Regional Freshwater Nitrogen Budgets for Scotland

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Abstract

Following Carnell et al. (2019) which provided a nitrogen (N) budget for Scotland, this short project aims to provide **freshwater N budgets** for 10 Scottish hydrometric regions. The regional N budgets quantify key N flows across the hydrosphere and terrestrial systems (agricultural and semi-natural) and include N from human waste and atmospheric deposition. The freshwater model used here 'LTLS-FM' provides estimates of total N inputs to freshwater in 2010. The results indicate that total N inputs vary between regions, from 1.7 kT N for Orkney and Shetland, to 33.2 kT N for NE Scotland. However, when N inputs are divided by the area of the region, it becomes apparent that two of the smallest regions, Tweed and Forth, have the highest N inputs/km^2. Across Scotland, LTLS-FM estimates of losses of freshwater N to coastal waters (151 kT N) and to the atmosphere (17.3 kT N) in 2010 were substantial, with more than half of the N losses originating from just 3 regions (Tay, Solway and NE Scotland). As much as 68% of Scotland's N in freshwaters comes from agricultural land management, for which improved nutrient use efficiency could increase environmental as well as economic benefits. These data will contribute to the development of the Scottish Nitrogen Balance Sheet (SNBS), which is mandated under the Scottish Climate Change Act 2019.

1. Introduction

This short project aims to develop Nitrogen (N) budgets for Scottish hydrometric regions by quantifying key N flows across the terrestrial and freshwater systems. In particular, the requirement is for regional data to quantify key nitrogen flows across the hydrosphere, terrestrial systems (agricultural and semi-natural), including human waste. The data are provided here for the year 2010 using a national scale freshwater macronutrient model (LTLS-FM), and will assist with the development of the Scottish Nitrogen Balance Sheet (SNBS) which is mandated under the Scottish Climate Change Act 2019. The derived N budgets for individual hydrometric regions should help to identify N sources where effective mitigation and improved nutrient use efficiency (NUE) could improve environmental issues while supporting a sustainable economy.

One of the first N budgets for the UK was provided by Leip et al. (2011) as part of the European Nitrogen Assessment (ENA, 2011). This combined the N budgets for atmosphere, agriculture and surface waters for the period 1995 to 2008. The UK N budget was updated recently (Bell et al., 2021) as part of the Long Term Large Scale (LTLS) macronutrient modelling consortium. The LTLS consortium developed and applied a suite of relatively simple process-based atmospheric, terrestrial and freshwater macronutrient models over a historical period of more than 200 years. These models take account of the interlinked cycles of N, Carbon (C) and Phosphorus (P) in UK soils and rivers, and include inputs from natural and agricultural terrestrial ecosystems, atmospheric deposition and sewage. Historical changes in climate, population and land-management were included in the model simulations using best available estimates. Over the period 1800 to 2010, the LTLS freshwater modelling of N fluxes (Bell et al., 2021) indicated that agriculture (improved grass and arable land) is the dominant source, although N from sewage has increased by 400% since 1900. The majority of N entering freshwaters is exported directly to coastal and estuarine waters, but 10% of N is removed by instream processes, mainly through conversion to N gas.

For Scotland, Carnell et al. (2019) compiled the most recent available data for soils, water, air and human consumption/production, with an emphasis on agriculture, nutrition and waste. Across Scotland, terrestrial N fluxes to freshwater (132 kT N yr^{-1}) were substantial, of which approximately 80% was from agriculture and ~7% was from human waste. Legacy stored groundwater contributed a further 27 kT N yr^{-1} to freshwaters, reflecting nitrate leaching from soils that had been stored in groundwater across Scotland over previous decades before being released to river and subsurface flows. The total N flux to coastal waters was 142 kT yr^{-1}, of which 62% was in rivers.

2. Methods

The study was carried out using a modelling approach that extends the terrestrial and freshwater budgets for Scotland presented by Carnell et al. (2019): Method 2- LTLS-IM. To derive budgets for individual Scottish regions, the LTLS freshwater model component (LTLS-FM) was re-run for 10 hydrometric regions for the year 2010. Further details are provided below, and a glossary of terms is provided in Appendix A (Table A.1).

2.1 Scottish hydrometric regions

Scottish hydrometric regions in the form of GIS “Shapefiles” of SEPA WFD boundaries have been used to delineate 10 hydrometric regions (https://www.sepa.org.uk/environment/environmental-data/ under ‘water general information’ – ‘Water Framework Directive (WFD) Sub-Basin Districts - Area Advisory Groups data’).

The SEPA WFD shapefiles were converted to a grid before being superimposed on the LTLS-FM 5km×5km resolution grid and associated river flow network (Figure 1). Visual inspection confirmed that the SEPA WFD regions coincided reasonably well with 5km regional catchment boundaries, but a modest number of manual adjustments were required to improve the fit. Two southernmost regions, Solway and Tweed, overlap the Scotland-England border, and for these regions, inputs and outputs across the border are quantified.

