Interim Report on Hydraulics modelling using HECRAS 5.0.1

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1. Introduction

Upgrading of an existing hydraulic structure 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., 2016). 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 funded "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, mitigation of low flows and improvement in wetland ecology through management of nutrient and sediment loads to sensitive areas.

The goals of the work introduced in this report are:

> 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 may impact (i) upstream water levels (ii) 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).
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> We also want to assess the impact of dredging accumulated sediment from the lade system, in conjunction with modified water management.

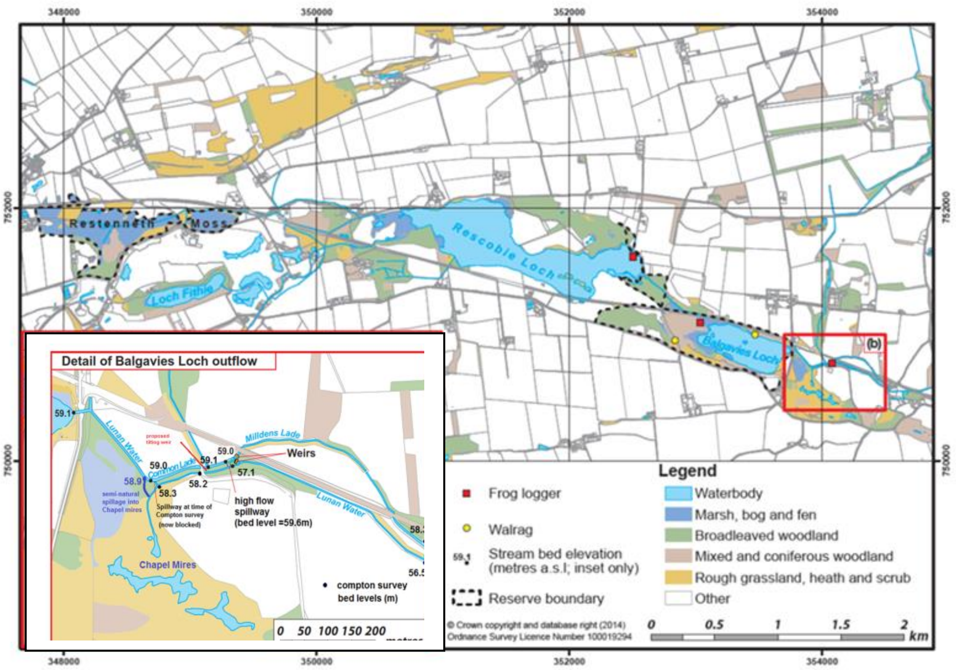

Figure 1. Overview of the upper Lunan Water catchment showing the main non-agricultural areas and positions of water level recorders in the current study (3 automated sites installed in 2014 and long term manual min-max-mean water level recording stations or WALRAGs). The inset shows detail of the Milldens weir and associated lades on the area downstream of the outlet to Balgavies Loch.

2. Methods

2.1 Hydraulic modelling

We are using the 1D/2D hydraulic modelling package HECRAS 5.0.1 (released 2016) to do this and have made a start on characterising the structures and flows. However, the system we are modelling is quite complex (see Appendix 1 for a depiction of the network), so we have simplified matters for a proof-of-concept approach. This simplified approach models steady, sub-critical in-channel flow along the mill lade as a uniform 3m wide channel from Balgavies Loch outlet (bed level 59.04 m) to the discharge of the mill lade at Milldens (bed level 58.3 m). An inline gate at Milldens weir delivers water to the downstream section of the lade via a constriction of flow to 0.9m and has a bed level of 59.0 m. We assume there are three potential lateral structures releasing water from the channel: the existing chapel mires spillway (CMS), the proposed tilting weir (TIW) and the existing return gate (RET) to the Lunan at Milldens weir. The bed level on TIW and RET can be varied. The discharge from Balgavies Burn is omitted from the proof of concept as this would require a 2D approach. We assume a normal depth boundary condition for steady flow at the inlet (slope =0.0012 m/m) and at the outlet (slope = 0.01 m/m) of the channel. We also explore the impact of deepening the channel upstream of Milldens weir by 30 cm dredging. The details of this schematic are shown in Figure 2 below.

