harmfully impacted by eutrophication, sparing the UK government ~£6 billion to implement tertiary sewage treatment across England and Wales.

2. Underpinning research (indicative maximum 500 words)

Eutrophication is the process by which a body of water acquires a high concentration of nutrients, especially Nitrate and Phosphate, promoting excessive growth of algae resulting in severe reduction in water quality. UHI research[1,2,3] shows that growth of algae may not occur where there is a lack of sunlight or where energy levels in the water are high enough to cause dispersion of the algae. The European Urban Waste-Water Treatment Directive (UWWTD) (1991) specifies that the amount of treatment required for discharge of urban wastewater depends, among other things, on the actual or potential level of eutrophication of the receiving water.

In response to the UWWTD, the UK government set up the Comprehensive Studies Task Team (CSTT) to produce guidelines for studies to check that British waters were not becoming eutrophic. To understand the potential of a water body become eutrophic, several factors have to be taken into consideration: water exchange and mixing relationships within the water-body, chlorophyll content and nutrient effects and light intensity.

Prof Tett proposed to the CSTT (1993) to develop a model which could accommodate all of these parameters to enable an effective means to screen a water body for eutrophic conditions. Model development and refinement took place from 1994-1997 during a number of collaborative research projects[2,3,4,5,6,7] of UHI, Napier University and University of Bangor.

The UHI component built on over 30 years of research into water exchange and mixing characteristics in sea-lochs and estuaries (Inall), phytoplankton growth theory (Droop) and nutrient effects on water quality (Gowen). This work was brought together with work on the other crucial parameters relating to photosynthetic efficiency and growth-related respiration in response to underwater light carried out at Napier University and University of Bangor, to develop the CSTT Model for Eutrophication.

The model uses the rate of exchange between water-bodies, the rate of addition of nutrients, and light levels to predict whether or not there will be eutrophication in a body of water under specified conditions and was published in the CSTT guidelines (1997).

From 1997-2003, the model was validated by UHI and Napier University during a joint PhD Studentship, against observations from the Mediterranean to the Arctic in the collaborative European project OAERRE[4]. Further tests were also carried out in Loch Creran by Napier-

SAMS PhD student Celine Laurent[5] (2002-2006). During this study, the CSTT model was applied to Loch Creran to assess the capacity of the loch to assimilate nutrients from fish-farms. Model simulations were found to retain a significant correlation with observations demonstrating the model's ability to replicate actual conditions of the water-body, in this case Loch Creran.

The model continues to be developed and adapted for wider use and with funding from the Scottish Aquacultural Research Forum (SARF, 2005–2011), UHI researchers led by Prof's Tett & Inall have been developing a new version of the model for predicting the environmental impacts of aquaculture in sea lochs[6] and has been developed further to the ACExR model for seasonal exchange and mixing in enclosed sea lochs.

3. References to the research (indicative maximum of six references)

1. CSTT (1997). Comprehensive studies for the purposes of Article 6 & 8.5 of DIR 91/271 EEC, the Urban Waste Water Treatment Directive, second edition. Report, pp. Edinburgh, Published for the Comprehensive Studies Task Team of Group Coordinating Sea Disposal Monitoring by the Department of the Environment for Northern Ireland, the Environment Agency, the Scottish Environment Protection Agency and the Water Services Association.
2. Gowen, R. J., **P. Tett** and **K. J. Jones**. 1992. Predicting marine eutrophication: the yield of chlorophyll from nitrogen in Scottish coastal phytoplankton. *Marine Ecology - Progress Series*, 85: 153-161.
3. Edwards, V. R., **P. Tett** and **K. J. Jones**. 2003. Changes in the yield of chlorophyll a from dissolved available inorganic nitrogen after an enrichment event -applications for predicting eutrophication in coastal waters. *Continental Shelf Research*, 23: 1771-1785.
4. **Tett, P**., L. Gilpin, H. Svendsen, C. P. Erlandsson, U. Larsson, S. Kratzer, E. Fouilland, C. Janzen, J.-Y. Lee, C. Grenz, A. Newton, J. G. Ferreira, T. Fernandes and S. Scory (2003). Eutrophication and some European waters of restricted exchange. *Continental Shelf Research*, 23, 1635-1671.
5. Laurent, C., **P. Tett**, T. Fernandes, L. Gilpin and **K. J. Jones**. 2006. A dynamic CSTT model for the effects of added nutrients in Loch Creran, a shallow fjord. *Journal of Marine Systems*, 61: 149-164.
6. **Tett, P**., E. Portilla, P. A. Gillibrand and **M. Inall** (2011). Carrying and assimilative capacities: the ACExR-LESV model for sea-loch aquaculture. Aquaculture Research, 42, 51-67.
7. Gillibrand, P. A., **M. E. Inall**, E. Portilla and **P. Tett** (2013). A Box Model of the Seasonal Exchange and Mixing in Regions of Restricted Exchange: Application to Two Contrasting Scottish Inlets. Environmental Modelling & Software, 43, 144-159.

4. Details of the impact (indicative maximum 750 words)

Eutrophication is a process involving the excessive build-up of nutrients in a water body leading to the deterioration of the water quality. Whilst eutrophication can happen naturally, human impacts such as sewage discharge can greatly enhance the process. As such, eutrophication status is controlled by The European Urban Waste Water Treatment Directive (UWWTD) of 1991. The UK set up the Comprehensive Studies Task Team (CSTT) to produce guidelines for studies to check that British waters were not becoming eutrophic. However, despite these guidelines, in 1999 the European Commission (EC) accused the UK of infracting the UWWTD, by failing to identify certain coastal waters in England and Wales as eutrophic. This accusation led to a court case in the European Court of Justice, which was finally decided in the UK's favour in 2009[7]. The CSTT model, developed by UHI, Napier University and University of Bangor was key to the UK's successful defence[1].

