SEVENTH FRAMEWORK PROGRAMME

THEME 6: Environment (including Climate Change)

Adaptive strategies to mitigate the impacts of climate change on European freshwater ecosystems

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1. The REFRESH project

At present, many water bodies across Europe fail to comply with Water Framework Directive (WFD) and Habitats Directive (HD) targets, an issue which may be exacerbated in the future under climate and land use change. The REFRESH project aims to develop a framework to enable water managers to design cost-effective restoration programmes for freshwater ecosystems, accounting for expected future impacts of climate and land use change. Here, we present an overview of work carried out in the River Dee catchment, in northeast Scotland, as part of the REFRESH project.

2. The River Dee catchment

The River Dee catchment is a large (*ca*. 2100 km^2), relatively unspoilt area, famed for its salmon fishing, shooting and hill walking. It has been designated at European level for the species it supports, in particular Atlantic salmon (*Salmo salar*), freshwater pearl mussel (*Margaritifera margaritifera*) and otter (*Lutra lutra*). The catchment is subject to significant pressures, including morphological alterations and nutrient inputs from sewage and agriculture, and the area remains a top conservation priority.

Two sub-catchments of the Dee were selected for more in-depth studies: (1) the Tarland Burn sub-catchment, an area of mixed land use in the middle reaches of the Dee and one of the furthest upstream tributaries to be influenced by agriculture (Fig. 1). In 2008 the Tarland Burn was classified as being at 'Moderate' ecological status, primarily due to morphological alterations, namely channel straightening and resultant loss or degradation of habitat. Water quality is also of concern, due to diffuse inputs of nutrients and sediments from agriculture; (2) the Loch of Skene sub-catchment in the lower reaches of the Dee, a predominantly agricultural catchment which feeds a shallow loch with an area of *ca.* 1 km^2 (Fig. 2). The main tributary to the Loch of Skene is the Corskie Burn. Both the stream and the lake were classified as having 'Poor' ecological status in 2008, due to phosphorus loading from sewage treatment works and diffuse agricultural inputs and barriers to fish migration. High nutrient inputs lead to annual cyanobacterial blooms within the lake, which may be toxic to humans, mammals and fish.