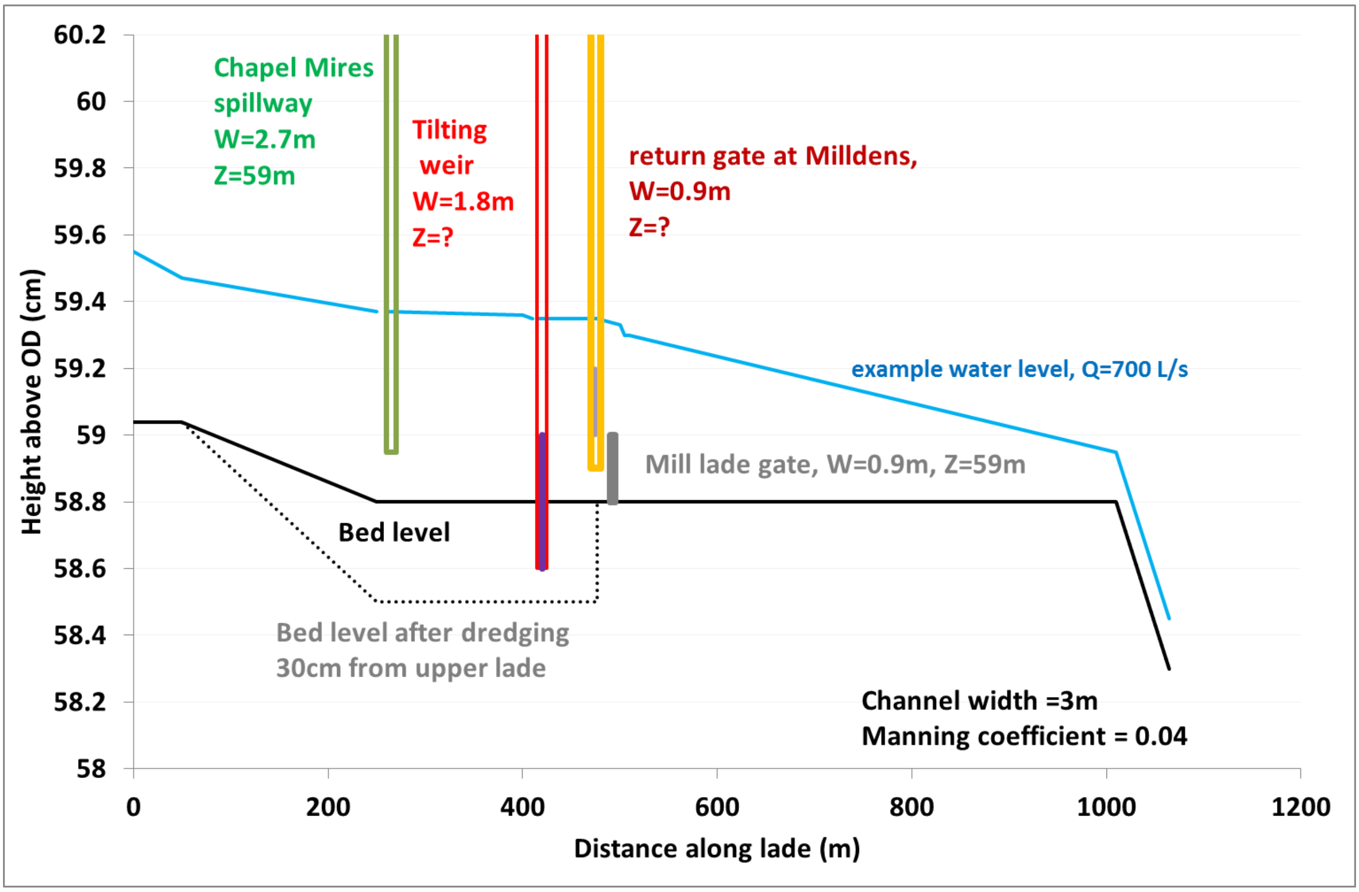

Figure 2. Schematic representation of the common lade and mill lade downstream of Balgavies Loch, and the outlet structures used for proof-of-concept work. Lateral structures discharge water to the main channel of the Lunan Water, which is assumed to act as an out-of-system tail water.