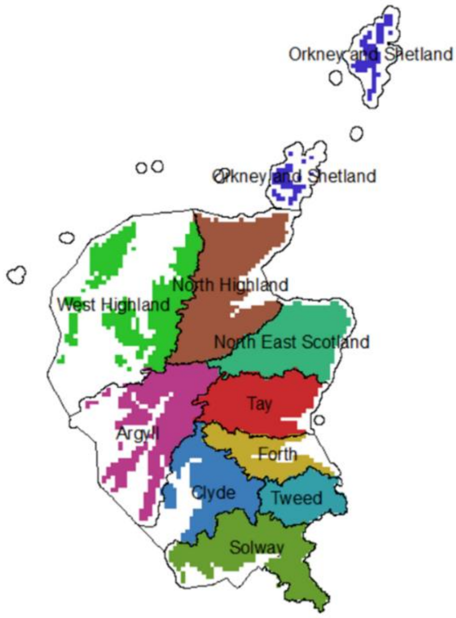

Figure 1. The 10 SEPA WFD Sub-Basin Districts superimposed on the 5km×5km LTLS-FM grid

2.2 The Model: LTLS

The approach builds on modelling work developed by the LTLS consortium (http://www.ltls.org.uk), funded under the NERC Macronutrient Cycles Programme. This comprised a national-scale integrated model (LTLS-IM) of the fluxes and stores of nutrients in the landscape at a 5 km by 5 km grid resolution, validated using long term (up to 100 years) N observations from across the UK. The LTLS-IM provides a national-scale modelling environment that combines simple process-based models for nutrient deposition (Tipping et al., 2017), runoff from semi-natural land (Davies et al., 2016a, b), agriculture (Muhammed et al., 2018), human waste (Naden et al., 2016) and water quality (Bell et al., 2021). The component models use readily-available driving data (climate, deposition, land cover, agricultural practices, topography) to reflect the heterogeneous response of the national landscape. The disadvantage of using a large-scale model that is not calibrated specifically to local conditions, is that it may be less accurate at the local scale (e.g. for a particular river) than a fully-calibrated site or catchment-specific water quality model. However, it provides spatially consistent estimates of freshwater nutrient sources and fluxes across Scotland and takes account of longer-term nutrient fluxes including groundwater. Carnell et al. (2019) noted the similarity of estimates of nitrogen sources (kt N y-1) to water in Scotland, as calculated by the freshwater modelling component, LTLS-FM, and values derived for Scotland based on Leip et al. (2011)'s UK budget (160 kt and 159 kt N respectively). Results presented here are also based on 2010 model output.

2.3 Model application

The freshwater model component of the LTLS modelling system, LTLS-FM (Bell et al., 2021) was re-run several times to provide the inputs and outputs required to estimate N for the selected hydrometric regions for 2010. The LTLS-FM total nitrogen estimates consist of the sum of **dissolved** and **particulate** phases in freshwaters, together with an estimate of **N gas** produced by river denitrification, as shown in Table 1.

Table 1. Nitrogen forms in the LTLS Freshwater Model: dissolved, particulate and gas phases.

Dissolved N	Particulate N	N Gas
Nitrate-N (NO_3-N)	Labile particulate organic nitrogen (PONL)	Nitrogen gas from denitrification (N_2)
Ammonium-N (NH_4-N)	Non-labile particulate organic nitrogen (PONNL)	
Dissolved Organic Nitrogen (DON)		

To quantify how much of this N comes from agriculture, semi-natural land, sewage, and from stored groundwater, the LTLS-FM was run twice for each Scotttish region: once to take account of the Nitrogen stored in groundwater, once assuming that all nitrogen runoff going into rivers is of recent origin. The difference between the 2 runs indicates how much of the N flux in freshwaters in 2010 originates from past decades.

Outputs of nitrogen from Scotland consist of freshwater fluxes to coastal waters and Nitrogen gas released from rivers by denitrification. The freshwater coastal fluxes for each Scottish region are estimated by summing the 2010 LTLS-FM dissolved and particulate nitrogen fluxes from coastal outflow locations. Total N fluxes to the sea are split between surface (river) and sub-surface (groundwater) components, the surface N fluxes (or concentrations) are most routinely sampled for water quality monitoring, sub-surface N fluxes are not routinely measured. Figure 2 shows the LTLS outflow cells (black squares) around the coast of Scotland, together with a map of land cover.

