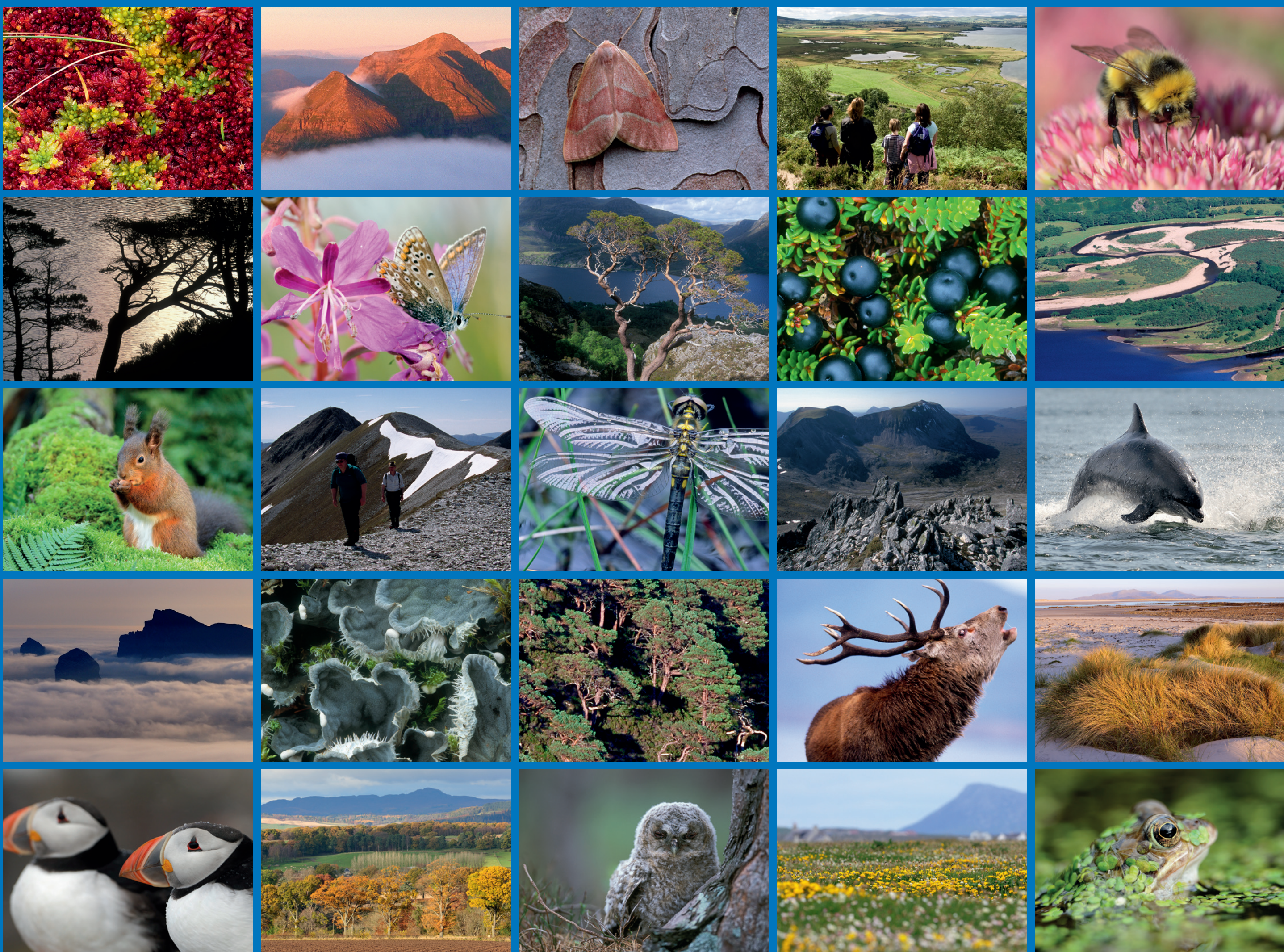
Scottish Natural Heritage
Commissioned Report No. 962

Loch Leven nutrient load and source apportionment study



COMMISSIONED REPORT

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COMMISSIONED REPORT

Summary

Loch Leven nutrient load and source apportionment study

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Keywords

Loch Leven; phosphorus; nitrogen; catchment; land use; climate change.

Background

Loch Leven is a shallow, eutrophic loch in the lowlands of Scotland that is currently in unfavourable condition. It is important to re-establish good water quality at this site to sustain its many designated conservation features (SSSI, SPA, Ramsar site & NNR). Long-term monitoring of water quality at Loch Leven has been undertaken by the Natural Environment Research Council (NERC) since the late 1960s. Over the first 20 years (1968-1987), the loch suffered serious degradations in water quality due to the combined effects of eutrophication, pesticide pollution and climate change. However, following management intervention in the early 1990s, nutrient inputs from the catchment were reduced and the site underwent a slow, but sustained, recovery. By 2007, water quality had improved and aquatic plants had re-established in deeper water; this provided better habitat and food availability for fish and aquatic birds (Winfield *et al.*, 2012; Carss *et al.*, 2012). However, since 2007, there has been a tendency for phosphorus (P) concentrations within the loch to start increasing again. It is unclear whether this is due to changes in internal recycling of P within the loch or to increasing inputs from its catchment.

In this study, research was undertaken to investigate the nutrient inputs to the loch and to determine whether further reductions are required to support the recovery process. A nutrient loading survey of the 11 main inflows to the loch, and its outflow, was undertaken. This survey has focused mainly on P, but some supporting information on nitrogen was also collected. The study also incorporated source apportionment studies that included sampling up- and down- stream of the large point sources at Kinross and Milnathort waste water treatment works and at the Kinross pumping station. In addition, a survey of the potential impacts of small on-site sewage treatment systems (mainly septic tanks) on water quality was undertaken in the Gairney catchment. The Gairney catchment was selected because it is a relatively large catchment with no large WWTW discharges, a large number of unsewered properties and easy access to a wide range of potential sampling sites along the length of the river and its tributaries. The results have been compared to those from three previous nutrient loading studies that were undertaken in 1985, 1995 and 2005.

Main findings

The results of the study suggested that about 12t of P entered the loch between July 2015 and July 2016; this is similar to the value recorded using similar methods in 2005. Of the 1.2t P y^{-1} that could, potentially, be discharged to the environment from unsewered properties if they were all served by traditional septic tanks, only about 0.34t P y^{-1} seems to be entering the loch via its inflows. This suggests that local campaigns to encourage better management of these systems is working well; it is recommended that this is continued. Some hotspots of P contamination were detected across the Gairney catchment. These suggested that some systems were not working as efficiently as others and may need to be investigated further. Similar hotspots of P pollution are likely to occur in other areas, too, and it is recommended that similar surveys are undertaken in other parts of the catchment to identify these.

Although discharges of P to the environment from point sources within the catchment have decreased significantly over time, on occasion discharges from the Kinross waste water treatment works were found to elevate in-stream P concentrations at Site 9 by up to 1,320µg L^{-1}. The reason for this should be investigated.

Whilst overall discharges from point sources appear to be decreasing, P from diffuse sources seems to be increasing especially in relation to particulate P; this increase may be due to changes in land use and/or climate. Catchment land use should be explored, especially around the Pow Burn and South Queich, to determine why increasing levels of particulate P appear to be entering the loch from these catchments and whether changes in land use could be used to mitigate this. Further analysis of the nutrient loading data from previous surveys should be undertaken to test the hypothesis that particulate P inputs to the loch are increasing due to changes in the weather as a result of climate change.

In inflows that do not receive effluent form waste water treatment works, there was a very strong relationship between the estimated total P load from rural point sources and the number of unsewered properties located upstream of each sampling point. The results suggested that, on average, each septic tank or small package treatment plant was delivering about 0.4kg P y^{-1} to the loch; in total about 0.34t P y^{-1} (3%) of the total P load to the loch appeared to be coming from these sources.

The measured P loads to Loch Leven were compared to those estimated by the PLUS+ model, which is used operationally by SEPA. The results suggested that, although catchment runoff figures were similar, modelled P discharges from urban wastewater were an order of magnitude higher in the modelled data than in the measured values. Reasons for this discrepancy should be investigated.

It is important to assess the long term progress of the catchment management and loch restoration activities that began in the late 1980s. So, another loading survey, with source apportionment data included, should be undertaken in 2025.

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Acknowledgements

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1. INTRODUCTION

1.1 Background

Loch Leven is in unfavourable condition. However, it is important to attain good water quality at this site to sustain its many conservation features (SSSI, SPA, Ramsar site & NNR). In the 1990s, a target for average open water total phosphorus (TP) concentrations of 40μg L^{-1} was set as a restoration target (LLCMP, 1999). More recently, a more stringent target of 35μg L^{-1} has been set under the EU Water Framework and Habitats Directives. Loch Leven is failing all of these water quality objectives and high inputs of nutrients to the loch from its catchment (especially of phosphorus, P) have been identified as a key driver of these water quality problems (Bailey-Watts, 1978).

Long-term monitoring of the water quality within Loch Leven has been undertaken by the Natural Environment Research Council (NERC) since the late 1960s. That work is currently undertaken by one of NERC's research centres, the Centre for Ecology & Hydrology (CEH). Some of the results of that monitoring are shown in Figure 1.

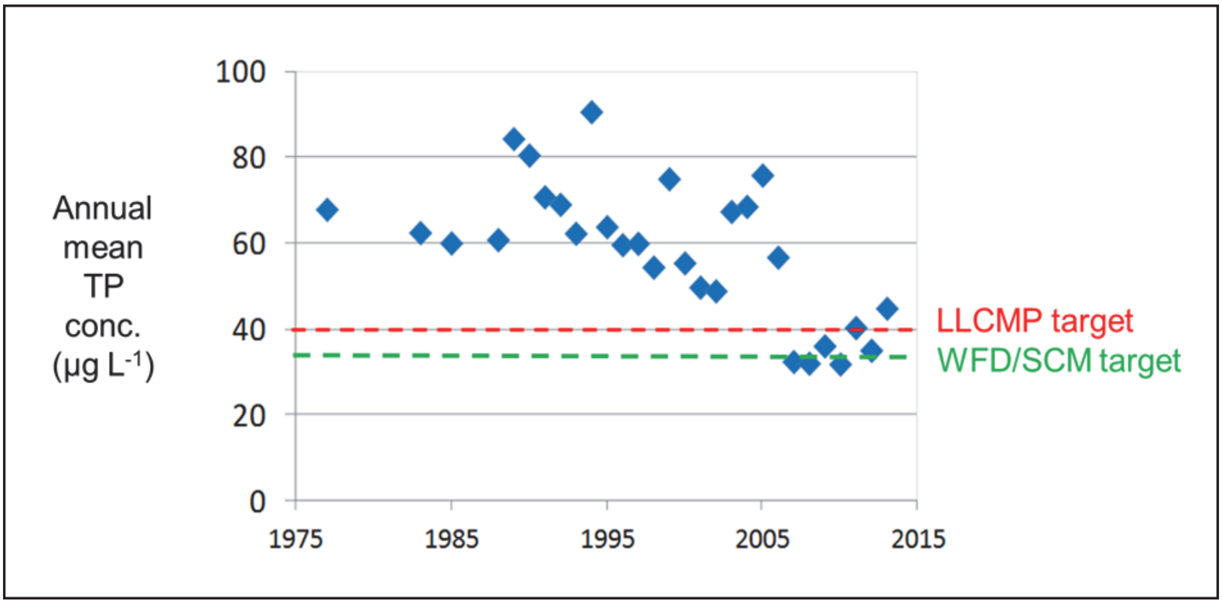

Figure 1. Annual mean total phosphorus (TP) concentration in Loch Leven, 1976-2015; the Loch Leven Catchment Management Plan (LLCMP) target (LLCMP, 1999) is shown in red and the current Water Framework Directive and Site Condition Monitoring (WFD/SCM) target is shown in green.

During the first 20 years of monitoring (1968-1987), the loch was suffering serious degradations in water quality due to the combined effects of eutrophication, pesticide pollution and climate change. However, following management intervention in the early 1990s to reduce nutrient inputs from the catchment, the site underwent a slow, but sustained, recovery. By 2007, water quality had improved and aquatic plants had re-established in deeper water; this provided better habitat and food availability for fish and aquatic birds (Winfield *et al.*, 2012; Carss *et al.*, 2012). However, since 2007, there has been a tendency for phosphorus (P) concentrations within the loch to increase again (Figure 1). At this stage it is unclear whether this is a short or long term trend, or whether this is due to changes in the internal recycling of P within the loch or to increasing P inputs from the catchment.

In this study, research has been undertaken to investigate the impact that existing catchment management activities have had on nutrient inputs to the loch and to determine whether further improvements are required to support the recovery process. This work has mainly comprised a nutrient loading survey of the 11 main inflows and the outflow of the loch, focusing mainly on P but with some supporting information on nitrogen (N). Nitrogen was included because there is some evidence that the loch may be becoming increasingly N limited during the summer months. The study also investigated nutrient source apportionment by sampling up- and down- stream of the large point sources at both Kinross and Milnathort waste water treatment works (WWTWs), and the Kinross pumping station. Also a survey of the potential impacts of small on-site sewage treatment systems (mainly septic tanks) on water quality was undertaken in the Gairney catchment. The Gairney catchment was selected because it is a relatively large catchment with no large point source discharges, a large number of unsewered properties and easy access to a wide range of potential sampling sites along the length of the river and some of its tributaries.

The overall objective of this project was to assess the current P and N inputs to Loch Leven and provide information on their likely sources. By building on the results from three previous nutrient loading studies undertaken in 1985, 1995 and 2005, this study ensured the continuity of a unique long-term data set that is invaluable for understanding how the loch responds to change, and for assessing the effectiveness of current policies and management activities relating to nutrient input.

Many of the findings are transferrable to other freshwater sites across the UK and beyond in terms of providing a scientific evidence base for the future development of cost effective loch management and restoration strategies.

2. METHODS

The study comprised a baseline survey of nutrient inputs to the loch from its main feeder streams, as well as more specific surveys to assess the contribution from up- and down-stream of point source discharges from waste water treatment works (WWTWs) and the potential impacts of small on-site sewage treatment systems (mainly septic tanks) on water quality in the Gairney Water. Information on the locations of WWTW effluent pipes were provided by SEPA.

2.1 Sampling locations and frequency

2.1.1 Baseline nutrient loading survey

Water samples were collected from the 11 main feeder streams to the loch, and from its outflow (Figure 2; Table 1) at weekly intervals from 9/7/15 to 6/7/16. Sampling sites were accessed from the Loch Leven Heritage Trail, which runs around the edge of the loch. More specifically, samples were collected where the bridges along this trail crossed these feeder streams.

The upstream (sub catchment) areas draining to the sampling sites are shown in Figure 2. These were delineated by CEH using a GIS-based watershed analysis approach, and are specific to the sampling sites used in this study. A 50m digital elevation model (IHDTM; http://www.ceh.ac.uk/services/integrated-hydrological-digital-terrain-model) was used to create an outflow grid and a cumulative catchment area grid. The two point locations were then snapped to the nearest 'pour point' on the outflow grid to ensure that the catchment generated was that of the river. A watershed function was then applied to the outflow grid at this point, creating the upstream catchment as a 50m output grid. This grid was converted to an ArcGIS (ESRI) shapefile.

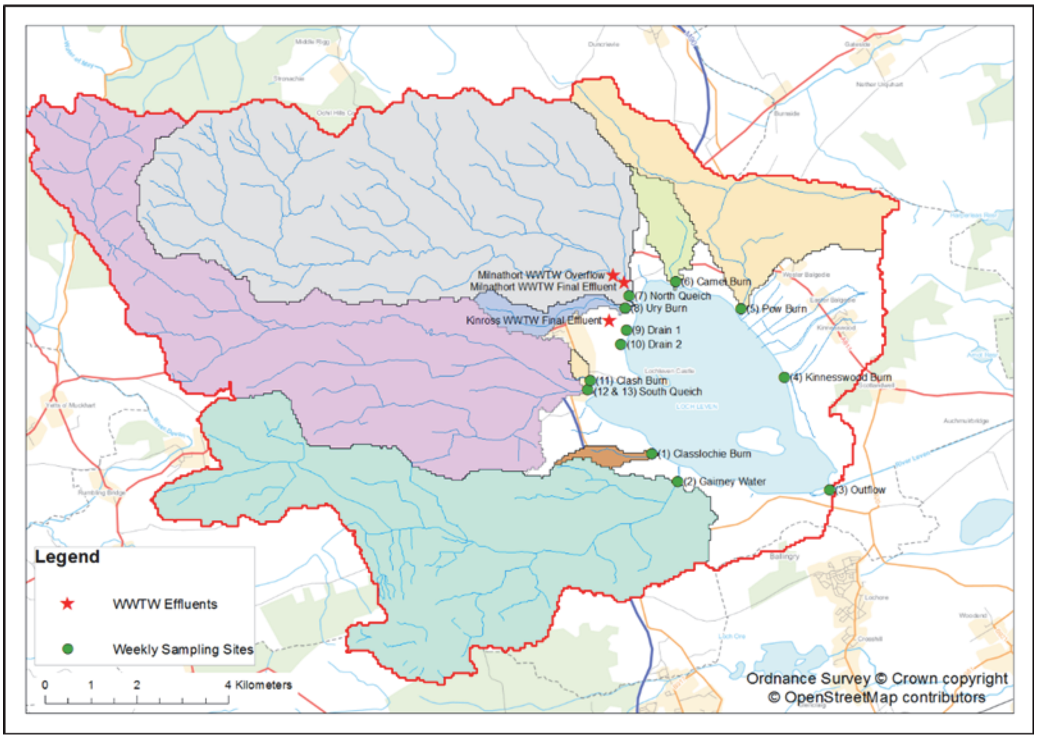

Figure 2. Map showing the routine weekly sampling sites used for the baseline nutrient loading survey, the locations of point source discharges from waste water treatment works (WWTWs) and the upstream sub-catchment areas that drain to each sampling point.

Table 1. Locations of the sampling sites for the baseline nutrient loading study

Sampling site	Easting	Northing
Site 1 – Classlochie Burn	313556	700209
Site 2 – Gairney Water	314107	699613
Site 3 – Loch outflow	317432	699424
Site 4 – Kinnesswood Burn	316439	701871
Site 5 – Pow Burn	315494	703370
Site 6 – Camel Burn	314022	703829
Site 7 – North Queich (downstream of Milnathort WWTW)	313067	703661
Site 8 – Ury Burn	312700	703463
Site 9 – Drain 1 (downstream of Kinross WWTW)	312997	702910
Site 10 – Drain 2	312881	702590
Site 11 – Clash Burn	312926	704449
Sites 12 & 13 – South Queich	312152	701616

2.1.2 Assessment of point source discharges

In addition to the above, weekly water sampling was undertaken at Sites 14 and 15 (above and below the Milnathort wastewater treatment works (WWTW), respectively) and Site 16, above the Kinross WWTW, at weekly intervals between 4/5/16 and 6/7/16 (Table 2). Samples were also collected at weekly intervals throughout the study at sites above and below the Kinross WWTW storm overflow point, located on the South Queich, between Sites 12 and 13 (Figure 2; Table 1).

Table 2. Locations of additional sampling points used to collect data up- and down- stream of WWTWs

Site	Easting	Northing
Site 14 – Upstream of Milnathort WWTW	312650	704122
Site 15 – Downstream of Milnathort WWTW	312877	703926
Site 16 – Upstream of Kinross WWTW	312365	703267

2.1.3 Septic tank impacts survey

Spatial surveys of stream water quality across the Gairney catchment, upstream of Site G0 (Figure 3)/Site 2 (Figure 2), were carried out under different flow conditions on 18/5/16 (low flow; 0.4 cumecs) and 14/9/16 (high flow; 1.4 cumecs). Sampling sites (Figure 3; Table 3) were chosen where there was easy access from the road, e.g. at a bridge. Images of each sampling site are shown in Figure 4.

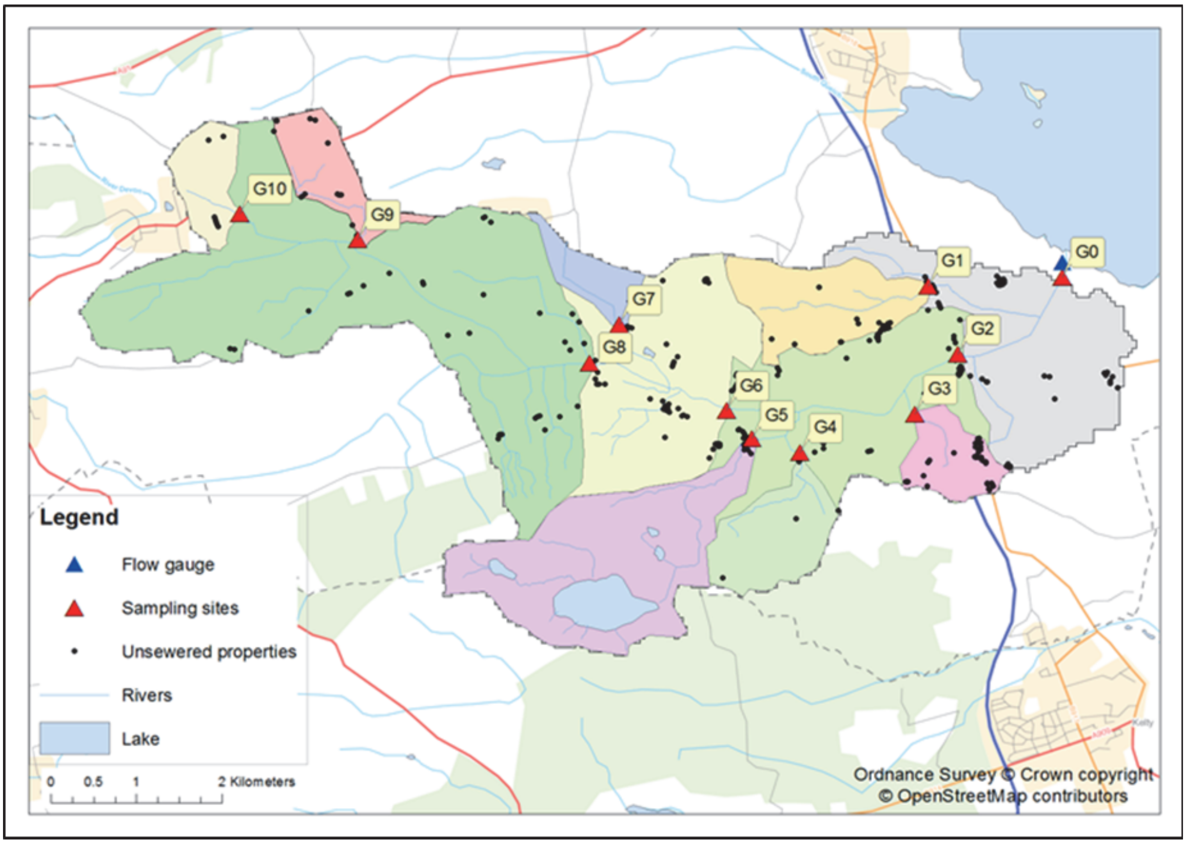

Figure 3. Location of sampling sites G0-G10 (red triangles) across the Gairney catchment showing the upstream catchments draining to each point (various colours); the flow gauge installed near to Site G0 is also shown (blue triangle).

Table 3. Locations of sampling locations across the Gairney Water catchment used for the septic tanks impact survey.

Site	Easting	Northing
G0	314107	699613
G1	312544	699505
G2	312888	698712
G3	312385	698010
G4	311049	697561
G5	310480	697719
G6	310189	698050
G7	308932	699056
G8	308588	698606
G9	305876	700048
G10	304501	700352

Figure 4. Sampling sites G0 - G10.

2.2 Water sampling methods

Access to most sampling sites was gained by cycling along the Loch Leven Heritage Trail, a track that circumnavigates the loch. However, Sites 16 and G1-G10 were accessed by car.

At each site, water samples were collected the bridge or river bank in 100ml capacity screw capped, polyethylene bottles. These were attached to the end of a 2m extendable pole (Sites 1, 4, 6, 8-13, 15, G1, G3-G5, G7-G10) or lowered into the water using a 5m extendable dog lead (Sites 2, 3, 7, 14, G0, G2, G6). The samples were returned to the laboratory for processing and analysis within two hours of collection.

