Analysis of benefits of water management controls and dredging at the outlet to Balgavies Loch for upstream flood risk and wetland ecology.

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Summary

The impact of modified management of the section of the Lunan Water comprising a mill lade and an associated complex of water channels downstream of Balgavies Loch, has been assessed. An important feature of this complex is the ecologically valuable Chapel Mires, which is fed by an overflow from the mill lade. Considered options include: management of existing weir gates; a proposed, flexibly managed, lateral structure (tilting weir) to release flow from the mill lade; and dredging of this lade.

Water levels in Balgavies Loch and Rescobie Loch (upstream) have been monitored from March 2014 and inflow to the lade from the Balgavies Burn tributary has been monitored since 2006. Some flow and water level measurements have made, but only under low flow conditions, partly due to access restriction in winter.

The channel was schematised using cross section data collected in 2015 and 2017, and also a detailed historical bed level survey by a local resident. The hydraulic modelling package HECRAS 5.0.1 was used to predict stage-discharge relationships for the outlet of Balgavies Loch. These, along with scaled inflows from Balgavies Burn, could be used in a simple daily time step hydrological model, to predict water levels in the Loch and compare with observations.

Modelling results show that in the undredged channel, the impact on loch water levels of the operation of the existing return gate, and/or the introduction of an additional lateral structure with 0.44m lower bed level (tilting weir), would be small. However, these hydraulic structures have a much larger effect on partitioning of flow of water between the lade and Chapel Mires.

If the channel were dredged, there is a much larger impact on upstream water levels, reducing the risk of economically damaging water levels in Rescobie Loch (60m above sea level) from the current observed value of 3% to 1%. There would also be additional impact on the partitioning flow of water levels into Chapel Mires associated with the operation of the tilting weir.

If dredging action were agreed between stakeholders, ongoing sediment management in the mill lade downstream of Balgavies Loch would also be needed. Several options could be considered in this discussion which include: (a) a management plan for repeated dredging; (b) moving the existing spillway into Chapel Mires back to the original spillway; (c) adding a manually or automatically operated lateral weir or sluice gate to help control sediment flushing and water flows; (d) "light touch" vegetation removal.

Introduction

Upgrading of existing hydraulic structures at the outlet to Balgavies Loch on the Lunan Water, Angus, Scotland, to allow more active management of water flows, using a tilting weir, has been proposed (Vinten et al., 2017a). In order to obtain consent for this proposal from both riparian owners and regulators, it is necessary to demonstrate benefit to the water environment across a range of pressures. In the Scottish Government “water for all” project (see http://www.hutton.ac.uk/research/projects/payments-ecosystem-services-lessons) we are focusing on 3 main areas of potential benefit – mitigation of flooding, improvement in wetland ecology through management of nutrient and sediment loads to sensitive areas, and also (not considered here) mitigation of low flows (Vinten et al., 2017b).

The goals of this report are:

a. To determine the impact of introducing a modified water management regime to the outlet of Balgavies Loch on the Lunan Water (eg using a tilting weir as a lateral structure on the common lade, releasing water to the main tailwater channel). This modification may (i) impact upstream water levels in the Loch through additional release of water, compared with that achievable with the existing hydraulic structures at Milldens weir; (ii) modify the distribution of flow and sediment between the Chapel Mires wetland and the Lunan Water downstream of the lade system (see Figure 1 for detail of the site).
b. to assess the impact on upstream water levels in Balgavies Loch, of dredging accumulated sediment from the lade, in conjunction with, or in place of modified water management using hydraulic structures.

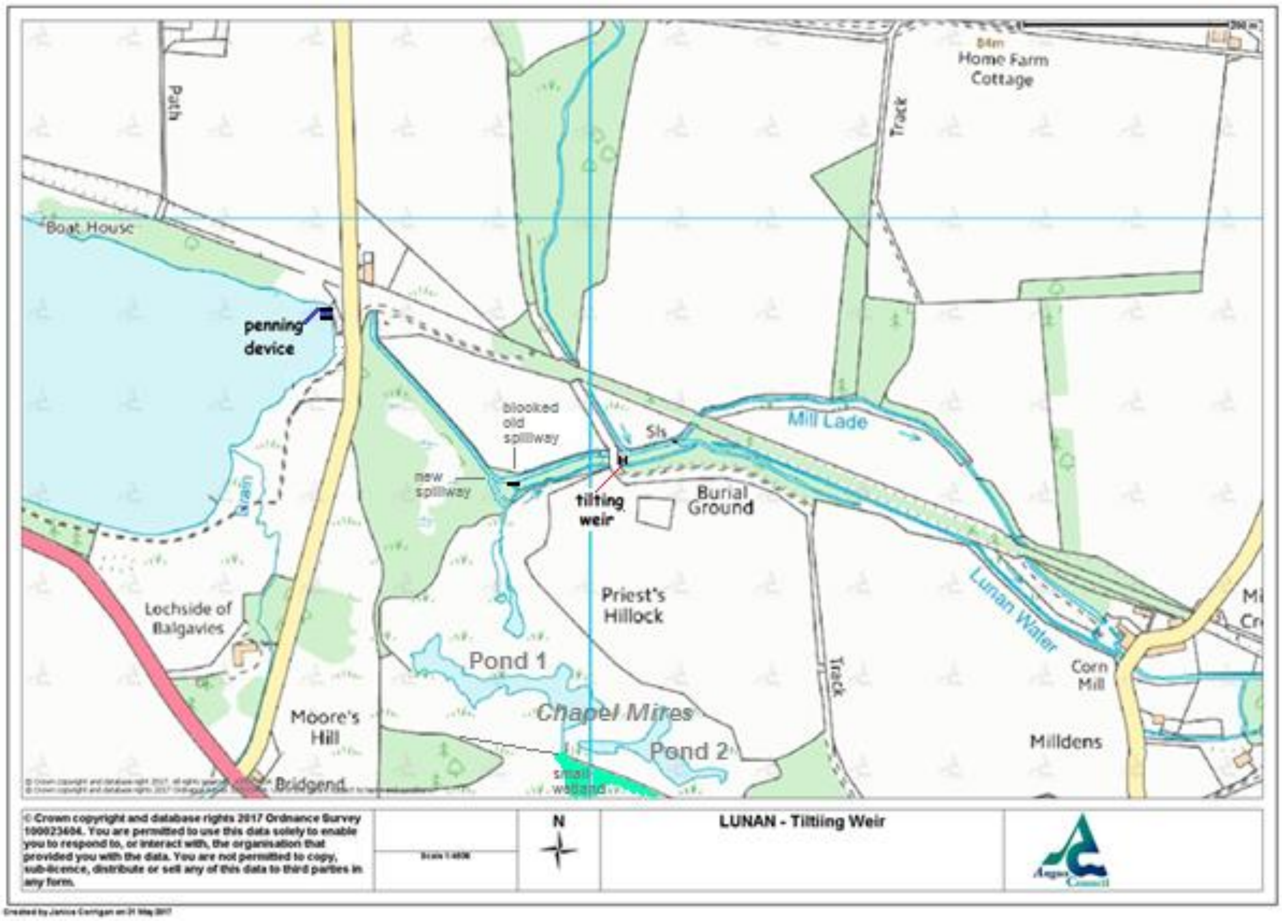


Figure 1. Overview of the section of the upper Lunan Water catchment downstream of Balgavies Loch, including common lade, Milldens weir, Milldens lade, spillways and tailwaters, in the area downstream of the outlet to Balgavies Loch.

Methods

Modelling objectives

Our hydraulic modelling objective is to obtain a suite of steady-state stage-discharge relationships to relate the discharge from Balgavies Loch (Q_O) to the water level in Balgavies Loch (H_L). These relationships are a function of (a) hydraulic control settings of the existing weir on the Common Lade at Milldens, (b) inflow to the Common Lade from the Balgavies Burn tributary (Q_B), (c) a proposed new tilting weir just upstream of the confluence of Balgavies Burn, (d) dredging.

Our hydrological modelling objective is to use this suite of stage-discharge relationships in a dynamic context, via a set of lookup tables, to model the water level in the Loch as a function of conditions of inflow on a daily timestep, using a simple water balance approach.

Hydraulic modelling

We are using the hydraulic modelling package HECRAS 5.0.1 (released 2016) to characterise the impact of lateral hydraulic structures and flows on the stage at Balgavies Loch outlet. The overall system we are dealing with is quite complex (see Appendix 1 for a depiction of the stream network in HECRAS geometry, including the Common Lade, tailwaters and marginal wetlands downstream of Balgavies Loch). We have used a simplified approach to model steady, sub-critical in-channel flow in the Common Lade, with hydraulic controls represented by lateral weir structures in the southern wall of this channel. In this simplification, water runs from the inlet of the Lunan Water (LW) eastwards into Balgavies Loch (BAL). The Loch itself (area 59 ha, average depth 3m) is modelled as a large river channel, with cross sectional dimensions defined by a 1903 bathymetric survey of the loch (see http://maps.nls.uk/bathymetric/chart/2006). The outlet of the loch (bed level 59.04 m) runs eastwards into a single channel or common lade (CLA). This continues along a nearly flat channel for 220m enclosed by well defined banks, until a lateral spillway 2.7m wide releases some of the water through a semi-natural spillway (Chapel Mires spillway, or CMS; bed level 58.9m) in the channel bank. The spillage water flows into a complex of natural floodplain wetlands and ponds (known as Chapel Mires), with typical water levels of 58.7-58.8m depending on flow conditions. At the southern extremity of these wetlands are particularly well conserved mesotrophic mires separated from the rest of Chapel Mires by an embankment . A culvert with bed level of 59.14m separates these near pristine *Carex* dominated wetlands from the rest of Chapel Mires, offering some protection from flood events of nutrient and sediment rich water. The Chapel Mires drain into a channel (the Lunan Water proper) which runs parallel to the Common Lade but with > 0.5m lower bed levels. Meanwhile, the CLA continues along a near-level channel for a further 184m until a stream, the Balgavies Burn (BB), joins it from the north. The discharge on the Balgavies Burn (Q_B) is monitored continuously. After the confluence with BB, the CLA continues for 67m until Milldens weir (MW). At MW, water is delivered to two channels via two engineered sluice gates. These gates are both 0.9m wide with a bed level of 59.04 m. The northernmost gate delivers water to the Milldens lade (MLA), which runs along an engineered channel for 555m to Milldens water mill and then returns to the Lunan Water (bed level 56.1m). The second gate at Milldens weir, the return gate (RET), returns water via a short return channel, to the Lunan Water (bed level at return to the Lunan Water =57.1m).