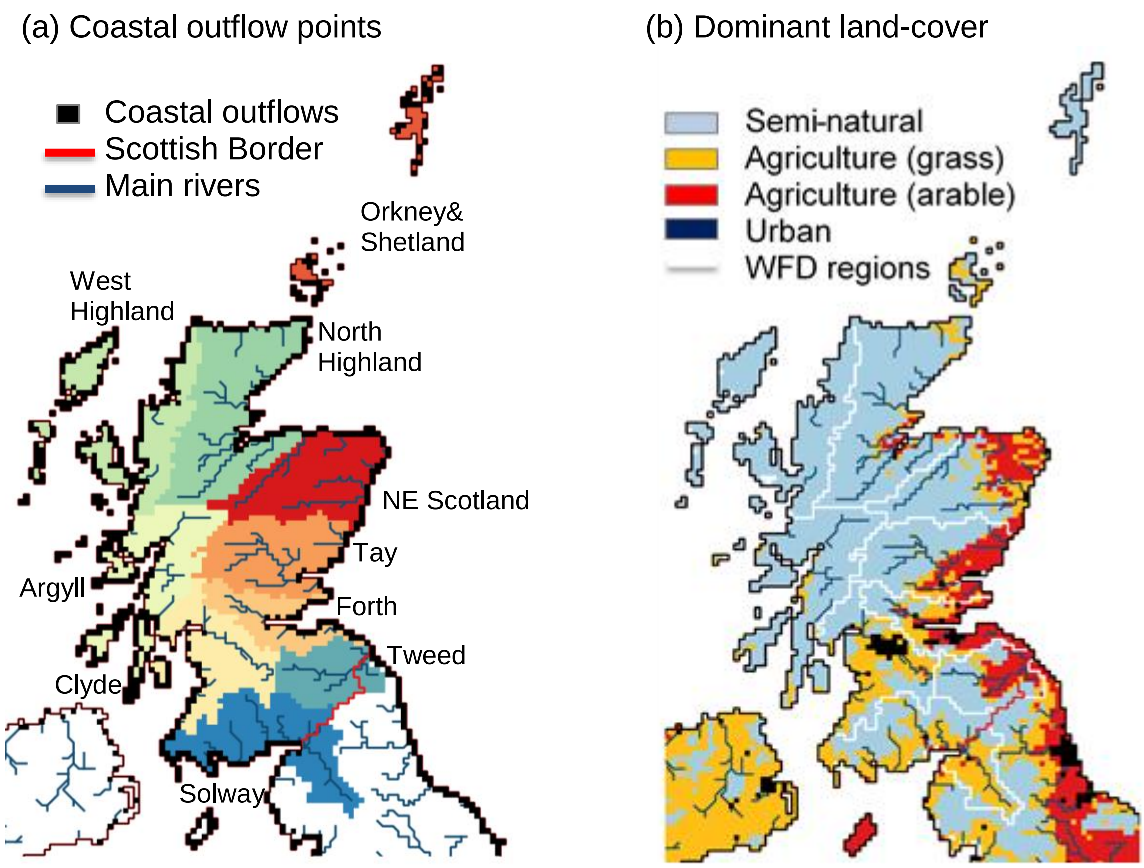

Figure 2. Maps of Scotland showing (a) coastal outflow points (black cells) superimposed on the 10 SEPA WFD regions, and (b) Dominant land-cover types. Main rivers are shown with blue lines and the Scottish border is shown in red.

On the mainland, there are fluxes to the sea via most, but not all, grid-cells on the coast, but on the Islands, rivers are smaller and not all coastal grid-cells are associated with a flux of nutrients to the sea.

3. Results

3.1 Inputs of N to freshwaters

A summary of total N fluxes (dissolved + particulate forms) to water bodies in each SEPA WFD basin region is provided in Table 2, and summarised visually in Figure 3. The basin regions are ordered by total N input to freshwater (lowest to highest).

Table 2. Summary of annual nitrogen inputs (kT N y^{-1}) to freshwater in SEPA WFD basin regions, as estimated by LTLS-IM for 2010, together with the total N inputs weighted by catchment area (T km^{-2}).

Region	Agricultural runoff/ leaching		Semi-natural	Human waste		Stored ground-water inputs	LTLS area	Total N	Total N /area
	Grass	Arable		Sewage	Septic		km^2	kT	T km^{-2}
Orkney and Shetland	1.0	0.1	0.5	0.0	0.0	0.1	2550	1.7	0.68
West Highland	0.8	0.0	2.8	0.0	0.1	0.1	10575	3.8	0.36
Argyll	2.3	0.1	2.2	0.0	0.1	0.6	10200	5.4	0.53
North Highland	4.9	2.1	4.0	0.0	0.1	1.0	14475	12.1	0.83
Tweed	5.0	8.4	0.8	0.2	0.1	3.6	5075	18.1	3.58
Clyde	9.7	1.8	1.9	2.9	0.2	2.1	8100	18.6	2.29
Forth	6.5	9.1	0.7	1.1	0.1	3.3	4850	20.8	4.30
Tay	8.1	11.0	1.6	0.4	0.1	5.4	8800	26.6	3.03
Solway	16.3	6.0	2.7	0.6	0.1	2.4	10275	28.1	2.74
NE Scotland	11.1	10.7	1.6	0.4	0.1	9.3	9875	33.2	3.36
Scotland Total/mean	**65.7**	**49.4**	**18.9**	**5.6**	**0.9**	**28.0**	**131485**	**168.5**	**2.17**