2.3 Water sample processing and storage

On return to the laboratory, samples for total soluble phosphorus (TSP) analyses were filtered through Whatman® GF/C Grade filter papers (1.2μm pore size). Those for total phosphorus (TP) determinations remained unfiltered. Analyses for all P determinations were begun within 4 hours of collection.

For total dissolved nitrogen (TDN) analyses, samples were filtered as described above and stored frozen in 15mL polypropylene tubes until they were analysed using the methods described below.

2.4 Chemical analyses

All water samples were analysed for total and total soluble fractions of phosphorus. Weekly inflow samples, and samples collected from up- and down-stream of the WWTWs, were also analysed for concentrations of total dissolved nitrogen (TDN).

2.4.1 Phosphorus

Samples for total phosphorus (TP) and total soluble phosphorus (TSP) determinations were analysed using a Perkin Elmer Lambda 25 UV/Vis spectrophotometer. The prepared samples were digested with acidified potassium persulphate in an autoclave at 120^{o}C for 30 minutes. The, TP and TSP concentrations were then determined by colorimetry using the molybdenum blue method. The detection limit was 0.007mg P L^{-1}. Standard solutions of known concentration were measured for QA/QC purposes.

Particulate phosphorus (PP) values, i.e. the amount of P that is bound to particles, were derived from the above as follows:

$$PP = TP – TSP$$

This value reflects the level of upstream soil erosion and sediment transport at each site.

2.4.2 Nitrogen

Samples for TDN determinations were de-frosted before analysis, acidified with 3M HCl, sparged with oxygen and then processed on a Skalar Formacs analyser.

2.5 Measurements of stream discharge

Measurements of stream discharges are required to calculate nutrient loads to the loch from nutrient concentrations. These discharges were obtained from calibrated water level gauges.

2.5.1 Water level measurements

Water level gauges were installed on the six main inflow streams that were not already being gauged by SEPA, i.e. Sites 1, 4, 6, 7, 8 and 10. Each installation comprised a submerged water pressure logger, to record water depth, and a land based barometric pressure gauge to enable changes in water pressure to be corrected for any changes in barometric pressure.

The water level sensors used in this study were Rugged TROLL 100 Data Loggers (https://in-situ.com/products/water-level-monitoring/rugged-troll100/). These were installed inside a protective piece of black plastic tubing (drainpipe) that was perforated with holes to allow the water level inside to track that of the surrounding water. The location of each of these gauges is indicated in Figure 5 and Table 4.

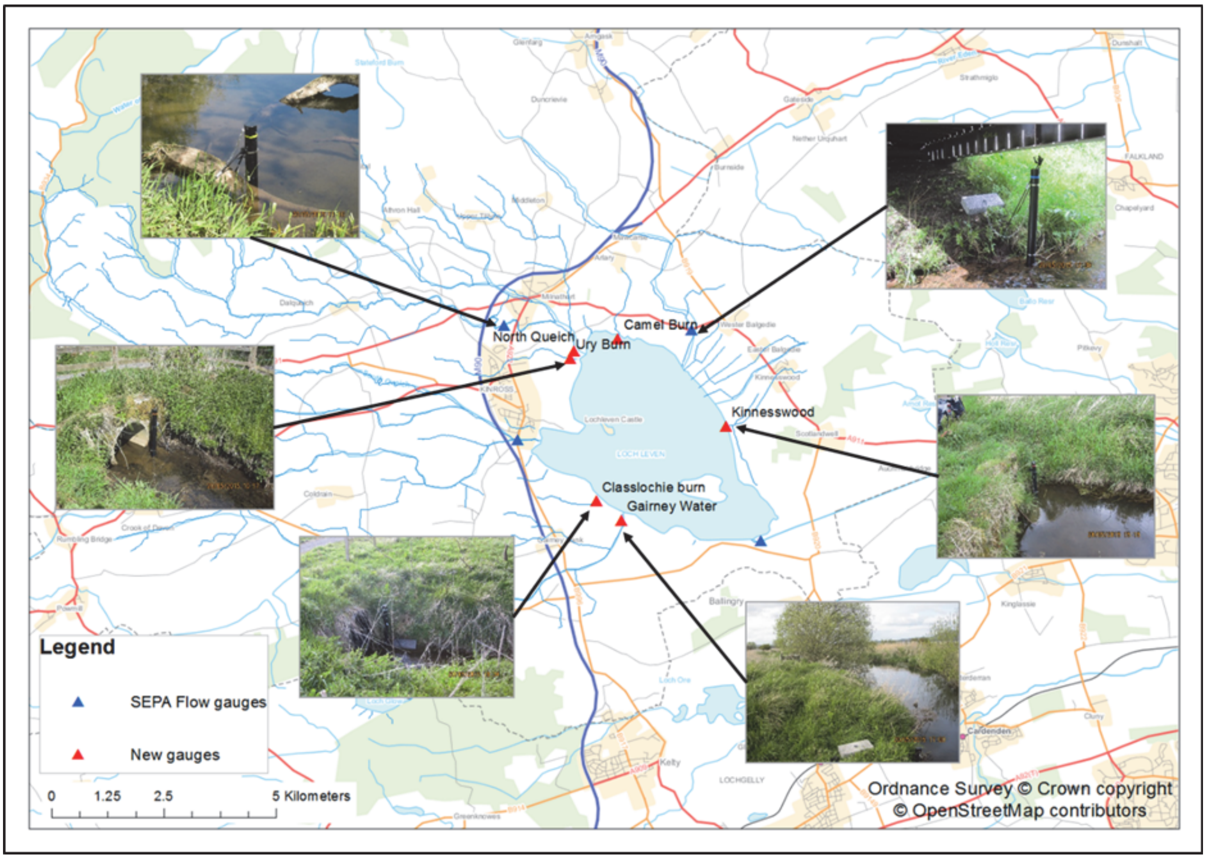

Figure 5. Water level gauges within the Leven catchment, with images of the locations of new gauges installed for this study.

Table 4. Locations of water level gauges installed for this study

Site	Easting	Northing
Site 1 – Classlochie Burn	313560	700210
Site 2 – Gairney Water	314110	699780
Site 4 – Kinnesswood Burn	316440	701870
Site 6 – Camel Burn	314033	703824
Site 7 – North Queich	313063	703554
Site 8 – Ury Burn	312970	703384

On deployment, each sensor was programmed to log water height or barometric pressure, as appropriate, at half hourly intervals throughout the sampling period. The data were downloaded to a laptop PC at approximately quarterly intervals and processed using bespoke software, to generate half-hourly water level data for each site. Rates of discharge at each site were calculated from these water levels using stage discharge calibration curves (see Section 2.5.2).

2.5.2 Stage discharge calibration curves

Rates of flow were measured at each site, over a range of water levels, to provide data for the stage discharge calibration curves. Two types of meter were used; a Valeport Ltd. Model 001 propeller based flow meter with suspension set, for deeper sites that were not suitable for wading; and a Valeport Ltd. 801 single axis flow meter, for shallower sites (Figure 6). The dates and method of measurement are shown in Table 5.

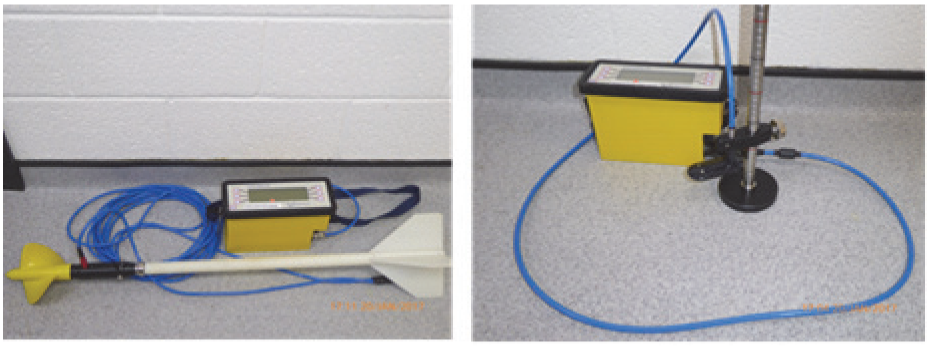

Figure 6. Valeport Model 001 Propeller based flow meter with suspension set (left) and a Valeport 801 single axis flow meter (right) used to develop stage discharge calibration curves for each water level gauge.

Figure 7. Measuring flow in the Kinnesswood Burn

At each gauging site, the width of the wetted area was measured and divided into several equally spaced intervals, usually 1m intervals at Sites 2 and 7, and 0.4m and 0.5m intervals at Sites 1, 4-6 and 8. At each point of measurement, the total depth and distance from the bank were recorded and the flow measured at approximately two-thirds of the total water depth (Figure 7). Ten values were recorded and averaged at each point of measurement.

Table 5. Dates of flow measurements at each gauging site

Site	**Type of flow meter**	**Date**					
		23/10/15	**15/12/16**	**30/3/16**	**14/9/16**	**24/11/16**	**28/12/16**
Site 1	Single axis	Y		Y	Y	Y	Y
Site 2	Propeller		Y	Y	Y		
Site 4	Single axis	Y		Y	Y		
Site 6	Single axis	Y	Y	Y	Y	Y	Y
Site 7	Propeller	Y	Y	Y	Y		
Site 8	Single axis	Y	Y	Y	Y	Y	

Discharge (as m^3s^{-1} or cumecs) was calculated by multiplying the average measured flow (ms^{-1}) at each point of measurement by the cross sectional area of the inflow at that point. The relationship between rate of flow and stage height, as measured by the automatic water level sensors, was determined for each of the inflows listed in Table 5. These relationships were used to calculate half hourly rates of discharge at each site.

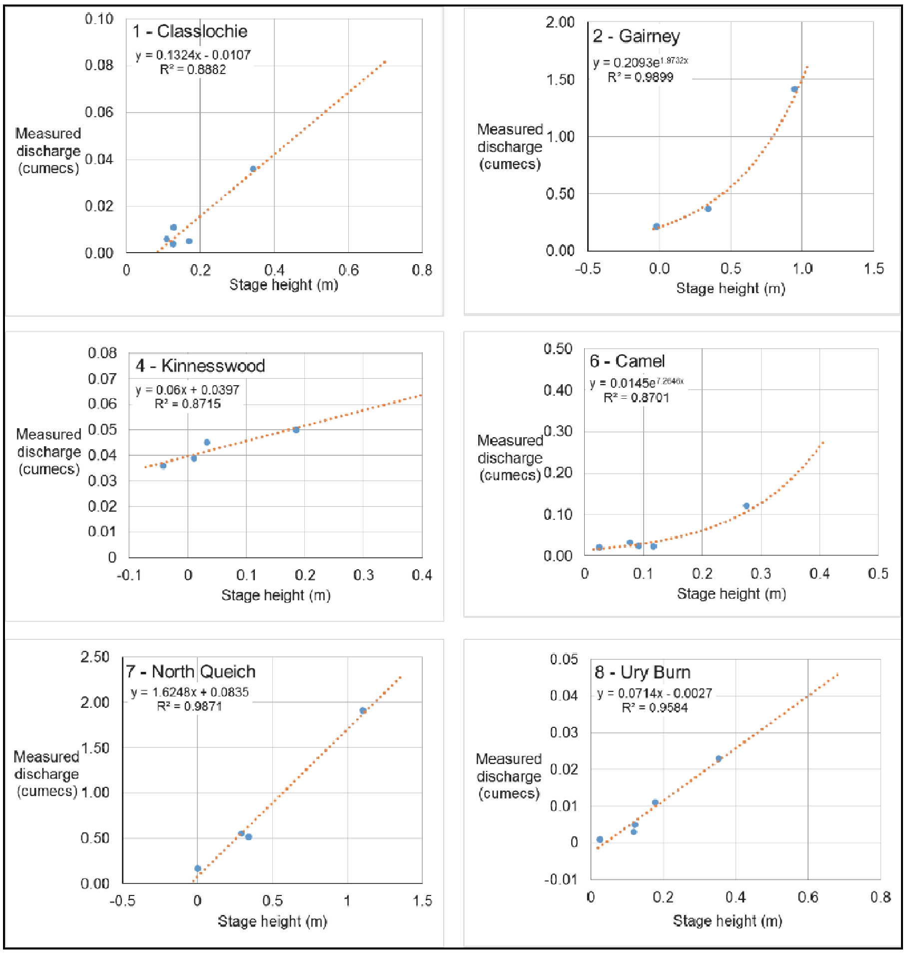

Figure 8. Stage discharge calibration curves for Sites 1, 2, 4 & 6-8

The resulting stage discharge calibration curves are shown in Figure 8. The linear relationship between water level and discharge at most of these sites reflects the very rectangular cross sectional area of these drainage channels, many of which have been modified to some extent.

2.5.3 *Third party inflow discharge datasets*

Discharge data collected at 15 minute intervals were supplied by SEPA for the sites listed in Table 6 and shown in Figure 5.

Table 6. SEPA flow gauging stations

Site	Easting	Northing
North Queich at Lathro	311503	704113
South Queich at Kinross	311809	701570
Greens Burn at Damley's Cottage	315663	704025
River Leven at sluices (loch outflow)	317210	699329

2.5.4 Ungauged catchments, geese and rainfall

The discharge from Site 9 – Drain 1 was not gauged on a regular basis. However, the depth of water and rate of flow were measured on two occasions using the Valeport 801 single axis flow meter. Rates of flow measured on 14/9/16 (0.023 cumecs) and 28/12/16 (0.037 cumecs) were 7.7 and 7.4 times greater, respectively, than corresponding values in the nearby Ury Burn, which was gauged continuously. So, discharge values for Drain 1 at Site 9 were estimated to be 7.55 times that of the corresponding values at the Ury Burn.

Inputs from other un-gauged areas were calculated by multiplying the total area of land that drains directly to the loch by an areal P export coefficient derived from the outlet data of catchments without WWTWs, i.e. Sites 1, 2, 4, 5, 6, 8 and 12). This value (0.06t P km^{-2}), was calculated as the average of the areal P export coefficients across all monitored catchments. Individual values ranged from 0.01t P km^{-2} for the Ury Burn catchment, to 0.14t P km^{-2} for the South Queich catchment.

Inputs of P to the loch from geese were calculated from the average number of pink footed and greylag geese roosting on the loch per day over the study period (i.e. 980; Dessborn *et al.*, 2016) using the values shown in Table 7.

Table 7. Parameters used to estimate annual P inputs to the loch from roosting geese

Parameter	Value	Units
Part of day roosting on loch	0.5	
Droppings per goose	56	g per day
P input from 1 goose per year	204	g per year
P input from 980 geese per year	200	kg per year

Inputs of P from rain falling directly onto the surface of the loch were estimated from values used by Defew (2008), i.e. an average rainfall of approximately 900mm with an average P content of 16µg P L^{-1}.

2.6 Land cover data

Information on the land cover in each sub-catchment and the whole catchment of the loch was derived from the UK Land Cover Map 2007 (LCM, 2007; Morton *et al.*, 2011). This is a parcel-based classification of UK land cover that uses 23 classes to map the UK. These classes are based on the UK Biodiversity Action Plan (BAP) Broad Habitats. LCM2007 was created from summer-winter composite satellite images with pixel dimensions of 20-30m. The data used in this study comprised a 25x25m raster image of the most likely Broad

Habitat for each pixel within the Loch Leven catchment. For further information on this dataset see https://www.ceh.ac.uk/services/land-cover-map-2007.

2.7 Calculations of nutrient inputs

All nutrient concentrations were combined with corresponding flow measurements to calculate the total instantaneous and annual inputs (loads) to the loch using the same method as Bailey-Watts & Kirika (1987) which was based on that of Rodda & Jones (1981):

$$L = K \sum_{i=1}^{n} \left(\frac{CiQi}{n} \right)$$

Where:

n = number of samples
Ci = instantaneous TP concentration in sample i
Qi = instantaneous flow when sample i was collected

Source apportionment of nutrient inputs between point and diffuse sources was determined using a model developed for this purpose by Bowes *et al*. (2008). This model uses the differences in the relationship between point and diffuse nutrient delivery and flow over time to separate point and diffuse sources. The underlying principle of the model is that point source discharges are diluted with increasing river flow, because they are relatively constant, while diffuse (non-point) inputs are driven by rainfall and runoff and usually increase with flow. This approach can provide a simple, robust and rapid nutrient source apportionment from most concentration–discharge data and provides a valuable and versatile tool for determining sources to determine suitable mitigation options. There was a very close relationship between the TP loads estimated using the approach of Bailey-Watts & Kirika (1987) from the 1985 survey and those estimated using the source apportionment approach developed by Bowes *et al*. (2008) (Figure 9).

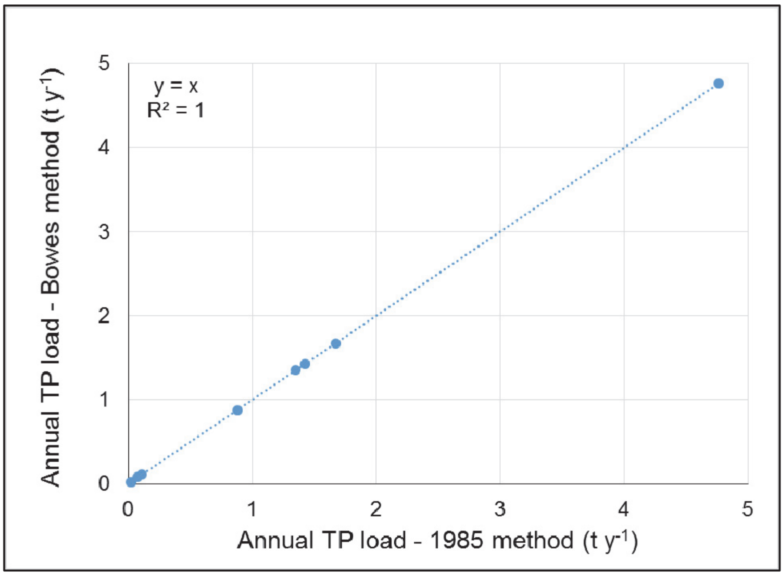

Figure 9. Comparison between two different methods of estimating annual total phosphorus (TP) inputs to Loch Leven from its feeder streams (i.e. 'Bowes method' is that of Bowes et al. (2008); '1985 method' is that used by Bailey-Watts & Kirika (1987) for the 1985 survey.

In addition to the above, nutrient concentrations were measured up- and down-stream of main point sources within the Loch Leven catchment (i.e. Kinross and Milnathort WWTWs). Nutrient discharges from these sources were calculated as the difference between the up- and down-stream results.

The impact of discharges from on-site waste water treatment systems (mainly septic tanks) were determined at the catchment scale through two surveys of water quality in the catchment of the Gairney Water (see Section 2.1.3). The amount of TP attributable to upstream point sources in catchments with no WWTWs was determined using the method of Bowes *et al*. (2008) and compared to the number of unsewered properties upstream of the sampling point.

3. RESULTS

The nutrient loading survey data are reported below. The results are presented by sampling site, in numerical order.

Temporal variation in calculated discharge is shown for each site, with the lower and upper limits of the flow calibration curves indicated. Although most discharge values fell within this range, very high flows fall outside of this range at some sites.

3.1 Site 1 - Classlochie Burn

Classlochie Burn drains a sub-catchment 0.52km^2 in area that comprises, a relatively flat area of improved grassland (74%) and some arable land (22%). The remainder of this sub-catchment (4%) consists of rough and heather grassland. There are no obvious point sources of nutrients within the catchment, apart from one unsewered property.

3.1.1 Discharge

The level of discharge within the Classlochie Burn at Site 1 ranged from 0 to 0.083 cumecs (Figure 10), and averaged 0.019 cumecs over the study period. During periods of high water level, flows were difficult to estimate due to flooding and, at times, the backing up of flood waters from the loch itself.

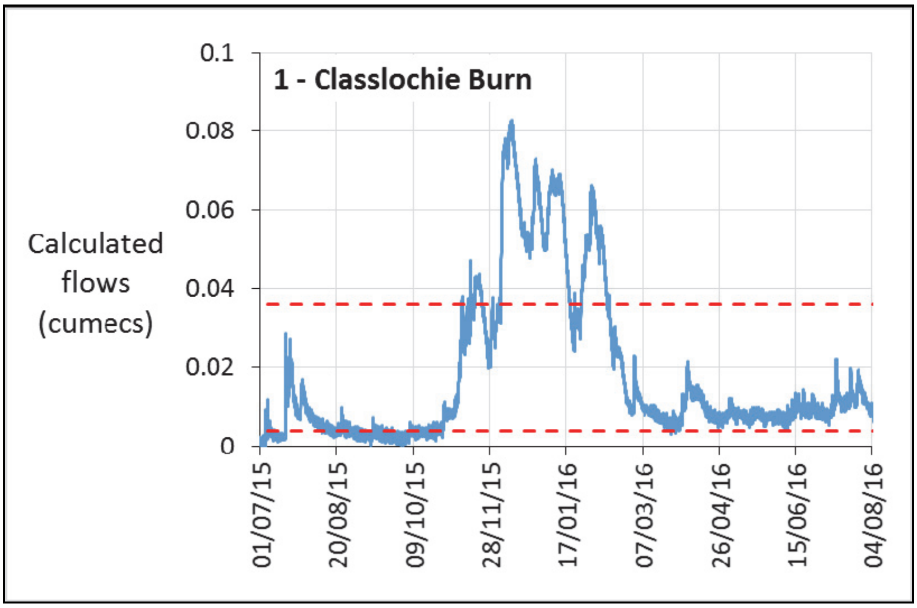

Figure 10. Discharge measured at Site 1, on the Classlochie Burn, showing upper and lower limits of the stage discharge calibration data (red dashed lines).

3.1.2 Nutrient concentrations

The minimum, mean and maximum values for TSP, TP and TDN are shown in Table 8. Although there were occasional high values, mean concentrations of 21μg P L^{-1} and 30μg P L^{-1} for TSP and TP, respectively, and of 3.8mg N L^{-1} are not unusually high for streams draining agricultural areas.

Temporal changes in stream discharge and nutrient concentrations over the study period are shown in Figure 11 and Figure 12.

Table 8. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 1, Classlochie Burn.

Site 1	TSP (µg P L^{-1})	TP (µg P L^{-1})	TDN (mg N L^{-1})
Min	4.17	11.93	0.74
Mean	21.03	30.00	3.82
Max	61.54	69.07	13.80

3.1.2.1 Phosphorus

Under low flow conditions, (July to November 2015), TSP and TP concentrations both rose steadily from about 12-15µg P L^{-1} to about 60-70µg P L^{-1}. Then, rates of discharge began to increase rapidly, from approximately 5 to 70 cumecs between early November and early December. In general, TSP and TP concentrations fell over this period, but the increased differential between TSP and TP over this period compared to the earlier period indicates high levels of PP, probably as a result of soil erosion and transport under these higher flow conditions.

The rate of discharge fell rapidly in late February/early March 2016. Initially, TSP and TP concentrations returned to the 'lower flow' levels that had been recorded in July and August 2015, but they began to increase again from early May onwards. The large differences between TSP and TP over that period suggest problems with P loads associated with soil erosion and sediment transport.

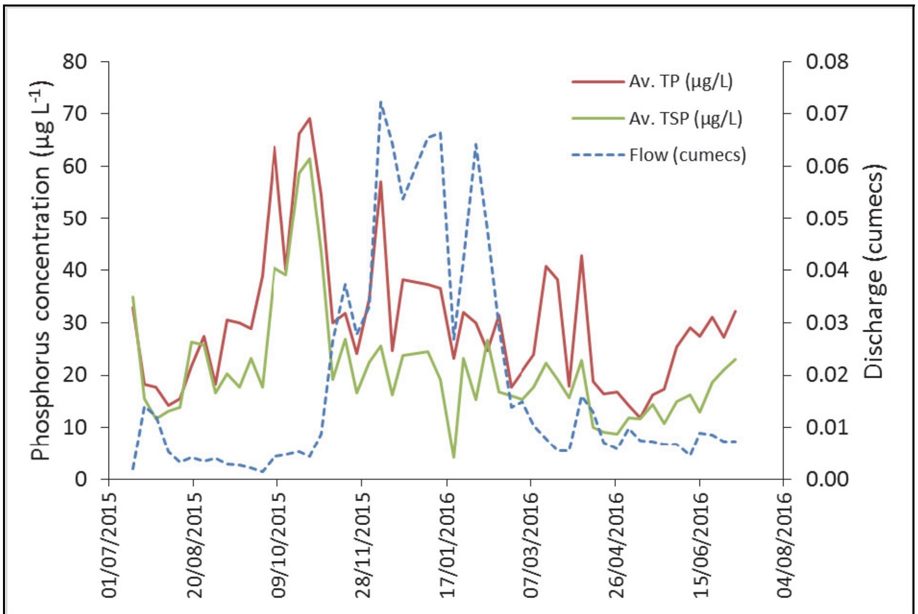

Figure 11. Instantaneous phosphorus concentrations and discharge at Site 1, on the Classlochie Burn; TSP = Total Soluble Phosphorus; TP = Total Phosphorus; NB PP = TP-TSP.

