# Water level management in the upper Lunan Water, Angus, Scotland: threat or opportunity for improved delivery of water ecosystem services?

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**Figure 1. Existing high flow spillway at Milldens weir and an example of tilting weir technology.**

**Abstract:**

This study explores the potential for water level management in the Lunan Water, an agricultural catchment in Eastern Scotland, to deliver improvements in ecosystem services across a range of beneficiaries. The catchment is subject to several water ecosystem pressures, including flooding of the upper and lower reaches, morphological pressures and diffuse pollution impacting standing waters and rare lowland mesotrophic wetlands, and water abstraction at low flows. Water level and flow management from upper catchment standing waters has the potential to mitigate some of these pressures. We make an assessment of the potential for managing water levels to (a) mitigate flood risk, particularly in the upper catchment (b) protect high value lowland wetlands from damaging inputs of nutrients from Balgavies Loch (c) deliver water for low flows. The analysis is based on (1) historic flow and water level records for river and wetland water bodies in the catchment; (2) empirical modelling of water level impact of existing and new weir gates associated with a water mill at the outlet to the Loch; (3) ecological requirements of river and wetland water bodies; (4) existing water abstraction licenses and returns on actual useage by irrigators; (5) economic analysis of impacts of restricted irrigation; (6) stakeholder perceptions. The resolution of technical barriers to achievement of this delivery is discussed, e.g. through adoption of flexible hydraulic controls allowing more adaptive management than is currently the case. Analysis suggests that implementation of flexible hydraulic controls linking ecological, flood risk and irrigation requirements through an agreed payment mechanism, could be successful. Infrastructure, such as upgrading of an existing weir using tilting weir technology, and management leading to reduced risk of flooding, improved aquatic and wetland ecology and wetland eutrophication and low flows could be perhaps be partially funded by the private and public benefits of enhanced flood protection and agricultural water availability through a Payments for Ecosystem Services scheme.

**Keywords:** water level control, abstraction, flood risk, lowland wetlands, ecosystem services.

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## 1. Introduction

Surface freshwaters provide a wide range of ecosystem services, such as wetland and aquatic biodiversity, irrigation, flood risk mitigation, fisheries, sanitation, drinking and recreational water supply. The management of such waters is often seen by stakeholders as a challenging trade-off between conflicting demands especially where water use for wetland ecology is in competition with agricultural and flood risk mitigation demands (eg. Galbraith et al., 2005; Ioris, 2012; Mitraki et al., 2004). There is ongoing debate as to how to achieve multiple objectives and trade-offs without incurring disproportionate costs (eg. Vinten et al., 2012) and the Payment for Ecosystem Services (PES) paradigm (Muradian et al., 2010; Martin-Ortega et al., 2015) is an emerging novel approach to financing and governance of water management.

If river and standing water levels are above optimal for ecological and flood mitigation requirements, economic drivers at a catchment scale may present opportunities for the catchment manager to facilitate convergence of stakeholder interests. The UK National Ecosystem Assessment highlighted some of the ways in which wetland ecosystem services can be beneficially exploited, for example as buffer zones as a means to protect water quality or in flood risk management, but there are also trade-offs inherent in different land uses (Maltby et al, 2013). Achieving consensus on approaches to be taken is highly site specific and depends on local objectives, such as the benefits of flood risk mitigation (Acreman and Holden, 2013; CRUE, 2009)), economic and ecological demands for river water at low flows (Crabtree et al., 2002; Acreman and Ferguson, 2010), and the ecological demand for water by river-fed wetlands (Acreman et al., 2009, 2011). The management and restoration of river flows (eg. Acreman and Ferguson, 2010), wetland habitats (eg. Lamers et al. 2015) and river water quality (UKTAG 2012) are the subject of much catchment planning and legislation, deriving, in Europe, from the Water Framework Directive (EEC, 2000), Flood Risk Directive (EEC, 2007) and Habitats Directive (EEC, 1992).

The Lunan Water drains an intensively farmed mixed arable catchment of 134 km$^2$ from its source near the town of Forfar to the North Sea at Lunan Bay in Angus, Eastern Scotland, UK. In the headwaters of the catchment , there are several protected wetland areas, including two eutrophic lochs (Rescobie and Balgavies) and rare lowland mesotrophic wetlands, including Chapel Mires just downstream of these lochs. Pressures on the catchment include water quality (N and P) issues (see Dunn et al., 2014; Balana et al., 2012, Vinten et al., 2017) and there are also flooding and low flow concerns. One of the main causes of downgrading of river ecological status is the impact of irrigation abstraction on low summer flows. Sediment accumulation in the river and its tributaries also leads to strong demand from farmers for dredging to alleviate flooding in the downstream reaches and concern has been expressed for many years by local residents about increasing wetness and flooding in the upper parts of the catchment (Rear, 2014).

Hydraulic structures in the Lunan include a complex of sluice gates and a delivery canal (or "lade") for a restored water mill downstream of Balgavies Loch which artificially control water levels (see Figure 2). Concern has been raised that the existing hydraulic structures are partly responsible for periodic flooding upstream of the lade.

**Figure 2. Common lade at Milldens, looking downstream towards weir gates delivering water to mill lade (LHS) and return to Lunan Water (RHS).**

Their management also impacts on water quantity and quality entering the Chapel Mires via a spillage zone. Decisions on management are currently left to the immediate riparian owners. Potential approaches to upgrading the water levels management in this system include use of a telemetered tilting weir, managed according to agreed plans by multiple stakeholders, which could be administered by a PES scheme. Our purpose in this paper is to explore some of the likely impacts on water ecosystem services of changing management of water levels and flows, with a focus on adaptive management and upgrading of these structures.

## 2. Materials and Methods

### *2.1 Catchment characterization*

#### 2.1.1. Geology, soils and land use.

Much of the Lunan Water catchment area is underlain by groundwater bodies in Devonian Sandstone. In the area beneath Balgavies Loch are andesitic and basaltic volcanic rocks. The superficial glacial sands and gravels which border the river channel network are classified in groundwater terms as a highly productive aquifer. Alluvium overlying these deposits occurs in the centre of the valley, including the area under Rescobie and Balgavies Lochs (British Geological Survey, 2005). Main soil types found within the catchment comprise brown earths and podzols with a small band of alluvial soils bordering the main channel. The main crops grown in the catchment are spring barley, winter wheat, potatoes and winter oil seed rape. Of these only maincrop (ware) potatoes and soft fruit grown in polytunnels use significant irrigation water. The remainder of the non-arable land use (primarily in the upper part of the catchment) is mainly grassland and forestry and there are only a few small settlements. Average annual rainfall is around 820mm and is quite uniformly distributed throughout the year. Estimated annual evapotranspiration is around 400mm. The maximum elevation is 250 m at Turin Hill, but most of the area lies along a flat broad valley.

#### 2.1.2. Rivers and standing waters

River morphology and hydraulic structures along the Lunan Water have been reviewed recently (EnviroCentre, 2014). The Lunan Water has been subjected to morphological alterations at various points in the form of constructed embankments, channel realignment and straightening to meet the needs of agriculture and forestry. On some sub-catchments, flow is impacted through small on-line ponds to meet the needs of fisheries. There are also a number of functional and derelict water mills on the river, with associated weirs and mill lades including Milldens, downstream of Balgavies Loch. Local stakeholders in the upper catchment (above the outlet of Balgavies Loch) have complained about flooding issues on their property for many years and flooding of the road on the north side of Rescobie Loch has led to local council pressure for improved flood controls. These discussions have led to a number of actions, including removal of obstructions between Rescobie and Balgavies lochs, to drain deepening in the Restenneth moss outflow to Rescobie Loch, water course diversions and enhanced culverting. Further downstream, fish passage has been improved at Boysack Weir.