Total annual nitrogen inputs to freshwater in 2010 vary considerably between regions, from 1.7 kT N for Orkney and Shetland, to 33.2 kT N for NE Scotland (Table 2). When total regional N inputs are weighted by the area of the region, it becomes apparent that two of the smallest regions, Tweed and Forth, have the highest N inputs/km^2 corresponding with comparatively higher proportions of agricultural land (41% and 47% respectively). The region with the highest freshwater inputs of N originating from human waste is Clyde region, where the city of Glasgow is situated. Naden et al. (2016) observed that in the mid 1990s, about 17% of the UK's sewage effluent was discharged through marine outfalls with little or no treatment. The Scottish nutrient budgets presented here take no account of direct marine discharges of human waste.

Note that although some regional N inputs, particularly for sewage, appear to be zero, most have small values (<0.1 kT y^{-1}).

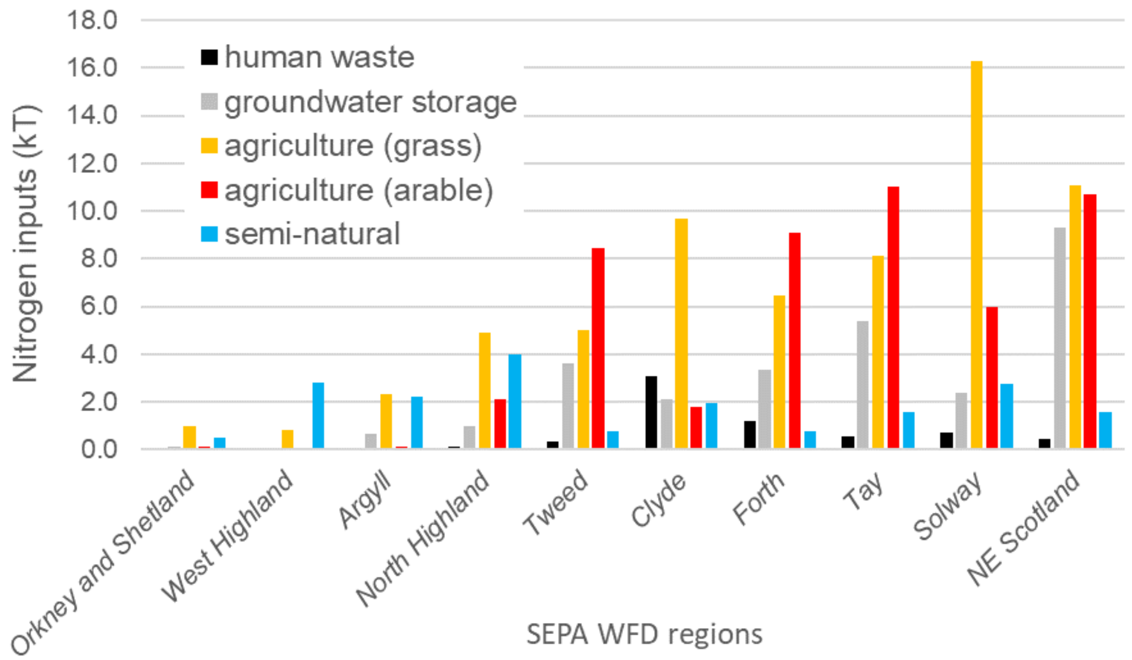

Figure 3. Histogram summarising the LTLS-FM model estimated total N inputs (kT) to SEPA WFD regions in 2010. Regions are ordered left to right by annual N input.

The LTLS freshwater model also provides the capability to estimate the impact of N stored in groundwater originating from several years/decades ago. Groundwater N stored in the unsaturated zone is predominantly derived from leaching from agricultural soils, but can also be from animal and human wastes, septic systems and from atmospheric deposition. Wang et al. (2013) quantify the temporal delay in nitrate concentrations in the water table, and these maps of temporal delays are included in the LTLS-FM (Bell et al. 2021). Across Scotland, the maps indicate that groundwater delay in nitrate delivery is between 0 and 50 years, and typically less than 10 years in lowland areas (particularly Forth, Clyde and Solway). The stored groundwater inputs to freshwater (Table 2) reflect nitrate leaching from soils that was stored in groundwater across Scotland in previous decades before release to rivers and subsurface flows. NE region stored groundwater N inputs to freshwaters in 2010 are the highest across all regions, even taking account of catchment area. Stored groundwater contributes 28% of the total N fluxes to freshwater in NE Scotland region, and ~20% in both Tay and Tweed regions. All three of these regions are estimated to have significant areas that store N leaching from 20 to 50 years ago, and are only now being released to freshwaters and the sea.