2.2 Flow and water level measurements

Maximum, minimum and periodic current water levels for Balgavies Loch were measured using water level maximum/minimum recorders (Bragg et al., 1994) were supplied for 2003-2014 by Scottish Wildlife Trust (Houghton, A., pers. comm.). Dynamic water level recorders (Frog systems and Van Walt) were installed from April 2014 at three points in the loch system, Balgavies Loch pier, Rescobie 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) 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 (which runs into the common lade from the north just upstream of the spillway (see Figure 1) have been monitored since 2006 (see Dunn et al., 2014 for details).

We used a simple empirical approach based on observations of impacts of weir gate management on water levels. We assume a similar hydrologic response of the Balgavies Loch catchment as a whole and the Balgavies Burn sub-catchment, the same runoff [mm/d] from both areas and no lag time. Then we can approximate the daily water balance for the above system as follows:

$$Q_O = (Q_B A_{LC}/A_{BC}) + Q_{GW} - A_L \frac{dH_L}{dt} \qquad (1)$$

Q_O = discharge through the culvert at the exit from Balgavies Loch (m^3/d).

H_L= Water level in the area of the lochs and associated wetlands which responds concurrently (T<1d) to stream and direct rainfall inputs and discharge from Balgavies Loch (m above ordinance datum).
A_L= Area of open water and wetlands which contributes to water level change observations (m^2).
A_{LC}= total catchment area of Balgavies Loch outlet (2370 ha or 23.7 x 10^6 m^2)
Q_B = daily discharge of Balgavies Burn (m^3/d)[1]
A_{BC} = catchment area of Balgavies Burn (440 ha or 4.40 x 10^6 m^2)
Q_{GW}= leakage/input of groundwater to lochs and wetlands, not accounted for by Q_B(m^3/d)
t = time (d)

Note that we assume that A_L and Q_{GW} are constants. They may vary with time, but we want to be parsimonious with the number of parameters in the empirical model at this stage. Using only days when the Milldens weir gates were both open, we solved equation (1) for Q_O.

Figure 3. A. Looking downstream to MIlldens weir mill lade gate (on left) and return gate to Lunan Water (on right).

B. Looking upstream on Common Lade showing lateral spillage to Chapel Mires Spillway (on left).

We then plotted results against Balgavies Loch outlet level H_L. We optimised the fit to a cubic polynomial with no quadratic term and no intercept (ie Q_{GW} =0) by changing the value of A_L (optimised value = 186 ha or 1.86 x 10^6 m^2). Using this calibration equation, we could simulate the water levels in Balgavies Loch using input values of Q_B, when the weir gates were open.

To assess the impact of gate closure/opening, we also analysed several experimental and other weir gate changes over 2014-2017, which give us a relationship between gate closure and Q_O, using equation 1.

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 were set to open on 21 July at 18:00. Discharge measurements were made on 26/27 July as follows:

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

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:
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 11 July 2016 to measure flows at Balgavies Loch outlet, the two weir gates, and the Chapel Mires spillway, and again on 30-31 October 2017 to measure flows at Chapel Mires spillway and a cross section just downstream of this spillway.

3. Results and discussion

3.1 HECRAS hydraulic modelling schematic of steady flow in channel.

We have used HECRAS 5.0.1 to explore the impact of introducing a tilting weir at H=59m on the system depicted in figure 2. We varied the inlet discharge from 100 to 2000 l/s. Fig 4 shows the impact on the flow through the Chapel Mires spillway lateral structure and the flow continuing on along the channel for four management options:

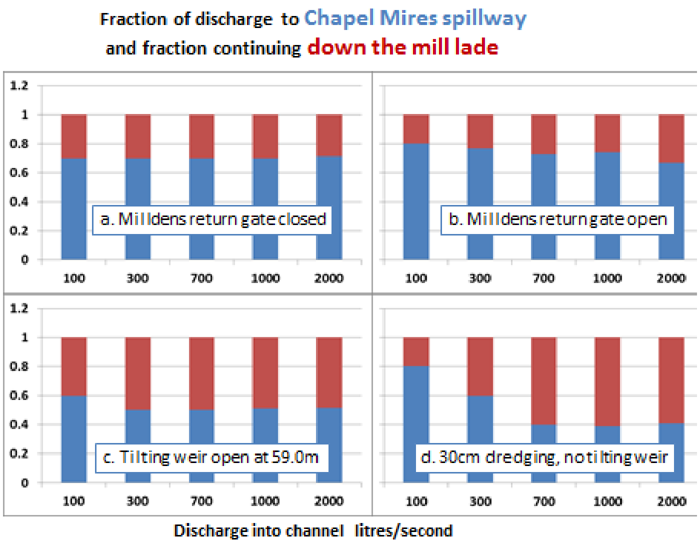

Figure 4. Fraction of discharge going into Chapel Mires and continuing down the channel as a function of lateral structure management.

a. **Milldens return gate (RET) closed, no tilting weir.** In this case around 70% of the discharge passes through CMS and 30% down the lade to the outlet. This fraction is not strongly influenced by channel discharge between 100 and 2000 litres/sec.
b. **Milldens return gate (RET) open, no tilting weir.** In this case the fraction of water passing through CMS is lower at low flows, but increases at higher flows, compared to option (a).The increased fraction at low flows is attributed to a backwater effect of the open return gate on water levels upstream.
c. **Tilting weir (TIW) also open, with bed level of 59.0m.** This leads to a decrease of the fraction of water flowing to CMS from 70% to 60% at low flows and to 50% at high flows.
d. **Dredging the channel upstream of the Milldens weir.** This leads to an increase in the fraction of flow through CMS to 80% at low flows, but a decrease to 40% at high flows.

This simplified approach demonstrates that both dredging and the tilting weir (options c and d) could reduce flow of water (and associated sediment and nutrients) through Chapel Mires, especially at higher flows. However it should be noted that the dredged channel will refill with sediment from Balgavies Burn, under current management. A tilting weir between the lade and the main channel would help to divert this sediment downstream and so help maintain the capacity of the lade.

Figure 5 shows the impact of management options on the stage-discharge relationship at the inlet to the channel.

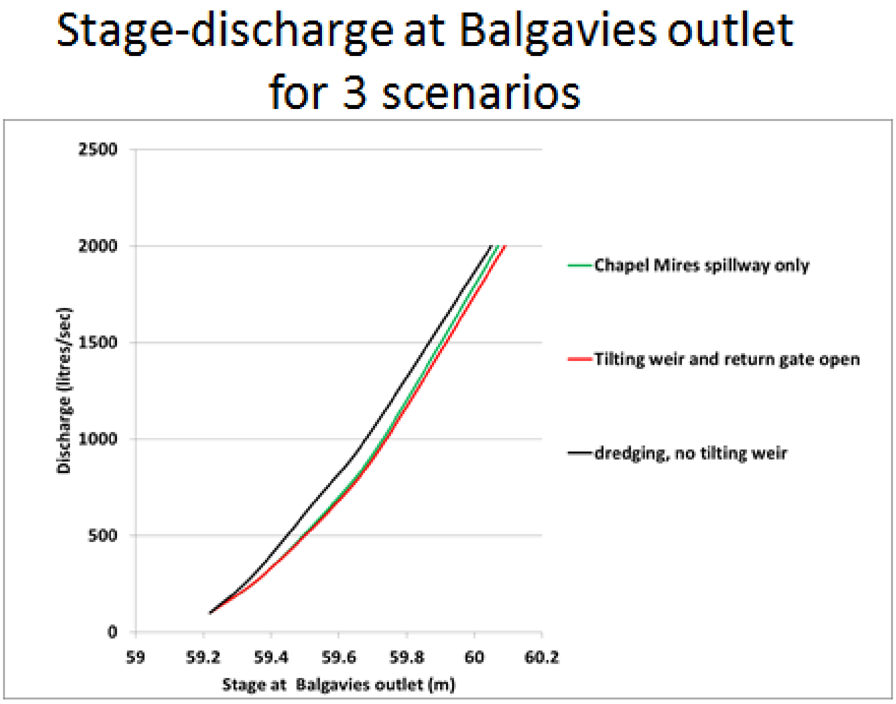

Figure 5. HECRAS modelling of steady flow in channel shown in Figure 2. Impact of management options (c) and (d) on the stage-discharge relationship at the channel inlet.

