A simple empirical model for simulation of water levels in Balgavies Loch and downstream discharge as a function of inflow to Loch and weir gate management.

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13.01.2017

Introduction

As part of a Scottish Government (RESAS) funded project (Payments for Ecosystem Services – Lessons or PESLES) JHI are exploring the potential for installing a tilting weir to assist water management and ecosystem service delivery downstream of Balgavies Loch in the Lunan Water catchment. We are building evidence that such flexible structures would have the potential to:

(a) Reduce risk of upstream flooding associated with winter storm events;
(b) Increase availability of water to downstream irrigators;
(c) Help protect rare floodplain wetland habitats by diverting phosphate rich water draining from Balgavies Loch in late summer.

In order to demonstrate quantitatively the impacts of introducing a tilting weir into the existing hydraulic arrangements at the exit to Balgavies Loch we need a model to show stakeholders what might happen to Balgavies Loch water levels and downstream flows with changing management. This report describes efforts to develop a simple empirical model and apply it to a selection of management scenarios, to demonstrate hydrological impact. Such scenarios can then form the basis for engaging stakeholders in a process leading towards detailed planning and implementation, if successful.

Previous work

We have previously described the hydraulics of the system (see Figure 1 and http://www.hutton.ac.uk/research/projects/payments-ecosystem-services-lessons)

In Figure 1, weirs refer to (a) the weir gate providing flow to the Milldens Lade, known as the Mill lade gate, (b) the weir gate returning flow to the Lunan Water is the Lunan return gate. Possible sites for introduction of a tilting weir are either the highflow spillway, or just upstream of the confluence of the Balgavies Burn and the Common Lade, to the west of the track crossing the watercourses.

Figure 2 shows the water level time series for Rescobie and Balgavies Loch, and Milldens weir for the period from March 2014 to December 2016. Note the periods when the Lunan return gate at Milldens weir is either closed or partially closed. The observations suggest we could assume the whole wetland area is fixed and responds, at daily resolution, as a single reservoir of water, though the absolute water levels may differ (Rescobie Loch is typically 20cm higher than Balgavies Loch, but merged to a single variable level at the peak of storm Frank in Dec 2015-Jan 2016).

The geometry of the system is quite complex for hydraulic modelling, so we are using a simple empirical approach based on observations of impacts of weir gate management on water levels.We assume a similar hydrologic response of Balgavies Loch catchments and Balgavies Burn catchment, the same runoff [mm/d] from both catchments and no lag time due to Loch. 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)

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 open (see Figure 2), we solved equation (1) for Q_O. We then plotted results against Balgavies Loch outlet level H_L. Figure 3 shows the data points

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.

Impact of existing weir gate management.

Also shown in Figure 3 are the data points for days when the gate is closed. When the Lunan return gate is closed, the water level upstream of the closed return gate quickly becomes similar to that of the Loch (see figure 2). The outflow remains unchanged by gate closure at low levels, since it is simply diverted to the Mill lade and to the Chapel mires spillway (see Figure 1). Historically, the Lunan return gate is usually only closed at relatively low flows to accommodate water supply to the mill lade for irrigation abstraction, drinking for cattle and operation of the restored water mill. At higher levels (H_L>59.35m) we observed an impact of closing Mildens lade on flows to chapel mires during experimental gate closures in summer 2016, suggesting that above this value of H_L, closing the return gate reduces the value of Q_O. We analysed several experimental gate changes (see for example fig 4) and other gate changes over 2014-2016, which give us a relationship between gate closure and Q_O, using equation 1. These data are presented in Figure 5, showing a relationship between change in flow rate and Lunan return gate opening/closing. This relationship is constrained to give Q_o=0 when H_L=59.04m. The value of Q_O decreases as a result of gate closure by about 12 L/s compared to that for the gate open condition, for every 1 cm of water in the Loch above H_L = 59.37m. We can now assess the likely impact of changing existing weir gate management on water levels in the Loch. Fig 6 shows the results for actual weir gate management, for Lunan return gate always closed, and for return gate always open. The fit of the simulated water levels to observed is mostly quite good, especially at higher levels, but there are discrepancies at low flows, which may reflect lack of calibration data for H<59.36m, incomplete gate closure and also channel blockages by sediment, debris or vegetation at some times. The assumption of the hydrological response being similar for the Loch and the Burn catchments may also be weak for low-flow conditions . We have one direct observation of Q_O made with the acoustic Doppler method, which gave Q_O = 120 L/s at H_L=59.46m on July 11 2016. This is lower than the simulated Q_O (231 L/s) at this value of H_L. It can be seen from Figure 6 that leaving the weir gates open all the time, relative to the current management, does not change levels significantly except in late summer/early autumn of 2015 and 2016, but closing the Lunan return gate all the time does increase water levels by significant amounts especially in late winter and spring, increasing the risk of flooding at these times.

Impact of adding an additional weir on flows and water levels at Balgavies/Milldens

In order to assess the impact of an additional weir gate at Milldens we need to be able to simulate the dynamic water levels there. Figure 7 shows the relationship between our estimate of Q_O, the discharge at the exit from Balgavies Loch, and H_w, the monitored water levels at Milldens weir, for days when the Lunan return gate is either closed or open. As can be seen, for Lunan return gate *closed* conditions the water level at Milldens lade approaches a minimum value of about 0.35m above the bed level at the exit culvert for Balgavies Loch. There are few data for higher flows with closed return gate position. Note that the two points infilled in blue are when we experimentally closed both gates for two days in November 2016. For Lunan return gate ***open*** conditions, when discharge is below ca. 10^4 m^3/d, the water level at Milldens lade approaches a minimum value of about 0.15m above the bed level at the exit culvert for Balgavies Loch(ie 59.2m), so we set this as the minimum water level at the weir, with both gates open and low flows. At higher flows than these limits, there is a moderately good log-linear relationship (r^2 = 0.68) between Q_O and H_W, where H_W = water head at Milldens lade. Figure 8 shows the simulated water levels at Milldens lade, compared with observations over 2014-2016. There is clearly some difference in behaviour between years, and we speculate that this make be because of removal/addition of debris blockages at various times.

We propose to use the log-linear component of the relationship in Figure 7 (extrapolated if needed), to simulate the head at Milldens lade, when an additional weir is included with the same or lower bed level than the existing return gate base of 59.1m. The additional estimated discharge on day t impacts the water level in the Loch and consequently discharge from the Loch and water level at the weir on day t+1.