Both Solway and Tweed are cross-border regions. Approximately 10% of the Tweed WFD basin lies in England, but the River Tweed flows into the sea on the English side of the border. Of the N inputs to freshwater in the Tweed Region, 21% (3.0 kT N) are from England, and 15.2 kT N are from Scotland. For Solway, approximately 25% of Solway region lies in England, but the whole region flows into the Solway Firth. Of the N inputs to freshwater in Solway Region, 36% (10.2 kT N) are from England but the majority (18.0 kT) are from Scotland.

3.2 Export of N from freshwater to sea

The total annual flux of N to the sea in dissolved and particulate form by the LTLS-FM was estimated as 142 kT N in 2010 (Carnell et al., 2019). This flux was broken down into the fluvial flux (~88 kT) and the subsurface, or groundwater flux to sea (~54 kT). No observations were available to assess these figures, but based on comparison with total fluvial fluxes of Nitrate and Ammonium measured at HMS sites across Scotland (51 kT, which excludes N in the form of DON and particulates), the estimate of 88 kT N of coastal flux from all rivers across Scotland seemed reasonable.

Here, the LTLS-FM estimates of N export for Scotland are split between the 10 SEPA WFD river basin regions (Table 3). The total fluxes to sea (151 kT) are higher than those estimated in Carnell (2019) because more of England is included in the SEPA WFD regions. The largest total N flux to air and sea is from the largest region, NE Scotland, but if N exports are weighted by region areas (final column), the largest exporter of N is the Tweed.

Across Scotland, the LTLS-FM indicates that the majority of the N flux to sea is transported by rivers, but approximately 38% of N flux to the sea is via sub-surface (groundwater) fluxes, with N in sub-surface fluxes varying from 22% in the Tweed to 48% in Argyll Region. The direct leakage of groundwater N to coastal waters can be significant but is often neglected as it can be challenging to quantify. Lewandowski et al. (2013) suggest that the total flux of SGD (Submarine Groundwater Discharge) to the Atlantic Ocean is similar in volume to the amount of riverine discharge into the ocean. Beusen et al., (2013) suggest that the global SGD export of nitrate (NO_3-N) to coastal waters after 2000 could well increase, but Bell et al. (2021) LTLS model estimates indicate that for the UK, the SGD flux of Nitrogen peaked around the year 2000, and has started to decline.

Table 3. Summary of annual nitrogen exports (kT N y^{-1}) from freshwaters to atmosphere and coastal waters for SEPA WFD basin regions, as estimated by LTLS-FM for 2010. Total N exports weighted by catchment area (T km^{-2}) are also provided.

Region	River flux exported to sea (kT)	Groundwater flux to sea (kT)	Total flux to sea (kT)	N gas flux (kT)	Total N flux to air and sea (kT)	Total N flux/area (T km^{-2})
Orkney and Shetland	0.9	0.7	1.6	0.1	1.7	0.67
West Highland	2.3	1.3	3.6	0.1	3.7	0.35
Argyll	2.7	2.5	5.2	0.2	5.4	0.53
North Highland	6.5	4.8	11.4	0.6	11.9	0.82
Tweed	12.0	3.4	15.4	2.7	18.1	3.57
Clyde	11.3	4.3	15.6	2.9	18.5	2.28
Forth	9.8	8.7	18.5	2.3	20.9	4.30
Tay	15.3	9.0	24.3	2.4	26.7	3.03
Solway	15.6	9.1	24.7	3.5	28.2	2.74
NE Scotland	18.3	12.4	30.8	2.6	33.3	3.38
Scotland Totals	**94.8**	**56.2**	**151.0**	**17.3**	**168.4**	**22.0**