This shows that there is little impact of the tilting weir on the relationship, and even a slight reduction in discharge for a given head, compared with the control, presumably due to a backwater effect of flow over the weir. There is however a significant increase in the discharge for a given channel inlet head, after dredging.

3.2 Observed stage-discharge relationship for outlet to Balgavies Loch.

Stage-discharge simulations for this schematic approach are compared with observed data derived using a water balance approach (eq (1) in Figure 6.

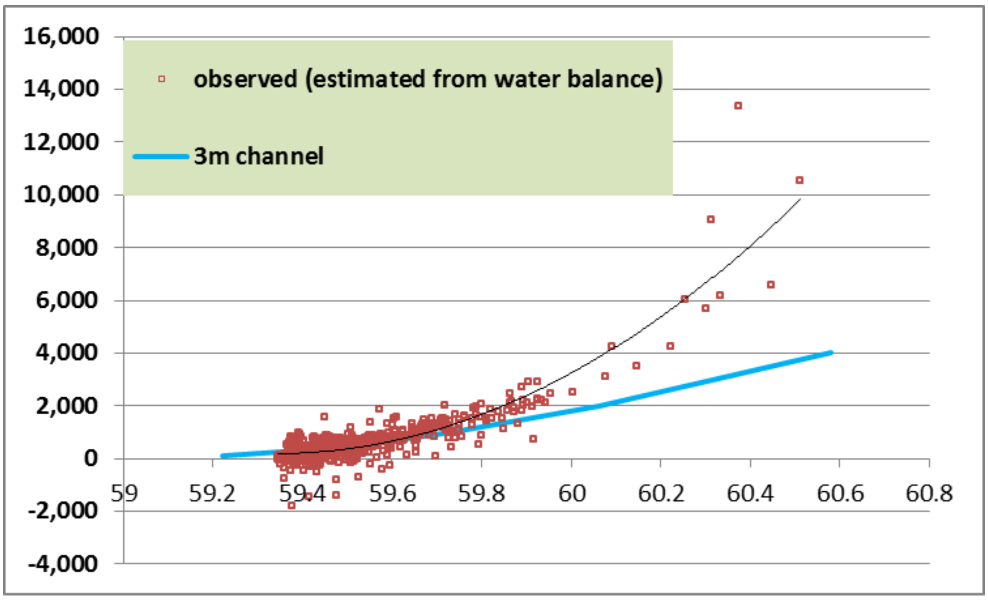

Figure 6. Channel inlet stage (water level above OD in m) vs discharge (in litres/second) compared with observed stage-discharge relationship based on eq (1). (see fig 9 in Vinten et al.,2016 for more details)

This shows that while the relationship agrees well with the polynomial fit to observed data at low discharge, it begins to deviate at higher flows (>1000 L s^{-1}). This is not surprising, as the impact on water levels of both flow out with the channel and of tail waters receiving the flows, is likely to increase as channel levels approach bankfull. Also the flow could become supercritical at high discharge, leading to lower head values for a given discharge.

3.3 Measurements of flow splitting between chapel mires spillway and the mill lade.

The results of 2016-2017 Valeport measurements of the split of discharge from Balgavies Loch down the Chapel Mires spillway, and onwards down the mill lade as a function of whether the Milldens return gate is open or closed, are summarised in Figure 6. This shows that the position of the existing return gate makes a difference to the fraction of flow travelling via the chapel mires spillway. However these measurements are only taken over a quite narrow range of discharge conditions. Note also that these are instantaneous flow measurements in a dynamic, non-steady state system, and cannot therefore be compared directly to the steady state modelling results shown in Figure 4. Further information on the observed dynamics of flow can be found in Vinten et al., 2016, which suggests that the position of the return gate makes a difference to overall discharge out of the loch, when the water level in the Loch exceeds about 59.4 m above OD.