We used Bazin's formula to estimate the flow over an additional weir, as a function of the head at Milldens lade:

$$Q_W = 0.66 \times cB \times (2g)^{0.66} \times H_W^{1.5} \qquad (2)$$

where;

Q_W = water flow rate, m^3/sec

B = width of the weir, metres*

c = discharge coefficient, average 0.62

g = gravitational constant, 9.81

H_W = Height of the water over the weir, measured behind the weir edge, m

(see http://www.aquatext.com/calcs/weir%20flow.htm)

Impact on downstream flows

What is the impact of the changes in flow caused by the additional weir on the exceedance data for the whole Lunan Water? We fed the daily flow changes as a result of introducing the weir into the observed Kirkton Mill daily flows at the lower end of the catchment (data recorded at http://www.ceh.ac.uk/data/nrfa/data/station.html?13005).

We carried out simulations over 2011-2016, a period for which we have complete data for Q_B, the daily discharge of Balgavies Burn. We compared water levels and discharge downstream at Kirkton Mill (A=178 km^2), for current management and introducing a new weir with W=1.5m and bed level of 58.9m. We assume the weir is fully open Sep-Jan, closed Feb-Jun, and with variable level to deliver an additional 35 L/s during Jul-Aug. Figure 9 shows an example of the simulations of the effects on discharge at Kirkton Mill and the water levels in Balgavies Loch for 2012-3. Note that additional water for irrigation is available in July 2013, when the natural flow in the Lunan Water at

Kirkton Mill is below Q95, the level at which irrigation restrictions to no more than 10% of Q_{95} could be imposed by the regulator. The impact at the high flow end at Kirkton is slight, but the impact on levels in Balgavies Loch is significant. A summary of impact on water level exceedance in Balgavies Loch is shown in Figure 10a. For example the % of time with levels >59.7m decrease from 12% to 8%. We also estimated the impact on Rescobie Loch, where the flooding has most impact, using an empirical relationship between Resocbie and Balgavies levels. Using simulations over the 2011-2016 period, we estimate managed use of such a facility would decrease the frequency with which the water level of Rescobie Loch is above 60m (which is 1m below the road at Rescobie Loch Boathouse, and when the water would overflow into the boathouse carpark) from 6% of the time to 3% of the time.

Further work is now needed to develop scenarios of management and their impacts on downstream flows and loch water levels. It should also be possible to make economic and ecological assessments of the impacts of these changes.

For that, the rainfall-runoff model TUWModel has been set up and parameterised for the Lunan catchment up to Kirkton. In the next step, this model will be spatially parameterised for the Balgavies Loch and the Balgavies Burn catchments. This hydrological model will then be used to simulate scenarios of management and to quantify their impacts on downstream flows.

Conclusions

The analysis so far shows that:

1. the existing weir gate closure regime (often closed for extended periods during May to October) does not significantly increase the risk of flooding compared to the situation when the Lunan return gate is open all the time. A change in management of the existing weir to gates always open is therefore likely to be ineffectual in reducing flooding risk.
2. However, closing the Lunan return gate continually, would affect the risk of flooding upstream quite strongly.
3. The introduction of an additional tilting weir at the high flow spillway at Milldens weir, or upstream of the confluence of Balgavies Burn and the Common Lade (Figure 1), 1.5-1.8m width, with a base level of 58.9m above OD is proposed.
4. The management regime would be the subject of negotiations, but a starting proposal is Open Sep-Jan, closed Feb-Jun, variable, delivering an additional 35 L/s Jul-Aug. Closed if H_L<59.04m. This would increase the ability of the weir hydraulics to reduce flood risk upstream .
5. This would not significantly increase the risk of flooding downstream in the Lower Lunan Water.
6. This additional tilting weir would have a beneficial effect on the lowest flows in the downstream river, and also reduce input of water to the Chapel mires in late summer, when the water is enriched with P released from Loch sediment.

7. The impact of an additional tilting weir at low flows is evident, but limited because water spills into Chapel mires, at a base level of 58.9m, limiting the capacity for storage in the Loch in early summer.
8. To improve the availability of water at low flows downstream of the Loch, water would need to be retained in the loch in early summer by a weir at the Loch outlet itself, as recommended in a previous report to the Lunan Water catchment group.
9. Siting of the additional weir upstream of the confluence of Balgavies Burn and the Common Lade (Figure 1) may help to increase potential for management of low flows.