Channel characterisation.

To model the whole system hydraulically in detail would require a very large investment in characterising the channels, wetlands, water levels, inflows and outflows, and we have therefore introduced a number of simplifying assumptions to help us represent schematically the main features of the lade which influence water levels upstream in Balgavies Loch. The details of this schematic are shown in Figure 2 with an example inflow of $5m^3/s$ from the upstream Lunan Water and $0.1m^3/s$ from the Balgavies Burn. The assumptions used are as follows:

1. We consider flow in the Lunan-Water-Balgavies Loch-Common Lade-Milldens Weir-Milldens lade - Milldens watermill – Lunan Water continuum as occurring in a well defined, confined channel. Nine cross sections of this stream were surveyed on the 31st October 2017 during low flow conditions. An Impulse 200 laser range finder (vertical accuracy: ±3 cm) was used to survey wetted cross sections and a Leica Geosystems 1200 differential global positioning system (dGPS; vertical accuracy: ±3 cm) was used extend cross sections over floodplain areas where there was dGPS satellite coverage available. This also enabled the laser range finder points to be tied into the OS British National Grid coordinate system. Points were taken to represent the major changes in floodplain and channel topography with more points taken over channel banks. On average points were taken every 1 m along each cross section. At each point, the dominant channel substrate or terrestrial vegetation/material type was visually classified to give further information to inform choice of Manning's n roughness values for the model. Water level points were also measured to allow model calibration. Some cross section data were also collected in May/June 2015 using the Leica Geosystems 1200 dGPS). We also used bed level data from a historical survey carried out by a local farmer, J. Compton of West Mains of Turin (pers. comm).
2. These cross section data have been used to define the channel, but banksides have been assumed to be high enough (61.0m) not to overtop. Steady inflow into this channel can be varied to generate a series of steady-state water levels in the Balgavies Loch and downstream, and hence generate the required stage-discharge relationships.
3. A key feature of this channel is a 0.9m wide in-line gate (bed level 59.04m, chainage from Balgavies Loch 451m) directing water into Milldens Lade at Milldens weir – see figure 3b below). This has been modelled as a 1m long, 0.9m wide constriction to flow. A further key feature of this channel is a culverted bridge (bed level 58.98m, chainage 370m) over the channel, which has been represented by a 4m long, 3.5m wide constriction.
4. We assume there are three potential lateral structures (rectangular weirs) releasing water from flow within the confines of this channel:
   a. the existing chapel mires spillway (CMS) (chainage from Balgavies Loch outlet 220m, width of rectangular section 2.7m, bed level 58.9m – see Figure 3a below) ,
   b. the proposed tilting weir (TiW) located just upstream of the confluence of Balgavies Burn (chainage from Balgavies Loch outlet 394m), with width of rectangular section 1.8m, bed level 58.6m. Note that without dredging, this is the furthest upstream a bed level for the weir as low as 58.6m can be achieved.
   c. The existing return gate (RET) to the Lunan Water at Milldens weir (chainage from Balgavies Loch outlet 453m, width of rectangular section 0.9m, bed level 59.04m – see figure 3b below).
5. The tributary, Balgavies Burn, also provides an inflow, which has been monitored since 2006. The dimensions of this channel were surveyed in October 2017.
6. We also explore the impact of deepening the Common lade channel between the outlet of Balgavies Loch and Milldens weir by 50 cm dredging. In principle, this could then allow the tilting weir to be sited further upstream (for example at the site of an old, blocked spillway at chainage 279m, with an option to close the existing Chapel Mires spillway).

Appendix 2 summarises the cross sectional data used for the HECRAS simulations. The HECRAS 5.0.1 model was run for a series of different steady-state simulations in the following combinations:

Q_o=0.1, 0.5, 1, 2, 4, 5, 6 or 8m^3/s; QB=0.1, 0.3, 0.7 or 1 m^3/s; only CMS open; CMS and RET open; CMS, TiW and RET open; common lade channel downstream of CMS was either undredged or dredged by 0.5m.

The results from these simulations were used to generate lookup tables of Balgavies Loch stage (H_L) vs discharge (Q_o) and the modelled discharges could then be used to simulate water levels in Balgavies Loch using the hydrological modelling.

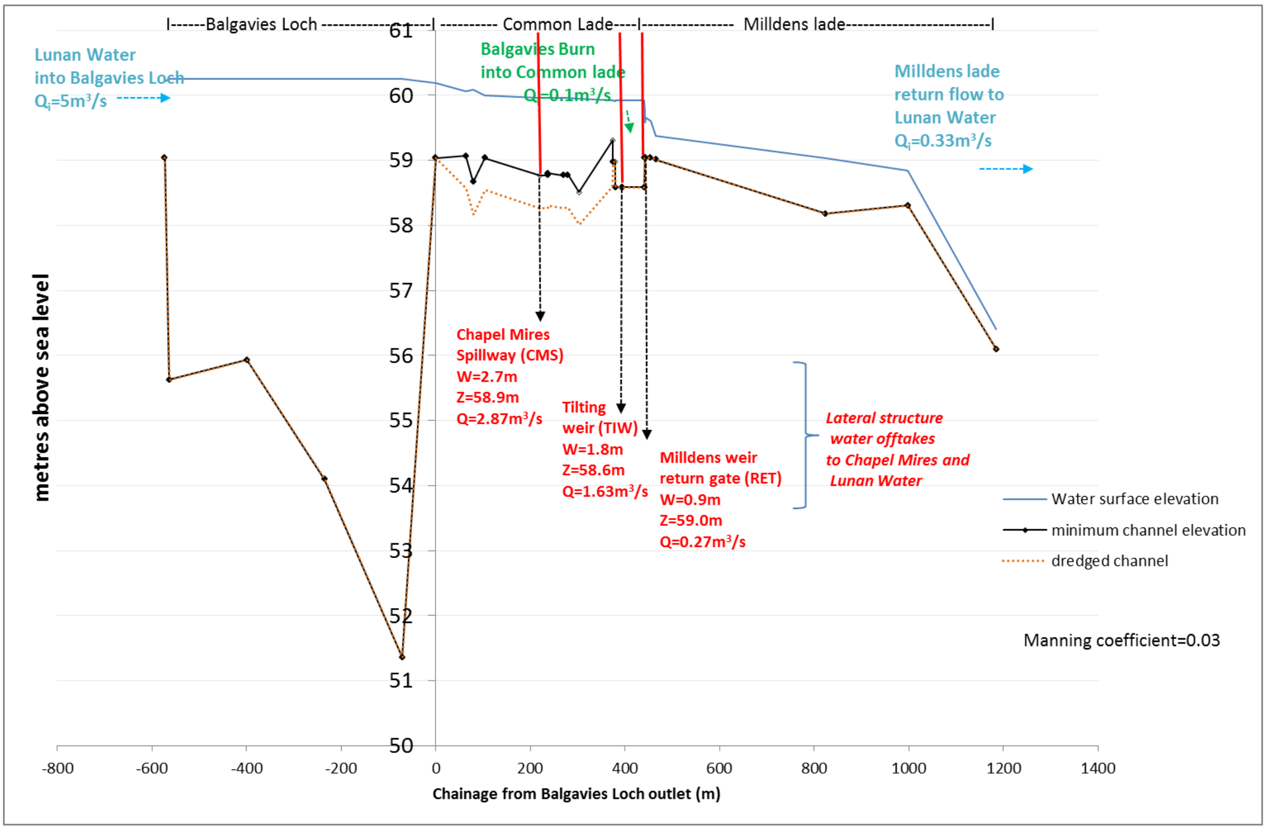


Figure 2. Example representation of the Lunan Water – Balgavies Loch – Common Lade – Milldens lade – Lunan Water channel, showing 3 lateral structures (red bars) used in steady-state hydraulic model simulation. Chapel mires spillway is simulated as a zero head rectangular weir, the tilting weir as a sharp crested weir and Milldens return gate as a broad crested weirs. These lateral structures discharge water to the Chapel Mires and/or the main channel of the Lunan Water, which is assumed to act as an out-of-system tail water. In this example the headwater inflow to the channel is 5 m^3/s and the inflow from the Balgavies Burn is 0.1 m^3/s. Manning coefficient 0.03 throughout.

Figure 3. (a) Looking upstream on Common Lade showing lateral spillage to Chapel Mires spillway (on left). (b) Looking downstream to MIlldens weir mill lade gate (on left) and return gate to Lunan Water (on right).

Note the turbid water associated with P rich autumn algal bloom outwash from Balgavies Loch in Figure 3a compared with the clear summer waters in Figure 3b.

Hydrological modelling

We simulated the daily change in water level in the Loch from the stage-discharge relationships and the previous day's water level, by scaling up the inflow from Balgavies Burn to the Loch catchment area:

$$H_L^{(t)} = H_L^{(t-1)} + ((Q_B A_{LC}/A_{BC}) - Q_o)/A_L \quad (1)$$

$H_L^{(t)}, H_L^{(t-1)}$ = Water level in the Loch on day t, t-1 (m above sea level)

Q_B = daily discharge of Balgavies Burn (m^3/d)[1]

A_{LC} = total catchment area of Balgavies Loch outlet (23.7×10^6 m^2)

A_{BC} = catchment area of Balgavies Burn (4.40×10^6 m^2)

Q_o = discharge from Balgavies Loch, from the modelled stage-discharge, $Q_o = f(H_L)$ (m^3/d).

A_L= Area of open water and wetlands which contributes to water level change observations (taken as 1.86×10^6 m^2).

Note that we can also solve eq (1) to obtain observed daily discharge from the loch, given observed daily water levels in the Loch and Balgavies Burn daily discharge.

Simulations of water levels were performed over the period from March 2014 to November 2017 for 6 different combinations of hydraulic controls:

1. Tilting weir closed, Milldens return gate closed
2. Tilting weir closed, Milldens return gate open
3. Tilting weir open, Milldens return gate open
4. Tilting weir closed, Milldens return gate open, channel dredged by 0.5m
5. Tilting weir open, Milldens return gate open, channel dredged by 0.5m
6. As 5, but tilting weir shifted to old, currently blocked spillway at chainage = 274m

In all these cases we assumed Chapel Mires spillway was open.