A number of the river and standing water bodies in the catchment are currently at less than Good Ecological Status, as defined by the Water Framework Directive (WFD). Downstream of the lochs, one of the main causes of downgrading of WFD ecological status is impacting of low summer flows by irrigation abstraction. Sediment accumulation in the river and its tributaries also leads to strong demand from farmers for dredging to alleviate flooding in the downstream reaches and concern is expressed by local residents of increasing wetness in the upper parts of the catchment, around the Lochs. Figure 3 shows the Water Framework Directive river water bodies comprising the whole Lunan catchment and the location of water abstraction licences. Water pollution point source inputs from 4 sewage treatment works as well as many septic tanks impact water quality while diffuse inputs come from mixed farming (Balana et al., 2012). The two main standing waters, Rescobie and Balgavies Lochs, fail the WFD standard for annual mean total P and chlorophyll a, although there has been a downward trend in recent years. Balana et al. (2012) estimated that a reduction in external loads to Rescobie Loch of around 360kg P would be needed to return it to good status. Both lochs show significant peaks is total and soluble P concentrations in late summer/early winter due to release from anaerobic sediments, which are reflected in discharges from Balgavies Loch into the Lunan Water and Chapel Mires. The underlying groundwater bodies are vulnerable to nitrate pollution and much of the area has been designated a Nitrate Vulnerable Zone. The Lunan Water quality at Kirkton Mill has

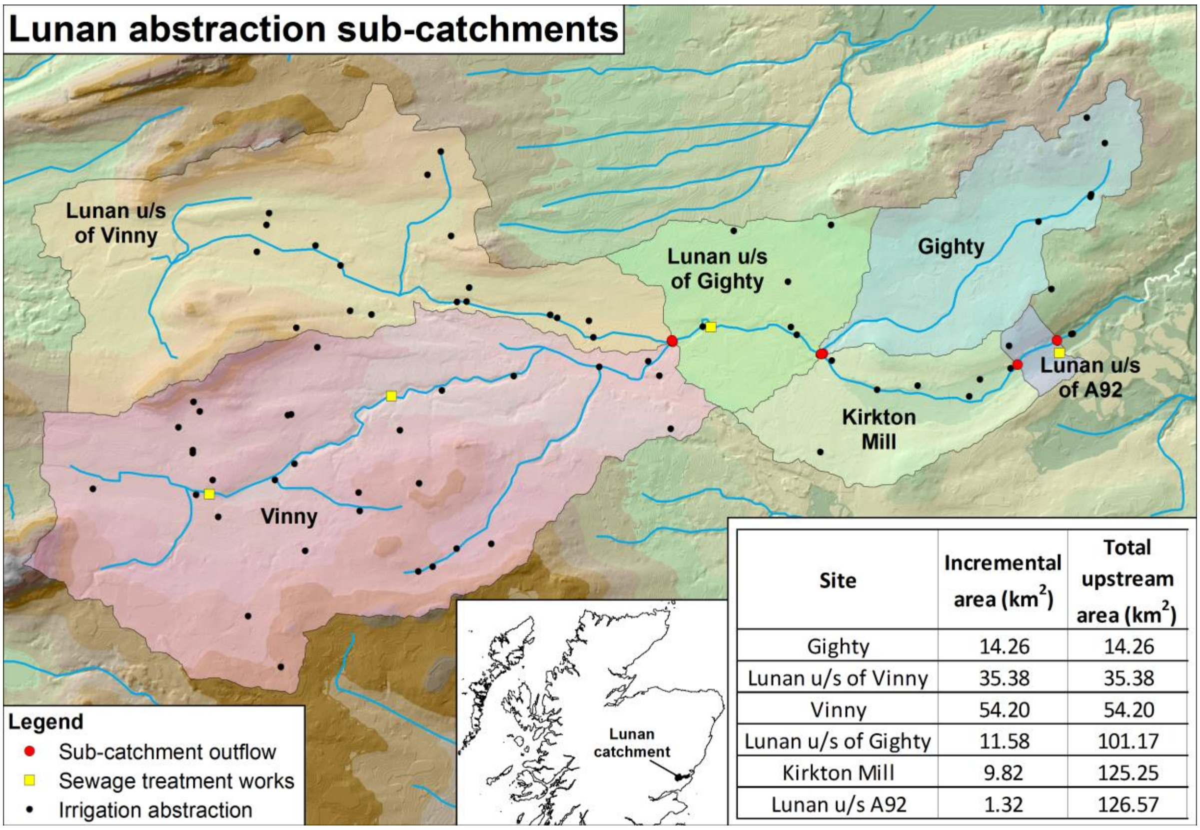



**Figure 3. River water bodies in the Lunan Water catchment and sites of irrigation water abstraction licences and sewage treatment works inputs.**

improved in recent years and now meets Good Ecological Status requirements with respect to soluble P. The Vinny Water however is still only at moderate status with respect to soluble P.

2.1.3. Wetlands

Figure 4 shows the distribution of some of the main non-agricultural land cover classes (Master Map) and surface waters in the upper Lunan Water catchment. Rescobie and Balgavies lochs, covering 1.78 km$^2$, support over 60 species of breeding birds and with their surrounds form a Site of Special Scientific Interest (SSSI). There are a number of aquatic species such as *Menyanthes trifoliata* (Bogbean) and *Utricularia australis* (Bladderwort) that occur in shallow water and any significant change in water levels are likely to affect them. There is also a rich mollusc fauna characteristic of calcareous waters and a range of uncommon aquatic invertebrate species. In the area south of the Lunan Water (Chapel Mires) there is a complex mosaic of open water, willow scrub and sedge-dominated fen vegetation including National Vegetation Classification classes M9 (*Carex rostrata-Calliergon* mire), M27 (Filipendula ulmaria –Angelica sylvetris mire), S28 (*Phalaris* swamp), S9 (*Carex rostrata* swamp)and S27a(*Carex rostrata–Equisetum fluviatile* sub-community ) occupying the lower lying areas. This has led to this area also being included in the Rescobie and Balgavies SSSI. The Nationally scarce *Cicuta virosa* (Cowbane) and *Lysimachia thyrsiflora* (Tufted Loosestrife), could be threatened by changes in water levels (Loizou, T. pers. comm). Note that the land cover classification shown in Figure 4 has insufficient discrimination to show the detail of the wetland mosaic. Work is in hand to map this mosaic more accurately. Other wetlands include Restenneth Moss a groundwater-fed lowland mesotrophic mire, Fonah Bog, a basin fen between Rescobie and Balgavies Lochs, which receives sediment, groundwater and surface runoff water from surrounding farmland , Clocksbriggs, west of

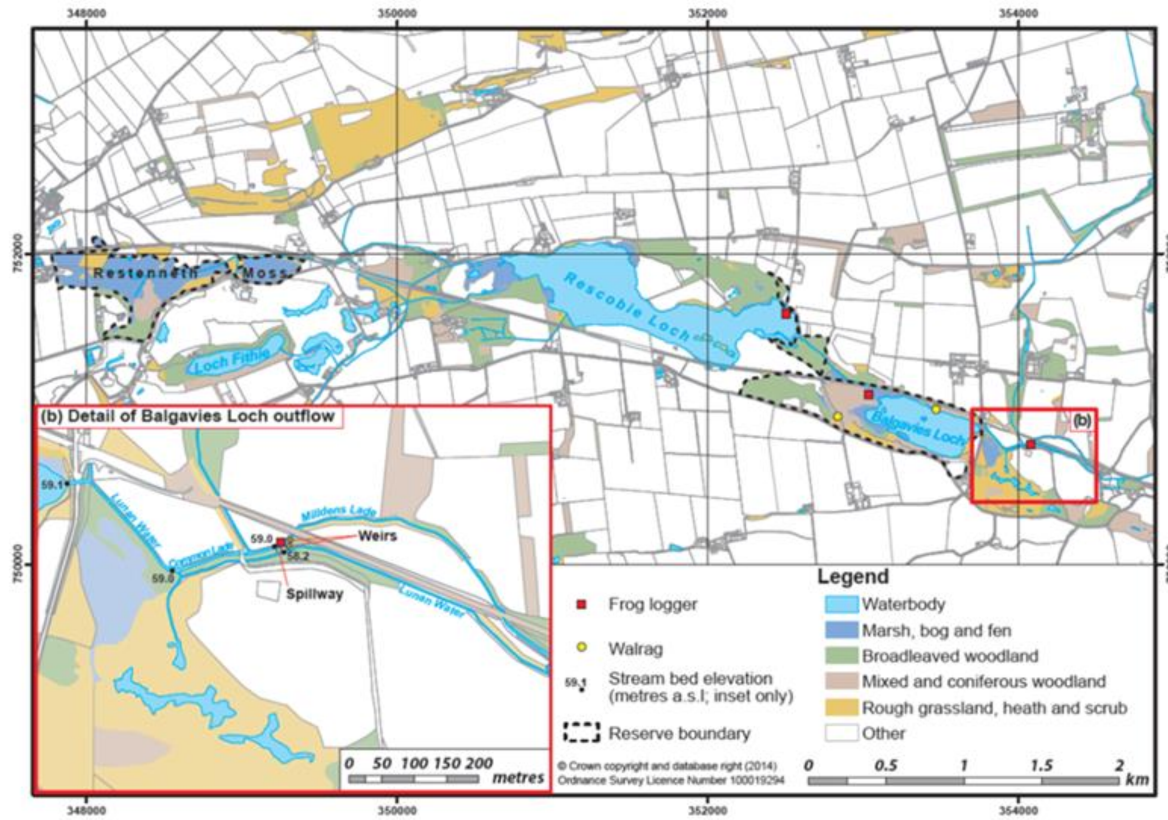



**Figure 4. Overview of the upper Lunan Water catchment showing the main non-agricultural areas and positions of water level recorders in the current study (3 automated sites installed in 2014 and long term manual min-max-mean water level recording stations orWALRAGs). The inset shows detail of the Milldens weir and associated lades on the area downstream of the outlet to Balgavies Loch. Elevations at key points in this system are also shown (Compton, J., pers.comm.).**

Rescobie Loch as well as marginal wetland vegetation round the lochs. Also shown in the inset of Figure 4 is the detail of the water courses in the region downstream of Balgavies Loch, where the water level control structures are located.