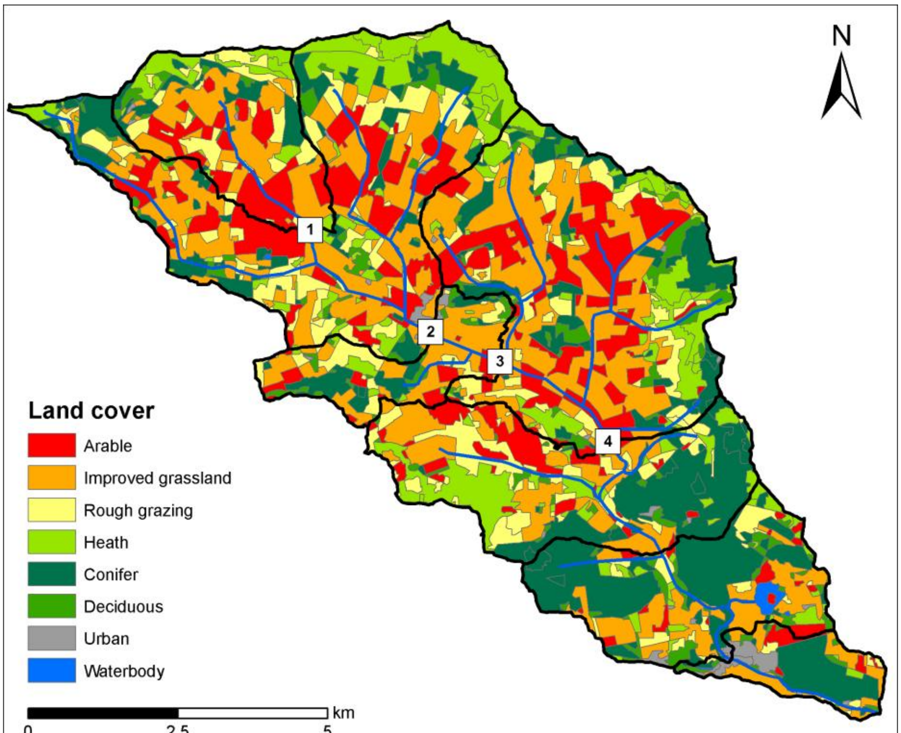

Fig. 1: Land use in the Tarland Burn sub-catchment. For the phosphorus modelling, the catchment was split into the numbered sub-catchments shown.

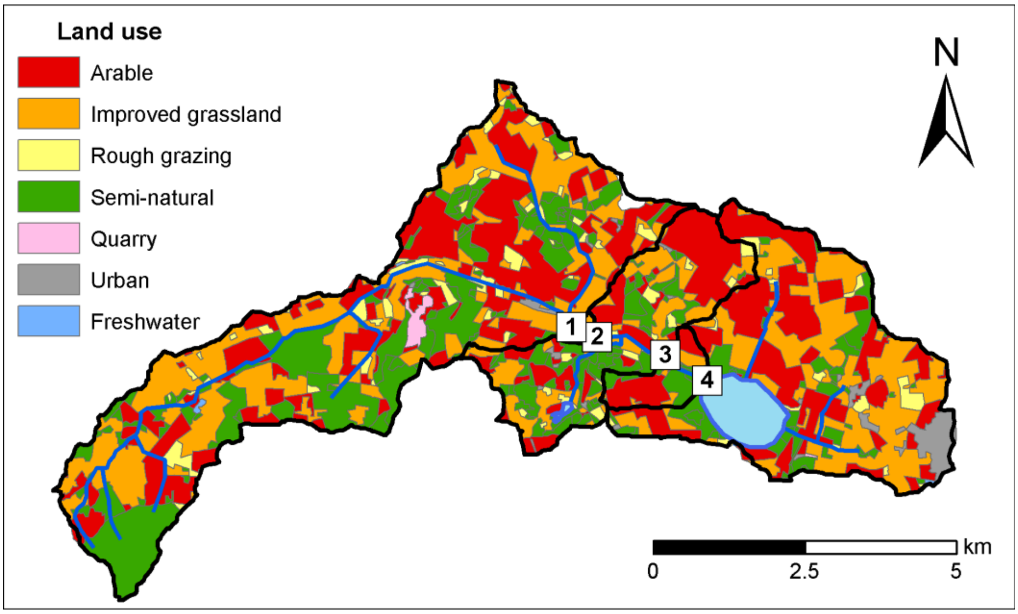

Fig. 2: Land use in the Loch of Skene sub-catchment. For the stream phosphorus modelling, the catchment was split into the numbered sub-catchments shown.

3. Main research activities and results from the Dee catchment

3.1 Generation of scenarios of future environmental change

A coherent suite of climate, land use and atmospheric nitrogen deposition scenarios were developed, to allow us to investigate the impact of potential environmental change on water quality and ecological status. Three climate model simulations were used, representing the average and upper and lower extreme projections from the EU FP6 ENSEMBLES project. Data was extracted for baseline (1981-2010) and future (2040-2060) periods and bias corrected. Four storylines of 2050 land use were developed, broadly corresponding to the quadrants of the IPCC SRES scenarios representing "World Market" (A1), "National Enterprise" (A2), "Global Sustainability" (B1) and "Local Stewardship" (B2). Consistent with the Land Use Strategy for Scotland (2011) targets, all scenarios incorporated an increase in woodland cover and two included an increase in arable land area. An important feature of the land use scenarios is that land use changes are unlikely to be evenly distributed, with some areas undergoing little change whilst other areas, which are suitable for a range of different uses, will be more vulnerable. Atmospheric deposition scenarios were generated from forecasts based on the Current Legislation Estimate emissions scenario (Gothenburg Protocol), provided by the European Monitoring and Evaluation Programme. Dry deposition fluxes were scaled to take changes in woodland cover under future land use scenarios into account.