Water level measurements and daily estimates of loch discharge for validation of model.

Maximum, minimum and periodic current water levels for Balgavies Loch were measured using water level maximum/minimum recorders (Bragg et al., 1994). The data was supplied for 2003-2014 by Scottish Wildlife Trust (Houghton, A., pers. comm.). Dynamic water level recorders (Frog systems and Van Walt) were installed from March 2014 at three points in the system, Rescobie Loch pier, Balgavies Loch railway bridge and Milldens weir. The locations are shown on Figure 1. Water levels were recorded at 15 minute intervals and referenced using an RTK-GPS (Balgavies Loch outlet and Rescobie Loch) or (Milldens weir) using historic data from J. Compton (pers.comm) to give absolute water levels relative to ordinance datum. Rainfall at Mains of Balgavies and discharge of the Balgavies Burn have been monitored since 2006 (see Dunn et al., 2014 for details).

Empirical impacts of existing gate closures

To obtain empirical validation data for this approach, flow measurements were made with a propeller base Valeport flowmeter model 001 on 26-27th July and 27-28th September 2016. Both the gates had been set to open on 21 July at 18:00. Discharge measurements were made on 26/27 July as follows:

a. On 26th July with both gates open:
discharge at outlet to Balgavies Loch, spillway to Chapel Mires and at both Milldens gates;
b. On 26th July after closing the return gate to the Lunan Water at 16:55:

[1] This is based on water level and discharge recording at Westerton, on the Balgavies Burn. http://www.hutton.ac.uk/research/groups/environmental-and-biochemical-sciences/monitoring-data/monitoring-data/lunan#latest

discharge at both Milldens gates;

c. On the 27th July both before and after closing (at 11:45) the Mill lade gate as well: discharge at spillway to Chapel Mires and at both Milldens gates.

Finally both the gates at Milldens were re-opened.

In addition we used acoustic Doppler based flow metering (Valeport flowmeter model 801) on 11th July 2016 to measure flows at Balgavies Loch outlet, the two weir gates, and the Chapel Mires spillway, and again on 30th -31st October 2017 to measure flows at Chapel Mires spillway and a cross section just downstream of this spillway.

Note that it was not possible to obtain observed impacts of gate closures, or measure the split between flow to CMS and flow continuing down the common lade, at higher winter water levels because access to Chapel Mires in winter was restricted due to recreational shooting activity.

Results

Hydraulic modelling of stage-discharge relationships for Balgavies Loch outlet

Figure 4 shows a suite of stage-discharge relationships between the water level in Balgavies Loch and the discharge from the Loch, for steady state flow, using HECRAS 5.0.1 model, for different conditions of inflow from Balgavies Burn and operation of gates providing lateral offtake, namely the return gate at Milldens weir, RET, and the proposed tilting weir (TiW) just upstream of the Balgavies Burn tributary. In figure 4a, it can be seen that the measured data points are in the same range as the modelled lines. The modelled impact of the Balgavies Burn inflow on discharge from Balgavies Loch is most marked at low Loch outflows and it can be seen that high Balgavies Burn discharge then severely hampers discharge from the Loch. At higher outflows, the impact of Balgavies Burn is less marked, but still present. The impact of the position of the Milldens return gate on the flow out of the Loch is most marked at very high and low water levels and is nearly non-existent at moderate to high levels, except for the largest Balgavies Burn tributary inflows. In Figure 4b we see the impact of adding a lateral tilting weir, compared with only the existing return gate operating. We see that below Balgavies Loch outflow of 4m^3/s, there is very little impact of the tilting weir on water levels in the Loch, but the impact increases at very high outflows. This smaller than expected impact is partly because of the accumulation of sediment, for example at chainage 237-279m and at the cattle drinking point just upstream of the culverted bridge at chainage = 374m (see Appendix 4E. Figure 5 shows the impact on stage-discharge relationships of 50cm of dredging of the Common Lade (see Figure 2 for location of dredging - shown by dotted line), with and without operation of the tilting weir. This dredging has an impact on Loch water levels much larger than the impact of the tilting weir operating in the undredged channel, except at very high outflows. For example at H_L = 59.6m, Loch outflow is doubled by dredging from 1 to 2 m^3/s. Once this dredging has occurred the tilting weir is also more effective, further increasing the flow from the loch when H_L>59.6m. Also shown in Figure 5 is the effect of moving the tilting weir site upstream of the bridge (feasible once the channel is dredged). We chose the site of an old, blocked spillway near the bend in the common lade, the tilting weir has a further incremental impact on flows from the loch, as it appears that the transfer of the spillway to the present, upstream Chapel Mires spillway, may have promoted accumulation of sediment in this portion of the common lade. This gives a further increment in the impact of the tilting weir at high water levels (HL>60.1m) (even if the Chapel Mires spillway is closed off).

Hydrological modelling of Balgavies Loch water levels

The suite of stage-discharge curves shown in Figures 4 and 5 have been used to generate "lookup tables" to allow the hydrological model to operate dynamically across a range of values of H_L, Q_B and weir settings (see equation 1). Figure 6a shows the simulated impacts of gate management for the Balgavies Loch water level time series from March 2014 to Nov 2017, using equation (1). Observed levels are also shown. This period includes two winters where water levels in Balgavies Loch rose to values >59.8m for 7d (2014/5) and 31d (2015/6) respectively, a level at which flooding of the car park and road at Rescobie Loch boathouse occurs (see Appendix 3 for a plot of the observed relationship between Rescobie Loch water levels and Balgavies Loch water levels). The base levels during summer fall to around 59.4m above sea level. Modelling of the water levels under current weir and channel conditions agrees reasonably well with the observed data, but there are periods where significant discrepancies occur. Note that the model is using upscaling of Q_B to generate the Loch water input, and if spatial variation in the rainfall across the catchment occurs, this may lead to significant discrepancies. Also, we assume no net impact of groundwater.

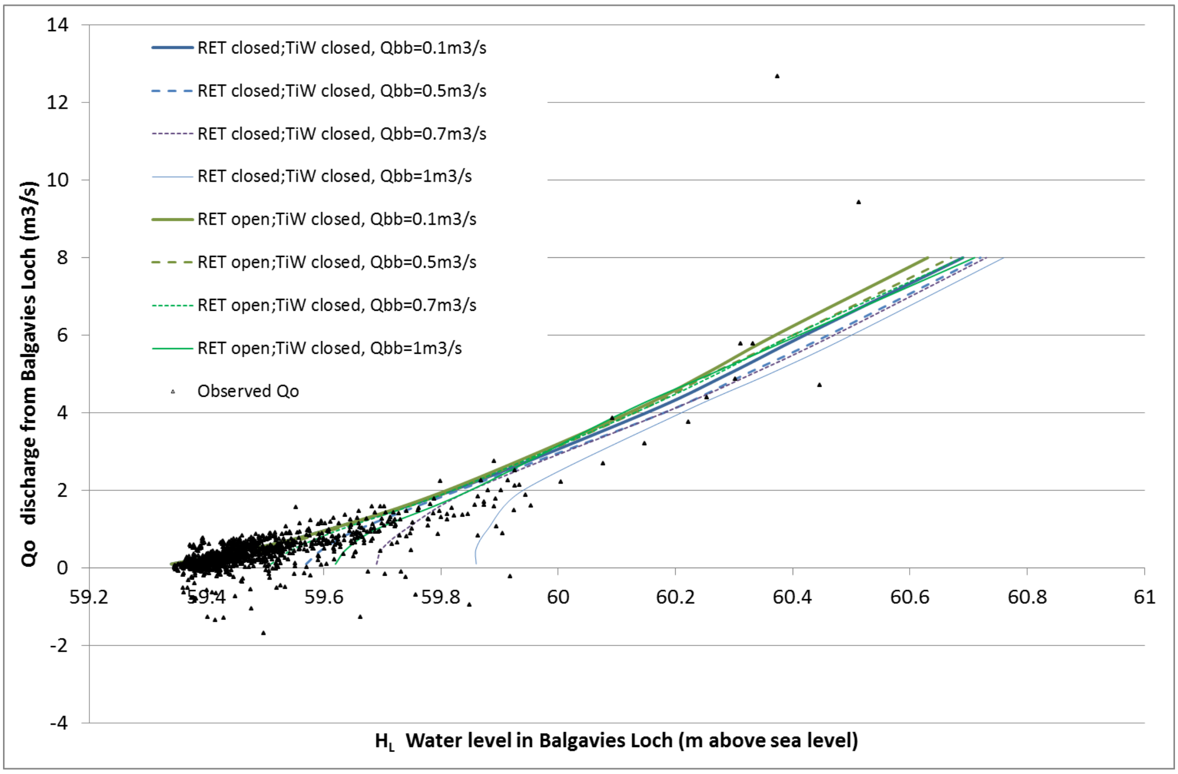
The impact of the position of Milldens return gate on simulated water levels is most evident at very high water levels, and very little additional impact of introduction of the tilting weir into the undredged channel is evident. However, there is a large impact of dredging on water levels in the Loch at all except the very highest water levels (H_L>60.0m). The modelled periods when water level in Balgavies Loch rise above 59.8m decreases to 0 days and 20 days for 2014/5 and 2016 respectively. The base level in summer is also about 0.5m lower. The water level exceedance curves (Figure 6b) show that the modelled risk of the water level exceeding 59.8m (the level when flooding of the road at Rescobie boathouse will occur) is decreased from a measured value of 3.0% (11 d/year) to 0.9% (3 d/year) by the dredging and marginally by the position of the Milldens return gate and the tilting weir. Thi impact of the gate/weir operation is larger at intermediate flows.

Modelling and measurements of flow through Chapel Mires spillway

As well as water levels in Balgavies Loch, the proportion of flow passing over the Chapel Mires spillway (CMS), with potential impact on nutrient, sediment and water loading to the ecologically sensitive Chapel Mires, is influenced by the position of the Milldens return gate and the tilting weir. Figure 7a shows examples of these modelled relationships. It can be seen that the fraction of water travelling through the CMS decreases with increasing discharge, and for a given discharge, the fraction decreases when the return gate is open, and further decreases when the tilting weir is open and when dredging occur. Reduction in flow across the Chapel Mires spillway is most marked for the dredged channel, with the tilting weir open, and located at the old spillway.