The UK was brought before the Court in 2007, and presented its defence in writing over the next two years, culminating in a hearing in Luxembourg in April 2009. Prof. Tett contributed written and oral evidence during this period and attended the hearing in person as an expert advisor, supporting the UK government solicitors and Defra officers.

The defence included data showing lack of undesirable disturbance due to nutrient enrichment of UK waters, and made the argument, based quantitatively on the CSTT model, that many of our coastal waters and estuaries were light-limited, and therefore not eutrophic[1].

As part of the judgement, the Court ruled that eutrophication comprises four linked steps: (1) enrichment with nutrients; (2) accelerated growth of algae, etc.; (3) an undesirable disturbance to the balance of organisms; (4) an undesirable disturbance to water quality; and that, for eutrophication to be proven, a causal relationship between each step must be demonstrated[1].

It was agreed that the relevant waters in question were nutrient-enriched (step 1), but the UK claimed that accelerated algal growth (step 2), was often prevented by turbidity. Results from the CSTT model were put forward to show that this was the case[1].

In December 2009 it was announced that the UK had won the relevant part of its case[1]. The CSTT model provided the scientific evidence which helped to uphold the reputation of British scientific research and save the British government and taxpayers a hefty bill for additional water treatment. A similar case was lost by the French government in 2004[2], resulting in heavy fines and the expensive obligation to build extra sewage treatment plants. Enforcement of the directive, if the UK had lost the case, would have required the installation of nutrient-stripping treatment systems to all waste water discharges identified as being eutrophic – affecting every major city and town from the east of England up to Liverpool, an area with a resident population of around 20 million. This tertiary level of sewage treatment would have cost on the order of £6 billion to implement, accounting for initial capital costs of installation, running costs and maintenance over a 20-year period[1]. It is assumed these extra water treatment costs would have been passed down to consumers.

Other impacts of the research include:

- The Centre for Environment, Fisheries and Aquaculture Science (Cefas) (with funding from the Environment Agency) continues research to combine the CSTT model with their *'combined macroalgae and phytoplankton model'* (CPM), for use in evaluating the trophic status of shallow coastal water bodies such as Poole harbour. UHI collaborates on this evaluation project[3].

- In 2011, Prof. Tett was invited to serve on a European Task Group set up by International Council for the Exploration of the Sea and the EC Joint Research Committee, chaired by Dr. João Ferreira, to provide guidance to the European Commission on implementing 'Qualitative Descriptor' 5, Eutrophication, of the Marine Strategy Framework Directive. Prof. Tett led clarification of the definition of eutrophication (Ferreira et al., 2011)[4].

- Further developments of the model by UHI for use in aquaculture by Profs. Tett & Inall (2005-2011 SARF (Scottish Aquacultural Research Forum) funded research) have been transferred to Marine Science Scotland and Scotland's Environment Protection Agency (SEPA) and reported to the industry at the Association of Scottish Shellfish Growers Conference in 2011. A report on the Development of Assimilative Capacity and Carrying Capacity Models for Water Bodies utilized for Marine Bivalve and Caged Fish-farming, was prepared by Prof. Tett on behalf of SARF and published on the SARF website to provide a guide to the model system and advice on model software for businesses and regulators[5].

5. Sources to corroborate the impact (indicative maximum of 10 references)

1. ECJ (2009). Commission of the European Communities v United Kingdom supported by Portuguese Republic. Judgement of the European Court of Justice (3rd chamber) on 10 December 2009, In Case C-390/07, under Article 226 EC for failure to fulfil obligations, pursuant to Articles 3(1) and (2) and 5(1) to (3) and (5) of, and Annex II to, Council Directive 91/271/EEC of 21 May 1991 concerning urban waste water treatment (OJ 1991 L 135, p. 40). http://curia.europa.eu/juris/document/document.jsf;jsessionid=9ea7d2dc30db12af24355e0046d080a3c6903dd5e118.e34KaxiLc3qMb40Rch0SaxuLc390?text=&docid=76787&pageIndex=0&doclang=EN&mode=lst&dir=&occ=first&part=1&cid=497124

2. ECJ (2004). Commission of the European Communities v French Republic. Judgement of the European Court of Justice (2nd chamber) on 23 September 2004, in case C-280/02, concerning: Failure of a Member State to fulfil obligations - Directive 91/271/EEC - Urban waste water treatment - Article 5(1) and (2) and Annex II - Failure to identify sensitive areas - Meaning of 'eutrophication' - Failure to implement more stringent treatment of discharges into sensitive areas.

3. The Centre for Environment, Fisheries and Aquaculture Science (Cefas) continue to use the CSTT model in collaboration with UHI. For more information contact named individual from Cefas as reported to the REF submission Team, or details are available from the UHI REF audit contact.

4. Ferreira, J. G., J. H. Andersen, A. Borja, S. B. Bricker, J. Camp, M. Cardosa da Silva, E. Garces, A. S. Heiskanen, C. Humborg, L. Ignatiades, C. Lancelot, A. Menesguen, P. Tett, N. Hoepffner and U. Clausen (2011). Overview of eutrophication indicators to assess environmental status within the European Marine Strategy Framework Directive. Estuarine, Coastal and Shelf Science, 93, 117-131.

5. SARF commissioned report http://www.sarf.org.uk/cms-assets/documents/48900-379750.sarf012a.pdf