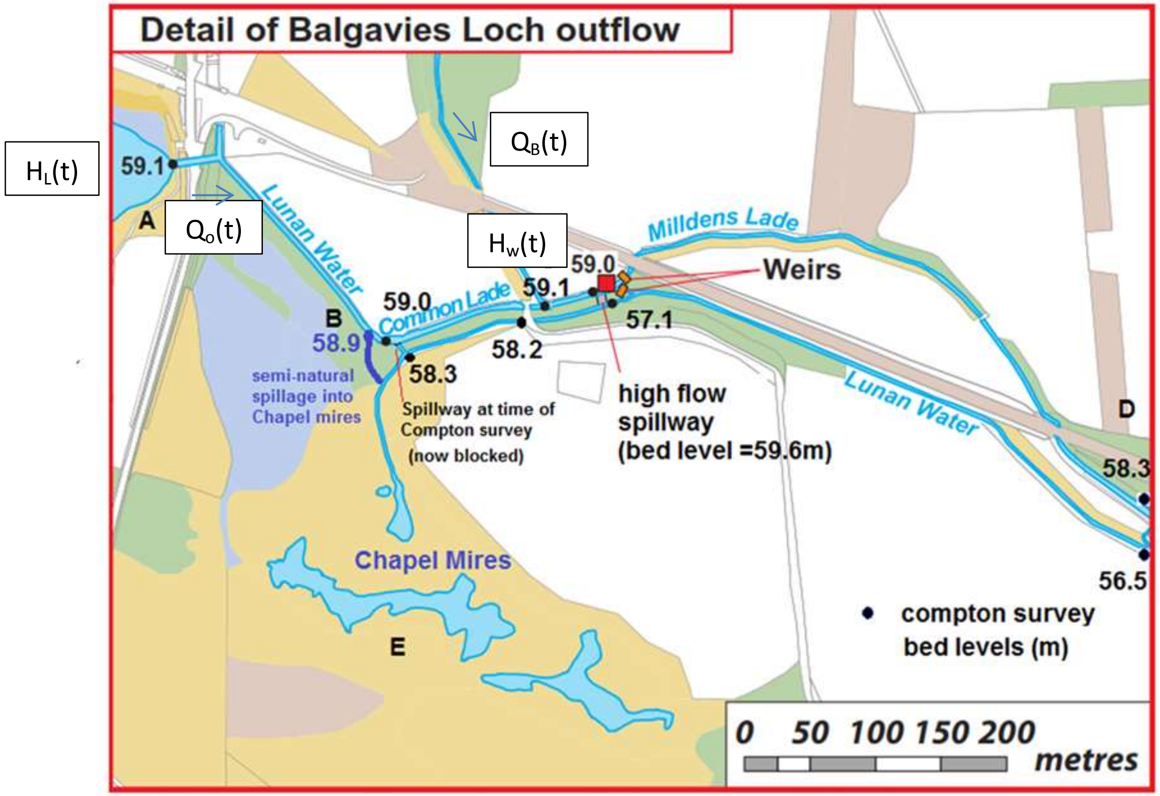

Figure 1. Hydraulics and bed levels downstream of Balgavies Loch. $H_L(t)$ = head in Balgavies Loch (m above OD), $H_W(t)$ = Head upstream of weir (m), Q_B=Discharge in Balgavies Burn (m^3/d), Q_o=discharge from Balgavies Loch (m^3/d). Weirs refer to (a) the weir gate providing flow to the Milldens Lade, known as the Mill Lade gate, (b) the weir gate returning flow to the Lunan Water is the Lunan return gate. Sites for introduction of a tilting weir are either the highflow spillway, or just upstream of the confluence of the Balgavies Burn and the Common Lade, to the west of the track crossing the watercourses.

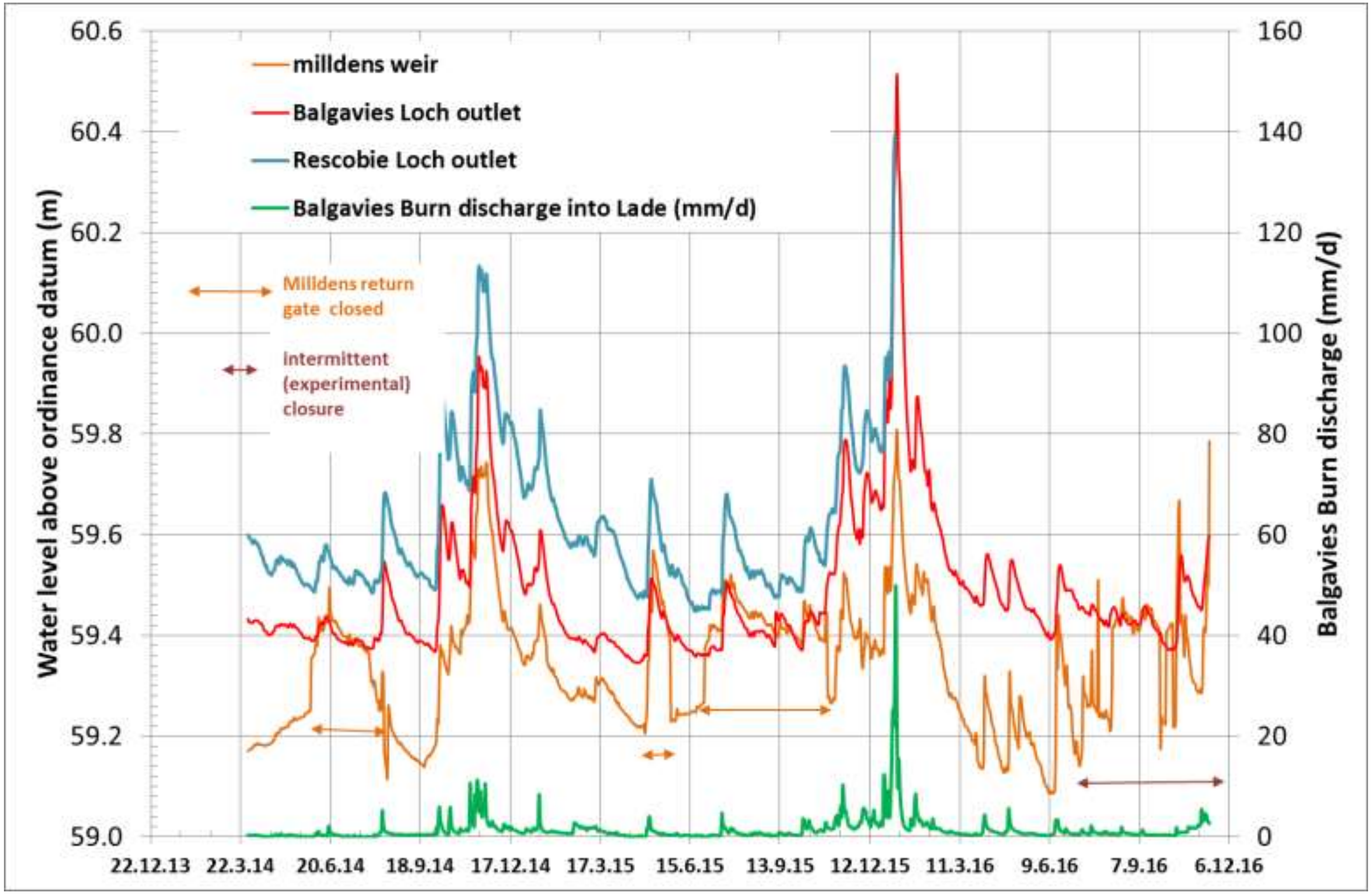

Figure 2. relationship between Qo (discharge from Balgavies Loch) estimated using eq 1 and H_L, water level in Balgavies Loch.