Note that the benefit of this reduction in flow through CMS is that there is less likelihood of the reduced river flows into Chapel Mires mixing with the much less polluted water in the Chapel Mires, especially in those mires protected by the culverted embankment on the southern edge of the wetlands (see Appendix 4 for pictures). High levels of sediment transport, which favour degradation of the Chapel Mires vegetation, are especially likely at high flows, while high levels of soluble P transport are likely to be associated with relatively low flows at the end of summer (see Vinten et al., 2017b).

The results of 2016-2017 flow measurements of the split of discharge from Balgavies Loch down the Chapel Mires spillway, and onwards down the mill lade, a function of whether the Milldens return gate is open or closed, are summarised in Figure 7b. This shows that the position of the existing return gate makes a difference to the fraction of flow travelling via the chapel mires spillway. At such flows, the model with just the return gate open simulated nearly all of the flow passing over CMS, but our observations showed only 37-90%. This may reflect the presence of entrapped vegetation across the CMS (see Fig 3a), increasing the resistance to flow across the spillway. Further information on the observed dynamics of flow can be found in Vinten et al., 2017A, which suggests that the position of the Milldens return gate impacts discharge out of the loch, when the water level in the Loch exceeds about 59.4 m above sea level.



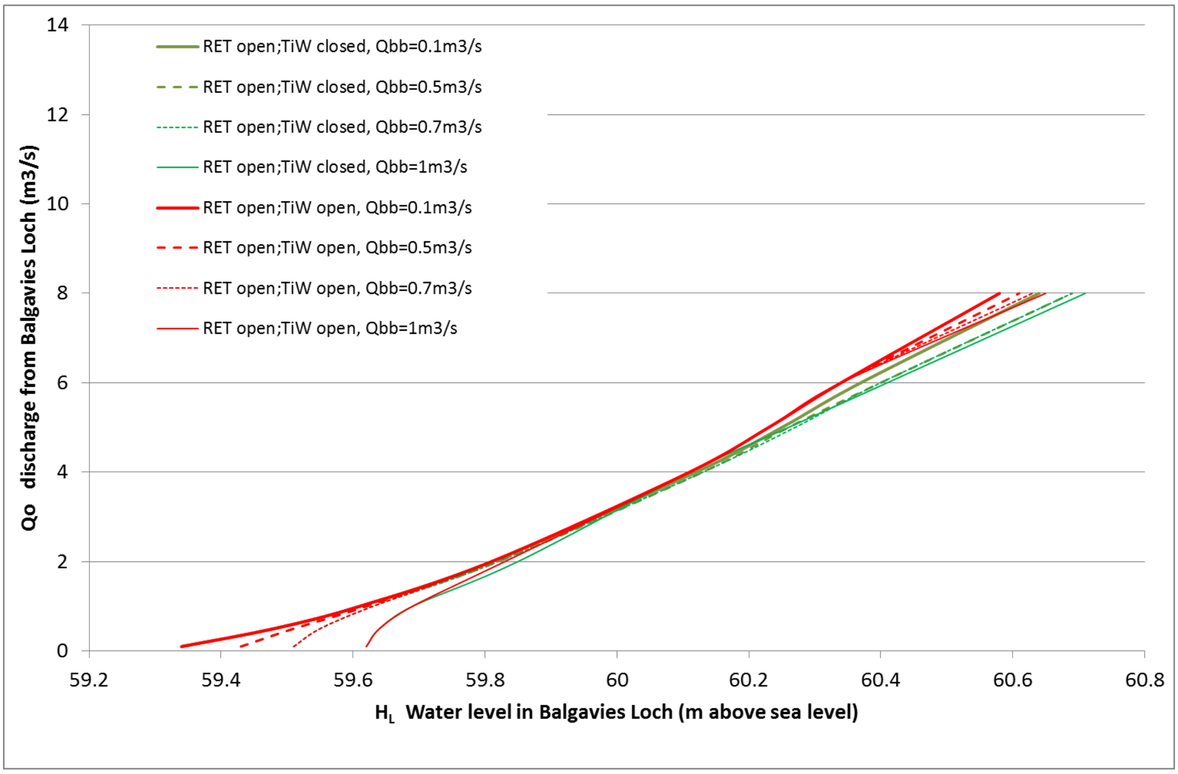


Figure 4. HECRAS modelled and observed Stage-discharge relationships. (a) Return gate closed (blue lines) and return gate open (green lines). Daily mean observed Q_o-H_L data also shown. Inflow from Balgavies Burn tributary varies from 0.1 to 1 m^3/s (b)Return gate open (green lines) and return gate+tilting weir open(red lines). Inflow from Balgavies Burn tributary varies from 0.1 to 1 m^3/s across four lines for each weir gate setting.

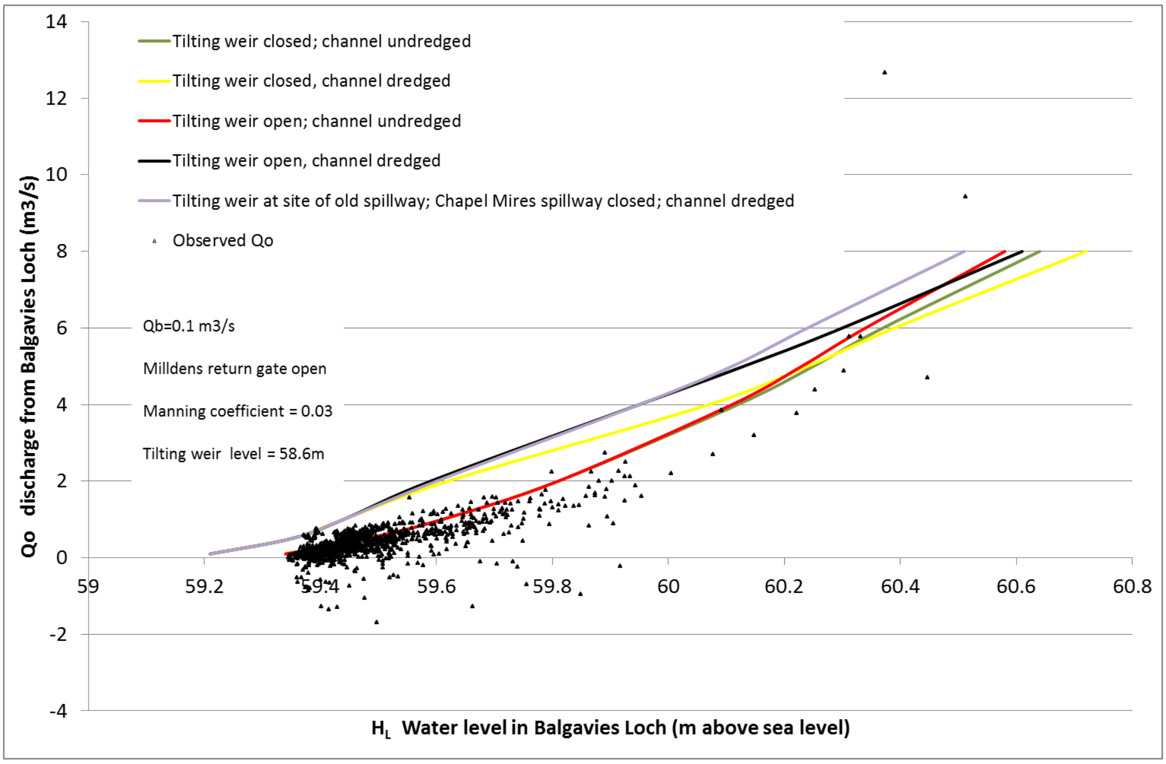


Figure 5. HECRAS modelled impact of 50cm of channel dredging of the Common Lade (see Figure 2 – dredging shown by dotted line), with and without presence of a tilting weir with level 58.6m. Also shown (grey line) is the impact of moving the tilting weir site to the (currently blocked) old spillway at chainage 274m, after dredging.

Discussion

This report on hydraulic and hydrological modelling of flows downstream of Balgavies Loch updates the report made to the 5th Lunan Catchment Management group, making use of surveys of channel cross sections undertaken in October 2017 by S. Addy and more detailed schematisation of the Balgavies Loch-Common Lade-Milldens Lade channel using HECRAS 5.0.1 model. This analysis is intended to assess the proof of concept of introducing (a) a tilting weir and (b)channel dredging, as methods to reduce risk of flooding and reduce risk of high sediment and nutrient loads entering Chapel Mires.

The analysis suggests that, under current lade conditions, introduction of a tilting weir with current common lade bed levels will only have a small impact on upstream flooding when levels in the Loch are <59.8m. Only at very high water levels (H_L>60.2m) do we see an upstream benefit of the proposed tilting weir. While reducing such risk may be valuable, it occurs very infrequently, and at such levels further release of water may lead to undue risk of increasing the flood peak downstream. We do not advocate the use of a tilting weir to relieve upstream flooding in these very high flow conditions.

The beneficial impact of dredging the common lade between the loch outlet and the Milldens weir on reduction of water levels in the loch under conditions where there is a risk of flooding, and on reducing the risk of high, sediment/nutrient laden flows into Chapel Mires, is clear. When dredging has taken place, the impact of the tilting weir, either at the site downstream of the bridge and upstream of the confluence of the Balgavies Burn, or at the site of the old, blocked spillway further upstream, is greater, especially at water levels >59.6m. However the additional direct benefit of the tilting weir on loch water levels still is quite small.