2.1.4. Hydraulic structures between Balgavies Loch to Milldens.

The hydraulic arrangements downstream of Balgavies Loch are a complex system originally designed to bring water to two water mills located at Milldens, via two lades, one of which (the North Lade) has been restored to use along with its water mill (? In the 1990's), the other (the South Lade) having been completely removed (within living memory, but some decades ago). A farmer in the catchment (John Compton of West Mains of Turin) carried out a survey of the bed levels in the region downstream of Balgavies Loch in the 1980's. These are summarised in Figure 5 (after updating to metric units and rounding to the nearest 0.1m. The original data were quoted to one decimal place in units of feet, so we assume an accuracy relative to true Ordinance Datum (OD) of ±0.05 ft or ±1.2cm).

Some of the flow in the common lade discharges through a semi-natural spillage zone into Chapel Mires under summer flow conditions. This rectangular gap (in the soft sediment wall of the lade) has a width of about 3.2m.

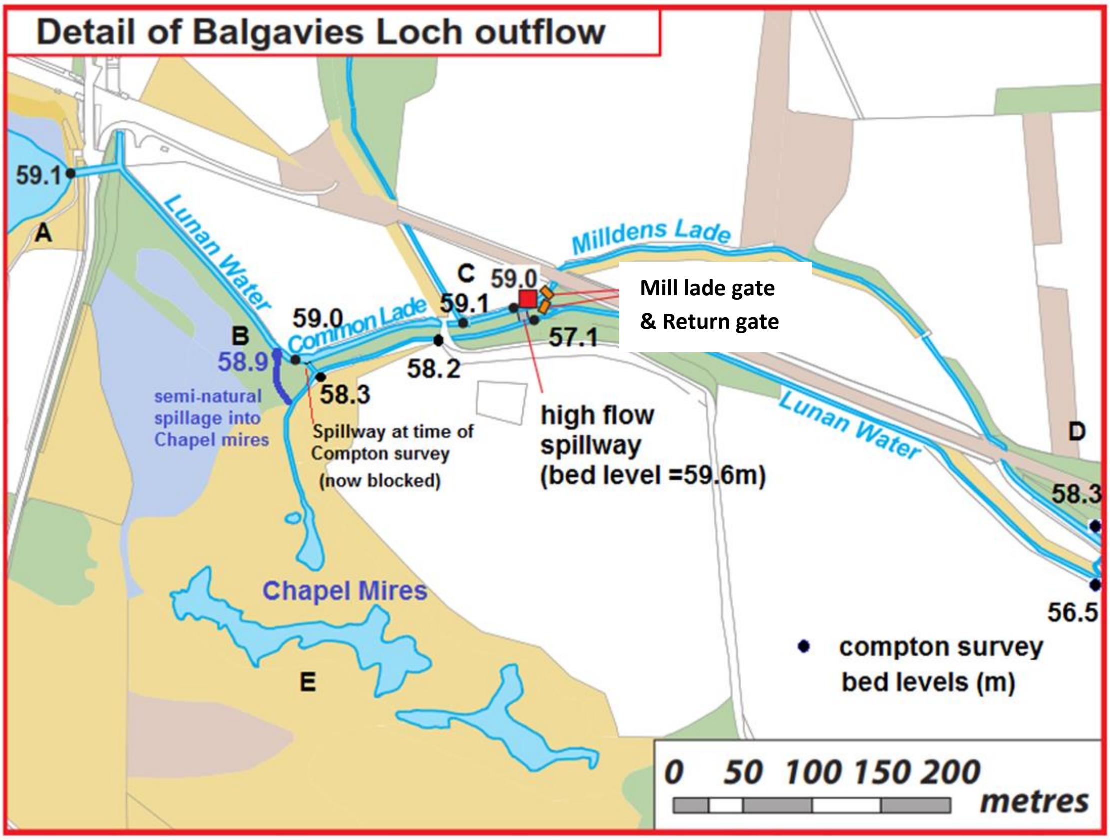



**Figure 5. Details of outlet to Balgavies Loch, showing bed levels and current spillage zone into Chapel Mires upstream of Milldens. Weirs refer to (a) the weir gate providing flow to the Milldens Lade, known as the Mill Lade gate, (b) the weir gate returning flow to the Lunan Water is the Lunan return gate. Note the Balgavies Burn input to the common lade from the north, the spillage zone into Chapel Mires and the high flow spillway. Potential site for introduction of a tilting weir is the highflow spillway. $H_L(t)$ = head in Balgavies Loch (m), $H_W(t)$ = Head upstream of weir (m), $Q_B$=Discharge in Balgavies Burn ($m^3/d$), $Q_o$=discharge from Balgavies Loch ($m^3/d$).**

There is also an engineered high flow spillway of width ca. 2m which begins to operate when water levels exceed 59.6m above OD. There may be potential to introduce an additional, flexibly managed hydraulic structure in the form of a tilting weir at the site of the existing high flow spillway.

*2.2 Regulatory requirements and water management objectives*

2.2.1. Flooding risk

Our objective is that the risk of flooding in the upper catchment is decreased significantly by change in water level management regime, while the risk of flooding in the lower catchment is either decreased or unaffected. The risk of flooding of the road system adjacent to Rescobie Loch is enhanced once the water level in that Loch exceeds 60.0m above OD, the bankful condition in the carpark at Rescobie Loch boathouse. This risk is a major driver for the local council responsible for upkeep of infrastructure and roads in the area, such as the B9113 at Rescobie. Previous approaches have dealt with the issue through dredging the Lunan Water upstream of Rescobie Loch and between Rescobie and Balgavies Lochs.

### 2.2.2 Wetlands

Our objective with respect to management of water levels and water quality in the wetlands is that there should be no decline in condition, and preferably an improvement, as a result of changes in water management. There are no specific regulations that we are aware of for water levels in fen/mire systems, although Acreman et al. (2009) describe optimal hydrological regimes for a number of UK wetland types. See also SNIFFER(2012), Wheeler et al.(2009) and Acreman and Holden (2013). Wheeler et al. (2004) give guidelines which state:

1. Most examples of fen/mire are characterised by winter water tables at or very close to the fen surface (-5 to +1 cm). The richest examples (with >20 characteristic species) occur exclusively in locations that exhibit a water table generally at the fen surface in winter and summer.

2. Very wet sites (summer water table usually above surface between tussocks) tend to be less species rich. However, whilst shallow pools and runnels are a natural feature, widespread inundation, particularly in the summer, is likely to be damaging.

3. The highest quality stands do not usually occur at sites where summer water tables are consistently >10 cm below ground level.

More detailed specification of wetland requirements, based on the National Vegetation Classification are underway for Scotland, but not yet available. We consulted with Centre for Ecology and Hydrology about requirements for S27a (key vegetation type for Chapel Mires), S11c*, S27*, S28b, S3, S9b yielded the following response (email of 27/1/17 from Linda May):

*CS consulted the EcoHydrological Guidelines for Lowland Wetland (Wheeler et al., 2004) and found that these vegetation types were not listed. He suggested that we explore whether any of these plants are similar to other plants whose ecohydrological requirements are described by Wheeler et al. (2009); no similar species are listed.*

### 2.2.3 Irrigation abstraction

Assessment of the risk of abstraction causing significant reduction in low flows rivers relative to natural conditions is required under the WFD (Copestake, 2006). The flow duration curve was used in the characterisation risk assessments for the WFD in Scotland (SEPA, 2005), using the criteria set out by UK Technical advisory group (UKTAG, 2004). UKTAG (2004) sets a ceiling of 10% flow reduction from Q95 for high sensitivity rivers. The Scottish Government (2009) standards for low flows used in the WFD River Basin Management Plans are shown in Table 1. We assume that the Lunan Water is a low sensitivity (A1) type water body for low flows. As it is a salmonid river, the principal regulatory requirement for low flows is that abstraction at <Q95 should not be more than 10% of Q95, using daily flows. Note that where an environmental standard for river flow equates to more than 25% of Q98, when the river flow is < Q98 SEPA may introduce such further restrictions on abstractions as it considers necessary for the purposes of protecting parts of the water environment, the aquatic plants or animals of which are, in SEPA's opinion, particularly sensitive to low flow conditions. Note also that the definition of a dry year is not specified in the regulations, and appears to be at the discretion of SEPA.