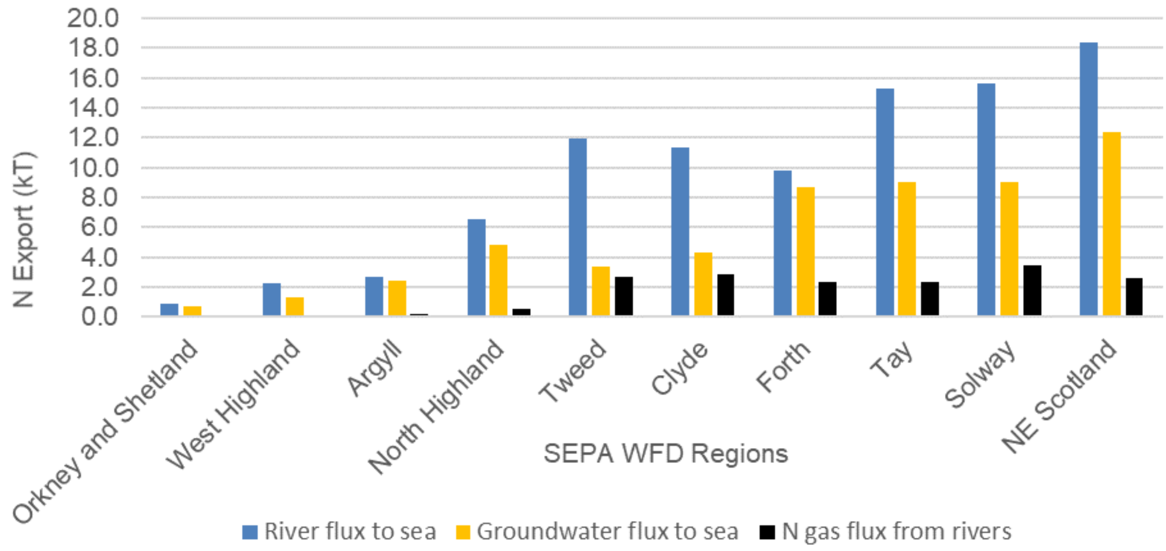

Figure 4. Histogram summarising the LTLS-FM model estimated N exports (kT) from SEPA WFD regions in 2010. Regions are ordered left to right by total N export.

For the cross-border Tweed region, approximately 10% of the Tweed WFD basin lies in England, but the whole of the River Tweed catchment flows into the sea on the English side of the border. LTLS modelling indicates that all N freshwater fluxes from the Tweed (16.2 kT) flow into the North Sea on the English side of the border. For Solway Region, for which ~25% lies in England, 1.2 kT N is output in freshwaters to coastal waters (Solway Firth) on the English side of the border, and 23.6 kT are output directly from Scotland in freshwater.

3.3 Export of N gas from freshwater to the atmosphere

The LTLS freshwater model estimates nutrient biogeochemistry parameters (primary production, organic matter decomposition, denitrification and oxygen balance) in rivers and lakes. For 2010, LTLS modelling indicated that approximately 10% of N in UK freshwaters was converted to N_2 gas by denitrification in rivers and lakes, and ~ 90% was exported directly to the coast (Bell et al., 2021). For Scotland as a whole, the estimated N gas flux from rivers in 2010 was 17 kT N (Carnell et al., 2019). Here, this value of N gas export for 2010 has been further divided between the 10 SEPA WFD regions (Table 3), and presented visually in Figure 4 (black bars). Values of total N gas flux in 2010 vary from 0.1kT (Orkney and Shetland, West Highland) to 3.5 kT (Solway region). The magnitude of the N gas flux in each region reflects the N inputs to freshwater, but will also be influenced by the surface areas of rivers and lakes in each region.

For the cross-border regions, LTLS modelling indicates that most of the N gas flux from rivers in Solway region (2.03 kT) comes from England, and 1.47 kT comes from Scotland, whereas for the Tweed, most of the N gas flux from rivers comes from Scotland (1.95 kT) and 0.78 kT is from England.

4. Summary and Discussion

4.1 Summary of N budgets across Scotland

The LTLS Freshwater Model (Bell et al., 2021) has been applied to 10 SEPA WFD regions to provide the sources and fluxes required to estimate N budgets for 2010. LTLS-FM estimates of N consist of dissolved (NO3-N, NH4-N and DON) and particulate phases (PONL and PONNL) in freshwaters, together with an estimate of N gas produced by river denitrification (Table 1). In the LTLS-FM, terrestrial fluxes of N are estimated for semi-natural areas (e.g. heathland, rough grass, broadleaf and needle-leaf trees, urban areas), agricultural areas (improved grass and arable crops), and from human waste (from sewage treatment works and septic tanks). The terrestrial fluxes also take account of annual N deposition (NH_4-N and NO_3-N).

Agriculture is the dominant source of N in Scottish freshwater, in line with other western European countries (e.g. ENA, 2011, Leip et al., 2011). The primary source is agricultural grass (39%), followed by arable crops (29%), stored groundwater (17%), semi-natural areas (11%) and sewage (4%). The dependence on land-use results in high spatial variability of N losses to the environment across Scottish regions (Table 2), with substantial N fluxes to freshwater in agricultural areas, but also significant N fluxes originating from stored groundwater sources. Solway and NE Scotland alone provide ~37% of the N fluxes to and from Scottish freshwaters, however, if the area of each region is taken into account, the Forth region contributes the greatest N flux per square km. Of the total N inputs to freshwater, Bell et al. (2021) indicate that for the UK, approximately 80% are in the form of nitrates (NO_3-N), with ~13% from ammonium-N (NH_4-N) and ~7% from DON. Similar proportions are expected for Scotland, as the dominant sources of N inputs to freshwater across the UK are broadly similar to Scotland (agricultural grass: 31%, arable: 34%). LTLS-FM estimates of sediment fluxes, including particulate N, are thought to be underestimates (Bell et al. 2021), and further work is needed to improve them before an assessment of particulate N in Scottish freshwaters can be provided.