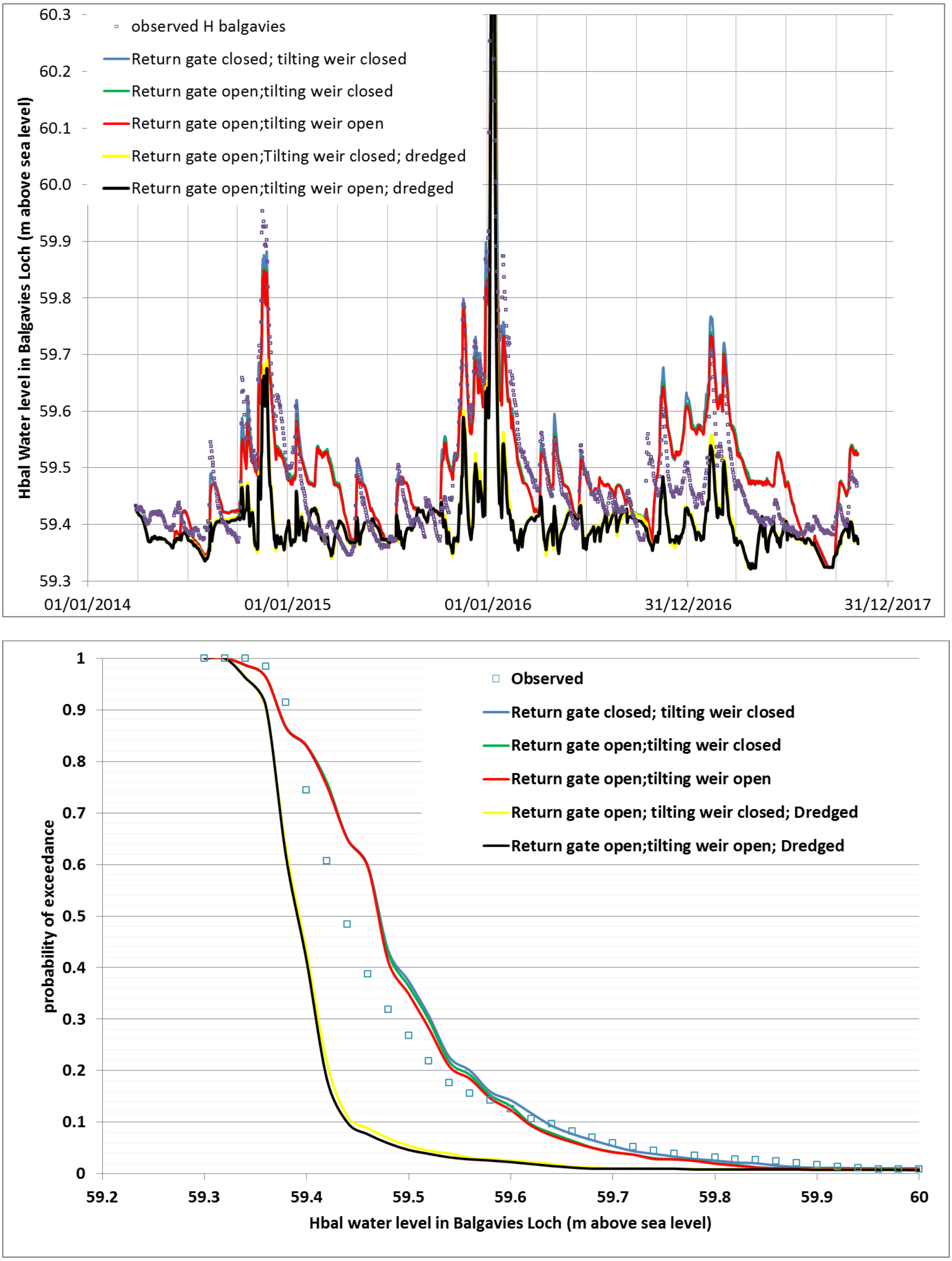
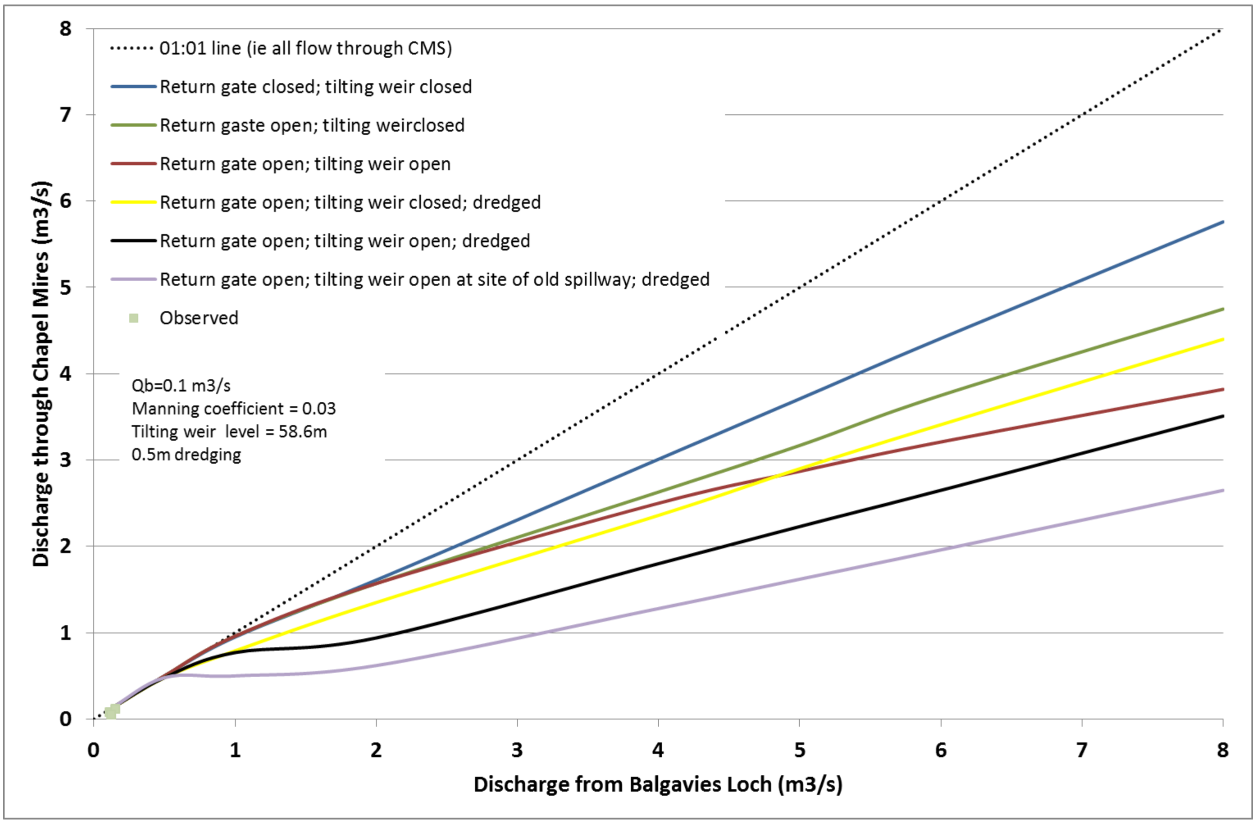


Figure 6. (a). Time series of observed water levels in Balgavies Loch, compared to simulated levels using the stage discharge relationship obtained from HECRAS, and equation (1). (b) Water level exceedance curves for Balgavies Loch – observed compared with modelled values for the period March 2015-Nov 2017.



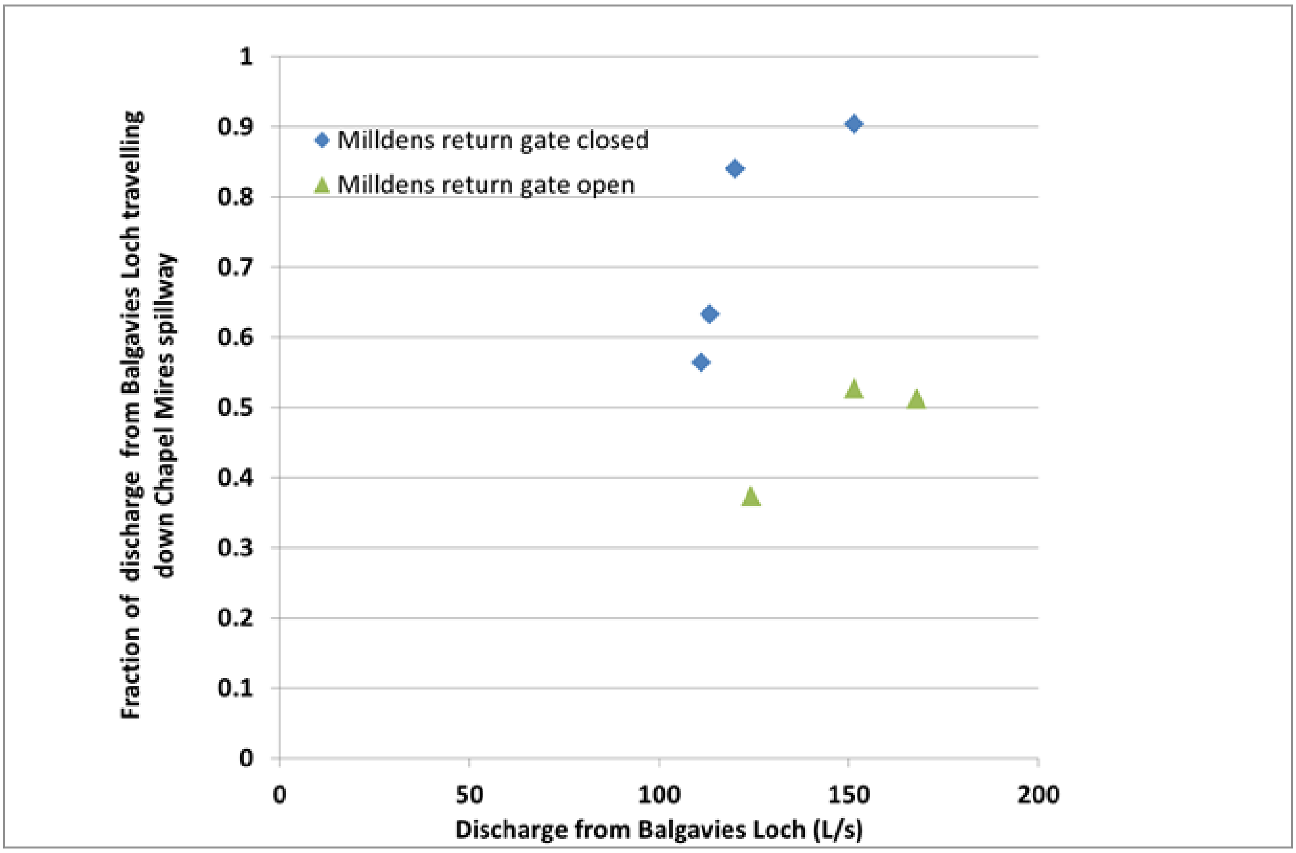


Figure 7. (a). HECRAS simulations of the split of flow between Chapel Mires spillway and continuation down the common lade to Milldens with different weir settings and dredging assumptions; (b) Summary of the observed split of instantaneous discharge measurements of discharge down Chapel Mires spillway and onward down the common lade (see figure 3a).