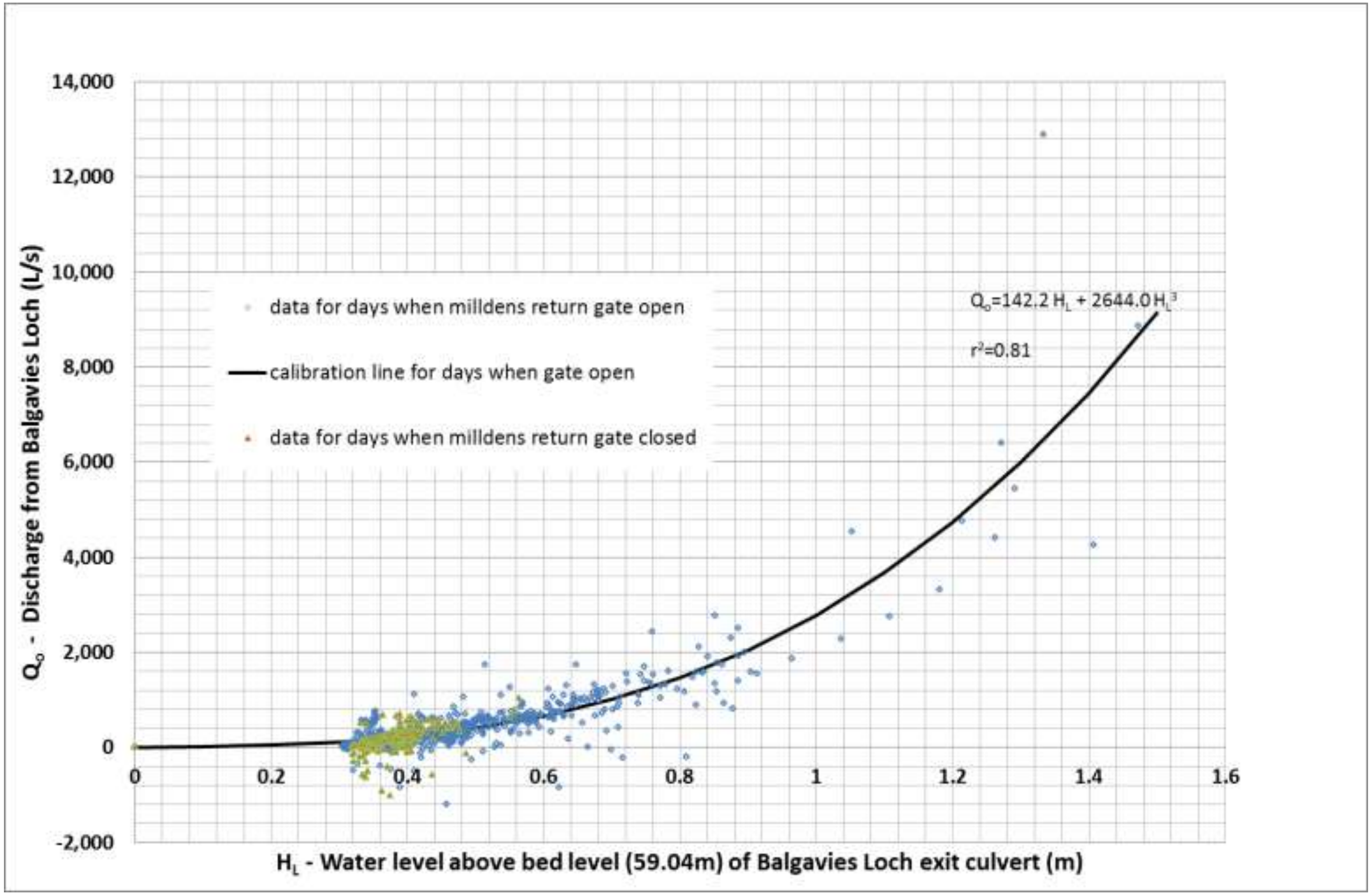

Figure 3. Calibration of discharge from Balgavies Loch as a function of water level, based on equation