Bell et al. (2021) estimated that for the UK only a small net balance of terrestrial nitrogen is held in groundwater storage over long (200 year) periods, but the model simulations indicated a net storage of nitrates in groundwater between the 1940s and 1990s following the post-war growth in agricultural fertiliser use, and a net release to coastal waters post-1990. Since then, changes in agricultural practice under the European Nitrates Directive (Council Directive, 1991) have led to a reduction in groundwater nitrate concentrations. However, for Chalk aquifers in Southern England, the thick unsaturated zone means that these improvements may not be seen for some decades in places, and the unsaturated zone remains an important store of nitrate (Ascott et al., 2016). The UK-wide map of travel times in the unsaturated zone (Wang et al., 2012) indicates there is a shorter groundwater “delay” in Scotland than for the UK as a whole. Across Scotland, N can be stored for between 0 and 50 years, and typically less than 10 years in lowland areas (particularly Forth, Clyde and Solway). It is likely therefore that any mid-20th century increase in agricultural fertiliser use, and subsequent storage in Scottish groundwater, will have been released by 2010, so the contribution of N from stored groundwater across Scotland may not rise much in later years.

Across Scotland, the LTLS-FM indicates that most N in freshwaters is transported to the sea in rivers (56%), but approximately 33% is transported to the sea via sub-surface (groundwater) fluxes, and a further 10% is converted to N gas in river biogeochemical processes (Table 3). LTLS-FM UK estimates indicate that most of the UK's freshwater N flux to sea is in the form of nitrate (~84%, Bell et al. 2021), and a similar proportion of nitrate in Scottish coastal N fluxes is expected. Nitrogen in rivers is routinely measured by water quality monitoring, however, losses of N to the marine environment through sub-surface channels and N gas release from freshwaters are less often measured. Carnell et al. (2019) summarised the N budget in Scottish freshwaters diagrammatically (Figure 1). Similar freshwater N budget diagrams are provided here for the 10 Scottish regions (Figure 5). Arrow widths are proportional to N fluxes, providing a simple visual representation of N fluxes across Scottish regions.

4.2 Limitations, suitability and robustness

The LTLS-FM is configured on a 5km × 5km square grid across Scotland, which is a relatively coarse resolution compared to the modest size of smaller island regions. The discretisation of complex islands and coastlines using a relatively coarse grid results in errors in derived catchment areas of 1 to 3% for most catchments, except for West Highland where the error is larger (9.7%), and Orkney and Shetland region which has a 3.3% overestimate in area. Thus N budgets derived using the 5km resolution LTLS model should be considered approximate for regions with small islands and complex coastlines.

The LTLS freshwater modelling approach and its limitations are summarised in Bell et al., (2021), which also demonstrated that present day LTLS-estimated dissolved N fluxes to UK coastal waters are broadly comparable with other published assessments. A comparison of observed and modelled dissolved nitrate fluxes between 1974 and 2010 at HMS locations indicated modest errors of -1% (95% CI of ±3%), but also indicated that the LTLS-FM model underestimates fluxes of particulate nutrients including particulate nitrogen, particularly from agricultural areas.

The LTLS-FM estimates of freshwater N fluxes to coastal waters are based on diffuse inputs from agriculture and semi-natural land, and direct inputs from waste water treatment works (WWTW). Inputs of N from industry are not taken into account, similarly, there has been no attempt to estimate the direct discharge of sewage (if any) to the marine environment. Thus the estimates of N fluxes to coastal waters provided here are most likely to be underestimates of the true fluxes.

5. Conclusions

Freshwater nitrogen (N) fluxes for 10 Scottish regions have been quantified in this study, bringing together recent available data (2010) for soils, water and air (including human waste). Across Scotland, losses of freshwater N to coastal waters (151 kT N yr^{-1}) and to the atmosphere (17.3 kT N yr^{-1}) are substantial, with more than half of the N losses originating from just 3 regions (Tay, Solway and NE Scotland). As much as 68% of Scotland's N in freshwaters comes from agricultural land management, for which improved nutrient use efficiency could increase environmental as well as economic benefits. Legacy nitrogen stored in Scotland's groundwater contributes approximately 17% of the N exported to coastal waters, some of which will have leached from soils up to 50 years ago. Further work will be needed to establish whether this source of N will increase or decrease in future years, but a future decrease is considered most likely, given that N storage in groundwater is for closer to 10 years in lowland agricultural areas.