3.1.2.2 Nitrogen

Temporal variation in rates of discharge and TDN concentrations are shown in Figure 12. Under low flow conditions, TDN concentrations were always relatively low (~ 3mg N L^{-1}).

However, when rates of discharge started to increase in early November, there was a sudden and relatively short-lived increase in TDN concentration that reached almost 14mg N L^{-1} before declining to about 3mg N L^{-1} over the following 2 months. TDN concentrations fell further to less than 2.0mg N L^{-1} in May and June, 2016, when stream discharge was low.

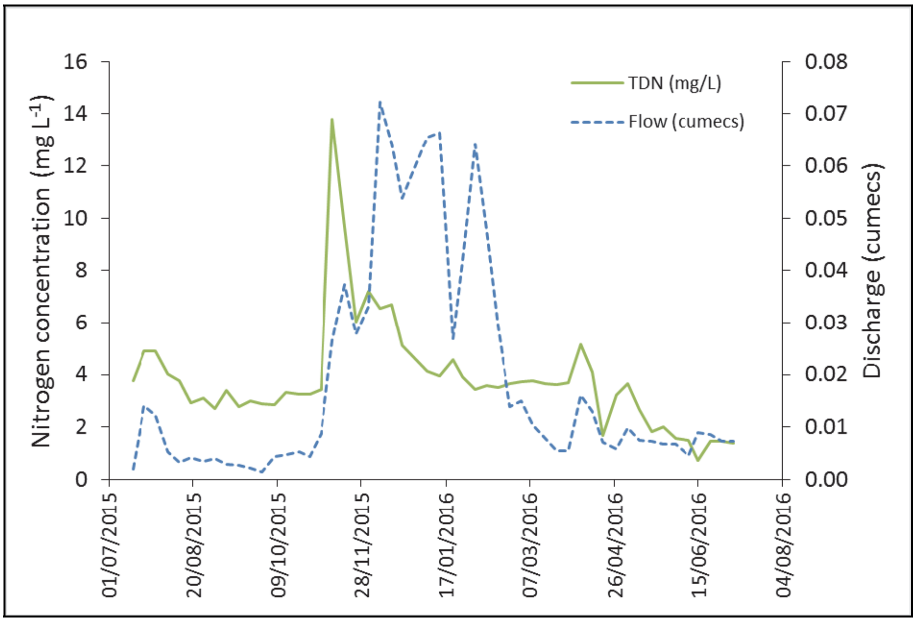

Figure 12. Instantaneous nitrogen concentrations and discharge at Site 1, on the Classlochie Burn; TDN = Total Dissolved Nitrogen.

3.1.3 Nutrient loads

3.1.3.1 Phosphorus

The TP load delivered to the loch by the Classlochie Burn over the study period was estimated to be 17.9kg P y^{-1}. In terms of source apportionment, the 'Bowes' method suggested that 6.1% of this was coming from point sources and 93.9% from diffuse sources.

3.1.3.2 Nitrogen

The Classlochie Burn was estimated to be delivering about 2706kg N y^{-1} of TDN to Loch Leven over the study period. The source apportionment modelling suggested that only 1.4% of this came from point sources, while the remaining 98.6% appeared to be coming from diffuse sources within this catchment.

3.2 Site 2 – Gairney Water

The catchment of Gairney Water drains an area of 34.3km^2. This is mostly improved grassland (45%) and arable land (27%), with small areas of coniferous woodland (9%), rough grassland (6%), acid grassland (5%), heather grassland (5%), broadleaved woodland (3%), and bog (1%). There are no obvious large point sources of nutrients within the catchment, but there are 263 unsewered properties and some farm buildings scattered across the area.

3.2.1 Discharge

The level of discharge within the Gairney Water at Site 2 ranged from 0.2 to 1.6 cumecs (Figure 13), averaging 0.49 cumecs over the study period. Relatively low flows (<0.6

cumecs) were recorded from July to early November 2015 and from March to August 2016. Higher flows were recorded during the winter months, late November 2015 to February 2016.

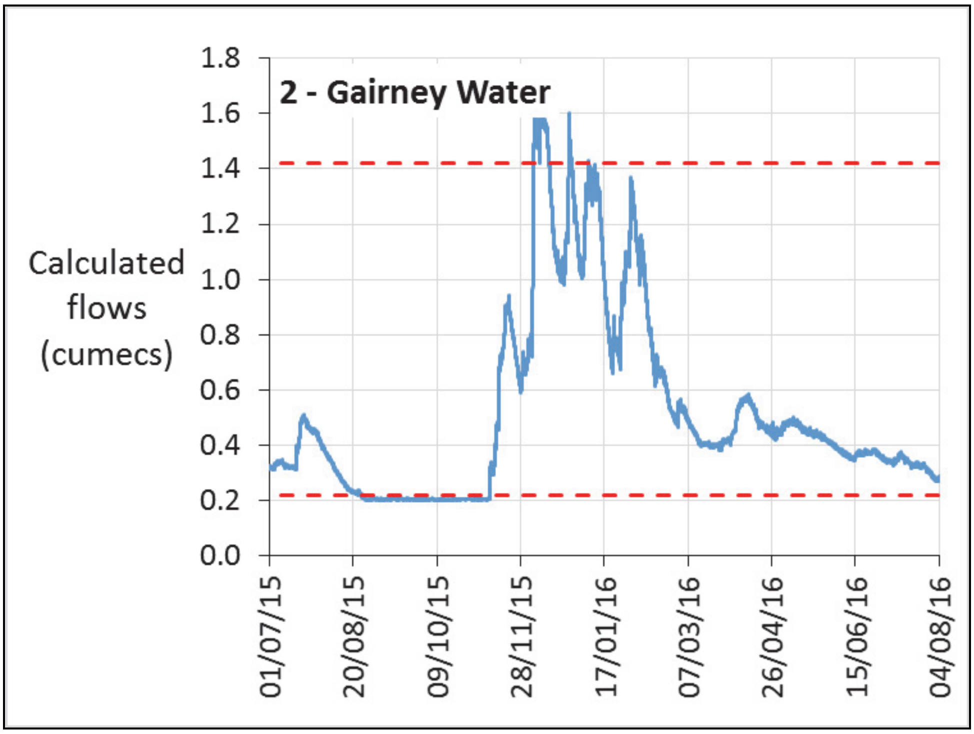

Figure 13. Discharge at Site 2, on the Gairney Water, showing upper and lower limits of calibration data (red dashed lines)

3.2.2 Nutrient concentrations

The minimum, mean and maximum values for TSP, TP and TDN are shown in Table 9. Mean concentrations of 21 and 42µg P L^{-1} were recorded for TSP and TP, respectively, and of 2.7mg N L^{-1} for TDN. Although the mean TP concentration at Site 2 was higher than at Site 1, the mean values recorded for TSP and TDN concentrations were very similar.

Table 9. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 2, Gairney Water.

Site 2	TSP (µg P L^{-1})	TP (µg P L^{-1})	TDN (mg N L^{-1})
Min	1.08	18.93	1.66
Mean	21.20	42.31	2.69
Max	46.15	191.07	4.58

3.2.2.1 Phosphorus

Temporal variation in stream discharge, and in TSP and TP concentrations, over the study period are shown in Figure 14. Values remained relatively low (30-40µg P L^{-1}) when flows were between 0.2-0.6 cumecs. However, very high flows (1-2 cumecs) were recorded between December 2015 and January 2016, and during this period, TP concentrations increased to more than 150µg P L^{-1}. TSP concentrations remained at background levels, which suggest that PP concentrations had increased dramatically, probably as a result of soil erosion or the resuspension of in-stream P-laden sediments.

The pattern of change in TP concentrations with flow suggests that most of the P sources in this subcatchment are diffuse. However, there are 263 unsewered properties within this subcatchment that may provide an additional source of P to this inflow.

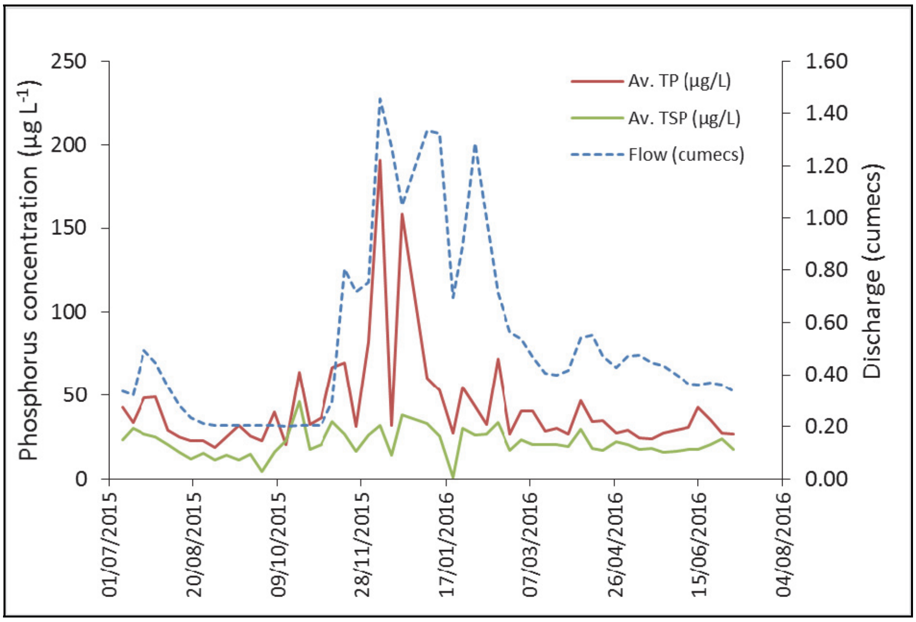

Figure 14. Instantaneous phosphorus concentrations and discharge at Site 2, on the Gairney Water; TSP = Total Soluble Phosphorus; TP = Total Phosphorus; NB PP = TP-TSP.

3.2.2.2 Nitrogen

Changes in river discharge and TDN concentration over the study period are shown in Figure 15. Although the flows varied from about 0.2 cumecs in autumn 2015 to about 1.4 cumecs in winter 2015/2016, TDN concentrations remained remarkably constant suggesting that any sources were diffuse. If the TDN had been emanating primarily from a point source, concentrations would have been noticeably diluted when levels of discharge were high. This is because nutrient discharges from point sources, such as WWTWs, tend to be relatively constant over time.

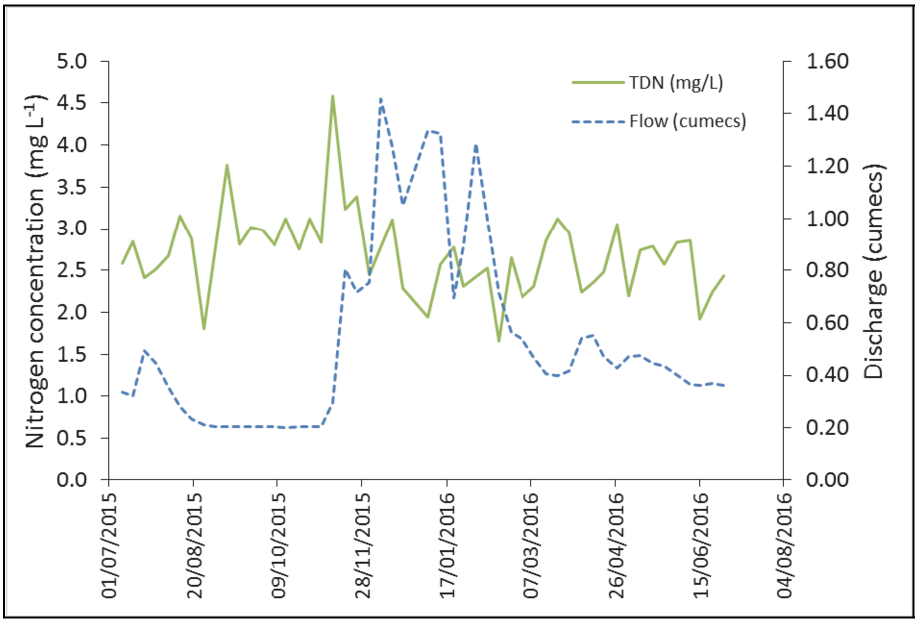

Figure 15. Instantaneous nitrogen concentrations and discharge at Site 2, on the Gairney Water; TDN = Total Dissolved Nitrogen.

3.2.3 Nutrient loads

3.2.3.1 Phosphorus

Over the course of the study 879kg P y^{-1} of TP was estimated to be delivered to Loch Leven by the Gairney Water. The modelling suggested that 16% of this came from point sources and 84% from diffuse sources, within this catchment.

3.2.3.2 Nitrogen

Gairney Water was found to be delivering about 43,024kg N y^{-1} of TDN to Loch Leven during the study period. Modelling suggested that 10.5% of this N load was coming from point sources within the catchment, whereas the remaining 89.5%, appeared to be coming from diffuse sources.

3.3 Site 3 – Loch outflow

The catchment of Site 3 comprises the entire loch and its catchment and covers an area of about 160km^2. Land cover for this area is summarised in Figure 16, with the dominant land cover types being improved grassland (35%) and arable land (27%). The catchment contains approximately 861 unsewered properties and two waste water treatment works.

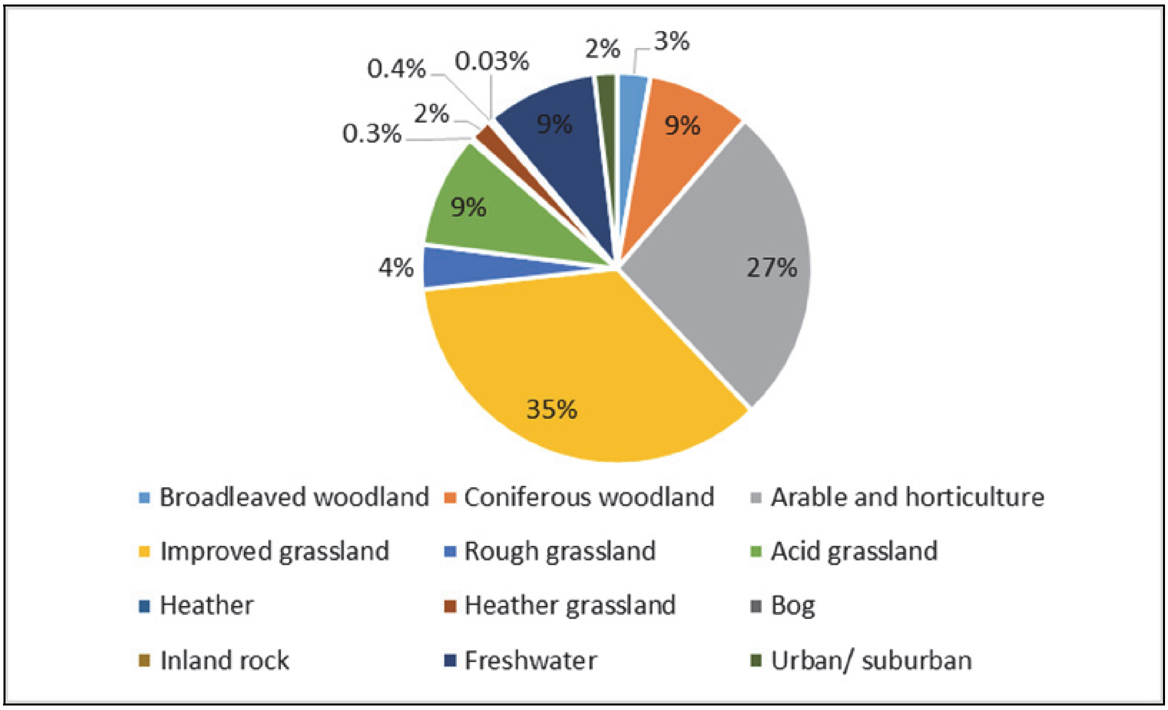

Figure 16 Summary of land cover across the catchment that drains to Site 3, the Loch Leven outflow.

3.3.1 Discharge

Temporal variation in discharge data from the Loch Leven outflow are shown in Figure 17. Discharges were generally low and fairly uniform (~2 cumecs) over the summer months when the outflow is regulated by the sluice gates to ensure an adequate supply of water to downstream industry. However, in winter, rates of discharge were much higher, ranging from 10-14 cumecs. There were two periods of missing data; 6/7/15 - 4/8/15 and 1/9/15-14/10/15. For Figure 18 and Figure 19, and the nutrient load calculations, these gaps were filled by linear interpolation.

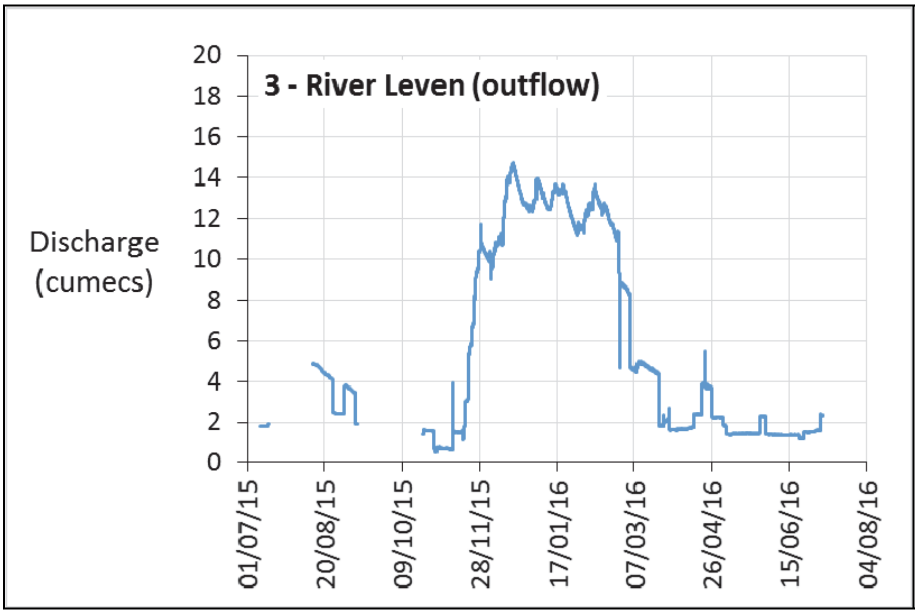

Figure 17. Discharge at Site 3, on the Loch Leven outflow; data supplied by SEPA; gaps show periods of missing data.

3.3.2 Nutrient concentrations

Nutrient concentrations in the outflow reflect those of the loch and the in-loch processing of nutrients. The minimum, mean and maximum concentrations of TSP, TP and TDN over the study period are shown in Table 10. The very high maximum TP concentration recorded reflects a single, very high, value recorded towards the end of October 2015. The relatively low TSP value recorded at that time (~ 10µg P L^{-1}) suggests a high level of PP (~280µg P L^{-1}) in the water sample from the outflow. The origin of this high PP value may have been P-laden sediment from the loch that had been disturbed by a strong wind event, an in-loch algal bloom or accidental disturbance of the river bed sediments whilst sampling.

Table 10. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 3, Loch Outflow.

Site 3	TSP (µg P L^{-1})	TP (µg P L^{-1})	TDN (mg N L^{-1})
Min	6.36	15.09	0.2
Mean	20.13	46.71	0.98
Max	63.20	289.39	1.76

3.3.2.1 Phosphorus

Temporal variation in TSP and TP concentrations in the loch outflow are shown in Figure 18. Values of TSP varied between about 10µg P L^{-1} and 40µg P L^{-1}, while those of TP were often much higher – especially during the summer months (July – September). The difference between TSP and TP in the loch outflow is very likely to be associated with PP in the form of algal cells. In general, while mean TSP values in the outflow were similar to those of many of the inflows, mean TP values were much higher and probably reflect biological processing and uptake within the loch.

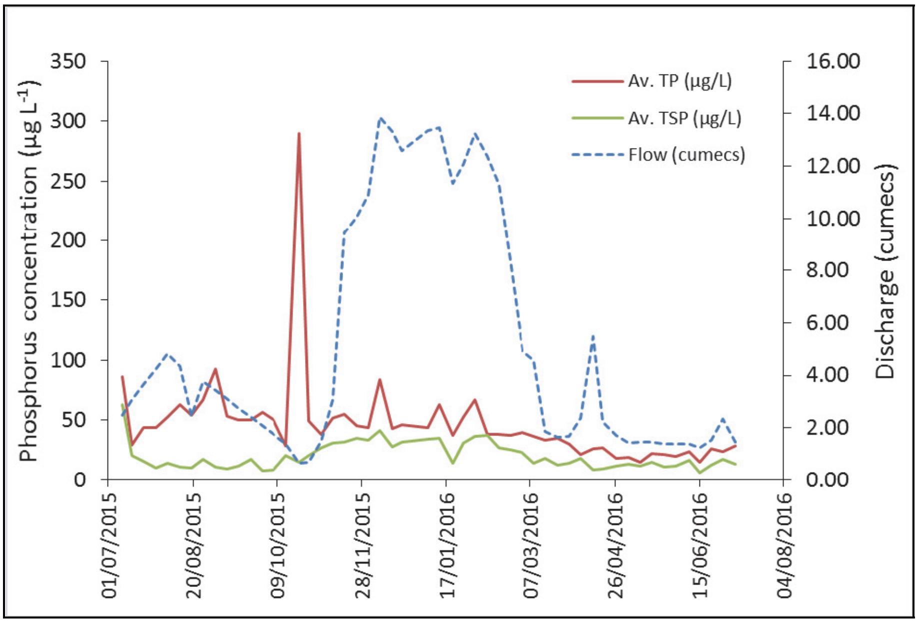

Figure 18. Instantaneous phosphorus concentrations and discharge at Site 3, on the Loch Leven outflow; TSP = Total Soluble Phosphorus; TP = Total Phosphorus; NB PP = TP-TSP.

3.3.2.2 Nitrogen

Temporal variation in TDN concentrations in the outflow are shown in Figure 19. The values recorded reflect biological processing and uptake of N within the loch. In general, TDN concentrations were mostly 0.2 – 0.6mg N L^{-1} during the summer months, suggesting that N limitation of algal growth might be occurring within the loch over this period. During the winter, in-loch TDN concentrations were higher, up to 1.8mg N L^{-1}.

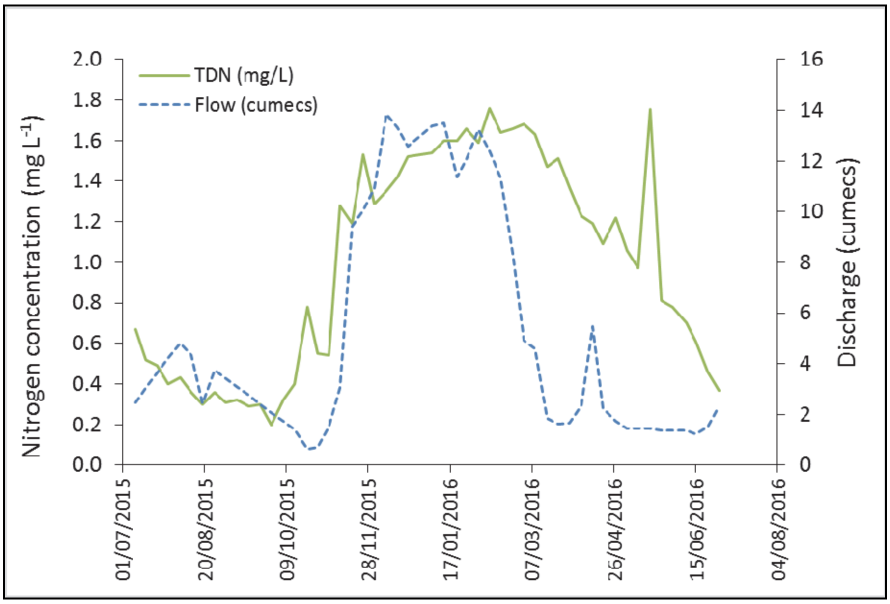

Figure 19. Instantaneous nitrogen concentrations and discharge at Site 3, on the Loch Leven outflow; TDN = Total Dissolved Nitrogen.