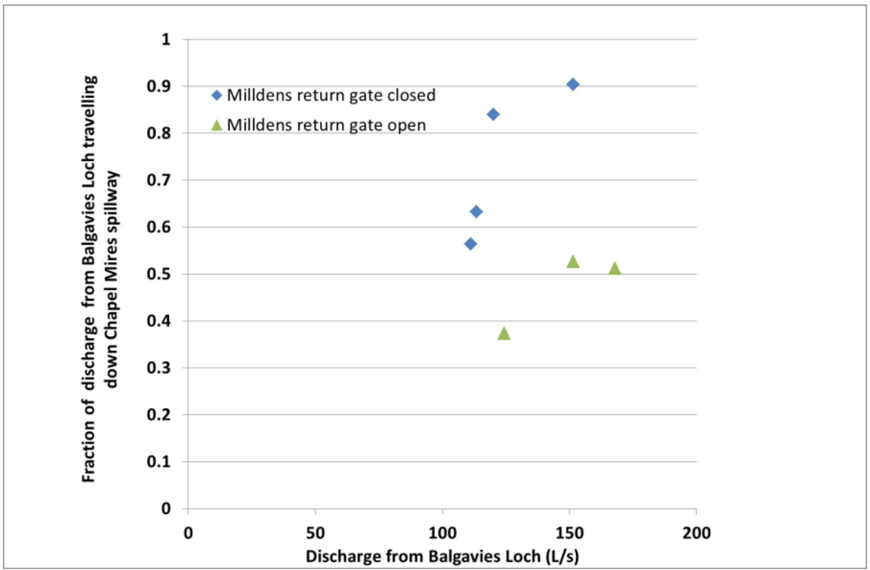

Figure 6. Summary of the split of instantaneous discharge measurements of discharge down Chapel Mires spillway and onward down the common lade (see figure 3b).

4. Conclusions

1. The above analysis is only intended as a proof of concept, and more detailed hydraulic analysis based on the observed topography and measured cross sections is required. This will take further time to deliver.
2. The analysis does show, however, that a tilting weir could be useful in delivering reduction of river flow to Chapel Mires at times when it carries a large burden of sediment and nutrients.
3. A tilting weir appears to be less useful for delivering reduction in water levels upstream, but to confirm this modelling which includes upstream standing water bodies (Balgavies Loch and Chapel Mires ponds) is needed, as well as considering supercritical flows.
4. Moreover, the impact of the introduction of flow from Balgavies Burn into the scheme at X=430m needs to be assessed. It is likely this will cause some 2D flow, and hence hold up drainage from the Loch at high flows. This will be alleviated by a tilting weir in the proposed location just upstream of the confluence (see Fig 1).
5. The beneficial impact of dredging the mill lade upstream of the weir is quite clear, and we recommend that a separate consent application to deliver this be drawn up, while the above hydraulic modelling is completed. The riparian owners are amenable to dredging, and as yet are not sympathetic to a consent application for hydraulic modification.
6. To maintain the benefit of the dredging through time, a management scheme needs to consider how to deal with the future ingress of sediment, and a tilting weir, or other structure to promote flushing, is likely to be beneficial.
7. There is minor indication of a backwater effect of opening the return gate at Milldens weir, and for this reason, it may be better to maintain both the return gate and the gate to mildens lade in closed position during winter.
8. To improve our modelling of the actual channels, a detailed survey of the channel cross sections for both the lade and Lunan Water is recommended, to supplement existing data.

5. References

Vinten AJA, Wilkinson, M, Sample J, Rear L, Hoang-Cong C, Novo P, and Halliday M. (2016). Water level management in the upper Lunan Water, Angus, Scotland: threat or opportunity for improved delivery of water ecosystem services? Report for 3rd Lunan Catchment Management Group Meeting, April 2017. http://www.hutton.ac.uk/sites/default/files/files/Lunan%20Water%20Managementv12.pdf

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Appendix 1. Hydraulic network of the area downstream of Balgavies Loch for future, more detailed modelling using HECRAS 5.0.1.