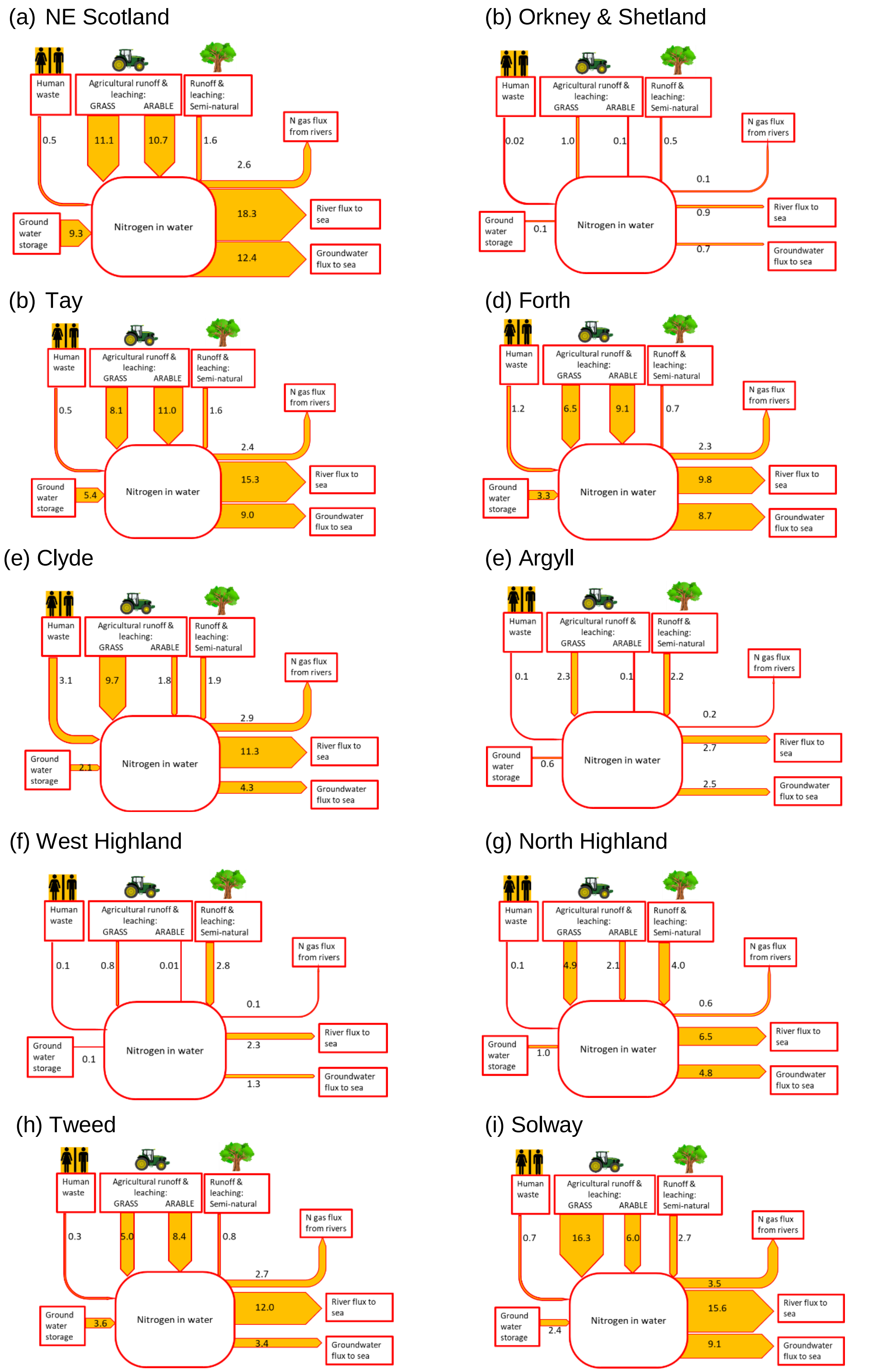

Figure 5. Hydrosphere/soil nitrogen budgets (2010) for SEPA WFD regions using outputs from the LTLS-FM macronutrient model (kT N yr^{-1}). Arrow widths are proportional to N fluxes.

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Appendix A

Table A1. Glossary

Acronym/Symbol	**Meaning**
C	Carbon
DON	Dissolved Organic Nitrogen
GIS	Geographical Information System
ENA	European Nitrogen Assessment
kT	1 KiloTonne (kT) = 10^3 Tonnes = 10^6 g
km	Kilometre
LTLS	Long Term Large Scale Macronutrients project
LTLS-FM	Long Term Large Scale - Freshwater Model
LTLS-IM	Long Term Large Scale - Integrated Model
NH_4-N	Ammonium-N
NO_3-N	Nitrate-N
N	Nitrogen (LTLS-FM N = NH_4-N + NO_3-N + DON + PONL + PONNL + N_2)
N_2	Nitrogen gas from denitrification
NE Scotland	North East Scotland
NERC	Natural Environment Research Council
NUE	Nutrient Use Efficiency
P	Phosphorus
PONL	Labile particulate organic nitrogen
PONNL	Non-labile particulate organic nitrogen
SEPA	Scottish Environment Protection Agency
SGD	Submarine Groundwater Discharge
SNBS	Scottish Nitrogen Balance Sheet
T	1 Tonne (T) = 10^3 g
UK	United Kingdom
WFD	Water Framework Directive
WWTW	Waste Water Treatment Works
yr	Year

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