3.3.3 Nutrient loads

3.3.3.1 Phosphorus

Loch Leven was estimated to be delivering about 7,581kg P y^{-1} of TP to the River Leven (outflow) over the study period.

3.3.3.2 Nitrogen

Loch Leven was estimated to have delivered about 197,034kg N y^{-1} of TDN to the River Leven during the study period.

3.4 Site 4 – Kinnesswood Burn

It was not possible to estimate the exact area of the catchment draining to the Kinnesswood Burn because the area is very flat and drained by a number of ditches. The main land cover in the area is arable land and improved grassland.

Although the exact subcatchment drained by this stream was unclear, it was still possible to measure in-stream water levels and flows and develop a stage discharge curve so that the nutrient load from this stream could be calculated.

Following the study period, there was evidence of sediment removal from this drainage channel. This was in the form of mud and aquatic plant material deposited along the banks of the stream and a large mechanical digger nearby. As this activity would have changed the flow characteristics of this stream, it was not possible to collect meaningful data for the stage discharge calibration curve beyond the end of the water sampling period.

3.4.1 Discharge

Variations in the rate of discharge of the Kinnesswood Burn over the sampling period are shown in Figure 20. Levels of discharge varied between about 0.4 cumecs at low flow (mainly in the summer months) and 0.09 cumecs at high flow, during the winter.

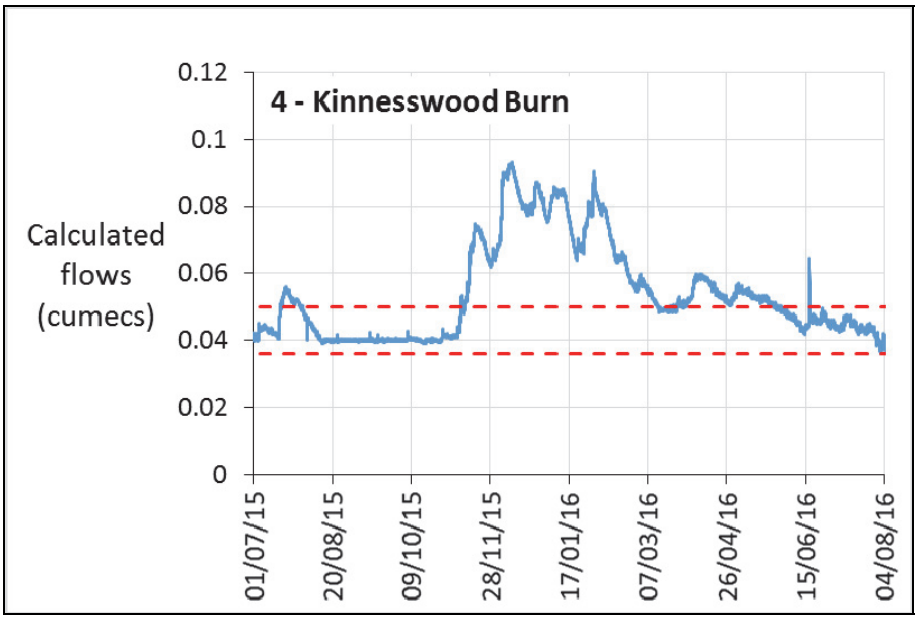

Figure 20. Discharge at Site 4, on the Kinnesswood Burn, showing upper and lower limits of calibration data (red dashed lines)

3.4.2 Nutrient concentrations

Minimum, mean and maximum TSP, TP and TDN concentrations recorded in the Kinnesswood Burn between July 2015 and July 2016 are shown in Table 11. Mean concentrations of TSP, TP and TDN were relatively high compared to those recorded at Sites 1 and 2, on the southern side of the loch. This probably reflects the more intensive agriculture that occurs in this area. The very high maximum value of TP in December 2015 was associated with a high flow event (Figure 20).

Table 11. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 4, Kinnesswood Burn.

Site 4	TSP (µg P L^{-1})	TP (µg P L^{-1})	TDN (mg N L^{-1})
Min	13.06	21.02	1.75
Mean	33.86	57.75	3.99
Max	95.08	253.50	7.94

3.4.2.1 Phosphorus

Temporal changes in TSP and TP concentrations in the Kinnesswood Burn at Site 4 are shown in Figure 21. In general, TSP values remained at about 25µg P L^{-1} during the summer months during low flows (~0.04-0.05 cumecs), rising to about 95µg P L^{-1} in winter months under higher flow conditions (~0.08 cumecs). In contrast, TP concentrations varied greatly. During the summer months they were very similar to the TSP concentrations recorded. But, in winter, TP concentrations reached values of up to 254µg P L^{-1}, with most of this increase comprising PP. The main sources of this PP are likely to have been soil erosion and/or disturbance of in-stream sediments during high flows. A second high TP event was recorded under low flow conditions in June 2016. This was also mainly due to an increase in PP concentrations and appeared to correspond to a relatively high but short lived increase in flow at this time (Figure 20).

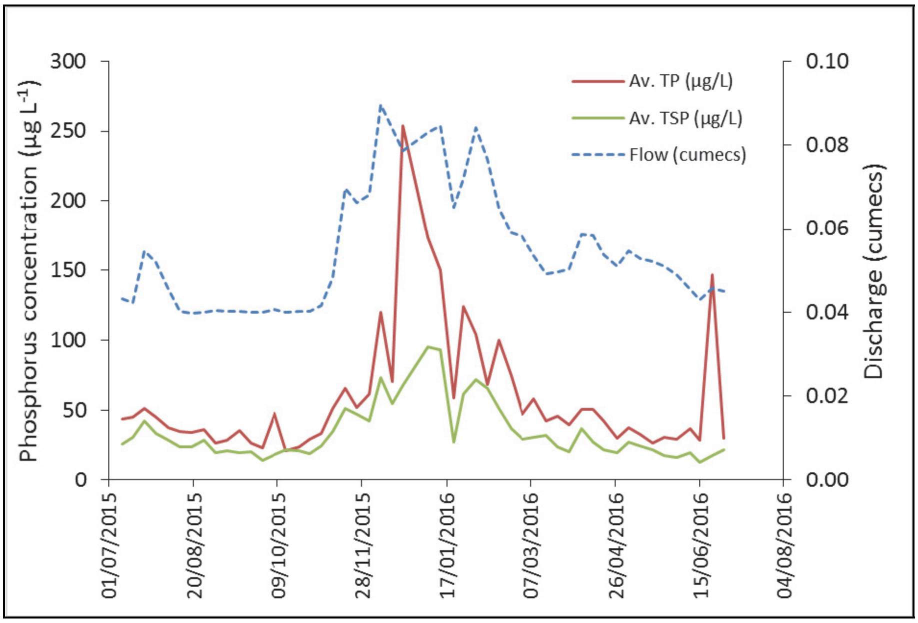

Figure 21. Instantaneous phosphorus concentrations and discharge at Site 4, on the Kinnesswood Burn; TSP = Total Soluble Phosphorus; TP = Total Phosphorus; NB PP = TP – TSP.

3.4.2.2 Nitrogen

The TDN concentration at Site 4 remained relatively constant, at between 3mg N L^{-1} and 4.5mg N L^{-1}, over most of the sampling period (Figure 22). However, relatively sudden increases in flows in late July 2015 and early November 2015 caused a corresponding, but short term, increase in TDN concentration.

Increases in TDN concentrations with flow suggest a diffuse rather than point source and, in this particular case, probably reflect the intensive agriculture that is widespread in this area. Although the inverse relationship between TDN concentration and flow during the high winter flows (November 2105 - February 2016) could be related to a point source of N-laden effluent in this area, this is unlikely because there are no obvious point sources of nutrients and few unsewered properties. It, therefore, seems likely that the store of N that was initially flushed out by the increasing water levels in early November 2015 became exhausted, and when flows remained high over the next few weeks TDN concentrations fell.

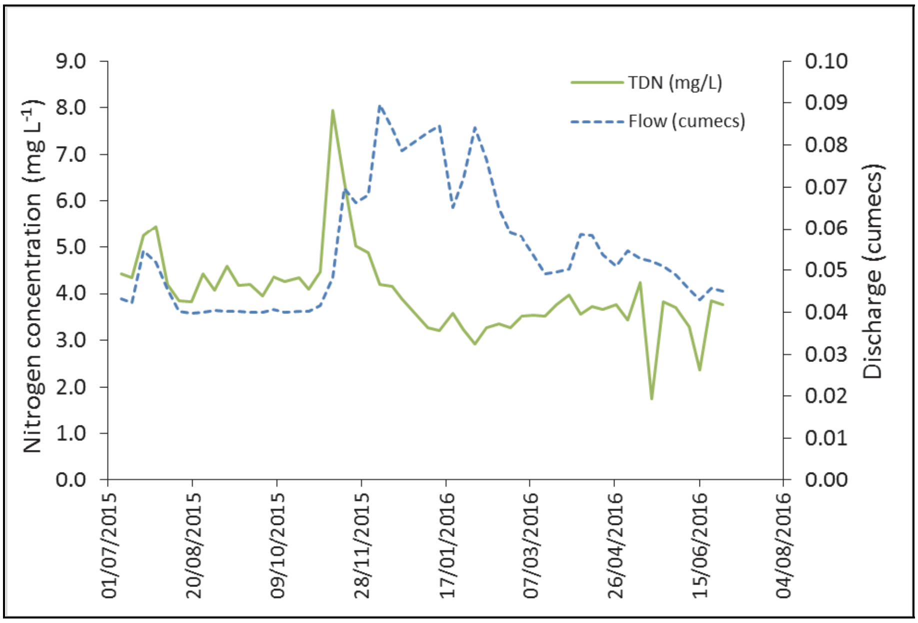

Figure 22. Instantaneous nitrogen concentrations and discharge at Site 4, on the Kinnesswood Burn; TDN = Total Dissolved Nitrogen.

3.4.3 Nutrient loads

3.4.3.1 Phosphorus

The Kinnesswood Burn was estimated to have delivered about 112kg P y^{-1} of TP to Loch Leven over the study period. Of this, only 1.1% came from point sources, while the remaining 98.9% appeared to be coming from diffuse sources.

3.4.3.2 Nitrogen

Kinnesswood Burn delivered about 6,780kg N y^{-1} of TDN to Loch Leven over the study period. With the source apportionment model suggesting that about 11.7% of this came from point sources, and the remaining 88.3%, from diffuse sources.

3.5 Site 5 – Pow Burn

The Pow Burn drains a subcatchment of 10.9km^2 that lies to the north of the loch and is predominantly used for arable farming (65%). Other types of land cover in this catchment include improved grassland (26%), acid grassland (5%), broadleaved woodland (1%), coniferous woodland (1%) and rough grassland (1%). There are no obvious large point sources of nutrients within the catchment, but the catchment does contain a number of farm building and 108 unsewered properties.

3.5.1 Discharge

Levels of discharge in the Pow Burn ranged from about 0.1 cumecs in the summer months to about 4.4 cumecs in the winter months (Figure 23). Flows were extremely variable over the winter, with a relatively high baseflow of 0.4-0.5 cumecs and short, but rapid, increases in flow due to rainfall events.

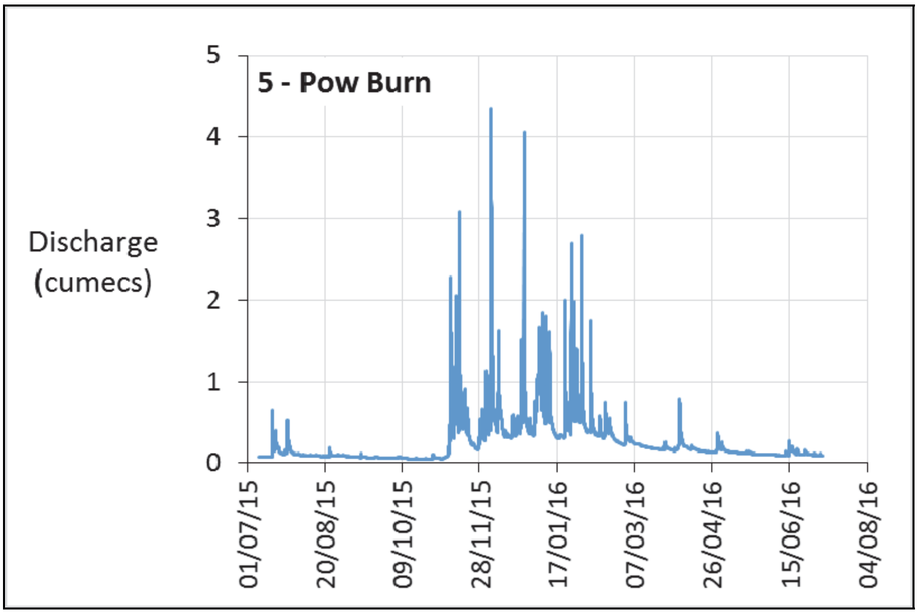

Figure 23. Discharge at Site 5, on the Pow Burn; data supplied by SEPA.

3.5.2 Nutrient concentrations

Minimum, mean and maximum concentrations of TSP, TP and TDN in the Pow Burn at Site 5 are shown in Table 12. Both P and N concentrations in the Pow Burn are very high compared to values recorded in other inflows – apart from those that receive WWTW effluent.

Table 12. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 5, Pow Burn.

Site 5	TSP (μg P L^{-1})	TP (μg P L^{-1})	TDN (mg N L^{-1})
Min	16.8	26.41	2.93
Mean	51.53	107.77	6.77
Max	483.47	1062.10	10.90

3.5.2.1 Phosphorus

Changes in TSP and TP concentrations in the Pow Burn over the period of sampling are shown in Figure 24. Summer TSP and TP concentrations were relatively low (50-60μg P L^{-1}), but, in winter, TP concentrations increased markedly reaching concentrations of up to 1062μg P L^{-1}. For the most part, winter TSP concentrations remained at similar levels to summer concentrations; the main increase was in PP. Increases in PP probably reflect elevated levels of soil erosion and sediment transport under high flow conditions.

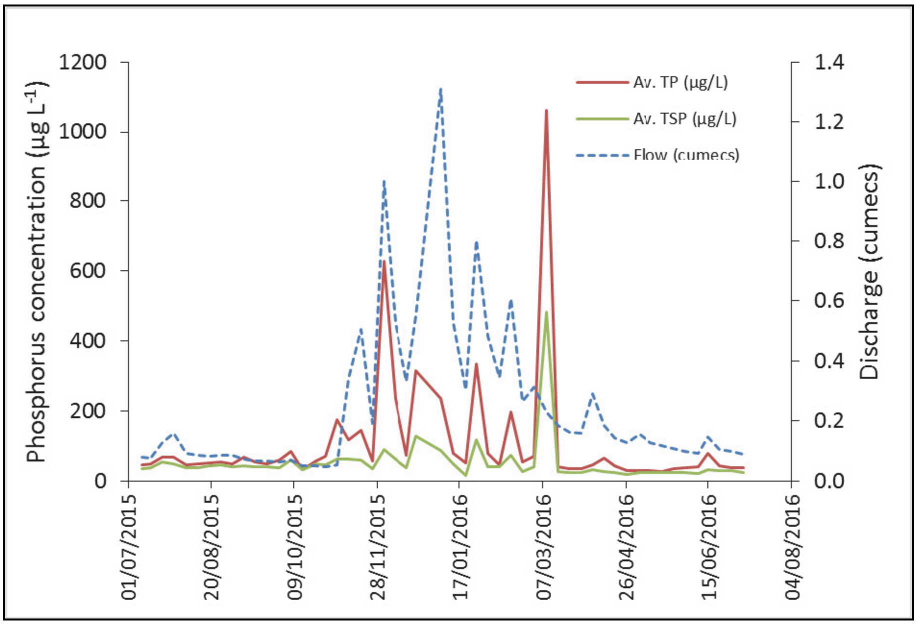

Figure 24. Instantaneous discharge and phosphorus concentrations at Site 5, on the Pow Burn; TSP = Total Soluble Phosphorus; TP = Total Phosphorus; NB PP = TP-TSP.

3.5.2.2 Nitrogen

Changes in TDN concentrations in the Pow Burn over the period of sampling are shown in Figure 25. There is a clear inverse relationship between TDN concentrations and flows, with TDN concentrations showing a strong dilution pattern under winter high flow conditions. TDN concentrations remained relatively high in summer – at about 7mg N L^{-1} – but fell to about 5mg N L^{-1} over the winter months.

3.5.3 Nutrient loads

3.5.3.1 Phosphorus

The Pow Burn was estimated to have delivered about 1424.3kg P y^{-1} of TP to Loch Leven over the study period. The source apportionment modelling suggested that only 2.6% was from point sources; the remaining 97.4% appeared to be coming from diffuse sources.

3.5.3.2 Nitrogen

About 42,722kg N y^{-1} of TDN was delivered by the Pow Burn to Loch Leven over the study period. With the source apportionment model indicating that about 10% of this N load was coming from point sources, and the remaining 90% was from diffuse sources within the catchment.

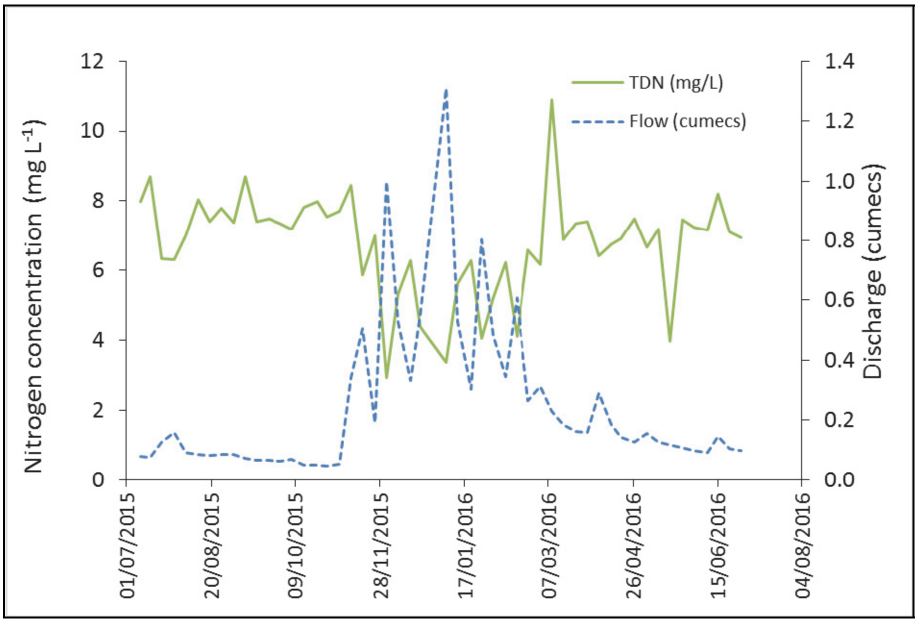

Figure 25. Nitrogen concentrations at Site 5, on the Pow Burn; TDN = Total Dissolved Nitrogen.

3.6 Site 6 – Camel Burn

The Camel Burn drains a subcatchment area of 1.9km^2, mainly comprising arable land (85%), but also with small areas of improved grassland (11%), rough grassland (2%) and broadleaved woodland (1%). There are no obvious point sources of nutrients within the catchment, but there are 20 unsewered properties.

3.6.1 Discharge

Changes in rates of discharge over the study period are shown in Figure 26. Flows were very low throughout most of the year, but high from November 2015 to February 2016. The highly variable flows recorded over time show that this stream responds rapidly to rainfall events and periods of drier weather.

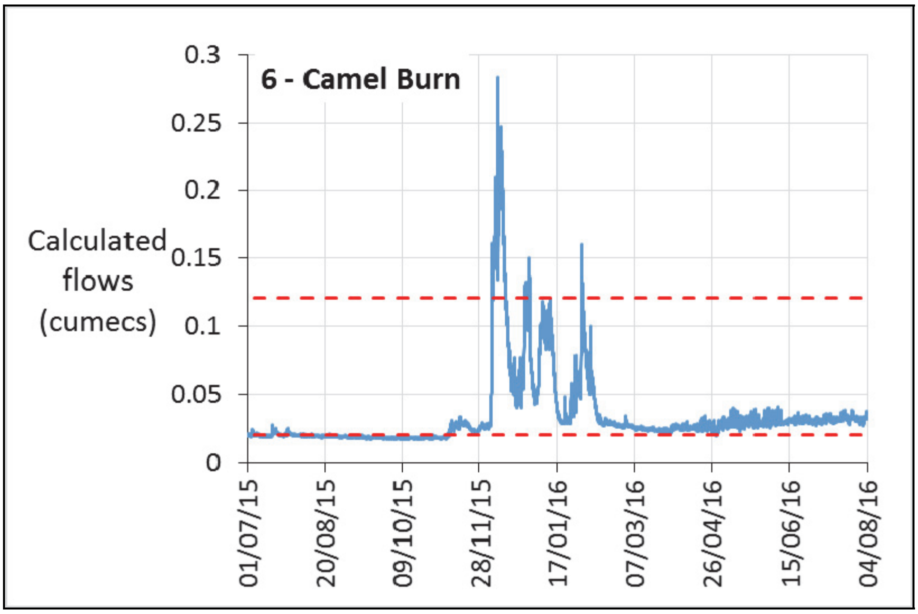

Figure 26. Discharge at Site 6, on the Camel Burn, showing upper and lower limits of calibration data (red dashed lines)

3.6.2 Nutrient concentrations

Minimum, mean and maximum concentrations of TSP, TP and TDN are shown in Table 13. Mean TP values are relatively high compared to other inflow streams in this catchment, and mean TDN concentrations were much higher than those recorded elsewhere.

Table 13. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 6, Camel Burn.

Site 6	TSP (µg P L^{-1})	TP (µg P L^{-1})	TDN (mg N L^{-1})
Min	4.32	15.84	3.20
Mean	27.96	55.74	7.02
Max	91.89	260.20	11.60

3.6.2.1 Phosphorus

Temporal variation in rates of discharge, and TSP and TP concentrations, are shown in Figure 27. TSP and TP concentrations were relatively low (20-40µg P L^{-1}) during periods of low flow but were much higher (up to 250µg P L^{-1}) during periods of high flow. Also, during periods of high flow, most of the additional P was in the form of PP, suggesting high levels of soil erosion and/or in-stream sediment resuspension when flows increased during the winter months.

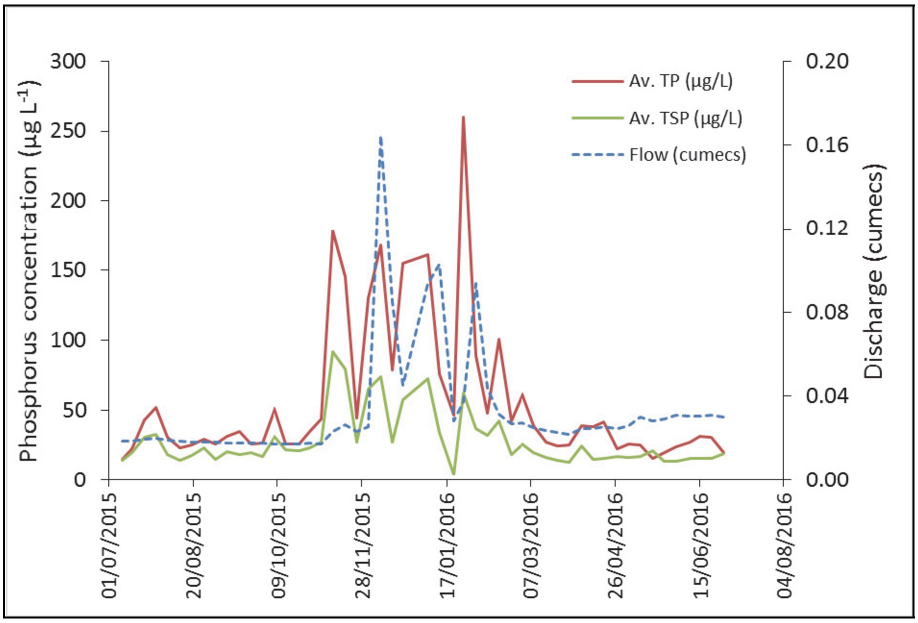

Figure 27. Instantaneous phosphorus concentrations and discharge at Site 6, on the Camel Burn; TSP = Total Soluble Phosphorus; TP = Total Phosphorus; NB PP = TP – TSP.