The analysis suggests that operation of the tilting weir is useful in reduction of river flow to Chapel Mires at times when it carries a large burden of sediment and nutrients. A joint report with CEH report will address the issue of when such large burdens of nutrients and sediment, occur, based on analysis of the loch outflow water quality. For example, in the most sensitive parts of Chapel Mires, water levels measured in May 2015 were 59.25-59.4m. Such water levels at Chapel Mires spillway are associated with loch outflow >1m^3/s, which occurs about 9% of the time. We have no detailed water level measurements in Chapel Mires at high flow periods, but Appendix 4 shows views of the Chapel Mires Pond 2 after the high flooding events in Jan 2016 and March 2018. Assessing the impact of reducing flows into Chapel Mires on mixing of river water and wetland waters under these circumstances requires further modelling and/or end member mixing analysis (see Vinten et al., 2017b).

The impact of the flow from Balgavies Burn into the common lade has been assessed for 1D flow conditions and it has been shown to significantly impact the flow of water from the Loch. Depending on the siting and operation of the tilting weir, It is likely this will actually cause some 2D flow (ie reverse flow) of water from Balgavies Burn to the tilting weir offtake, which will increase the impact of introducing the tilting weir, compared to the 1D modelling undertaken until now.

To maintain the benefit of dredging through time, a management scheme needs to consider how to deal with the future ingress of sediment. Installation of a tilting weir, or a manually operated weir gate with bed level around 58.6m to promote flushing, is likely to be beneficial at some point after dredging has been carried out.

Our modelling of the introduction of a tilting weir has assumed that siting is just upstream of the confluence of the Balgavies Burn. However, we note the existence of an old, blocked up spillway near measured cross section X4 (chainage 279m, see Appendix 2) at the bend in the Common Lade . At this blocked spillway there is a visible accumulation of sediment and vegetation, and a broadening of the channel. This suggests that the moving of the spillway from this old site to its current position at some point in the past (?1978) has led, along with other factors, to the observed sediment accumulation, and contributed to the observed upward trend in water levels in Balgavies Loch (see Vinten et al., 2017a). We also note the presence of a cattle drinking area and associated sediment accumulation at cross section X5, chainage 369m (see Appendix 4). Our modelling of the impact of having a weir at this site is that it would have a similar effect on water levels in Balgavies Loch, but provide for greater flexibility in terms of diversion of waters from the existing Chapel Mires spillway. Closure of the existing spillway to direct all spillage water through the old spillway, with a similar bed level, leads to similar results.

We therefore suggest that agreement be pursued between riparian owners, Angus Council and regulatory Agencies to carry out dredging of the common lade between Balgavies Loch outlet and Milldens Weir. To ensure long term benefit of such action, and to deliver reduction in nutrient and sediment input into Chapel Mires, installation of a tilting weir, or a manually operated weir gate, at the site of the old, blocked spillway, would be valuable. Given the challenges of agreeing long term governance of a tilting weir (Shortall, 2018), it may be better to pursue a manually operated structure, whose management could be incorporated into the management scheme operated currently for the existing Milldens weir gates by the riparian owners. Results of the project are being reported to Angus Council and Agencies through the Lunan Catchment Management Group for consideration.

In a willingness to pay survey in the catchment (Kuhfuss 2017), opinion about the scheme among local residents was positive, but farmers were more divided. The preferred option for governance, among those surveyed, was through local government. As noted by Shortall (2018), options for water management other than the status quo are currently restricted by absence of viable long term governance structures. “Water for all” project work will now shift focus to consideration of water “governance gaps” on a national basis, and to provision of expert input to Angus Council. Options for filling “governance gaps”, include the development of drainage boards (eg. http://www.parliament.scot/parliamentarybusiness/Bills/103888.aspx).

Conclusions

1. The existing hydraulic structures in the reach of the Lunan Water downstream of Balgavies Loch, and their management, lead to a current risk of roadside flooding at Rescobie Loch of 3%, based on observations from 2014-2017.
2. Neither the introduction of a lateral tilting weir with minimum level 0.44m below the current in-line and lateral control structures at Milldens weir, nor management of the existing lateral structures can reduce this risk significantly.
3. Carrying out dredging of the channel would reduce the current observed risk of flooding of Rescobie Loch to >60m above sea level from the current observed level of 3% to around 1%, based on model simulations.
4. Both under current and dredged channel conditions, the operation of a lateral tilting weir, provides opportunity for diversion of seasonal nutrient/sediment rich water from Balgavies Loch away from Chapel Mires wetland.
5. To maintain this benefit, a lateral weir (either a remotely operated tilting weir, or a manually operated structure), could be installed at the site of an old, blocked spillway further upstream, where sediment currently accumulates. This would help to keep the channel free from sediment in future.
6. Results of the project are being reported to Angus Council and Agencies through the Lunan Catchment Management Group for consideration. See PESLES website (2018).
7. The project will now explore, at a wider scale, how "governance gaps" which prevent development of long term water management can be bridged.

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AV 20.3.2017

Acknowledgements

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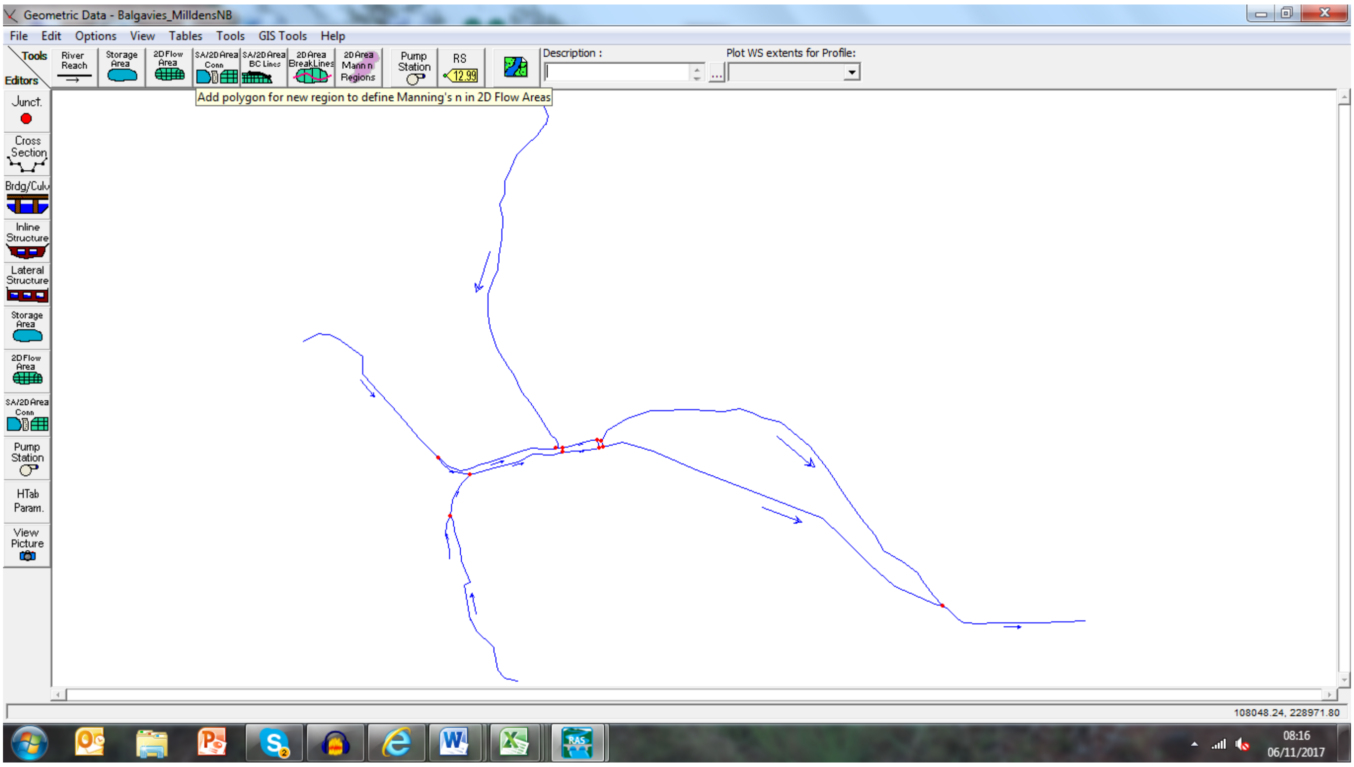
Access permission and ongoing dialogue with riparian owners in the Lunan Water catchment is also gratefully acknowledged.

Appendix 1. **Hydraulic network of the area downstream of Balgavies Loch in the HECRAS 5.0.1 Geometric data editor. Note: Balgavies Loch not shown.**



Appendix 2. Summary of cross section data used for HECRAS 5.0.1 steady state flow modelling in the the Lunan Water – Balgavies Loch – Common Lade – Milldens lade – Lunan Water channel.