**Table 1. Standards for reductions in flow due to abstraction in Scottish Government (2009) regulations.**

| *A1 river Type Ecological status* | *Maximum volume of water removed per day at daily flows > $Q_{95}$ (% of long term $Q_{95}$)* | *Maximum volume of water removed per day at daily flows < $Q_{95}$ (% of long term $Q_{95}$)* |
|---|---|---|
| *High* | 10% | 5% |
| *Good* | 25% | 20% |
| *Good (dry year)* | 20% | 15% |
| *Good (salmonid rivers)* | 15% | 10% |
| *Good (salmonid,dry year,winter)* | 15% | 7.5% |
| *Moderate* | 50% | 45% |
| *Poor* | 75% | 70% |

### *2.3 Hydro-ecological monitoring and data analysis*

2.3.1. Loch water levels and water balance

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 4. Water levels were recorded at 15minute intervals and referenced using an RTK-GPS (Balgavies Loch outlet and Rescobie Loch) or historic data from J.Compton (Milldens weir) 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 3) have been monitored since 2006 (see Dunn et al., 2014 for details).

2.3.2 Empirical modelling of water levels and Impact of weir gate management on water levels

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 open (see Figure 5), we solved equation (1) for $Q_O$. 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 2014-2016, 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 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:

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 on 11 July 2017 to measure flows at Balgavies Loch outlet, the two weir gates, and the Chapel Mires spillway.

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. We identified a log-linear 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. We then used Bazin's formula (see http://www.aquatext.com/calcs/weir%20flow.htm) 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

[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

g = gravitational constant, 9.81
$H_W$ = Height of the water over the weir, measured behind the weir edge, m

2.3.3 Impact of changes in flow on Lunan Water and Balgavies Loch

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. 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 (a) current management and (b) after introducing a new weir with W=1.8m 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. We assumed the new tilting weir was closed if the level of water in Balgavies Loch , $H_B$, fell below 59.04m.

2.3.4 Ecological surveying of Chapel Mires

Plant identification quadrats (3m x 1.5m) were established in May 2015 at 2 points in the most botanically rich portion of Chapel Mires in order to obtain evidence for change of site condition compare with historical records (data from 1979 and 2008, courtesy of Peter McPhail of Scottish Natural Heritage and Ruth Mitchell of James Hutton Institute) and for repeat sampling during the course of the project. The next sampling is due in June 2017.

The position and elevation of the water margin at several key points in Chapel Mires (and elsewhere) were measured in May, June and July 2015 using a Real Time Kinematic Global Positioning System or RTK-GPS (topographic survey) instrument.

2.3.5. Impacts of abstraction on river flows.

Discharge data for Kirkton Mill gauging station (the catchment outlet at position L in Figure 1), for 1983-2012 (124 $km^2$) were obtained from the NERC archive. (data recorded at http://www.ceh.ac.uk/data/nrfa/data/station.html?13005). The long term Q95 at the catchment outlet discharge monitoring station at Kirkton Mill is 0.195 $m^3$/s. The driest year (1995) and wettest year (2012) in the discharge time series had an annual Q95 of 0.115 $m^3$/s and 0.700 $m^3$/s respectively.

Maximum permitted abstraction rates for each licence were supplied by the public registry. These were used to estimate impact of abstraction at low flows. Actual abstraction returns were also obtained from the public registry for 2011, 2012 and 2013. We assumed that ware potato fields are the principal areas using irrigation water. Other small areas likely to receive irrigation are other vegetables and soft fruit grown in polytunnels in the lower catchment. In Scotland, an Integrated Administration and Control System (IACS) provides an annual, spatially explicit register of land use and agricultural activity at a detailed field scale. These data have been made available for the Lunan catchment by the Scottish Government from 2000 to 2009 and cover all areas where agricultural support is provided through a Single Farm Payments Scheme. They show the mean area of ware potatoes grown in the catchment was 4.8 $km^2$ or 4.0% of the catchment area.

For assessment of the impact of abstraction on water flows, it is necessary to know how the irrigation abstraction is distributed through the year. The assumptions made by SEPA for this are summarised in Table 2 (Gosling, R. pers.comm).

**Table 2. Assumed distribution of water abstraction for irrigation over the season.**

| *Month* | *April* | *May* | *June* | *July* | *August* | *September* | *October* |
|---|---|---|---|---|---|---|---|
| *Proportion* | 0.04 | 0.12 | 0.2 | 0.28 | 0.2 | 0.12 | 0.04 |

The principal regulatory requirement for low flows is that abstraction when flow is less than the long term $Q_{95}$ should not be more than 10% of long term $Q_{95}$, using daily flows. Although regulation is currently based on licensed maxima, there is an aspiration by the regulator to use actual returns instead, if the return rate by licensees becomes adequate in future, an approach being piloted elsewhere in Scotland.

To compare the impacts of using actual vs licensed maxima to determine ecological status and availability of water, we split up the Lunan Water catchment into WFD water bodies and allocated discharge to each water body on an area basis. The abstraction licences were allocated to the relevant water body (see Figure 3). Using (a) the water body discharge figures; (b) the data from irrigation abstraction returns for sites allocated to each water body; (c) the seasonal pattern of irrigation water use assumed in Table 2; we assessed the outcome of the regulatory test for three alternative assumptions about the abstraction rates. The alternative assumptions we considered were:

A. Assuming irrigation occurred as per positive actual returns;

B. Where entries with "no data returned" occur in the database, licencees are assumed to be abstracting water at the weighted mean ratio of actual/maximum abstraction (19.7%) observed for licences with positive returns;

C. Assuming irrigation occurred as per maximum abstraction on licence.

## 3. Results

### *3.1 Loch Water levels*

#### 3.1.1. Historic data on Loch water levels

Water levels measured using a WALRAG by the Scottish Wildlife Trust Warden at Balgavies Loch, during 2003-2014, and subsequently fortnightly samples from 15 minute water level recordings with automated water level recorder are shown in Figure 7. Both datasets have been referenced to the outlet of Balgavies Loch (59.13m bed level above OD). Figure 8 shows the hourly records of water levels collected during 2014-2016. Several points can be noted:

a. Annual water level fluctuations show an amplitude of up to 1m at Rescobie Loch, up to 1.2m at Balgavies Loch and up to 0.75m at Milldens weir. The amplitude was much larger in 2015/6 than in 2014/5 because of storm Frank (which generated serious flooding to roads and residential property upstream of Rescobie Loch and in fields downstream of Balgavies Loch in the Milldens area, as well as further downstream in the lower catchment).
b. Water levels at low flows are about 0.2m higher in Rescobie Loch than in Balgavies Loch, but this difference is smaller at high flows, with the levels almost merging near the beginning of storm Frank. Note that the logger at Rescobie failed during this period and has not yet been replaced.
c. There is little lag (<1d) between the response of Rescobie and Balgavies Lochs, or between Milldens Lade and Balgavies Loch, with Milldens Lade generally responding first, then Balgavies Loch, due to the input from Balgavies Burn.

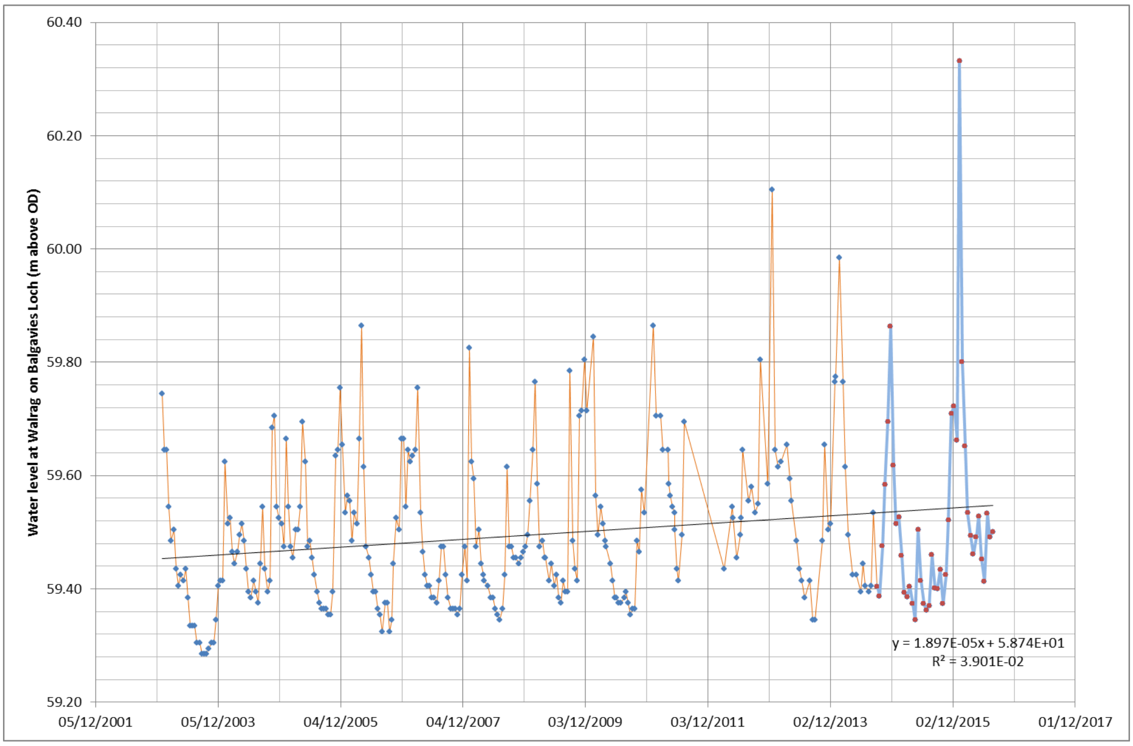



**Figure 7. Fortnightly water levels measured by using a WALRAG by Scottish Wildlife Trust Warden at Balgavies Loch, 2003-2014, and subsequently fortnightly samples from 15 minute water level recordings with automated water level recorder (Frog logger). Both datasets have been referenced to the outlet of Balgavies Loch (59.13m bed level above OD).**