3.6.2.2 Nitrogen

Changes in TDN concentration over time are shown in Figure 28. TDN concentrations were higher than in most other inflows to the loch and varied little over time, mostly ranging between 5mg N L^{-1} and 9mg N L^{-1}. However, occasional relatively sudden increases in flow tended to generate a corresponding, if slightly delayed, peak in TDN concentration. This suggests that TDN is generated by diffuse sources within this subcatchment. There is no obvious explanation for the sudden decrease in TDN concentration in May 2016.

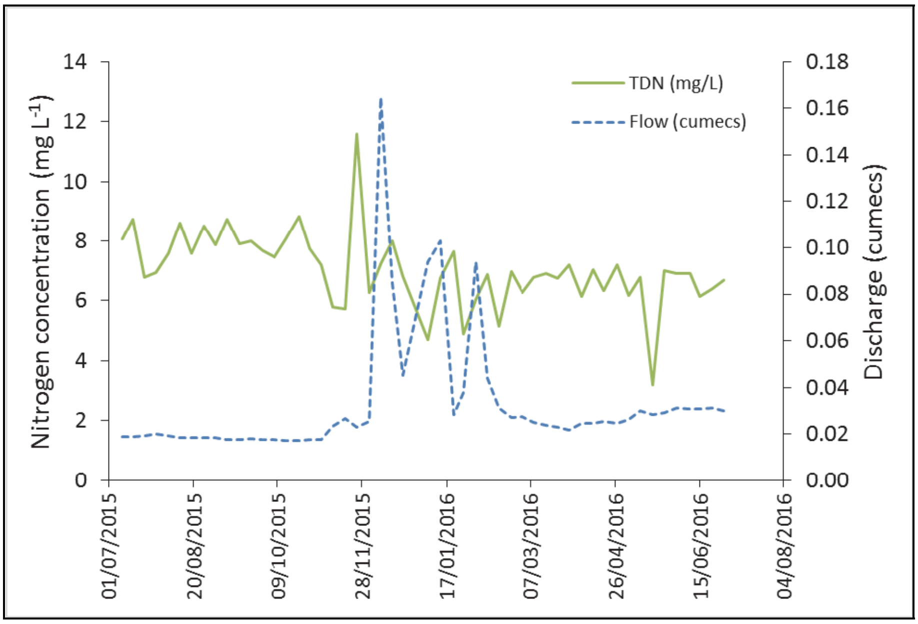

Figure 28. Instantaneous nitrogen concentrations and discharge at Site 6, on the Camel Burn; TDN = Total Dissolved Nitrogen.

3.6.3 *Nutrient loads*

3.6.3.1 Phosphorus

It was calculated that the Camel Burn delivered about 78kg P y^{-1} of TP to Loch Leven over the study period. The source apportionment model suggested that all of this came from diffuse sources.

3.6.3.2 Nitrogen

It was also estimated that the Camel Burn delivered about 7,032kg N y^{-1} in the form of TDN to Loch Leven during the 2015-2016 study. The source apportionment model suggested that 44.3% of this N load was attributable to point sources; the remaining 55.7% appeared to be coming from diffuse sources.

3.7 Site 7 – North Queich

The North Queich drains a catchment area of 42km². This mainly comprises improved grassland (43%) and arable land (23%). There are also some large areas of coniferous woodland (13%) and acid grassland (13%), and smaller areas of broadleaved woodland (2%), rough grassland (2%), urban and suburban areas (2%) and bog (1%). There is a large WWTW within the catchment at Milnathort, upstream of the sampling point. This discharges treated effluent into this river. There are also 177 unsewered properties in this catchment.

3.7.1 *Discharge*

Rates of discharge in the North Queich at Site 7 ranged from about 0.05 cumecs at low flows to about 2.3 cumecs at high flows (Figure 29). However, in this larger river, response to rainfall is clearly dampened in comparison to smaller rivers in the same area. For example, the period of low flows in summer 2015, which began before the beginning of July in the nearby but much smaller Camel Burn, did not begin until the end of August in the North Queich. In addition, the high winter flows subsided more slowly in early summer 2016. This reflects the greater water storage capacity of this larger catchment, which dampens the response to rainfall.

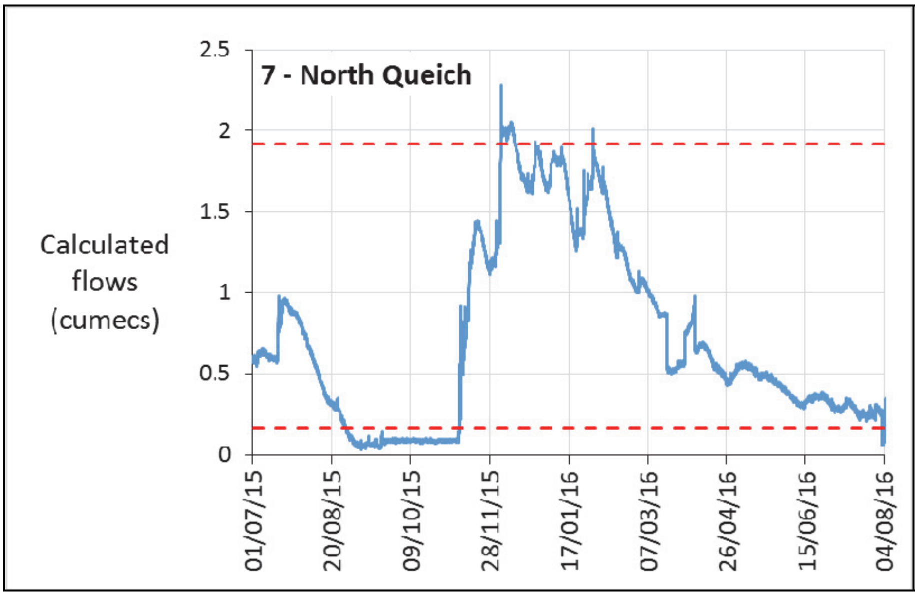

Figure 29. Discharge at Site 7, on the North Queich, showing upper and lower limits of calibration data (red dashed lines).

3.7.2 Nutrient concentrations

Minimum, mean and maximum values for TSP, TP and TDN concentrations at Site 7 in the North Queich are shown in Table 14. Mean TSP and TP concentrations were relatively high compared to other loch inflows, but mean TDN concentration was relatively low.

Table 14. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 7, North Queich.

Site 7	TSP (µg P L^{-1})	TP (µg P L^{-1})	TDN (mg N L^{-1})
Min	14.7	20.1	1.02
Mean	33.4	60.3	2.19
Max	118.5	377.0	3.64

A WWTW at Milnathort discharges effluent to the North Queich, upstream of Site 7. To estimate the nutrient output from this works, samples were collected up- and down-stream of the effluent discharge point and storm overflow, at Sites 14 and 15, respectively. The summary data in Table 15 and Table 16 indicate that mean in-stream TP concentrations upstream of the WWTW was about 24µg P L^{-1} while that below was about 32µg P L^{-1}. Both of these values are less than the mean TP concentration of 60µg P L^{-1} recorded downstream of these points at Site 7. However, it should be noted that the period of sampling at Sites 14 and 15 was only May to July 2016, i.e. during the summer low flow period.

Table 15. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 14, North Queich.

Site 14	TSP (µg P L^{-1})	TP (µg P L^{-1})	TDN (mg N L^{-1})
Min	12.9	17.9	0
Mean	15.6	23.8	2.24
Max	21.3	32.8	4.85

Table 16. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 15, North Queich.

Site 15	TSP (µg P L^{-1})	TP (µg P L^{-1})	TDN (mg N L^{-1})
Min	12.4	18.5	0
Mean	21.0	32.2	2.21
Max	33.7	44.5	5.17

3.7.2.1 Phosphorus

Temporal variation in levels of discharge and concentrations of TSP and TP for Site 7 on the North Queich are shown in Figure 30. Concentrations of TSP remained relatively low (mainly between 25µg P L^{-1} and 50µg P L^{-1}) throughout the sampling period. However, under increasing and high flow conditions, TP concentrations increased – mainly as a result of rapid increases in PP. This was the case in winter, particularly, suggesting high levels of soil erosion and sediment transport in the North Queich at this time of year. The sudden but short lived increase in TSP concentration in early November, when flows were low, suggests a point source discharge.

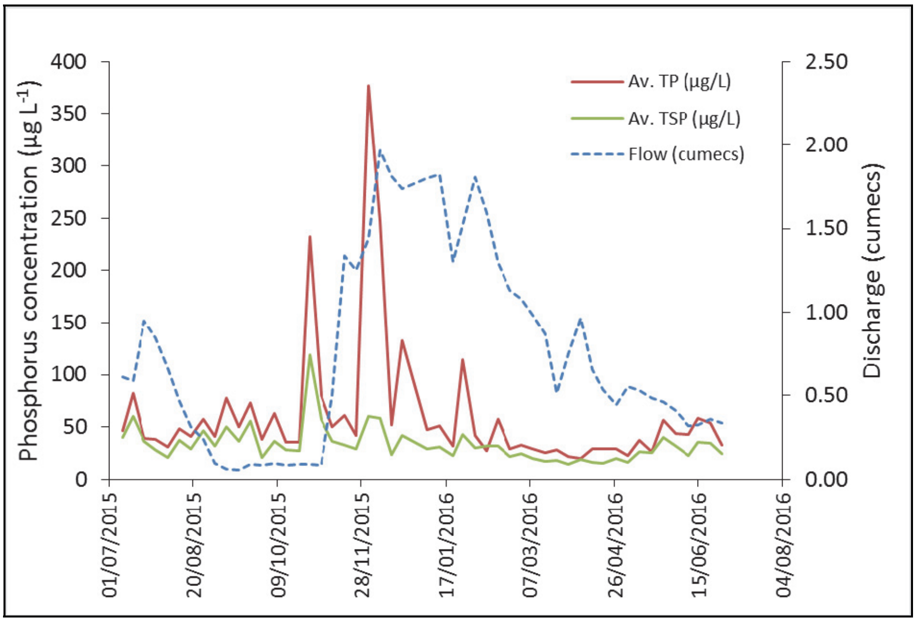

Figure 30. Instantaneous phosphorus concentrations and discharge at Site 7, on the North Queich; TSP = Total Soluble Phosphorus; TP = Total Phosphorus; NB PP = TP – TSP.

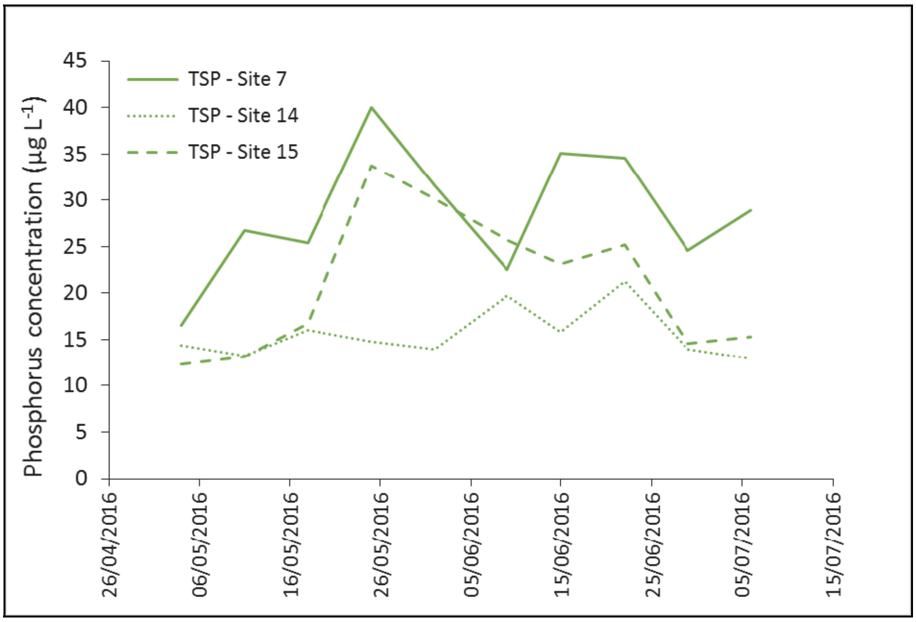

Figure 31. Total soluble phosphorus (TSP) concentrations upstream (Site 14) downstream (Site 15) of Milnathort WWTW, and at Site 7 (near the loch); data for sites 14 & 15 were collected only for May – July 2016.

Additional samples were collected at Sites 14 & 15 from May to July 2016 to quantify the P output from the Milnathort WWTW. As most of the P discharged from a WWTW is in the form of soluble P, TSP values at Sites 14 & 15 are compared to corresponding values at Site 7 in Figure 31. The data show that most of the increase in TSP within the river between Sites 14 and 7 occurred between Sites 14 and 15. The Milnathort WWTW effluent pipe discharges to this part of the river, apparently raising the average TSP concentration from 15.6µg P L^{-1} concentration to 21µg P L^{-1} under relatively low flow conditions of about 0.4-0.5 cumecs.

3.7.2.2 Nitrogen

Temporal changes in TDN concentrations in the North Queich at Site 7 are shown in Figure 32. Concentrations in this inflow were about 2mg N L^{-1} throughout the study, with concentrations being higher under low flow conditions than under high flow conditions.

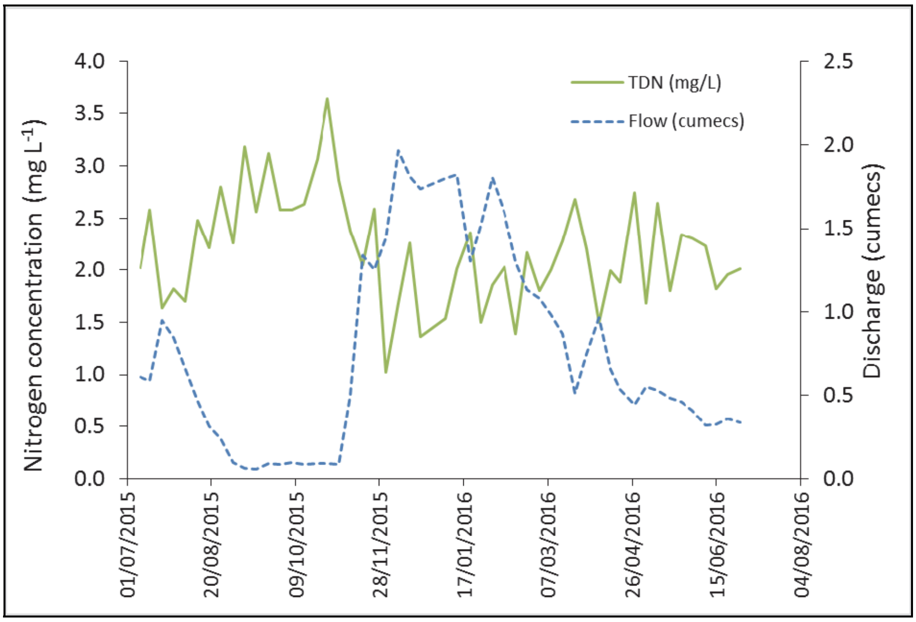

Figure 32. Instantaneous nitrogen concentrations and discharge at Site 7, on the North Queich; TDN = Total Dissolved Nitrogen.

When TDN concentrations were compared upstream (Site 14) and downstream (Site 15) of the Milnathort WWTW effluent pipe (Figure 33), the data suggested that in-stream TDN concentrations were being increased by about 0.5mg N L^{-1} by these WWTW discharges under low flow conditions.

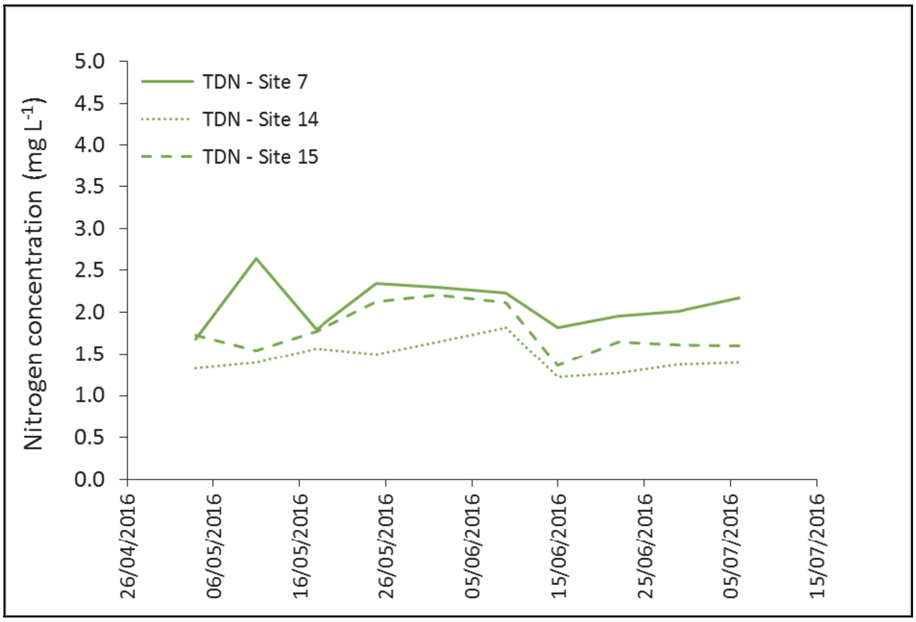

Figure 33. Total dissolved nitrogen (TDN) concentrations upstream (Site 14) downstream (Site 15) of Milnathort WWTW, and at Site 7 (near the loch); data for sites 14 & 15 were collected only for May – July 2016.

3.7.3 Nutrient loads

3.7.3.1 Phosphorus

The North Queich was estimated to have delivered about 1673kg P y^{-1} of TP to the loch over the study period. The source apportionment modelling suggested that about 10.5% (175kg P y^{-1}) of this came from point sources, while 89.5% appeared to be coming from diffuse sources within this catchment.

The monitoring undertaken up- and down-stream of the Milnathort WWTWs suggested that the TP load from this source was about 125kg P y^{-1}. When compared with the above, this suggests that about 50kg P y^{-1} may be coming from other upstream point sources such as unsewered properties.

3.7.3.2 Nitrogen

About 2373kg N y^{-1} of TDN was delivered from the North Queich to the loch between July 2015 and July 2016. Around 5% of this N load was from point sources and 95% was from diffuse sources.

3.8 Site 8 – Ury Burn

The Ury Burn drains a catchment area of 1.5 km^2. The main land cover types in this catchment are improved grassland (53%), urban/suburban areas (22%), arable land (12%), rough grassland (8%), broadleaved woodland (3%) and heather grassland (2%). In addition to the WWTW, there are eight unsewered properties in this catchment.

3.8.1 Discharge

Temporal variation in rates of discharge in the Ury Burn are shown in Figure 34. Discharge was relatively low (below 0.005 cumecs) between July and November 2015, then increased dramatically to about 0.046 cumecs. The average rate of discharge over the study period was 0.01 cumecs.

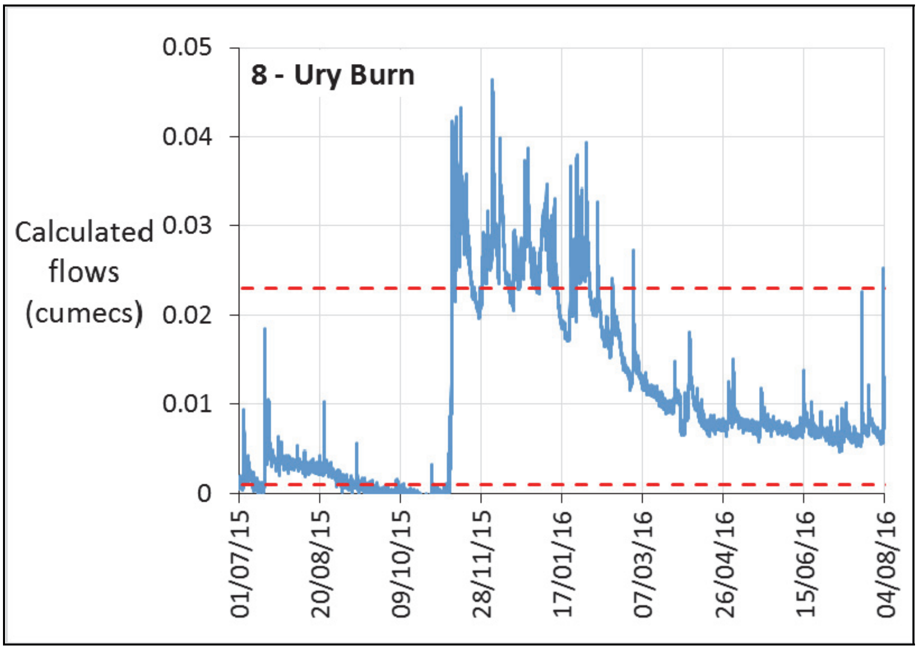

Figure 34. Discharge at Site 8, on the Ury Burn, showing upper and lower limits of calibration data (red dashed lines)

3.8.2 Nutrient concentrations

Minimum, mean and maximum values for TSP, TP and TDN concentrations at Site 8 on the Ury Burn are shown in Table 17.

Table 17. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 8, Ury Burn.

Site 8	TSP (µg P L^{-1})	TP (µg P L^{-1})	TDN (mg N L^{-1})
Min	7.13	16.75	1.12
Mean	31.15	49.38	2.03
Max	126.58	190.81	3.18

3.8.2.1 Phosphorus

Temporal variation in rates of discharge, and TSP and TP concentrations, are shown in Figure 35. TSP and TP concentrations were relatively low (10-50µg P L^{-1}) during periods of low flow but were much higher (up to 180µg P L^{-1}) during periods of high flow. Also, during periods of high flow, much of the additional P was in the form of PP, suggesting high levels of soil erosion and/or in-stream sediment resuspension when flows increased during the winter months. The relatively large increase in in-stream TSP concentrations at this site under high flow conditions during the winter months is unusual in comparison to other inflows to Loch Leven. The reason for this anomaly is unclear.

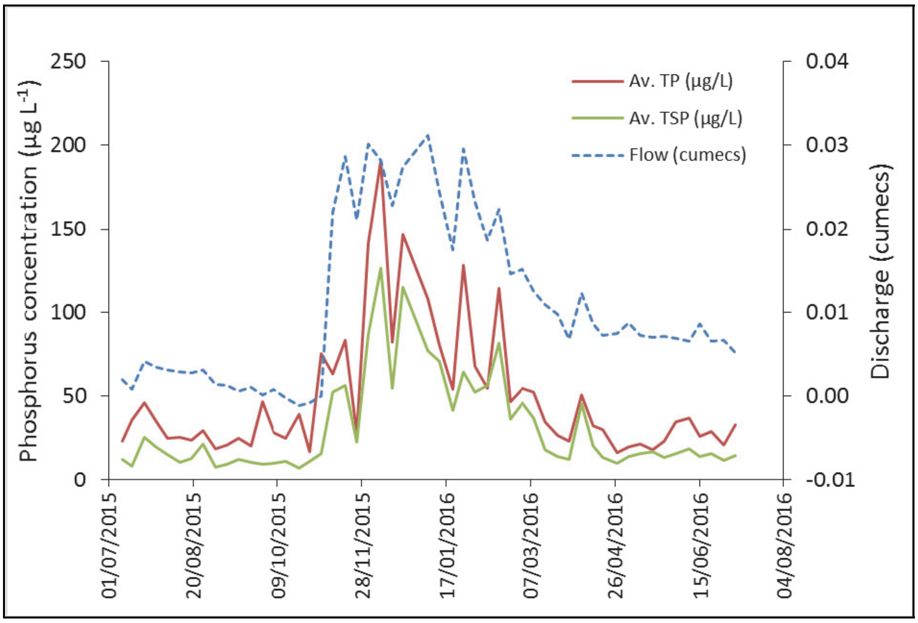

Figure 35. Instantaneous phosphorus concentrations and discharge at Site 8, on the Ury Burn; TSP = Total Soluble Phosphorus; TP = Total Phosphorus; NB PP = TP – TSP.

3.8.2.2 Nitrogen

Temporal changes in TDN concentrations in the North Queich at Site 8 are shown in Figure 36. Concentrations in this inflow ranged from about 4mg N L^{-1} to about 18mg N L^{-1} over the study period, with concentrations being higher under low flow conditions (July to early November 2015 and March to July 2016) than under high flow conditions (late November 2015 to February 2016). This type of relationship between discharge and concentration tends to suggest a point source of TDN within this catchment; the location of this point source is unclear.