3.2 Linking hydrochemical models to measures of ecological impact

Three ecological indicators were identified: freshwater pearl mussel (*Margaritifera margaritifera*), macroinvertebrates and macrophytes. To be able to link hydrochemical model output to ecological impact, relationships were developed between nutrients and these ecological indicators. Water quality requirements for the freshwater pearl mussel are highly uncertain, and so a conservative threshold of 0.013 mg SRP-P l^{-1} was adopted, as required for an average low alkalinity, high altitude waterbody to have 'High' chemical status according to the revised 2013 UKTAG standards. Empirical relationships were used to link nutrient status and macrophyte and invertebrate response. Analysis of macrophyte data for the catchment indicated a weak correlation between Mean Trophic Rank (MTR) and phosphate concentration, with a decrease in MTR as phosphate levels exceed 0.01 to 0.02 mg SRP-P l^{-1}. For invertebrates, there was a weak correlation between Average Score per Taxon (ASPT) and land use and nitrate concentrations. The highly uncertain nature of these relationships means predictions of ecological response due to changing water quality should be treated as preliminary. A wider range of nutrient concentrations and MTR and ASPT scores are required for the relationships to be more robustly defined.

3.3 Hydrochemical modelling to investigate potential future water quality under climate and land use change scenarios

In-depth hydrochemical modelling applications were carried out in the two study sub-catchments of the River Dee. In the Tarland Burn sub-catchment, stream flow, nitrogen (N), suspended sediment and phosphorus (P) were simulated using the dynamic, process-based STREAM-N and INCA-P catchment models. In the Loch of Skene sub-catchment, the INCA-P model was used to simulate stream flow, suspended sediment and P concentrations in the Corskie Burn, the main tributary to the loch. Total phosphorus in the loch was simulated using the simpler export-coefficient based PLUS+ model.

Satisfactory INCA-P and STREAM-N model calibrations were obtained in the Tarland sub-catchment. Automated inverse modelling procedures were applied and output was used to estimate model uncertainty and to explore model sensitivity to the calibrated parameters. The INCA-P calibration was less satisfactory in the Skene sub-catchment, where there was a paucity of good quality observed data. As such, scenario results here need interpreting with particular caution. Key findings from the scenario analysis are that:

1. Between now and 2050, climate change alone is not projected to be large enough in this region to bring about significant changes to water quality. Land use change driven by socio-economic factors and climate could have a more significant impact.
2. In the Tarland Burn sub-catchment, simulated changes in suspended sediment, total phosphorus and nitrate concentrations were large enough to be significant despite uncertainty in model output; phosphate concentrations showed a smaller response. However, the direction of these changes varied, with the potential for water quality to improve or worsen, depending on the land use scenario.
3. In the Skene sub-catchment, projected changes in climate and land use are very small, leading to little change in simulated nutrient status in either the stream or the loch between now and 2050. As such the loch is predicted to remain at 'Poor' ecological status (according to the WFD classification).
4. Predicted ecological response is highly uncertain, but preliminary findings are that: (i) neither the Tarland nor the Skene sub-catchments are likely to meet water quality targets for the freshwater pearl mussel; (ii) macroinvertebrates in the Tarland Burn are likely to remain in the 'Clean' category, with a shift towards the 'Clean'/'Doubtful' boundary under some scenarios.

3.4 Identify a suite of mitigation measures to alleviate water quality problems in the study catchments

A literature review was carried out to identify a suite of potential mitigation measures that could be used in the two study catchments to reduce nutrient levels and improve water quality. Workshops were then carried out, attended by local farmers, land managers, agency representatives and other interested parties. The aim was to discuss key local sources of pollution, the feasibility of implementing a range of mitigation measures and their perceived cost-effectiveness. This resulted in a set of mitigation measures considered relevant for the two sub-catchments.