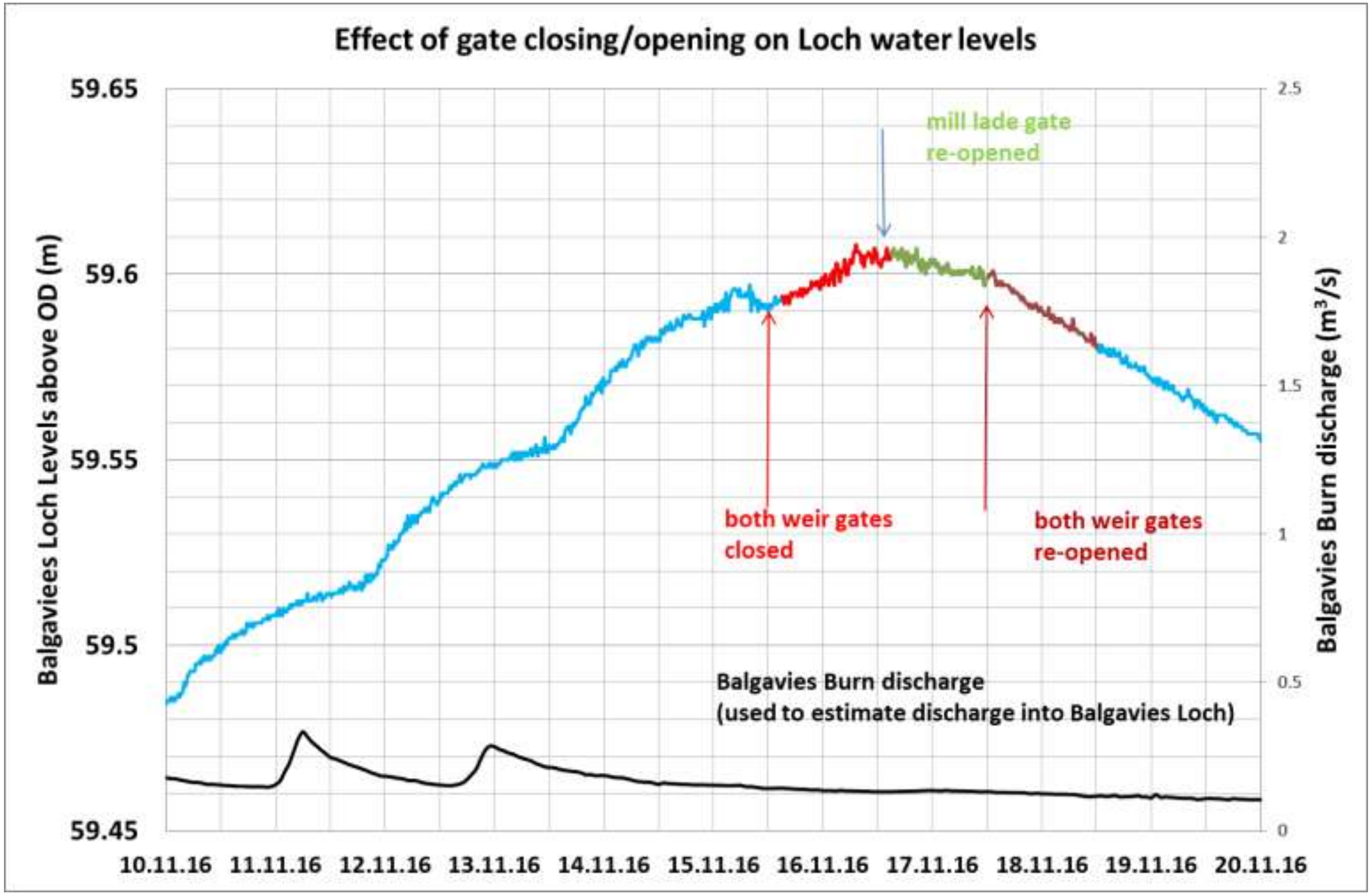

Figure 4. Example of impact of changing weir gate position on water levels in Balgavies Loch

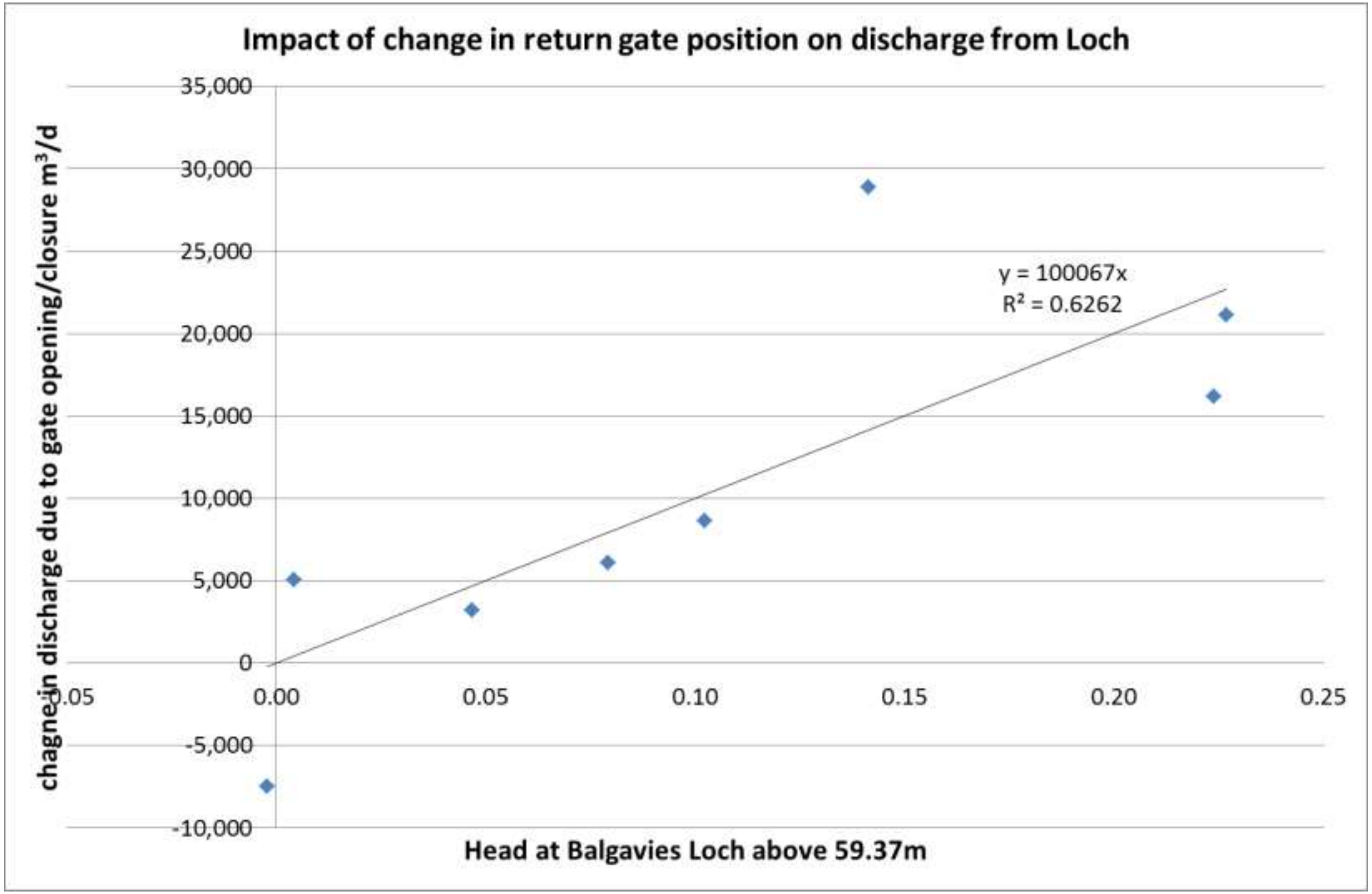

Fig 5. Estimation of impact of change in Lunan return gate position on discharge from Loch. Below H=59.37m, we assume the position of the Lunan return gate has no impact on discharge.