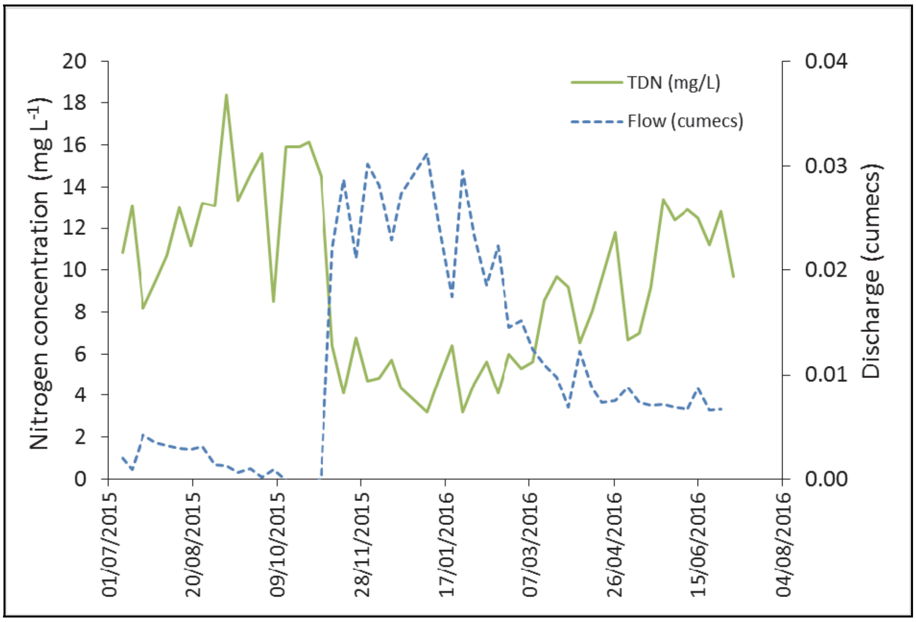

Figure 36. Instantaneous nitrogen concentrations and discharge at Site 8, on the Ury Burn; TDN = Total Dissolved Nitrogen.

3.8.3 Nutrient loads

3.8.3.1 Phosphorus

The Ury Burn was estimated to have delivered about 25.5kg P y^{-1} of TP to Loch Leven over the study period, with 100% of the TP load appeared to be coming from diffuse sources.

3.8.3.2 Nitrogen

The Ury Burn was also found to deliver about 824kg N y^{-1} of TDN to Loch Leven during the study period. Application of the source apportionment model developed suggests that only 0.3% of this N load comes from point sources; the rest (99.7%) appeared to be coming from diffuse sources.

3.9 Site 9 – Drain 1

Drain 1 drains a relatively small, flat area mainly comprised of grassland that is used as a golf course. Due to the flatness of the terrain and the artificial drainage in this area, it is not possible to define the exact catchment that drains to Site 9. However, there is a large WWTW (Kinross) upstream of the sampling point, that discharges treated effluent into the drain.

3.9.1 Discharge

Discharge at Site 9 was calculated from the continuous monitoring data collected on the Ury Burn, which was close by. Flows were generally low (<0.04 cumecs) from July until early November 2015. Then, flows increased rapidly, and much higher flows of around 0.2-0.25 cumecs were sustained over the winter period. Flows began to drop again in February 2016, reaching a relatively stable level of about 0.05 cumecs for the remainder of the sampling period.

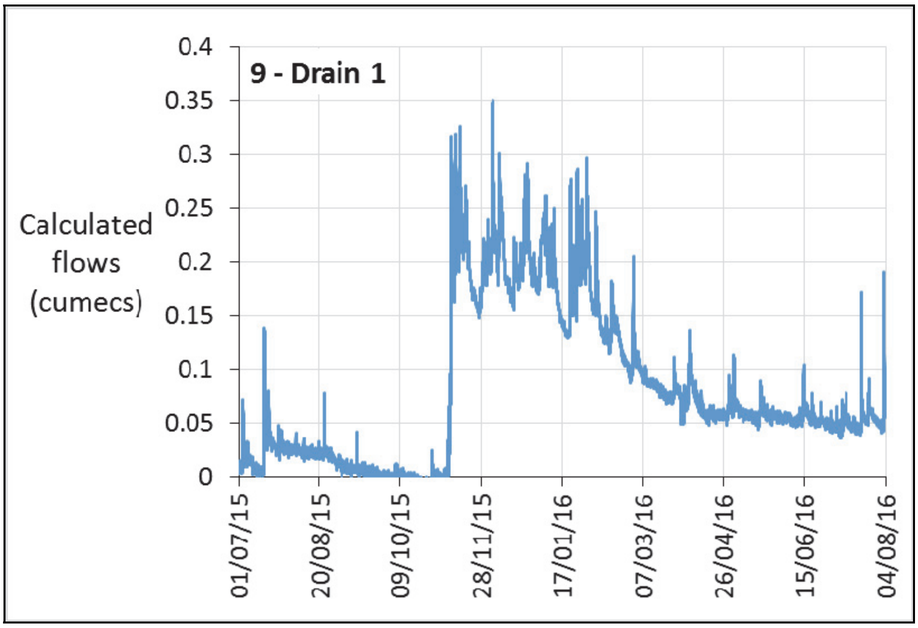

Figure 37. Discharge at Site 9, in Drain 1; data derived from continuous monitoring data collected at Site 8, Ury Burn.

3.9.2 Nutrient concentrations

Minimum, mean and maximum concentrations of TSP, TP and TDN above and below the WWTW discharge pipe that discharges into Drain 1 are shown in Table 18 and Table 19. Values were much higher at the downstream site for TSP, TP and TDN, suggesting that this discharge has a very large impact of on water quality in this waterbody. For example, mean TP concentrations increased by a factor of 25 between the up- and down-stream sampling sites, and TSP concentrations by a factor of 27.

Table 18. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 9, Drain 1, downstream of the effluent pipe from Kinros WWTW.

Site 9	TSP (μg P L^{-1})	TP (μg P L^{-1})	TDN (mg N L^{-1})
Min	99.6	165.2	3.18
Mean	480.3	605.6	9.44
Max	1344.6	1614.4	18.40

Table 19. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 16, upstream of Kinross WWTW, Drain 1.

Site 16	TSP (μg P L^{-1})	TP (μg P L^{-1})	TDN (mg N L^{-1})
Min	10.7	18.4	1.88
Mean	17.4	24.1	4.06
Max	25.3	34.9	9.62

3.9.2.1 Phosphorus

Temporal variation in rates of discharge, and TSP and TP concentrations, are shown in Figure 38. TSP and TP concentrations were very high (150-1600μg P L^{-1}) throughout the year, especially under low flow conditions. There was little evidence of increases in P in the form of PP under high flow conditions. This and the inverse relationship between flows and concentrations in this stream is typical of nutrient concentrations that are dominated by point. sources. In this case, that point source is the effluent pipe from Kinross WWTW.

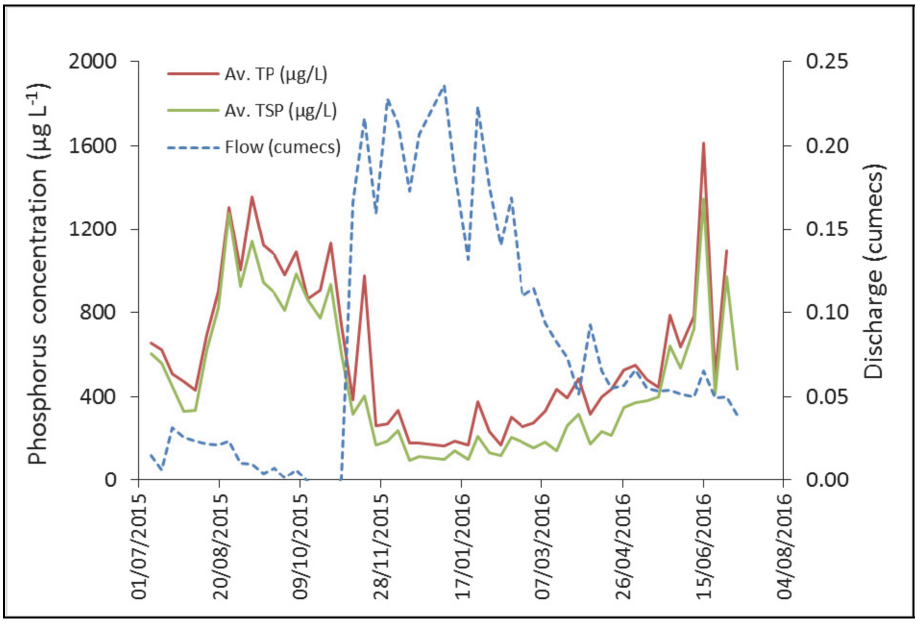

Figure 38. Instantaneous phosphorus concentrations and discharge at Site 9, in Drain 1; TSP = Total Soluble Phosphorus; TP = Total Phosphorus; NB PP = TP – TSP.

3.9.2.2 Nitrogen

Temporal variation in rates of discharge and TDN concentrations are shown in Figure 39. TDN concentrations were very high (4-18mg N L^{-1}) throughout the year with the highest levels being recorded under low flow conditions. The inverse relationship between flows and concentrations in this stream is typical of a stream where nutrient concentrations are dominated by point sources. In this case, that point source is the effluent pipe from Kinross WWTW.

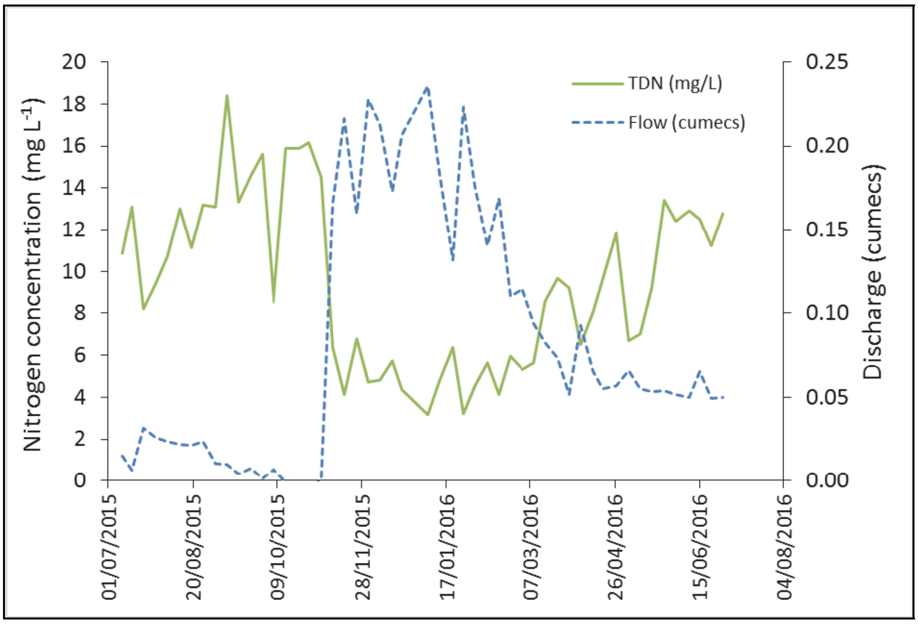

Figure 39. Instantaneous nitrogen concentrations and discharge at Site 9, in Drain 1; TDN = Total Dissolved Nitrogen.

3.9.3 Nutrient loads

3.9.3.1 Phosphorus

Drain 1 delivered an estimated 1,349kg P y^{-1} of TP to Loch Leven over the study period. Output from the source apportionment model suggested that about 20% (273kg P y^{-1}) of this came from point sources, while about 80% appeared to have come from diffuse sources, on the basis of the relationship between flows and concentrations.

However, assumed no change in flow or background P concentration had occurred between the sampling sites upstream and downstream of the Kinross WWTW effluent pipe, comparison of the data collected up and down-stream of the effluent pipe suggested that the actual P load to the lake from this works could be much higher i.e. about 1,257kg P y^{-1}. This may be because the source apportionment model was run on a relatively short set of summer data, only, which may have caused it to underestimate this value.

3.9.3.2 Nitrogen

It was estimated that Drain 1 delivered about 16,018kg N y^{-1} of TDN to Loch Leven over the study period. The source apportionment modelling suggested that only 0.9% of this N load came from point sources. The remainder, 99.1%, appeared to be from diffuse sources within this catchment. In contrast, comparing upstream and downstream flows and concentrations, as above, the estimated TDN load to this drain from the Kinross WWTWs was 11,290kg N y^{-1}. Again, this discrepancy may be due to insufficient monitoring data being available for the source apportionment model to work properly.

3.10 Site 10 – Drain 2

Drain 2 is an artificial drainage channel, with an unknown exact catchment size. The surrounding land is mostly relatively flat grassland, used, primarily, as a golf course. There are no obvious point sources of nutrients discharging into this drain.

3.10.1 Discharge

Rates of discharge from Drain 2 were not measured. So, no flow data were available for this Site.

3.10.2 Nutrient concentrations

Minimum, mean and maximum values for TSP, TP and TDN concentrations at Site 10, Drain 2 are shown in Table 20.

Table 20. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 10, Drain 2.

Site 10	TSP (µg P L^{-1})	TP (µg P L^{-1})	TDN (mg N L^{-1})
Min	15.06	20.42	0.70
Mean	24.04	34.43	1.56
Max	45.77	72.64	2.39

3.10.2.1 Phosphorus

Temporal variation in TSP and TP concentrations are shown in Figure 40. Over the study period, TSP concentrations ranged between 18µg P L^{-1} and 42µg P L^{-1}, and TP concentrations between 20µg P L^{-1} and 70µg P L^{-1}. In general, P concentrations remained relatively constant and failed to reflect the periods of high and low flows that were observed elsewhere across the catchment. However, no discharge data were collected for this stream.

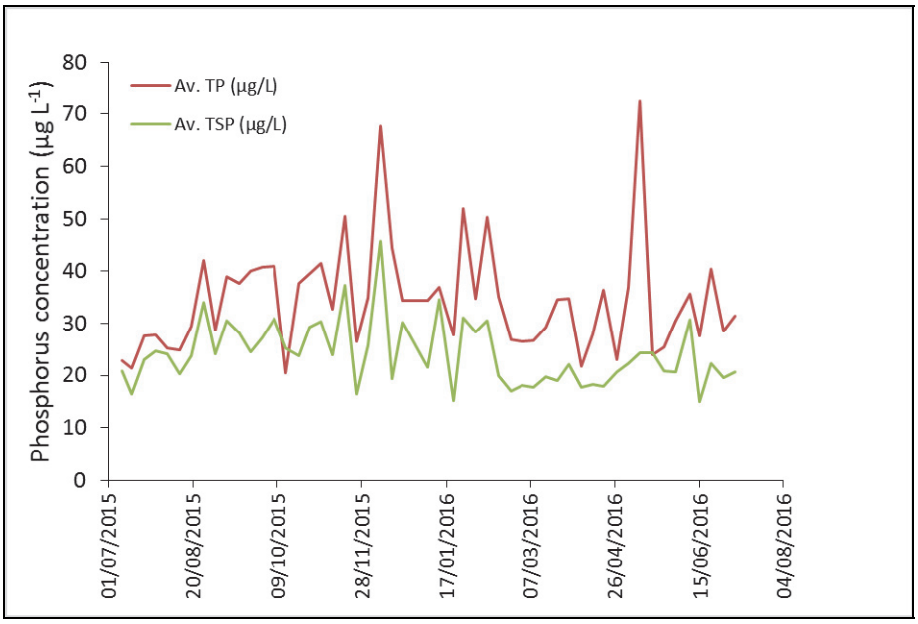

Figure 40. Phosphorus concentrations at Site 10, in Drain 2; TSP = Total Soluble Phosphorus; TP = Total Phosphorus; NB PP = TP – TSP. No flow data were available for Site 10.

3.10.2.2 Nitrogen

Temporal variation in TDN concentration is shown in Figure 41. Over the study period, concentrations ranged from 0.6mg N L^{-1} to 2.3mg N L^{-1}, with most of the concentrations recorded being between 1.5mg N L^{-1} to 2.0mg N L^{-1}. The reason for the sharp drop in concentration in September/October 2015 is unclear, because this seems to occur before the beginning of the period of high flows that was recorded at the other monitoring sites.

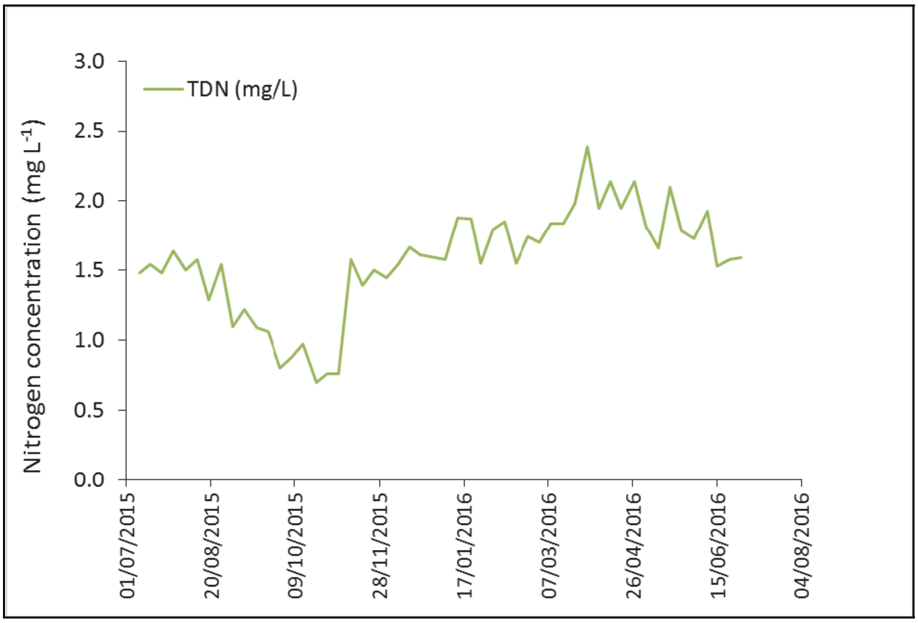

Figure 41. Nitrogen concentrations at Site 10, in Drain 2; TDN = Total Dissolved Nitrogen. No flow data were available for Site 10.

3.10.3 Nutrient loads

Nutrient loads delivered to the loch by this drain could not be calculated from the nutrient concentration data because rates of discharge were not measured. They were, therefore, estimated as part of the calculations relating to ungauged areas of the catchment (see Sections 2.5.4 and 4).

3.10.3.1 Phosphorus

See sections 2.5.4 and 4.

3.10.3.2 Nitrogen

See sections 2.5.4 and 4.

3.11 Site 11 – Clash Burn

The Clash Burn drains an area of about 0.2 km^2 that is mainly (82%) urban or suburban. In addition, 9% of the catchment is broadleaved woodland, 8% is improved grassland and small amount (1%) is arable land. All of the houses in this area are sewered.

3.11.1 Discharge

Temporal variation in rate of discharge was not recorded for this stream.

3.11.2 Nutrient concentrations

The minimum, mean and maximum concentrations of TSP, TP and TDN in the Clash Burn at Site 11 are shown in Table 21. Although TSP concentrations were relatively low (10-30µg P L^{-1}) and varied little throughout the year, TP concentrations were relatively low in the summer months (mostly 25-45µg P L^{-1}) and much higher (25-80µg P L^{-1}) and more variable in the wetter winter months.

Table 21. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 11, Clash Burn.

Site 11	TSP (µg P L^{-1})	TP (µg P L^{-1})	TDN (mg N L^{-1})
Min	9.75	17.46	1.30
Mean	17.84	40.59	2.51
Max	38.87	81.08	3.62

3.11.2.1 Phosphorus

Temporal variation in TSP and TP concentrations in the Clash Burn are shown in Figure 42. Most of the variation in P concentrations recorded in the Clash Burn was caused by changes in PP. This indicative of particles of soil being washed off this predominantly urban area during periods of heavy rainfall.

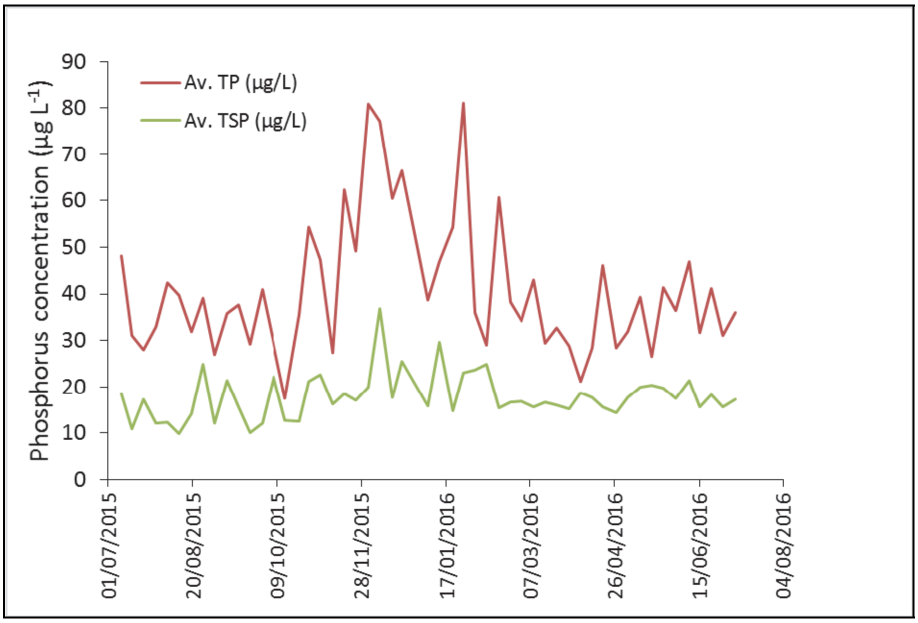

Figure 42. Phosphorus concentrations at Site 11, on the Clash Burn; TSP = Total Soluble Phosphorus; TP = Total Phosphorus; NB PP = TP – TSP.

3.11.2.2 Nitrogen

Temporal variation in TDN in the Clash Burn are shown in Figure 43. TDN concentrations were fairly stable at about 3mg N L^{-1} in the summer of 2015. They then became more variable during the winter of 2015/16, with average concentrations falling to about 2.3mg N L^{-1}. More stable N concentrations were re-established during the summer of 2016, but at a lower level (~2.3mg N L^{-1}) than those recorded over the previous summer. The reason for this is unclear.

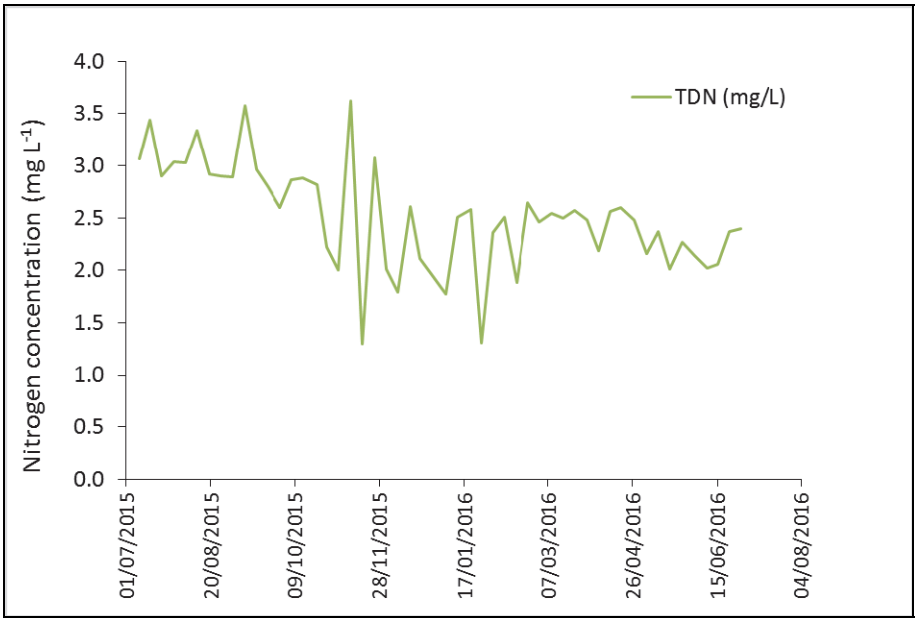

Figure 43. Nitrogen concentrations at Site 11, on the Clash Burn; TDN = Total Dissolved Nitrogen.