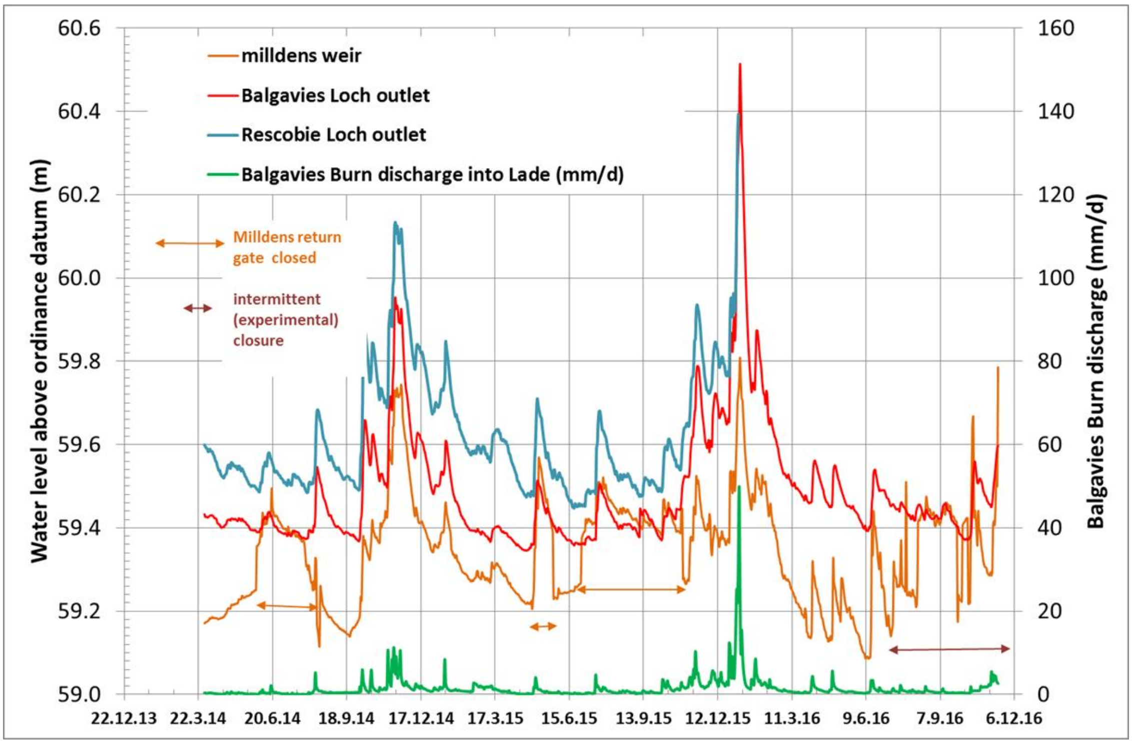



**Figure 8. Hourly water level data collected at Rescobie Loch outlet, Balgavies Loch inlet and Milldens Weir 2014-2016. Also shows discharge from Balgavies Burn, which flows into the system above mildens weir and the soluble P concentration in the outlet water from Balgavies Loch.**

d. The position of the return gate delivering water from the common lade to the Lunan Water at Milldens Weir is critical to the difference in water levels between the common lade upstream of Milldens Weir and Balgavies Loch.

e. With the return gate closed there is very little difference (±4cm) in water levels between the Balgavies outlet and upstream of Milldens weir/downstream of Balgavies Burn. There may be situations where flow reversal occurs if the return gate or both gates are closed.

f. The Balgavies Loch water levels do not show any obvious short term response in level from changing the position of the return gate at the Milldens weir.

We hypothesise that the lack of response of water level to changing gate position referred to in (f) occurs because (1) Historical return gate closures occur only during low flow conditions (2) the large area of the lochs and wetlands buffers short term water level changes associated with restricted outflow, relative to the small area of the lade into which the Balgavies Burn discharges; (3) Excess water (either from Balgavies Loch or from Balgavies Burn) that exceeds the capacity of the the Milldens lade at high water levels has the opportunity to spill into Chapel Mires.

3.1.2. Empirical modelling of water levels and impacts of gate changes

Using only days when the Milldens weir gates were open, we solved equation (1) for $Q_O$. We then plotted results against Balgavies Loch outlet level $H_L$. Figure 9 shows the results. 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.

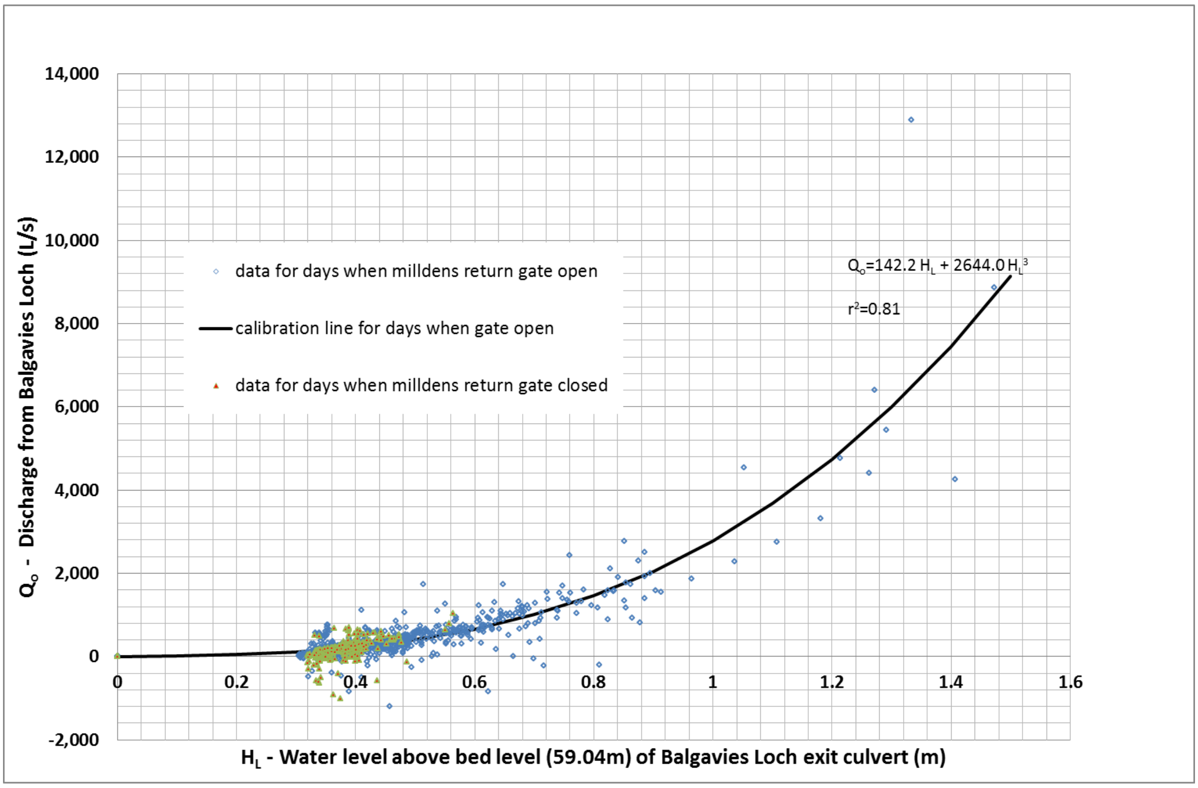



**Figure 9. Calibration of discharge from Balgavies Loch as a function of water level, based on equation (1).**

Also shown in Figure 9 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 4). The outflow remains unchanged by gate closure at low water levels, since it is simply diverted to the Mill lade and to the Chapel Mires spillway (see Figure 5). Historically, the Lunan return gate at Milldens weir 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 Milldens 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 10) 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 11, 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 12 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 in some instances and also channel blockages by sediment, debris or vegetation at some times.