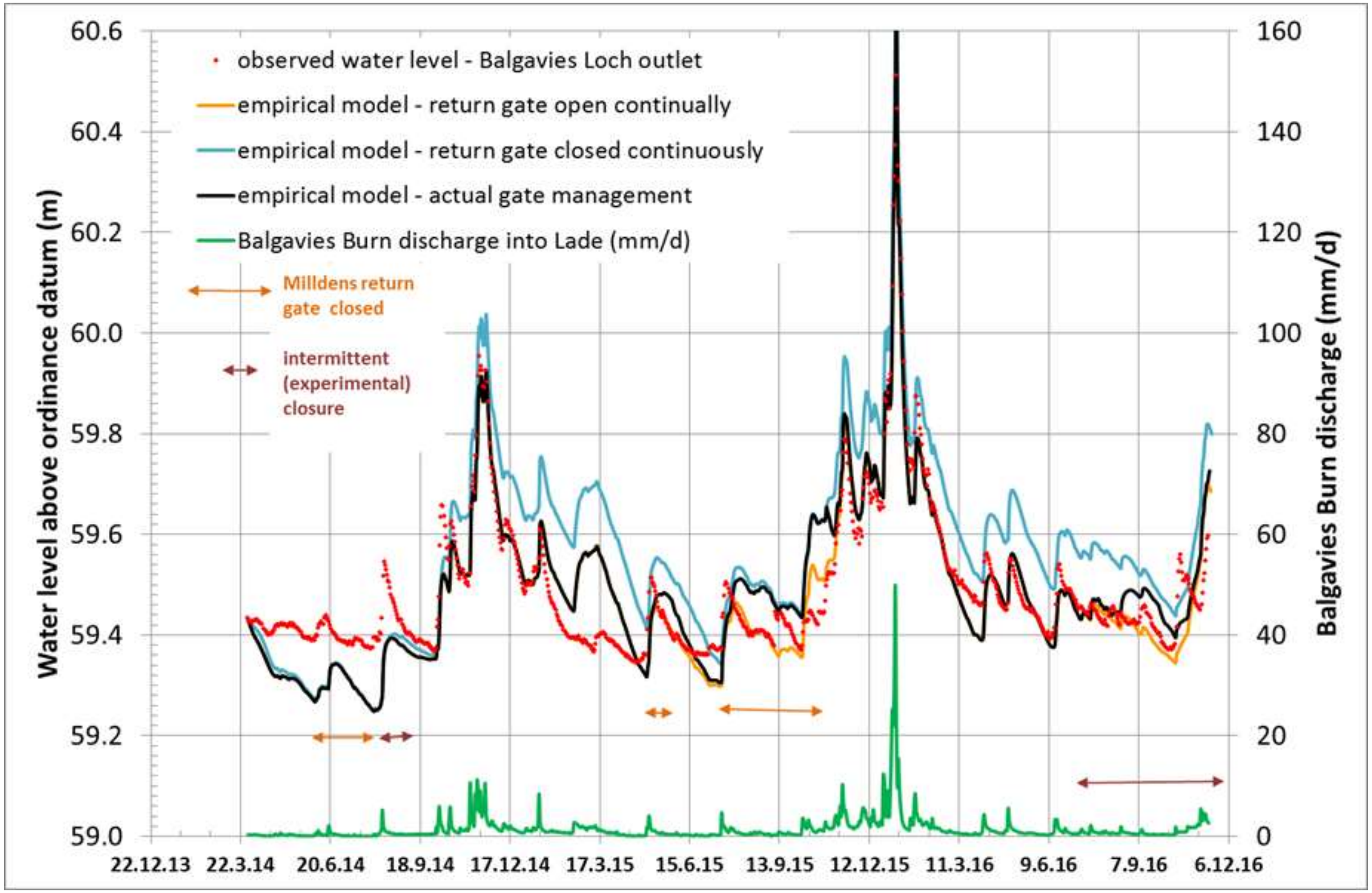

Figure 6.Comparison of measured water levels at Balgavies Loch outlet with empirical model for 3 Lunan return gate management assumptions (a) actual management (b) gate closed continually (c) gate open continually.

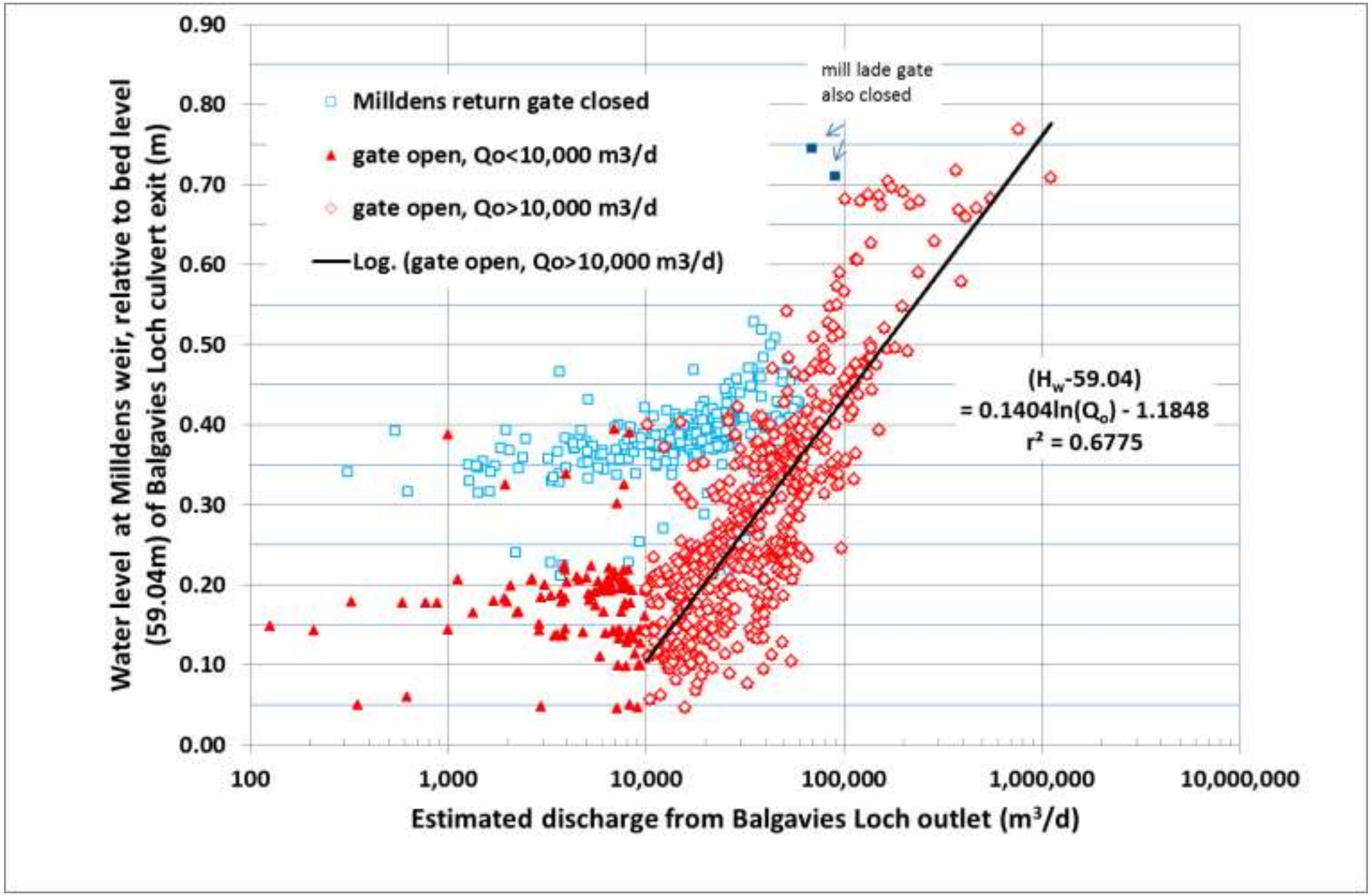

Figure 7. Relationship between Balgavies Loch discharge and water level at Milldens weir