3.5 Assessment of the cost-effectiveness of measures to improve water quality

The hydrochemical models were used to predict the catchment-scale effectiveness of measures to reduce stream nitrate concentrations in the Tarland Burn and stream phosphate concentrations in the Corskie Burn. Estimates of the costs of measures were based on losses to farm income, capital investment (if applicable to a particular measure) and any additional operating costs resulting from implementing management options.

Setting appropriate nutrient reduction targets is problematic. Neither the WFD nor the HD specify target nitrate concentrations, so a target 10% decrease in mean annual stream nitrate concentration was decided on, based on expert judgement of likely reductions required for low nutrient invertebrate communities. In the Skene sub-catchment, the Corskie Burn was classified by SEPA as having 'Moderate' phosphate chemical status, which should have enabled a clear target reduction to be set to bring it up to 'Good' status. However, on examination of the monitoring data the stream was found to have been misclassified, with several outlying points exerting undue influence on the annual mean. In fact, when four outliers were excluded, the stream shifts to 'Good' chemical status for the entire 2000-2010 period. More, better quality monitoring data is clearly needed, and this highlights the unsuitability of means as summary statistics; medians would be far more robust. Instead, a target 30% reduction in mean annual phosphate concentration was chosen, enough to cause a potential shift to a more oligotrophic macrophyte community.

Cost and effectiveness data were combined and optimized using the 'Risk Solver Platform' optimization tool in excel. The result was a set of the best measures for achieving target nutrient reductions at minimum economic cost. In the Tarland sub-catchment, results suggest that the target is most cost-effectively achieved by: (1) a 20% reduction in applied nitrogen fertilizer to cropland, (2) constructed farm wetland areas, and (3) managed 10 m buffer strips adjacent to arable land. In the Corskie Burn, the target was best achieved by: (1) a reduction in sewage treatment work effluent phosphate concentration to 1 mg SRP-P l^{-1}, (2) a 50% decrease in fertilizer phosphorus application to improved grassland, and (3) a 20% reduction in fertilizer phosphorus application to arable land. Of these, sewage-related measures appear to be the most effective, although large uncertainties in the hydrochemical model output mean that further analysis is required to determine whether this finding is robust. It is also important to note that it relates to stream phosphate concentrations, not to total phosphorus loadings to the loch.

The effectiveness of these mitigation measures was then re-tested under scenarios of future climate and land use, to see whether they are 'future-proof'. Under the worst case scenario of climate and land use change, the measures to reduce nitrate concentration in the Tarland Burn resulted in similar nitrate concentrations to the baseline, as the reduction in fertilizer usage is balanced by the increased area of arable land. However, under the best case scenario nitrate concentrations may decrease by up to 30%. In the Corskie Burn, the projected changes in climate and land use are small enough that the effectiveness of measures is unlikely to change.

3.6 How do the costs of implementing these measures compare to the benefits to society of improved water quality?

Where the cost of meeting environmental objectives is more than the resulting benefits, the WFD may allow less stringent targets to be imposed, or exemption altogether from having to meet targets. To investigate whether this applied in the study sub-catchments, the costs of implementing mitigation measures were compared against non-market benefits resulting from the achievement of good ecological status. The latter were derived through the use of stakeholder participatory techniques and benefit transfer.

Societal benefits were found to outweigh the costs of meeting WFD targets. However, some of the measures may not be affordable for farmers, particularly for example the conversion of arable land to grassland and the creation of 10 m buffer strips. In addition, distributional effects need considering. Often farmers or water companies bear the greatest burden in terms of paying for improvements to water quality, whilst the benefits are enjoyed by the general public, often in a separate location to where the measures were put in place.