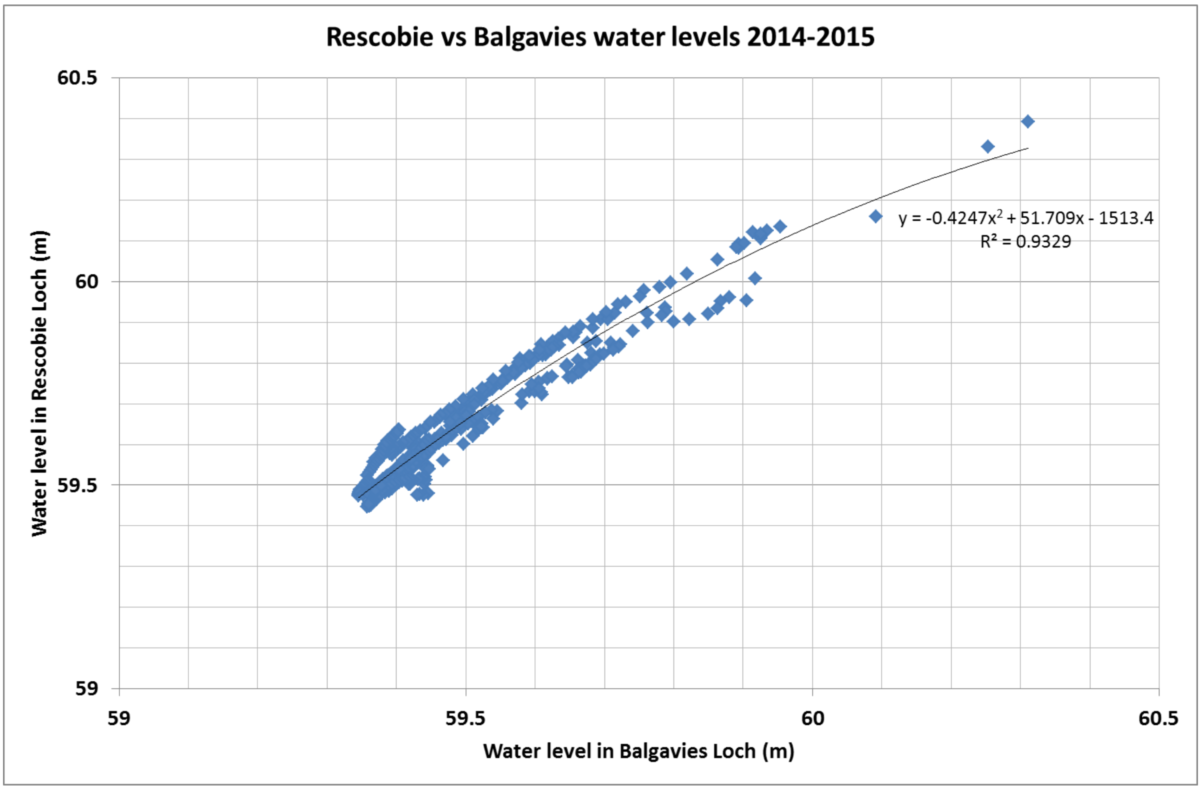
Surveyor and date	Vinten 2015			Loch bathymetry 1903				Vinten 2015		Compton 1978		Vinten 2015		Compton 1978		Addy 2017	
Chainage of upstream reach (m)		0		10	164	164	164		71		64		15		25		116
Cum. Chainage from Balgavies Loch outlet (m)		-573		-563	-399	-235	-71		0		65		79		104		220
LHB Easting		353204							353744		353789		353790		353807		353885
LHB Northing		751108							750916		750870		750885		750866		750780
crosssection no.		30		29	28	27	26		25		24		23		22		21
Description of cross section	Lunan Water at railway bridge			Balgavies Loch				Balgavies Loch outlet		Culvert outlet		bend		sluggish section		upstream of Chapel Mires spillway (X1)	
	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	bed elevation (m)	bed elevation (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)
	0.00	61.00	0.00	64.28	64.28	64.28	64.28	0.00	61.00	0.00	61.00	0.00	61.00	0.00	61.00	0.00	61.00
	0.01	59.48	5.00	58.98	59.28	59.28	59.28	0.01	59.48	0.01	59.48	0.10	59.12	0.01	59.48	0.01	59.73
	0.02	59.04	86.97	58.06	58.37	59.28	59.28	0.02	59.04	0.02	59.07	0.20	58.67	0.02	59.04	0.82	59.70
	5.00	59.35	168.93	55.63	56.24	56.54	58.37	5.00	59.35	5.00	59.35	1.10	58.72	5.00	59.35	1.59	59.67
	5.00	59.48	250.90	56.24	55.93	55.32	56.54	5.00	59.48	5.00	59.48	1.53	58.86	5.00	59.48	2.32	59.62
	5.01	61.00	332.87	58.98	58.06	54.10	51.36	5.01	61.00	5.01	61.00	3.84	58.71	5.01	61.00	3.15	59.61
			414.84	59.28	59.28	57.15	56.24					6.72	58.80			3.39	59.29
			496.80	64.28	64.28	64.28	64.28					6.73	58.80			3.69	59.05
												6.74	61.00			4.15	58.95
																4.58	58.86
																5.26	58.77
																8.32	58.85
																8.81	59.26
																9.61	59.44
																15.91	59.34
																15.92	61.00

Surveyor and date			Addy 2017		Addy 2017		Vinten 2015		Addy 2017		Addy 2017				Addy 2017			Addy 2017		Addy 2017
Chainage of upstream reach (m)	5			12		33		9		24		71	1	4		1	1		12	1
Cum. Chainage from Balgavies Loch outlet (m)	225			237		270		279		303		374	375	379		380	381		393	394
LHB Easting	**353883**			353897		353918		353927		353947		354015								354035
LHB Northing	**750775**			750768		750743		750747		750759		750777								750782
crosssection no.	20.1			20		19		18		17		16	15.9	15.8		15,78	15.1		15	7.1
Description of cross section	Lateral outflow through Chapel Mires spillway		downstream of Chapel Mires spillway (part of X2)		wide, vegetated section (X3)		at barrier to old spillway into Lunan Water		just d/s of bend (X4)		just u/s of bridge/culvert (lade part of X5)		4m culvert		just d/s of bridge/culvert u/s of BB (copy of X7)		Proposed tilting weir lateral outflow just d/s of bridge	just u/s of BB (copy of X7)		Balgavies Burn tributary inflow
	CMS spillway		distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)		distance from LHB (m)	bed elevation (m)	
	0.00	61.00	0.00	61.00	0.00	61.00	0.00	61.00	0.00	61.00	0.00	61.00	0.00	61.00	0.00	61.00		0.00	61.00	
	0.01	58.90	0.01	59.91	0.01	59.34	0.01	59.16	0.01	60.37	0.01	60.08	0.10	58.98	0.10	60.19		0.01	60.19	
	2.69	58.90	1.02	59.94	0.37	58.78	0.20	58.90	1.18	60.16	1.34	59.87	3.40	58.98	1.10	60.26		1.10	60.26	
	2.70	61.00	2.05	59.97	1.04	58.79	0.65	58.81	2.28	60.16	3.04	59.71	3.50	61.00	2.41	60.47		2.41	60.47	
			3.22	59.99	2.20	58.85	1.49	58.80	3.38	60.23	4.57	59.57			2.76	60.42		2.76	60.42	
			4.15	59.82	3.06	58.82	2.58	58.78	4.43	60.11	5.29	59.72			4.12	59.95		4.12	59.95	
			5.01	59.72	4.06	58.77	3.61	58.83	5.07	59.82	6.61	59.54			4.53	59.43		4.53	59.43	
			5.53	59.42	4.50	58.88	4.48	58.84	5.50	59.34	7.62	59.66			5.16	59.14		5.16	59.14	
			6.16	58.85	4.87	59.08	5.35	58.89	5.69	59.10	7.96	59.61			5.32	59.10		5.32	59.10	
			6.27	59.08	5.12	59.37	5.44	59.16	6.71	58.87	8.56	59.46			5.75	58.93		5.75	58.93	
			6.34	59.02	6.08	59.77	5.45	59.88	8.69	58.51	9.37	59.36			6.45	58.80		6.45	58.80	
			6.37	58.97	7.35	59.78	5.47	61.00	9.45	58.83	9.83	59.32			7.20	58.59		7.20	58.59	
			6.73	59.04	7.36	61.00			9.99	59.12	10.65	59.31			7.84	58.70		7.84	58.70	
			6.83	58.80					10.44	59.57	11.12	59.32			8.43	58.72		8.43	58.72	
			7.10	59.22					11.59	59.81	11.51	59.45			8.18	58.88		8.18	58.88	
			11.01	59.45					12.53	59.76	11.57	59.56			8.94	59.09		8.94	59.09	
			12.08	59.43					13.56	59.83	11.77	60.36			9.96	60.88		9.96	60.88	
			13.35	59.41					14.90	59.99	12.38	60.89			9.97	61		9.97	61	
			13.36	61					14.91	61	13.17	60.84								
											14.47	60.76								
											15.41	60.86								
											16.45	60.87								
											16.46	61								

Surveyor and date	Addy 2017		Compton 1978		Addy 2017		Compton 1978		mpton 1978		Vinten 2015		Vinten 2015		Vinten 2015		Addy 2017		Compton 1978		Compton 1978	
Chainage of upstream reach (m)	13		46		1		1		1		1		10		11		359		174		187	
Cum. Chainage from Balgavies Loch outlet (m)	407		453		454		455		456		457		467		478		838		1012		1199	
LHB Easting	354049		354097								354097		354102		354111		354400		354521			
LHB Northing	750780		750802								750802		750811		750818		750710		750585			
crosssection no.	7		6.8		6.75		6.74		6.73		6		5		4		3		2		1	
Description/label of cross section	d/s of bridge and BB inlet(X7)		Lateral Return flow weir to Lunan Water		copy of of X7		start of Inline weir gate to Milldens lade		end of Inline weir gate to Milldens lade		Start of Milldens lade		u/s railway culvert going N		d/s railway culvert going N		just u/s of railway culvert going S (X8)		based on d/s railway culvert (station 4) adjusted to Compton bed level		based on c/s of Lunan at Milldens weir, adjusted to Compton bed level at Mill Bridge	
	distance from LHB (m)	bed elevation (m)	distance (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)
	0.00	61.00	0.00	61.00	0.00	61.00	0.00	61.00	0.00	61.00	0.00	61.00	0.00	60.82	0.00	60.79	0.00	60.18	0.00	60.09	0.00	56.41
	0.01	60.19	0.01	59.04	0.01	60.19	0.01	59.04	0.01	59.04	0.01	60.19	0.01	60.19	0.01	60.16	0.01	59.55	0.01	59.46	0.40	56.21
	1.10	60.26	0.90	59.04	1.10	60.26	0.90	59.04	0.90	59.04	0.28	59.59	0.28	59.59	0.28	59.56	0.28	58.95	0.28	58.86	0.80	56.11
	2.41	60.47	0.91	61.00	2.41	60.47	0.91	61.00	0.91	61.00	0.84	59.48	0.84	59.48	0.84	59.45	0.84	58.84	0.84	58.75	1.20	56.10
	2.76	60.42			2.76	60.42					1.00	59.45	1.00	59.45	1.00	59.42	1.00	58.81	1.00	58.72	1.60	56.43
	4.12	59.95			4.12	59.95					1.36	59.07	1.36	59.07	1.36	59.04	1.36	58.43	1.36	58.34	2.00	56.13
	4.53	59.43			4.53	59.43					1.82	59.06	1.82	59.06	1.82	59.03	1.82	58.42	1.82	58.33	2.40	56.19
	5.16	59.14			5.16	59.14					1.90	59.04	1.90	59.04	1.90	59.01	1.90	58.40	1.90	58.31	2.80	56.21
	5.32	59.10			5.32	59.10					2.55	59.14	2.55	59.14	2.55	59.11	2.55	58.50	2.55	58.41	3.20	56.26
	5.75	58.93			5.75	58.93					3.04	59.11	3.04	59.11	3.04	59.08	3.04	58.47	3.04	58.38	3.60	56.34
	6.45	58.80			6.45	58.80					3.46	59.29	3.46	59.29	3.46	59.26	3.46	58.65	3.46	58.56	4.00	56.46
	7.20	58.59			7.20	58.59					3.54	59.49	3.54	59.49	3.54	59.46	3.54	58.85	3.54	58.76		
	7.84	58.70			7.84	58.70					3.67	59.59	3.67	59.59	3.67	59.56	3.67	58.95	3.67	58.86		
	8.43	58.72			8.43	58.72					4.02	59.77	4.02	59.77	4.02	59.74	4.02	59.13	4.02	59.04		
	8.18	58.88			8.18	58.88					4.29	59.78	4.29	59.78	4.29	59.75	4.29	59.14	4.29	59.05		
	8.94	59.09			8.94	59.09					5.11	61.00	5.11	59.82	5.11	59.79	5.11	59.18	5.11	59.09		
	9.96	60.88			9.96	60.88											5.8599	59.136				
	9.97	61			9.97	61											6.02	59.0657				
																	6.8269	58.974				
																	8.024	58.845				
																	8.6396	58.555				
																	9.5936	58.38				