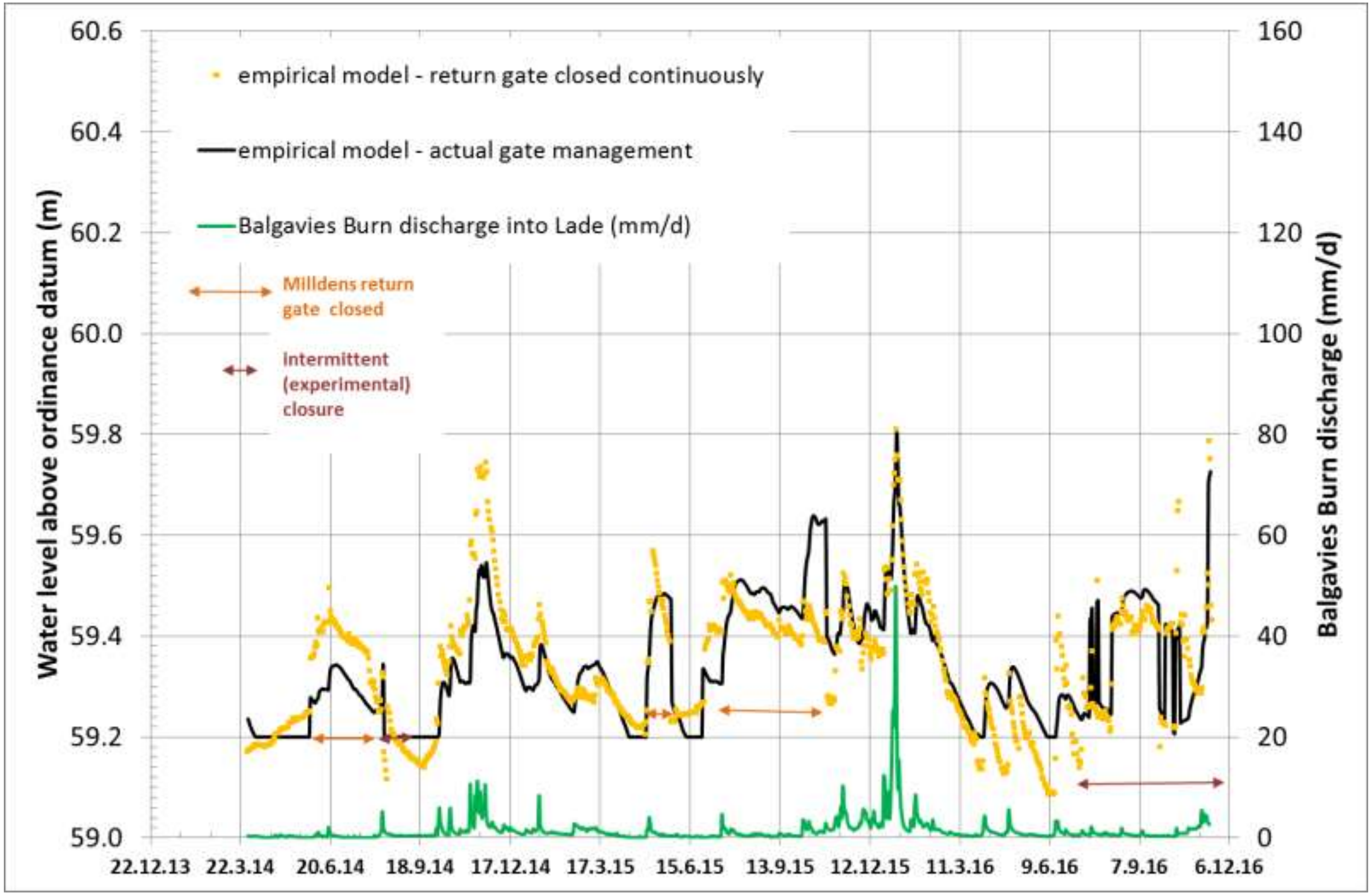

Figure 8.Comparison of measured water levels at Milldens weir with empirical model. Assumed minimum value of H_w=59.2m.