3.11.3 Nutrient loads

Nutrient loads delivered to the loch by this drain could not be calculated from the nutrient concentration data because rates of discharge were not measured. They were, therefore, estimated as part of the calculations relating to ungauged areas of the catchment (see Sections 2.5.4 and 4).

3.11.3.1 Phosphorus

See Sections 2.5.4 and 4

3.11.3.2 Nitrogen

See Sections 2.5.4 and 4.

3.12 Sites 12 & 13 – South Queich

The South Queich drains a catchment area of 35km^2. The dominant land use in this area is improved grassland (38%). Arable land accounts for a further 24% of the catchment, with other main land cover types being acid grassland (17%) and coniferous woodland (12%). In addition, 3% of the catchment is covered by rough grassland and the remaining 2% is suburban. There are 177 unsewered properties in this catchment and the Kinross storm overflow discharges into the river at a location between Sites 12 and 13.

3.12.1 Discharge

Temporal variation in discharge in the South Queich at a location slightly upstream of Site 12 is shown in Figure 44. Apart from a high value (~22 cumecs) recorded in mid July 2015, flows were generally very low (<3 cumecs) over the summer months. However, in winter, rates of discharge varied rapidly ranging from about 2 cumecs to about 36 cumecs.

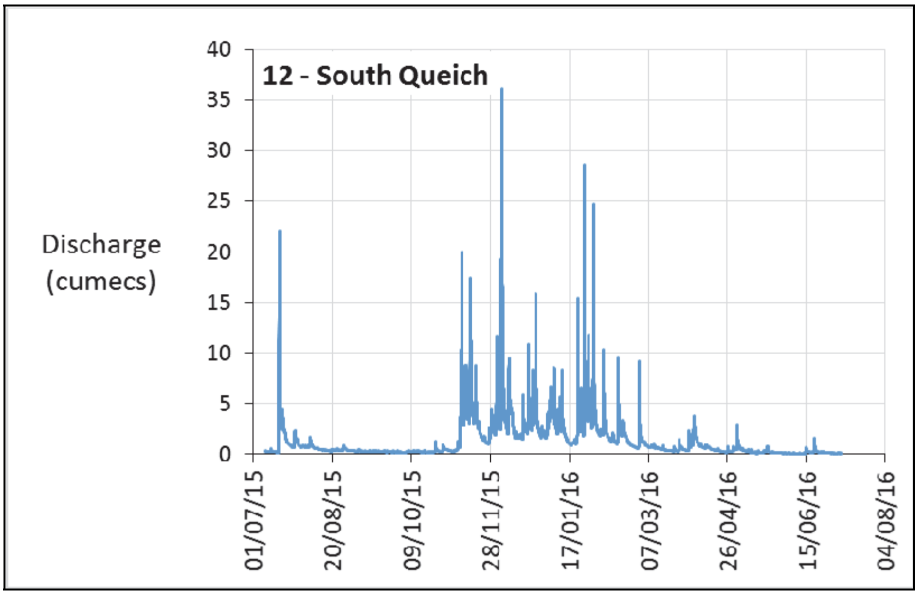

Figure 44. Discharge at Site 12, on the South Queich; data supplied by SEPA.

3.12.2 Nutrient concentrations

Minimum, mean and maximum concentrations of TSP, TP and TDN above and below the WWTW overflow discharge pipe are shown in Table 22 and Table 23. Values were similar at both sites suggesting a negligible input from this pipe to the South Queich over the year. Maximum concentrations of TSP and TP were high at both sites, but TDN concentrations were low in general compared to other inflows to the loch.

Table 22. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 12, upstream of WWTW overflow discharge point, South Queich.

Site 12	TSP (µg P L^{-1})	TP (µg P L^{-1})	TDN (mg N L^{-1})
Min	10.27	17.35	0.93
Mean	23.78	49.65	1.62
Max	62.09	266.82	2.72

Table 23. Minimum (Min), mean and maximum (Max) concentrations of Total Soluble Phosphorus (TSP), Total Phosphorus (TP) and Total Dissolved Nitrogen (TDN) measured at Site 13, downstream of WWTW overflow discharge point, South Queich.

Site 13	TSP (µg P L^{-1})	TP (µg P L^{-1})	TDN (mg N L^{-1})
Min	10.88	18.77	0.93
Mean	24.7	50.56	1.62
Max	67.9	277.04	2.74

3.12.2.1 Phosphorus

Temporal variation in TSP and TP concentrations in the South Queich are shown in Figure 45. The data show that, in general TSP concentrations remained relatively stable throughout the year rarely exceeding 50µg P L^{-1}. In contrast, TP concentrations varied widely, ranging from 30-40µg P L^{-1} during the summer months when flows were low (often < 1 cumec) but increased rapidly under high flow conditions in winter (December to January). The main increase was in PP, which suggest increased levels of soil erosion and sediment transport under high flow conditions.

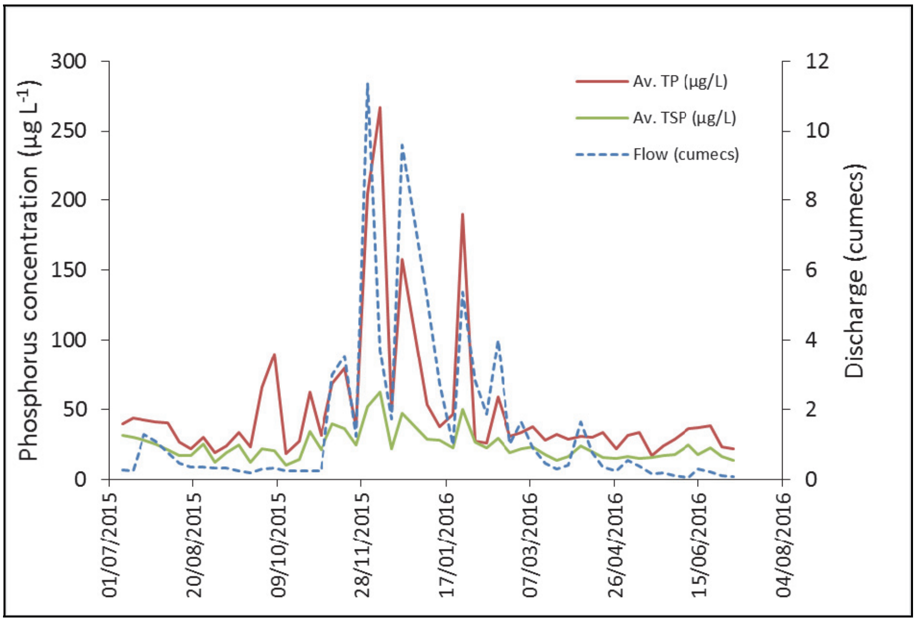

Figure 45. Instantaneous phosphorus concentrations and discharge at Site 12, on the South Queich; TSP = Total Soluble Phosphorus; TP = Total Phosphorus; NB PP = TP – TSP.

3.12.2.2 Nitrogen

Temporal variation in TDN concentrations at Site 12 on the South Queich are shown in Figure 46. Concentrations are relatively low (average 1.62mg N L^{-1}) compared to other inflows to Loch Leven, although they are slightly higher in summer under lower flow conditions than in winter under higher flow conditions. Periods of very high flows resulted in strong dilution effects characterised by an inverse relationship between flow and concentration.

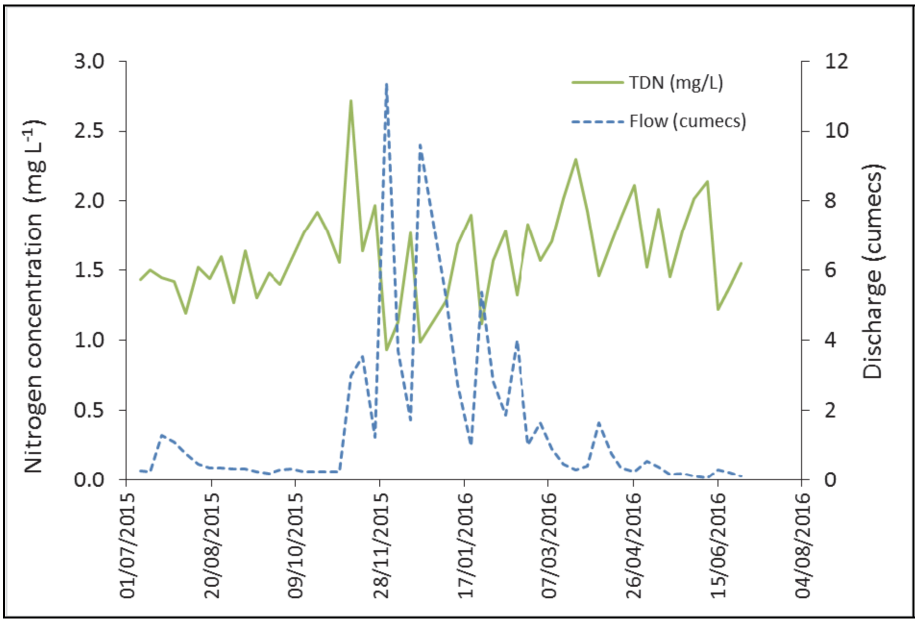

Figure 46. Instantaneous nitrogen concentrations and discharge at Site 12, on the South Queich; TDN = Total Dissolved Nitrogen.

3.12.3 Nutrient loads

3.12.3.1 Phosphorus

The South Queich was found to have delivered about 4,762kg P y^{-1} of TP to Loch Leven over the study period. The source apportionment modelling suggested that only 1.7% of this came from point sources, while the remaining 98.3% appeared to be coming from diffuse sources within this catchment.

3.12.3.2 Nitrogen

The South Queich also delivered about 62,706kg N y^{-1} of TDN to Loch Leven during the study period. The source apportionment model suggests that only 0.9% of this N load comes from point sources. The remainder, 99.1%, appears to be from diffuse sources within this catchment.

4. OVERVIEW OF PHOSPHORUS LOADS AND SOURCE APPORTIONMENT

4.1 Estimated phosphorus inputs from inflows, direct runoff, geese and rainfall in 2015/16

The combined total phosphorus (TP) load to Loch Leven from its inflows, direct runoff from the ungauged part of the catchment, geese and rainfall are shown in Table 24 and Figure 47. The largest input over the study period was from the South Queich, followed by the North Queich and then the Pow Burn. Overall about 11.8t P y-1 was found to be entering the loch from these sources.

Table 24. Summary of the Total Phosphorus (TP) load delivered to Loch Leven from its inflows and other sources.

Site	Annual TP load	
	t P y^{-1}	% contribution
1 - Classlochie Burn	0.02	0%
2 – Gairney Water	0.88	8%
4 – Kinnesswood Burn	0.11	1%
5 - Pow Burn	1.42	12%
6 - Camel Burn	0.08	1%
7 - North Queich	1.67	15%
8 - Ury Burn	0.03	0%
9 - Drain 1	1.35	9%
12 - South Queich	4.76	41%
Direct runoff	1.14	10%
Geese	0.20	2%
Rainfall	0.17	1%
Total	11.8	

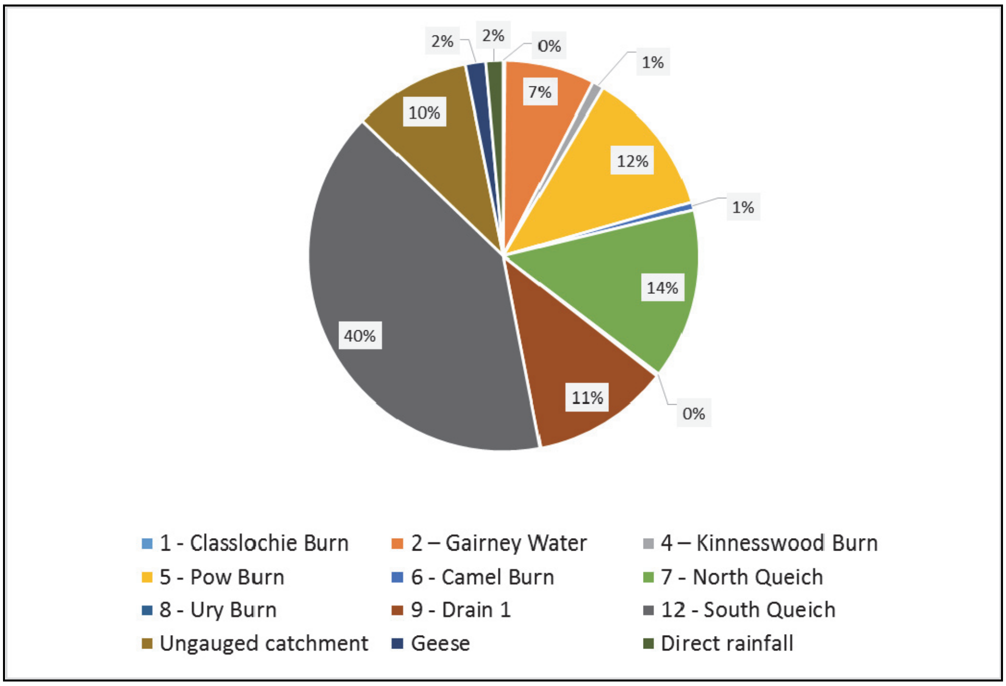

Figure 47. Summary of the Total Phosphorus (TP) load delivered to Loch Leven from its inflows and other sources, expressed as a percentage of the total input.

In terms of source apportionment, only about 1.7t P y^{-1} (14%) of the TP that was delivered to the loch by its inflows, direct runoff, rainfall and birds seemed to have come from point sources such as WWTWs and septic tanks. The majority (10.1t P y^{-1}; 86%) appears to have come from diffuse sources (Figure 48). A possible reason for this relatively high figure for diffuse source inputs was the large amount of particulate P (PP), associated with soil erosion and sediment transport, that was delivered to the loch during the very stormy and wet winter of 2015/16 (see Section 3).

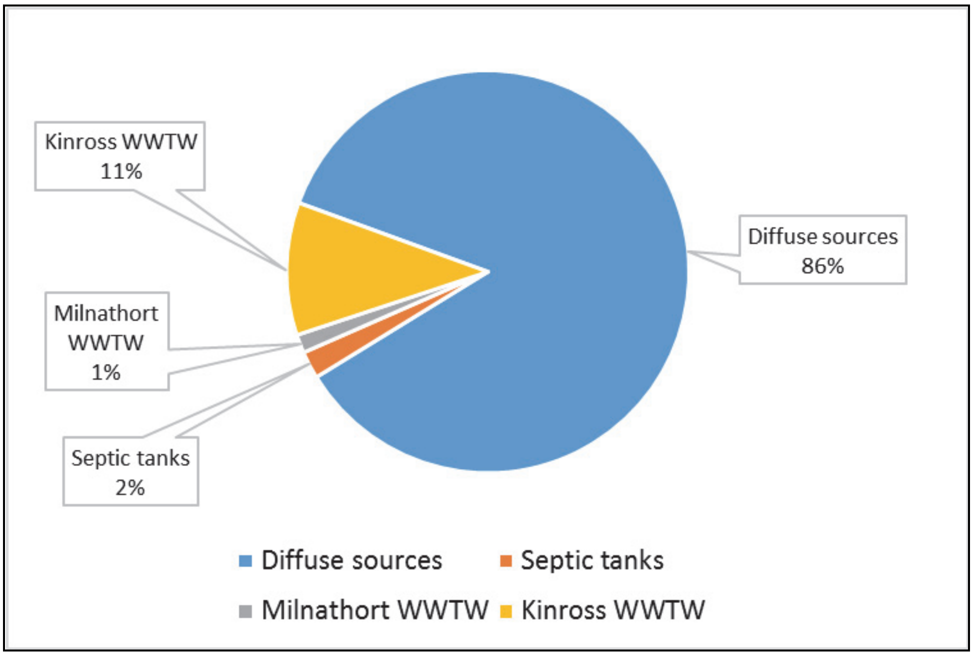

Figure 48. Proportion of TP load to Loch Leven from point and diffuse sources during 2015/16.

4.2 Comparison of P concentrations and loads in 2015/16 with those determined in 2005

Average total and particulate P concentrations and loads in the main inflows to Loch Leven were compared for 2005 and 2015/16, where comparable data were available (Table 25, Table 26, Table 29, Table 30). These comparisons highlighted some areas where P concentrations and loads had increased and others where they had decreased. Changes in these values per catchment are described in detail, below.

4.2.1 Comparison of TP and PP concentrations in the main inflows

In terms of total P (TP; Table 25), the biggest increases were recorded in the South Queich (+12%) and the Pow Burn (+15%). In contrast, average P concentrations in the Gairney Water were 47% lower in 2015/16 than in 2005.

In terms of particulate P (i.e. the portion of TP that comprises P attached to eroded soil and sediment particles; Table 26), the biggest increase was observed in the Pow Burn (+61%), followed by the South Queich (+21%) and the North Queich (+19%). However, as with TP, the average PP concentration in the Gairney Water was 52% lower in 2015/16 than in 2005.

Table 25. Comparison of average total phosphorus (TP) concentrations in the main inflows, 2005 and 2015/16

Catchment	**Average TP conc. in 2005 (µg L^{-1})**	**Average TP conc. in 2015/16 (µg L^{-1})**	**Change in TP conc. (%)**
Pow Burn	93.5	107.8	+15%
North Queich	57.6	60.3	+5%
South Queich	44.3	49.7	+12%
Gairney Water	56.9	30.0	-47%
Camel Burn	57.4	55.7	-3%

Table 26. Comparison of average particulate phosphorus (PP) concentrations in the main inflows, 2005 and 2015/16

Catchment	**Average PP conc. in 2005 (µg L^{-1})**	**Average PP conc. in 2015/16 (µg L^{-1})**	**Change in PP conc. (%)**
Pow Burn	34.8	56.2	+61%
North Queich	22.7	26.9	+19%
South Queich	21.5	25.9	+21%
Gairney Water	18.6	9.0	-52%
Camel Burn	24.2	27.8	+15%

One possible explanation for the increase in PP concentrations in runoff from some catchments and not from others may be the type of land cover that is dominant in the upstream catchment, especially in winter when erosion rates are likely to be higher. This was explored by comparing the average winter PP concentrations in each inflow to the amount of improved grassland in the upstream catchment. The results showed an inverse relationship between these variables (Figure 49).

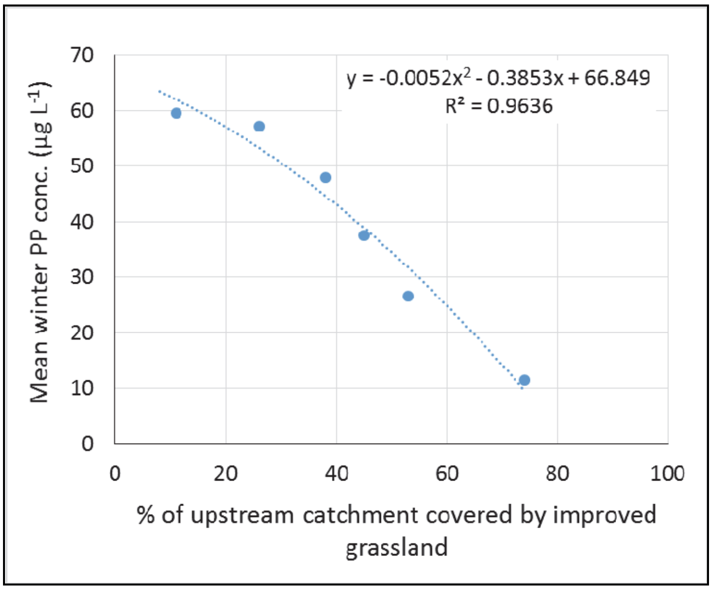

Figure 49. Relationship between average winter PP concentrations and percentage cover of the upstream catchment by improved grassland.

4.2.2 Comparison of TP and PP loads in the main inflows

In terms of total P loads (TP; Table 27), the biggest increases were recorded in the Pow Burn (+71%) and the South Queich (+35%). In contrast the biggest decreases were recorded in the North Queich (-57%), followed by the Camel Burn (-43%) and the Gairney Water (-35%).

Table 27. Comparison of average total phosphorus (TP) loads in the main inflows, 2005 and 2015/16

Catchment	TP load in 2005 (t y^{-1})	TP load in 2015/16 (t y^{-1})	Change in TP load (%)
Pow Burn	0.83	1.42	71%
North Queich	3.92	1.67	-57%
South Queich	3.54	4.76	35%
Gairney Water	1.36	0.88	-35%
Camel Burn	0.14	0.08	-43%

The TP loads for 2005 and 2015/16 for each inflow are compared in Figure 50, with sites above the 1:1 line showing and increase in 2015/16 compared to 2005, and those below the line showing a decrease.

In terms of particulate P (i.e. that proportion of TP that is associated with eroded soil and sediment particles; Table 28), the biggest increase in loads was found to be in the Pow Burn (+129%) and the South Queich (+45%). In contrast, average PP loads in the remaining streams fell by 29-53%. These results suggest that soil erosion and sediment transport are an increasing source of P inputs to the loch via the South Queich and Pow Burn catchment.

Table 28. Comparison of average particulate phosphorus (PP) loads in the main inflows, 2005 and 2015/16

Catchment	PP load in 2005 (t y^{-1})	PP load in 2015/16 (t y^{-1})	Change in PP load (%)
Pow Burn	0.4	0.92	129%
North Queich	1.96	0.92	-53%
South Queich	2.15	3.13	45%
Gairney Water	0.70	0.50	-29%
Camel Burn	0.06	0.04	-32%

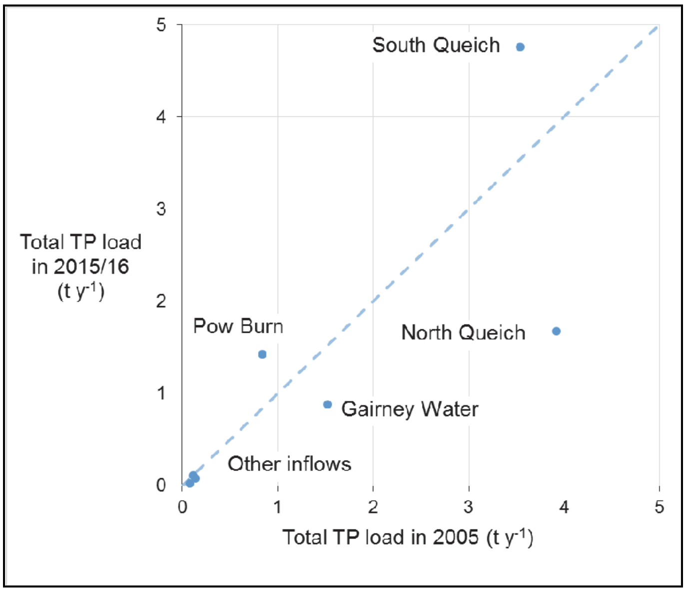

Figure 50. Comparison of total phosphorus (TP) inputs to the loch from its inflows in 2005 and 2015/16.

A long term comparison of the P loads delivered to the loch from these inflows in terms of PP and TSP is shown in Figure 51. The data show that while TSP loads from these sources have been fairly stable or decreased markedly over this period, PP loads have been increasing in recent years. This is likely due to the combined effects of changes in land use, and the increasing number of storm events (Defew, 2008). The very marked reduction in TSP loads in the South Queich between 1985 and 1995 was due to the reduction of effluent discharges from point sources (Bailey-Watts *et al*., 1995).

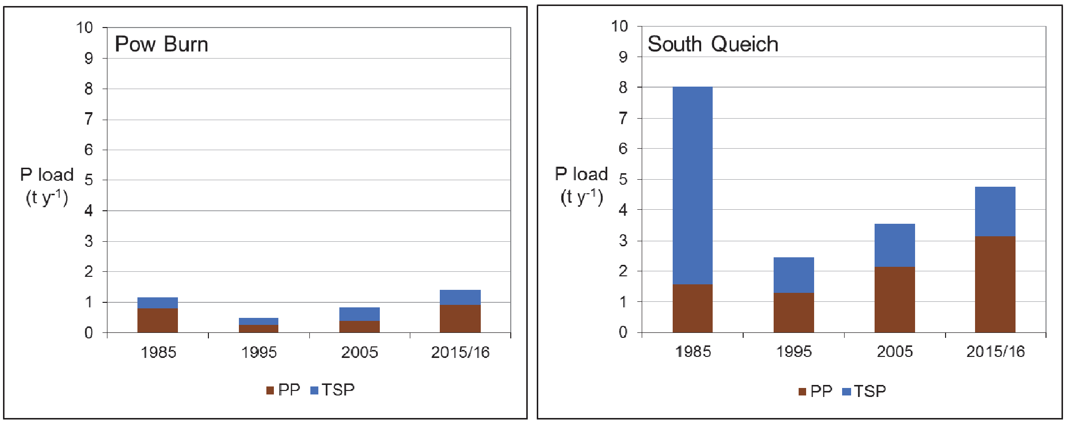

Figure 51. Long term comparison of the particulate and total soluble phosphorus (PP and TSP, respectively) to Loch Leven from the Pow Burn and South Queich, 1985-2015/16.