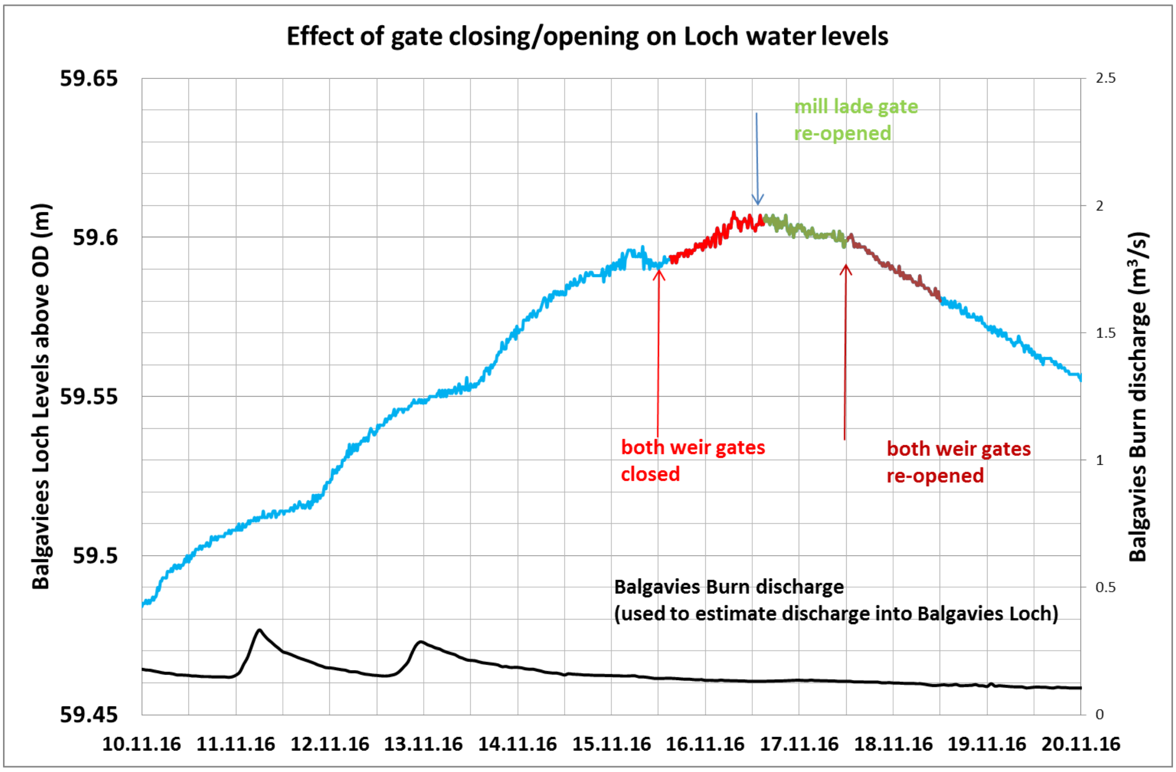



**Figure 10. Example of impact of changing weir gate position on water levels in Balgavies Loch.**

The assumption of the hydrological response being similar for the Loch and the Balgavies 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 10 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.

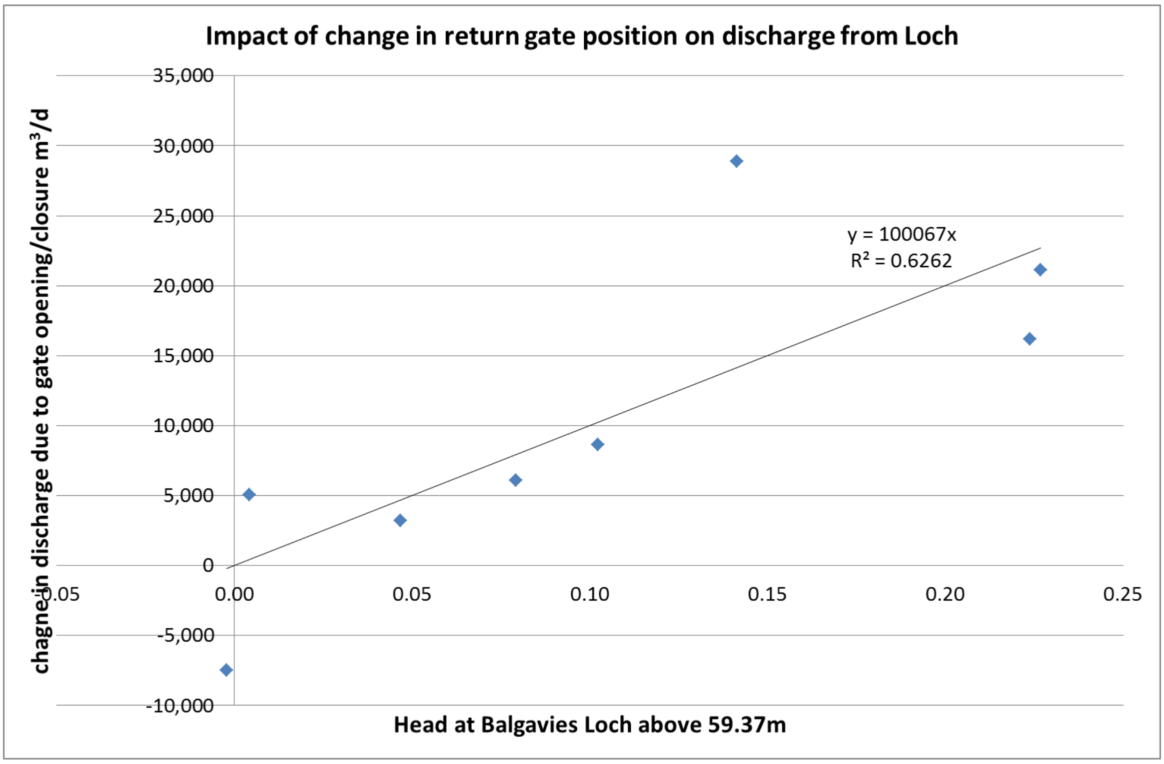



Fig 11. Estimation of impact of change in Lunan return gate position on discharge from Loch. Below H=59.37m, we assume the position of the Lunan return gate has no impact on discharge.

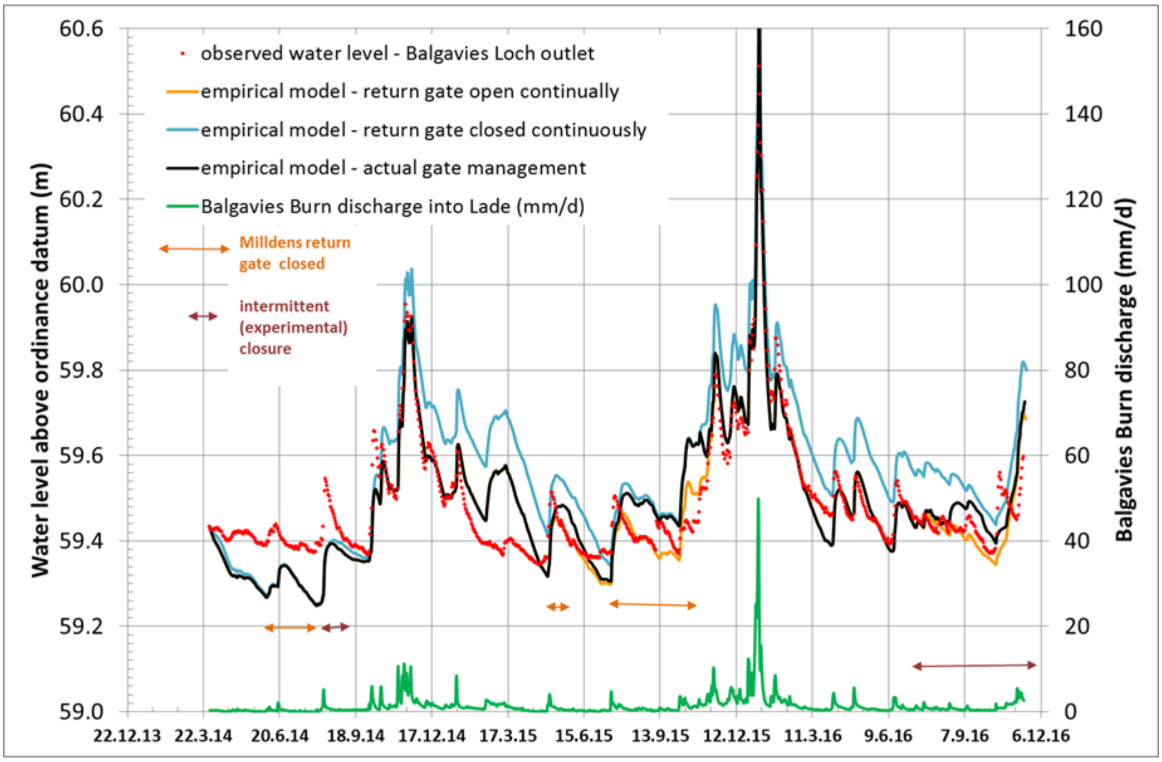



Figure 12. Comparison of measured water levels at Balgavies Loch outlet with empirical model for 3 Lunan return gate management assumptions (a) actual management (b) gate closed continually (c) gate open continually.