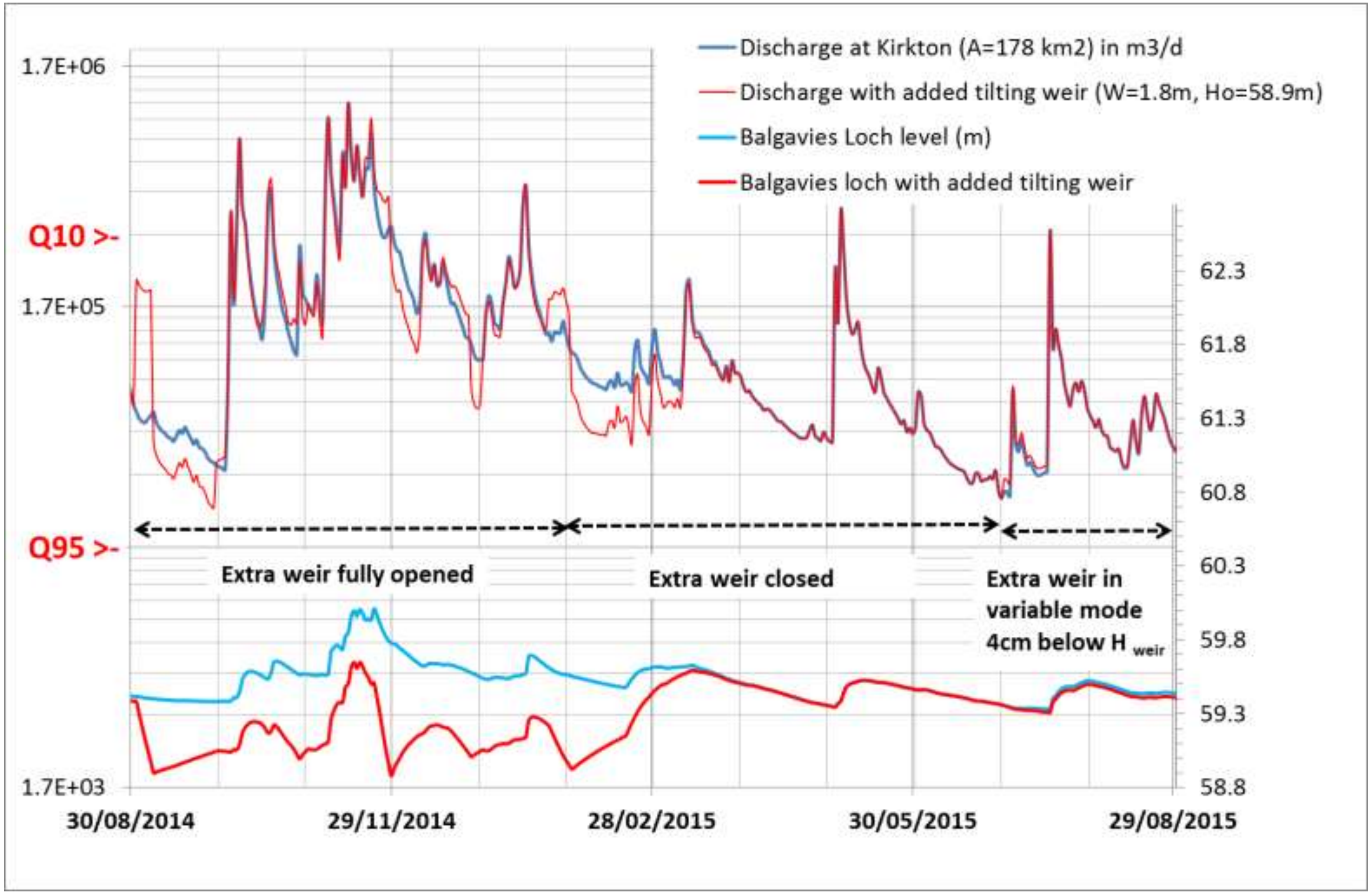

Figure 9. Impact of additional 1.8m wide weir gate at H= 58.9m at Milldens Weir. Open Sep-Jan, closed Feb-Jun, variable, delivering an additional 35 L/s Jul-Aug. Closed if H_L<59.04m.

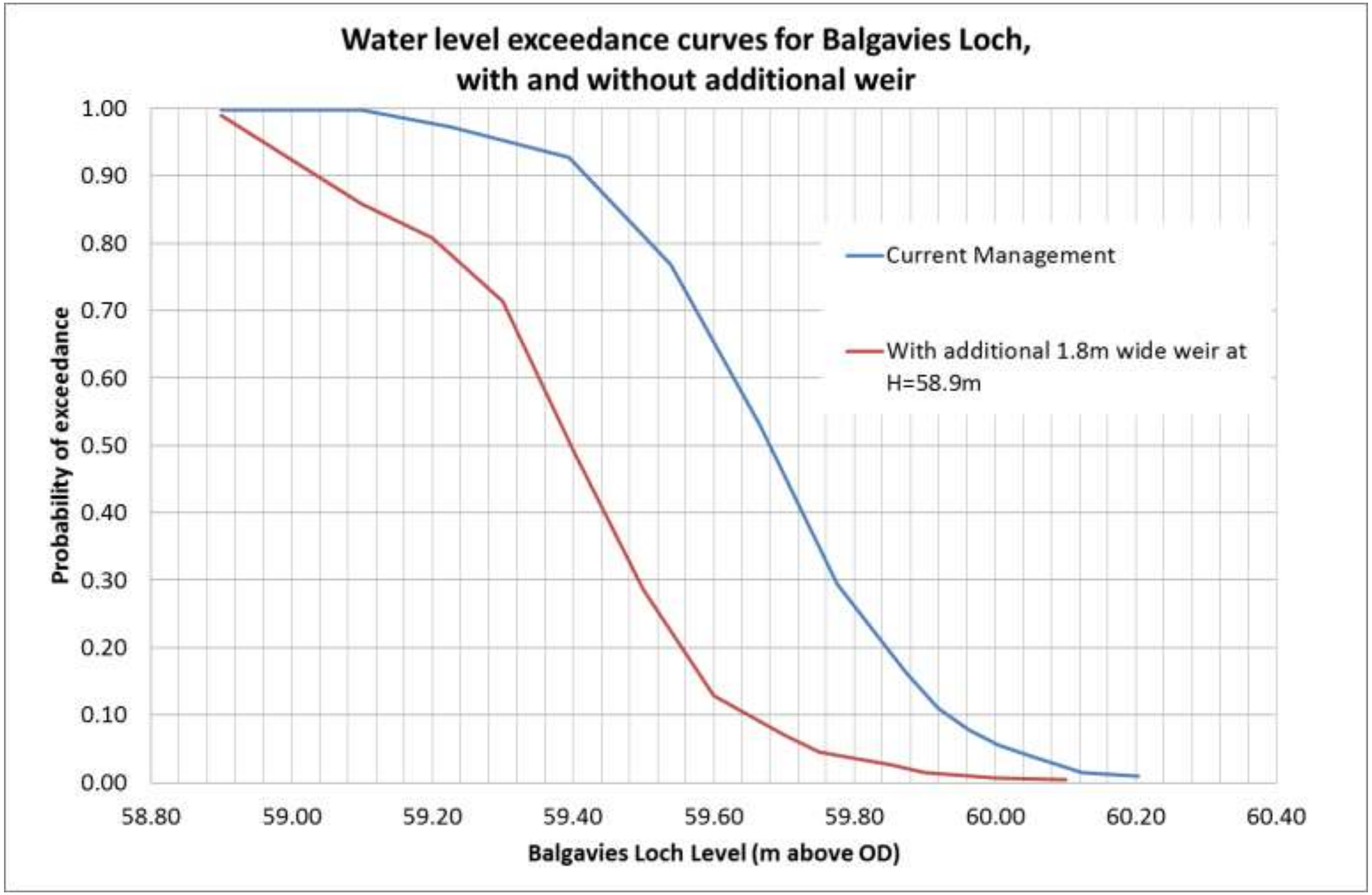

Figure 10. Impact of introduction of an additional 1.8m wide weir with base level of 58.9m on water level exceedance curve (2011-2016) for Balgavies Loch. Open Sep-Jan, closed Feb-Jun, variable, delivering an additional 35 L/s Jul-Aug. Closed if H_L<59.04m.