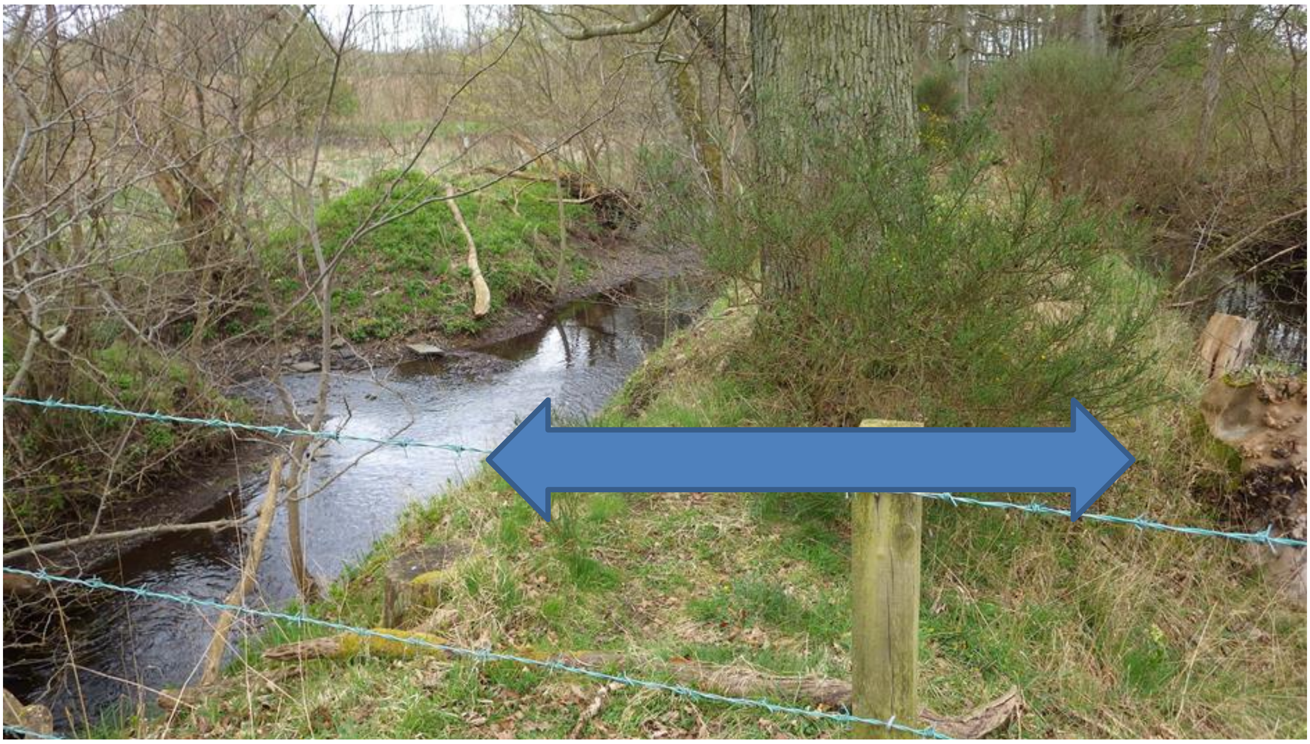
The table shows 3 lateral structures (cross sections 20.1, 15.1 and 6.8, in grey) and one in-line weir gate (cross section 6.73 to 6.73, in dark grey grey). Balgavies Burn inlet is shown in medium grey. Columns are colour coded according to the source of the data. Note that the channel boundary on cross sections at some points is set at 61.0m (in white) where necessary, to ensure no overtopping of the water from the channel, except at the modelled lateral structures. The grid reference of the left hand bank and the chainage from the outlet of Balgavies Loch is shown.

Appendix 3. **Plot of observed water levels in Rescobie Loch vs Balgavies Loch. March 2014-Jan 2016. The Rescobie Loch level recorder was lost in the floods of Jan 2016. The road at Rescobie boathouse floods when the level in Rescobie Loch exceed 60.0m.**



Appendix 4. **Picture gallery.**

A. Small, well conserved wetland on southern edge of Chapel Mires in (a) summer 2017 and (b) March 2018.



B. Proposed site of tilting weir at chainage 381m (see arrows). Note Balgavies Burn coming into Common Lade (on left) and the tailwater channel on the right. Looking east from bridge.

C. View of the Chapel Mires Pond 2 after the high flooding event in Jan 2016.

D. Milldens Lade in March 2018 at chainage 838m.

E. Cattle drinking area on Common Lade, chainage 374m in summer 2017.

F. Milldens weir at chainage 674m looking from East in spate.

G. Rescobie Loch Boathouse after storm Frank, Jan 2016 (not on map below).

H. Small wetland, Chapel Mires in June 2017

I. Pond 2 looking east

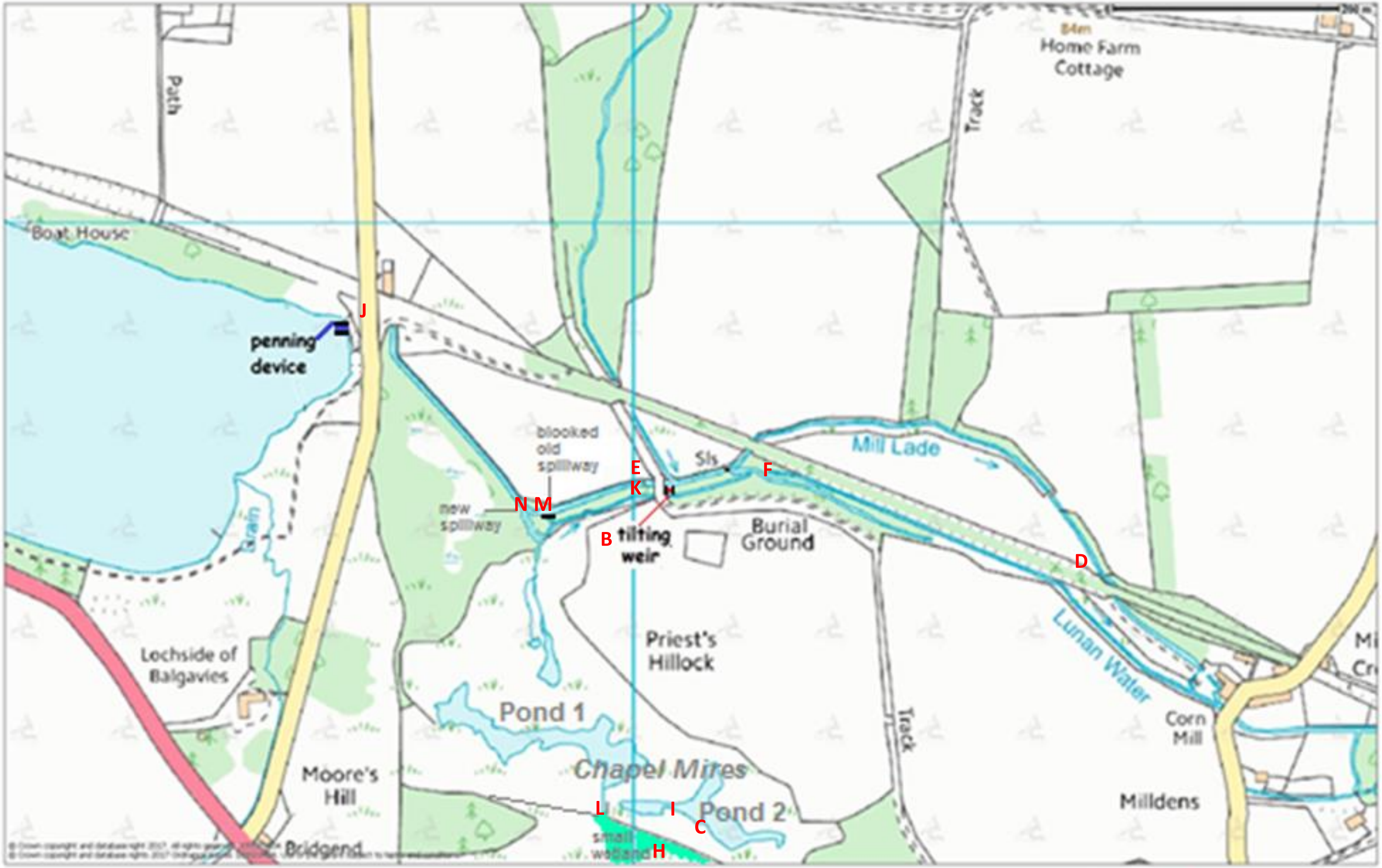
J. Outlet of Balgavies Loch (chainage =0m).

K. Debris dam above cattle bridge

L. Culverted embankment between small wetland (on right) and channel to Ponds 1 and 2 (on right). Looking west.

M. Wider section with sediment accumulation on bend just upstream of blocked spillway (chainage = 270m)

N. Chapel Mires spillway with Balgavies Loch level at H_L=59.7m



A

Scale 1:4836

N

LUNAN - Tiltiing Weir

Angus Council

Created by Janice Corrigan on 31 May 2017