### 3.1.3. Modelling impact of new weir gate on water levels and flows

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 13 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.

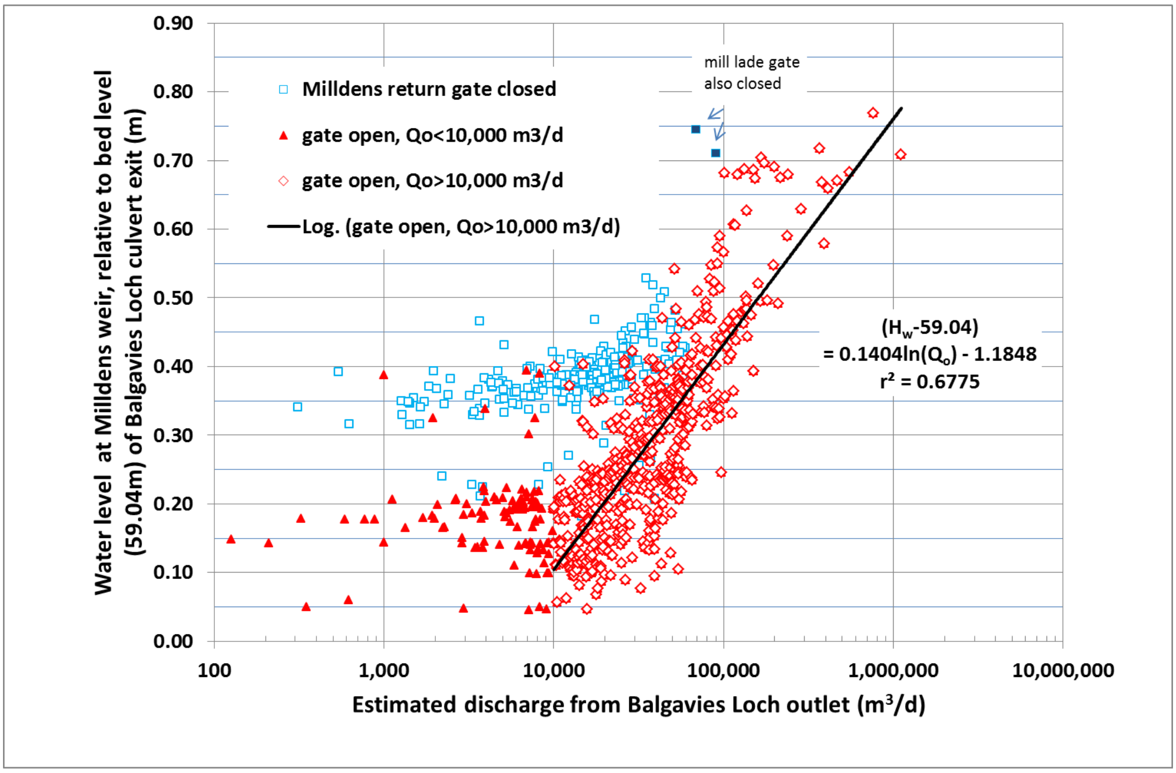



**Figure 13. Relationship between Balgavies Loch discharge and water level at Milldens weir**

We propose to use the log-linear component of the relationship in Figure 13 (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.

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=1.8m 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 14 shows an example of the simulations of the effects on discharge at Kirkton Mill and the water levels in Balgavies Loch for 2012-3.

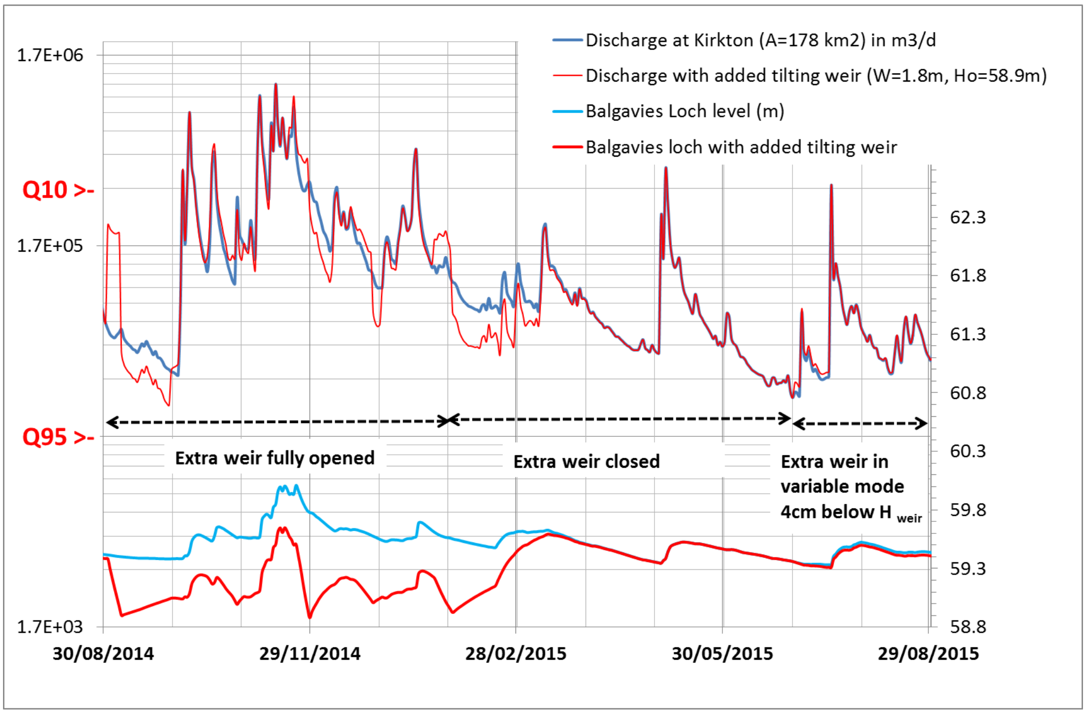



**Figure 14. Impact of additional 1.8m wide weir gate at H= 58.9m at Milldens Weir. Open Sep-Jan, closed Feb-Jun, variable, delivering an additional 35 L/s Jul-Aug. Closed if $H_L$<59.04m.**

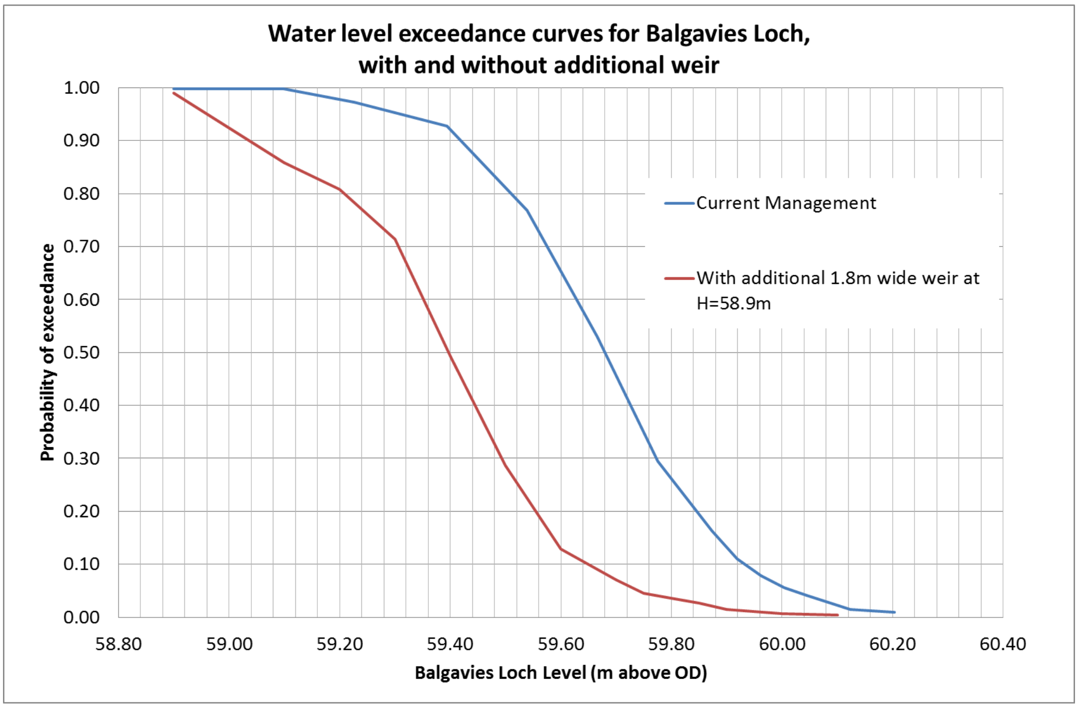



**Figure 15. Impact of introduction of an additional 1.8m wide weir with base level of 58.9m on water level exceedance curve (2011-2016) for Balgavies Loch. Open Sep-Jan, closed Feb-Jun, variable, delivering an additional 35 L/s Jul-Aug. Closed if $H_L$<59.04m.**

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. This is an important result which demonstrates the potential for control of water levels in the upper catchment using a tilting weir without causing detriment to flood risk further down.