Changes in the absolute values and source apportionment of the overall TP load to the loch between 1985 and 2015/16 are shown in Figure 52. In 1985, point sources were the main source of TP, comprising about 60% of the input. However, point sources have become less significant over time as a result of better controls on the quality of effluent discharges (D'Arcy, *et al*. 2006). By 2015/16, the dominant, and in some cases increasing, sources of TP entering the loch were diffuse. These are likely to be mainly associated with agricultural land and are likely to be driven by a combination of changes in land use and climate.

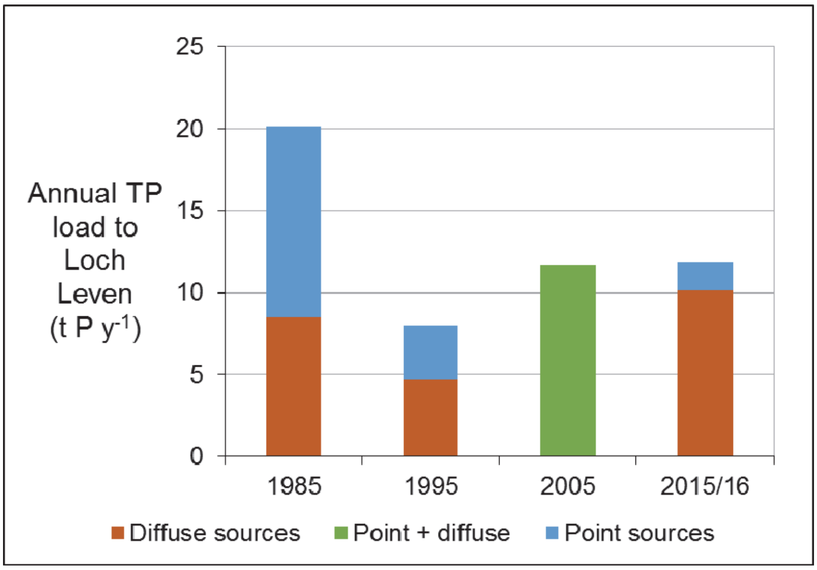

Figure 52. Long term changes in the relative importance of point and diffuse sources of phosphorus entering the loch, 1985 - 2015/16. NB No source apportionment data were collected during the 2005 loading study.

4.2.3 Comparison with phosphorus load values predicted by the PLUS+ catchment nutrient delivery model

The Phosphorus Land Use and Slope model (PLUS+) is a nutrient source apportionment model that has been developed by SEPA and the James Hutton Institute to investigate the present day P concentrations in Scottish standing waters (Donnelly *et al*., 2011).

Calculations of P loads from land (diffuse sources) are based on three classifications of slope (low, medium and high) with threshold values of 0-4 degrees, 4-13 degrees and 13+ degrees, respectively, and landcover based on the land Cover of Scotland (LCS88) data. Average P export coefficients are then applied to each slope and land use category. These loss coefficients were calibrated by Ferrier *et al*. (1996) using data from the 1995 quinquennial Scottish Water Quality Survey scheme. The model does not take into account inputs of P from roosting birds or rainfall.

Calculations of P loads from point sources are based on 2001 census data using a threshold of 0.3 people per hectare to differentiate between urban (sewered) and rural (unsewered) populations. The per capita P loss coefficients to water for each of these populations are 0.91kg P y^{-1} and 0.25kg P y^{-1}, respectively.

Table 29. Phosphorus (P) loads to Loch Leven predicted by the Phosphorus Land Use and Slope (PLUS+) source apportionment model; data were supplied by SEPA.

Land Cover	**Predicted P input (t y^{-1})**
Point sources	
Urban Population (7659 p.e.)	6.99
Rural Population (1013 p.e.)	0.253
Total P from point sources	***7.24***
Diffuse sources	
Arable	6.62
Improved grassland	0.45
Factories & urban	0.37
Recently ploughed land	0.31
Water	0.19
Smooth grassland	0.13
Coniferous plantation	0.1
Sum Upstream Input	0.07
Coarse grassland	0.03
Broadleaved woodland	0.03
Mixed woodland	0.03
Woodland recently felled	0.02
Heather all types	0.009
Wetland	0.003
Blanket bog & peatland	0.002
Bracken	0.002
Cliffs	0.001
Total P from diffuse sources	***8.37***
Total P from point and diffuse sources	**15.6**

The model was run for the Loch Leven catchment and the outputs from the model were supplied by SEPA. These are shown in Table 29. The overall input from sewage related sources was predicted to be about 7.24t P y^{-1} and that from diffuse sources about 8.37t P y^{-1}. By comparison, the measured values for 2015/16 were 1.7t P y^{-1} from point sources and 10.1t P y^{-1} from diffuse sources. While the predicted and measured P loads from diffuse sources are similar in size, there is an order of magnitude difference in the predicted P loads from point sources within the catchment. Although the predicted value for P from unsewered properties (0.25t y^{-1}) is similar to that derived from the measured values (0.34t y^{-1}), the predicted value for P discharges from WWTWs within the catchment is very high (6.99t y^{-1}) compared to the measured value (0.3t y^{-1}).

4.2.4 Potential contribution of phosphorus from septic tanks

There are approximately 861 properties in unsewered areas across the catchment of Loch Leven. Most of these properties are likely have septic tanks (STs), although new builds or properties that have been upgraded recently may be served by individual or communal package treatment plants (PTPs). Perth and Kinross council have in place planning guidance that is aimed at controlling or reducing P discharges from on-site waste water treatment systems to the loch (http://www.pkc.gov.uk/media/26870/14-09-03-Item-8-14-370-/pdf/14-09-03 -_Item_8_(14-370)); this is the so-called 125% rule. The rule assumes that

1.8g P per capita d^{-1} is discharged to the environment by a traditional ST, while only 0.9g P per capita d^{-1} is discharged by a PTP.

Given that the average number of people per household in Perth and Kinross is estimated to have been about 2.18 in 2015 (NRS 2016), and that there are an estimated 861 unsewered properties within the Loch Leven catchment, these figures equate to a total discharge to the environment of about 1.2t P y^{-1}, if all on site systems were STs, and about 0.6t P y^{-1}, if all on-site systems were PTPs. So, given that there are a mixture of STs and PTPs across the Leven catchment, with exact numbers of each type unknown, it can be concluded that the collective total P discharges from these systems are likely to be within the range 0.6t P y^{-1} to 1.2t P y^{-1}.

The greater the number of PTPs within the catchment, the lower the amount of P being discharged to the loch by on site waste water treatment systems is likely to be. However, in most of these systems, this effluent is not discharged directly to water; instead, it receives additional treatment, including P removal, from a soil soakaway and/or constructed wetland. So, the actual delivery of P to Loch Leven from these sources is likely to be lower than that discharged in the raw effluent from these systems.

The potential contribution from STs and PTPs to the overall TP load to Loch Leven was determined by applying the source apportionment model (Bowes *et al*. 2008) to the data from the inflows, that drain catchments with no large scale WWTW, or other large point sources of P. The results were compared to the number of unsewered properties upstream of each study site (Figure 53) and a strong relationship was found between these two variables; this suggested that, on average, each unsewered property was contributing, about 0.4kg P y^{-1} to the loch. With an estimated 861 unsewered properties across the catchment, this equates to a TP load to the loch from these sources of about 0.34t y^{-1}. However, it should be noted that this figure excludes P sources from systems that behave more like diffuse sources in response to rainfall, i.e. those receiving further treatment in a soakaway and/or constructed wetland, and probably reflects the level of discharge from these systems that are associated with misconnections or direct discharges to a watercourse.

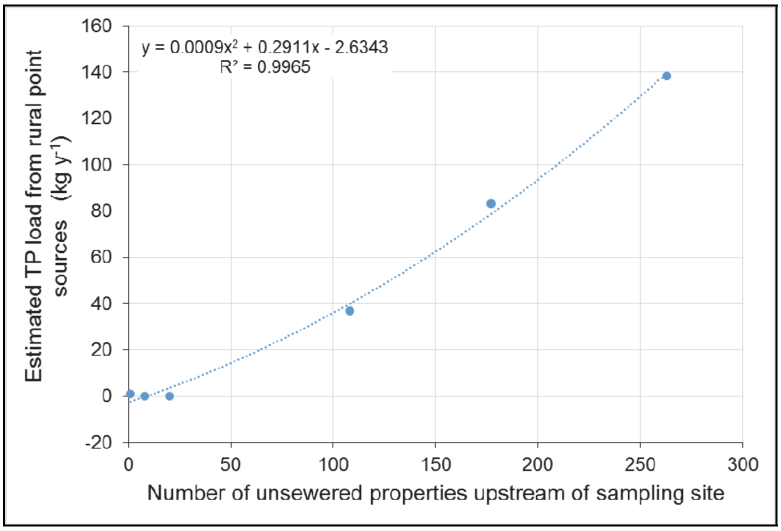

Figure 53. The relationship between estimated total phosphorus (TP) load from rural point sources and the number of unsewered properties upstream of the sampling point for inflows with no known waste water treatment works.

Table 30. Upstream area draining to each sampling point (G0-G10) and estimated stream flows at each sampling point on each sampling occasion

Site	Upstream area (km^2)	Estimated flow on 18/5/16 (cumecs)	Estimated flow on 14/9/16 (cumecs)
G0	34.30	0.447	1.447
G1	1.84	0.024	0.078
G2	28.22	0.368	1.190
G3	0.88	0.012	0.037
G4	1.45	0.019	0.061
G5	4.46	0.058	0.188
G6	17.18	0.224	0.725
G7	0.64	0.008	0.027
G8	12.32	0.161	0.520
G9	1.03	0.013	0.043
G10	0.85	0.011	0.036

Two spatial surveys of the P concentrations in stream water were undertaken across the Gairney catchment; one under low flow conditions (18/5/16) and the other under higher flow conditions (14/9/16). Flows were estimated for each sampling site by apportioning the rates of flow measured at the most downstream site (G0) across sites G1-G10 according to upstream catchment area. Estimated flows for each sampling site are shown in Table 30.

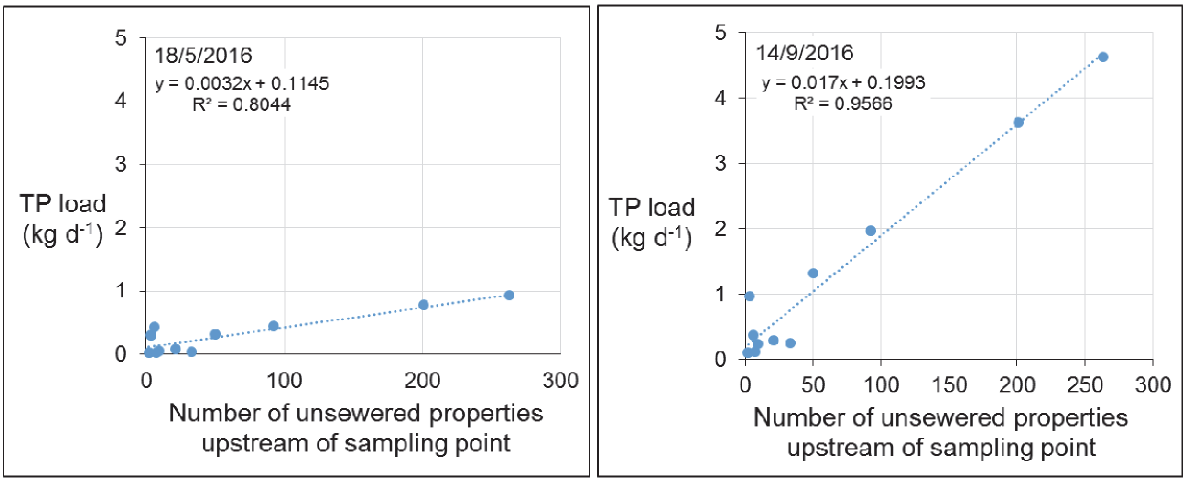

Figure 54. Relationships between TP load at each sampling point visited within the Gairney catchment and the number of unsewered properties within the corresponding upstream catchment under different flow conditions; left panel: low flow; right panel: high flow.

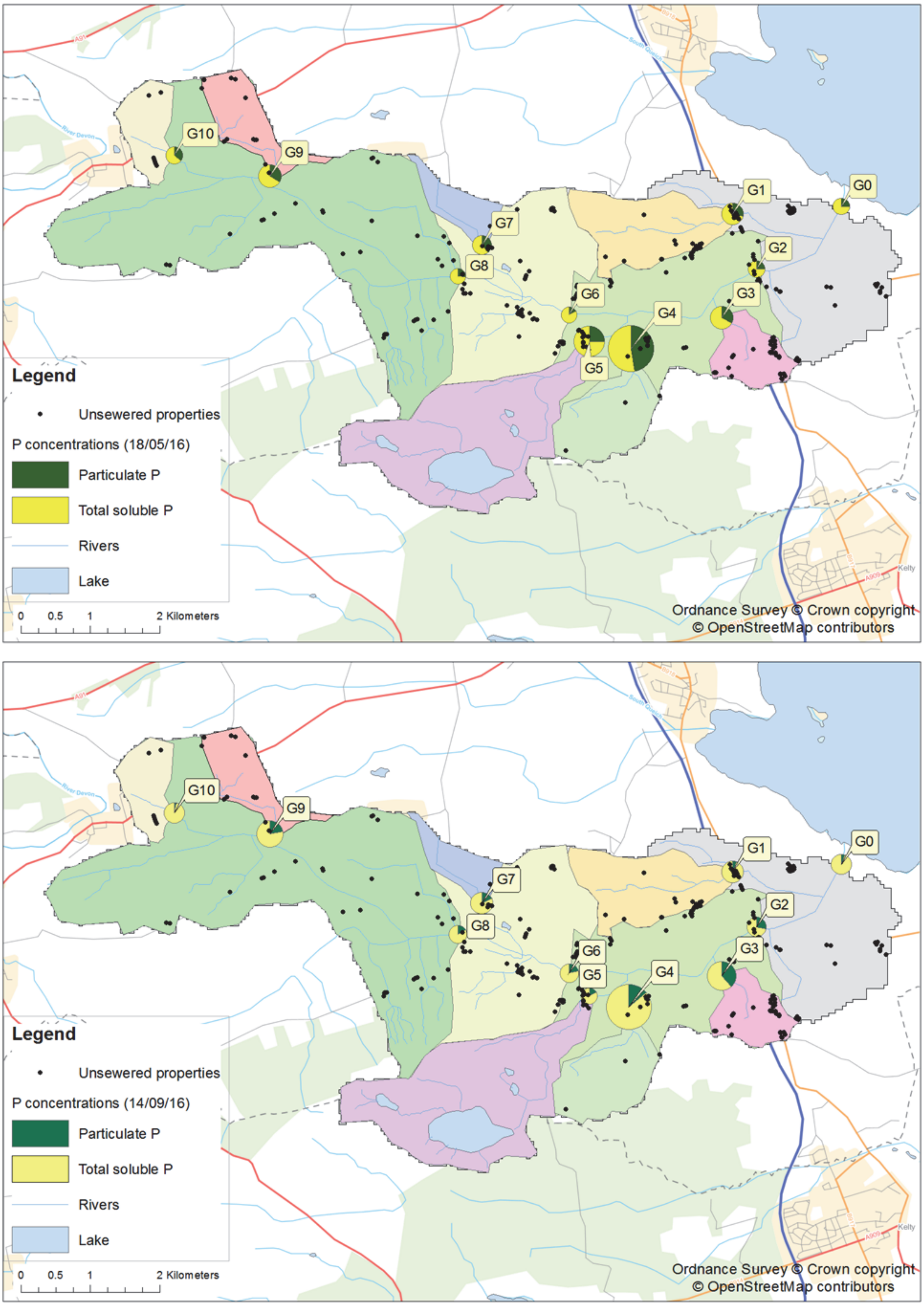

Figure 55. Relative concentrations of particulate phosphorus (P) and total soluble phosphorus (P) concentrations in streams across the Gairney catchment, 18/05/16 (top panel) and 14/09/16 (bottom panel); the relative magnitude of the overall total phosphorus (TP) concentration is indicated by the area of each pie chart.

The results of the survey of P concentrations in streams across the Gairney catchment under different flow conditions are shown in Figure 55. The spatial distribution of unsewered properties across the catchment is also shown. In general, P concentrations are similar across all sites but some notable hotspots of P pollution were found. These were at sites G4 and G5 on (under low flow conditions) and at sites G3 and G4 under higher flow conditions. All of these sites were close to clusters of unsewered properties. The high proportion of TSP at these sites suggests on site waste water treatment systems, which discharge directly to water, or are misconnected, as a likely source that should be investigated.

The data collected during the surveys was explored in relation to the estimated TP loads at each sampling point and the number of unsewered properties situated upstream of the sampling point. The results are shown in Figure 53. Although the TP load on the day of sampling was lower under low flow conditions (left panel), than under high flow conditions (right panel), on both occasions there was a strong relationship between in-stream TP load and the number of unsewered properties upstream of the sampling point. This is a similar pattern of response as that observed across other areas of the Leven catchment.

5. GENERAL DISCUSSION

Loch Leven is the largest lowland loch in Scotland and lies within an area of increasing population and intensive agricultural production. It has a long history of eutrophication problems, exacerbated by the fact that the loch is very shallow and as such very sensitive to nutrient enrichment (Bailey-Watts & Kirika, 1987). By the mid-1980s, water quality had degraded to such an extent that troublesome, and sometimes toxic, blooms of cyanobacteria were common. These led to demands for improvement. Previous research had indicated a strong link between algal blooms and P concentrations in the loch and there was evidence that a partial reduction in P inputs to the loch in the 1970s had resulted in a decrease in algal abundance (Bailey Watts 1978). So, it was then recognised that further improvements could only be achieved by controlling nutrient inputs further. At the beginning of this process, a nutrient source apportionment study was undertaken to assess the size of the problem and its main causes (Bailey-Watts & Kirika, 1987). The study, undertaken in 1985, concluded that the P input to Loch Leven was about 20t y^{-1}, with about 30% coming from an industrial source, about 27% from waste water treatment works and most of the remainder from runoff.

An action plan was put in place to set targets for water quality restoration at the site and to reduce P inputs to the loch to achieve these (LLCMP, 1999). As a result, inputs from point sources were significantly reduced in the early 1990s and controls on diffuse pollution (e.g. buffers strips) were implemented in parts of the catchment to reduce runoff from farmland.

The P source apportionment survey was repeated in 1995 to assess progress. The results showed that levels of P input to the loch had fallen to about 8t y^{-1}, with 46% then coming from point sources and the remaining 54% from diffuse sources. However, it should be noted that 1995 was an exceptionally dry year; this will have reduced the amount of runoff entering the loch from diffuse sources in comparison to 1985 (Bailey-Watts & Kirika, 1999) and subsequent surveys (Defew, 2008).

The P load to the loch was re-assessed in 2005 (Defew, 2008). Applying the method of calculation used in 1985 and 1995 to the data collected in 2005, the P input to the loch during 2005 was estimated to be about 11.7t y^{-1}. Unfortunately, because the 2005 loading study did not collect the data required for source apportionment to be undertaken, it was not possible to distinguish point and diffuse sources of P within the catchment.

In the current study, the P input to the loch was estimated to be about 12t y^{-1} over the 12 month period between July 2015 and July 2016. This was very similar to the P load estimated in 2005. However, in 2015/16, samples were collected from up- and down-stream of effluent pipes from Milnathort and Kinross WWTWs and Kinross effluent pumping station, which allowed apportionment of point and diffuse sources. The results showed that about 10t P y^{-1} was entering the loch from diffuse sources, and only about 2t P y^{-1} from point sources. This indicated that diffuse sources are now the main source of P entering the loch. These should now become the main focus of further plans to maintain or improve loch water quality.

High levels of PP appeared to be entering the loch from the catchments of the South Queich and Pow Burn during high flow events in 2015/16. Also, when compared to the historical data, it was found that these PP loads were increasing. It has been hypothesised that these increases may be due to a combination of land use and climate change. Further work is needed to test this hypothesis. This could be carried out by exploring existing data for each inflow and its catchment.

The results of the survey of the impacts of waste water discharges from properties in unsewered areas showed a strong relationship between number of unsewered properties upstream of sampling sites and the TP load in each inflow. This appeared to be true when different inflows were compared within the Loch Leven catchment as a whole, and when different subcatchments of the Gairney Water were compared. The data suggest that, of the potential 1.2t P y^{-1} that would be discharged to the environment if all of these unsewered properties were served by septic tanks, only about 0.34t P y^{-1} seemed to be entering the loch. This probably reflects the success of local campaigns to encourage better management of these systems and it is recommended that these continue. However, hotspots of P contamination were found across the Gairney catchment, suggesting that some systems are not working as efficiently as others and may need further investigation. It is likely that there are similar hotspots of P pollution in other areas, too.

The comparison of measured P loads to Loch Leven and those estimated by the PLUS+ model found that, while catchment runoff figures were similar, there was a large discrepancy between the two sets of data in relation to discharges from WWTWs. This may be due to the per capita P export coefficient that is used in the PLUS+ model for urban wastewater (0.91kg P y^{-1}). This seems exceptionally high given that the per capita P content of untreated domestic wastewater is only about 0.91kg P y^{-1} (US EPA 2002) and a removal rate of about 90% would be expected from a WWTW with tertiary treatment. A value of 0.09kg P y^{-1} might be more realistic. This requires further investigation.

Overall, there appears to have been little change in the overall TP load to Loch Leven since 2005, but the proportion of point to diffuse sources has changed compared to previous years. There is now a much greater emphasis on PP, which is associated with soil erosion and sediment transport, than on TSP, which is more commonly associated with point sources. The next phase of the restoration and recovery of Loch Leven needs to focus more on reducing diffuse inputs of P to the loch. Until now, the main focus has been on better control of point sources.

6. CONCLUSIONS AND RECOMMENDATIONS

The results of this study suggest that about 12t of P entered the loch between July 2015 and July 2016; this is similar to the value recorded using similar methods in 2005.

Although discharges of P to the environment from point sources within the catchment have decreased significantly over time, on occasion discharges from the Kinross works were found to elevate in-stream P concentrations at Site 9 by up to 1,320µg L^{-1}. The reason for this should be investigated.

Of the 1.2t P y^{-1} that could be discharged to the environment from unsewered properties if they were all served by traditional septic tanks, only about 0.34t P y^{-1} seems to be entering the loch via its inflows. This suggests that local campaigns to encourage better management of these systems are working well; it is recommended that these are continued.

Some hotspots of P contamination were detected across the Gairney catchment, suggesting that some systems were not working as efficiently as others and may need to be investigated; similar hotspots of P pollution are likely to occur in other areas, too, and it is recommended that similar surveys are undertaken across the Loch Leven catchment to identify these.

While discharges from point sources are still decreasing, P from diffuse sources appear to be increasing especially in relation to PP; this increase may be caused by changes in land use and/or climate. This requires further investigation.

Land use should be explored around the Pow Burn and South Queich to determine why increasing levels of PP seem to be entering the loch from these catchments and whether changes in land use could be used to mitigate this.

Further analysis of the nutrient loading data from previous surveys should be undertaken to test the hypothesis that particulate phosphorus (PP) inputs to the loch are increasing due to changes in the weather as a result of climate change.

The comparison between measured P loads to Loch Leven and those estimated by the PLUS+ model concluded that, although catchment runoff figures were similar, modelled P discharges from urban wastewater were an order of magnitude higher than the measured values. Reasons for this discrepancy should be investigated.

Another loading survey, with source apportionment data included, should be undertaken in 2025 to assess the long term progress of the catchment management and loch restoration process at Loch Leven.

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