A summary of impact on water level exceedance in Balgavies Loch is shown in Figure 15. 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.

### *3.2. Ecohydrology of Chapel Mires*

3.2.1 Species quadrats

Figure 16 shows the mapped extent of wetted area in the Chapel Mires wetlands in May of 2015. The area is considerably larger than the open water area depicted on Master Map and amounts to a total of about 5 ha. Note that the two quadrats located inside the wetted margin are those taken in 2015. The other two quadrats are both located in the position shown to the SE of this area.

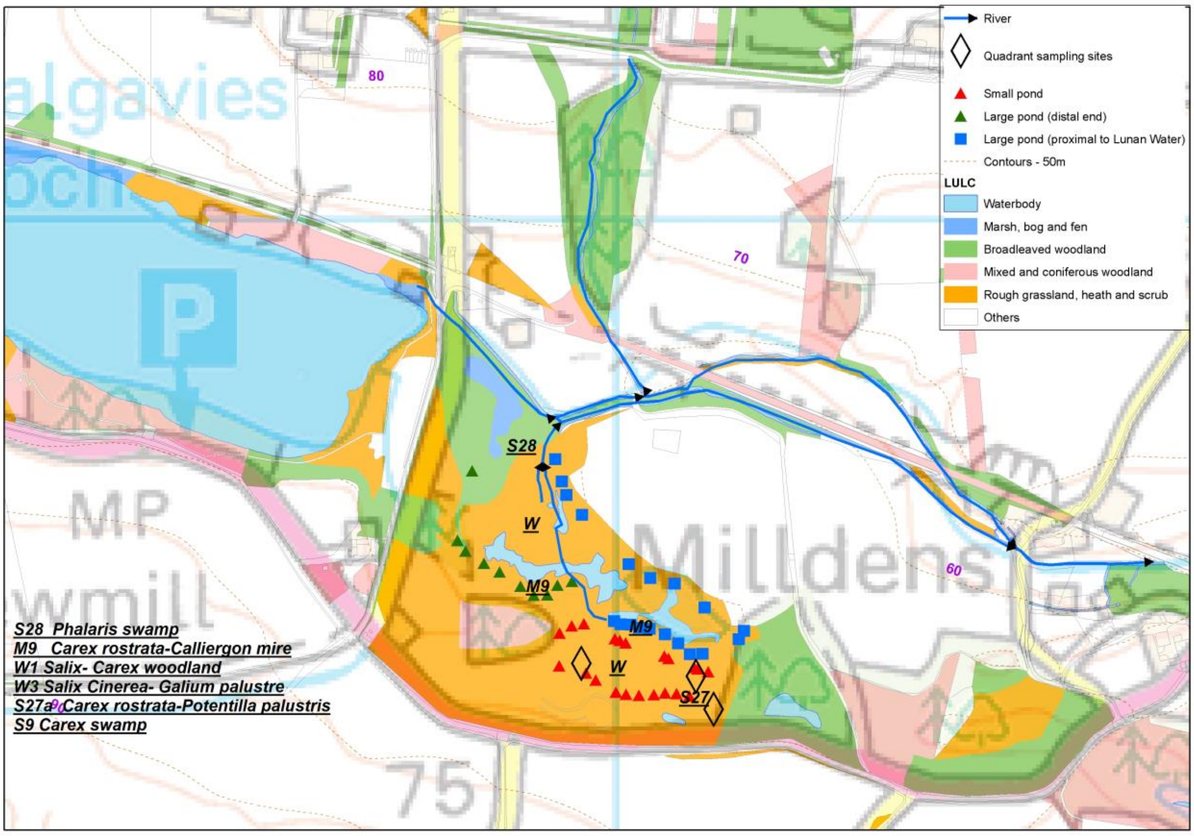



**Figure 16.** Extent of wetted area of the wetlands at Chapel Mires measured with RTK-GPS (mean surface level = 59.12m SD 0.14) May 2015 (mean surface level = 60.04m SD 0.08). Mean water levels at Milldens = 59.52m (return gate closed), Balgavies outlet= 59.51m and Rescobie Loch= 59.68m. Master map background vegetation types.

Table 3 shows the main species observed in quadrats in the Chapel Mires area taken from 1979 to 2015.

| | 1979 | | 2008 | 2015 | 2015 | 2015 | 2015 |
|---|---|---|---|---|---|---|---|
| | Aug | | July | May | July | May | July |
| quadrat number | 79308 | | 79308 | 1 | 1 | 2 | 2 |
| quadrat corner grid reference | NO541503 | | NO5412650360 | NO5410350403 | NO5410350403 | NO5395350420 | NO5395350420 |
| | 1 | | 2 | 3 | 3 | 4 | 4 |
| NVC | S27a | | S27a | | | | |
| | Domin | % cover | % cover | % cover | % cover | % cover | % cover |
| Water soluble/total P (ug/L) | | | 2/20# | | | | |
| Water soluble/total N (ug/L) | | | 34/844# | | | | |
| pH | | | 5.88 | | | | |
| **Agrostis stolonifera** | | | | <1 | | | |
| Angelica_sylvestris | | | 10 | | | | |
| Brachythecium_rutabulum | | | 3 | | | | |
| **Bryophytes cover** | | | | | | | 75 |
| Calliergon_cordifolium | 4 | 4-10 | 2 | | | | |
| Calliergonella_cuspidata | | | 3 | | | | |
| **Carex disticha** | | | | | <1 | | |
| **Carex rostrata** | 6 | 26-33 | 10 | <1 | <1 | 5 | 20 |
| **Carex sp.** | | | | <1 | | | |
| **Cicuta virosa** | 4 | 4-10 | | 3 | 15 | <1 | 2 |
| **Comarum palustre** | | | | <1 | 3 | | <1 |
| Drepanocladus_aduncus | 4 | 4-10 | | | | | |
| **Epilobium ciliatum** | | | | | | | 4 |
| **Epilobium palustre** | | | | 2 | | 4 | 10 |
| **Equisetum fluviatile** | 4 | 4-10 | <1d3 | <1 | <1 | <1 | 2 |
| Galium_palustre | | | <1d2 | | | | |
| **Iris sp.** | | | | 4 | 5 | 25 | 40 |
| **Juncus articulatus** | | | | 1 | <1 | <1 | 1 |
| Juncus_effusus | | | 2 | | | | |
| **Lemna minor** | | | <1d3 | 3 | 1 | 1 | <1 |
| **Litter** | | | | | | 20 | 5 |
| **Lysimachia thyrsiflora** | 5 | 11-25 | | | 20 | | 1 |
| **Menyanthes trifoliata** | 6 | 26-33 | 75 | 1 | 50 | <1 | 10 |
| **Myosotis scorpioides** | | | | | | | 1 |
| **Myrica gale** | | | | <1 | 1 | | |
| Plagiomnium_ellipticum | | | <1dx | | | | |
| **Potamogeton polygonifolius** | | | | 8 | 10 | | |
| Potamogeton_natans | x | 1 individual | | | | | |
| Potamogeton_spp | | | <1d3 | | | | |
| Potentilla_palustris | 5 | 11-25 | 5 | | | | |
| Saccogyna_viticulosa | | | 2 | | | | |
| Salix_cinerea_/_atrocinerea | | | <1dx | | | | |
| **Utricularia sp.** | | | | <1 | <1 | | |
| **Vascular plant cover** | | | | | | | 20 |

**Table 3. Species present in quadrats in the Chapel Mires in 1979, 2008 (Courtesy of Ruth Walker) and 2015 (courtesy of Theo Loizou).**

### 3.2.2 Water margin mapping

Figure 17 shows the water levels plotted on the North-South component of the co-ordinates in May, June and July 2015, for the small wetland (green symbols), the large wetland and the inlet zone from the Lunan Water (blue symbols). In May, the small wetland levels are scattered around 59.2-59.4m AOD while the large wetland levels are lower, 58.9-59.1m. The return gate at Milldens was closed at this time, and there is a clear gradient for the inlet zone from the Lunan Water to the large wetland. However the small wetland is protected from input from the polluted river water because of its higher levels. In June, the small number of data points show a ca. 15cm decline in water levels in the small wetland, and a ca. 30cm decline in the large wetland. The return gate at Milldens was open at this time and this is reflected in the much lower levels in the inlet zone, which means there is little hydraulic gradient into the large wetland from the river, so both wetlands are protected from input from poor quality river water. In July, the Milldens weir gate was again closed, and so levels in the inlet zone are high. However the levels in the large wetland are still low, and levels in the small wetland have also declined, so there is a large gradient from river to large wetland, and a small gradient into the small wetland at this time so there is potential for both wetlands to be receiving polluted river water. This data set illustrates that there is potential for water level controls to influence the input of unwanted additional nutrients and other pollutant species into these wetlands.

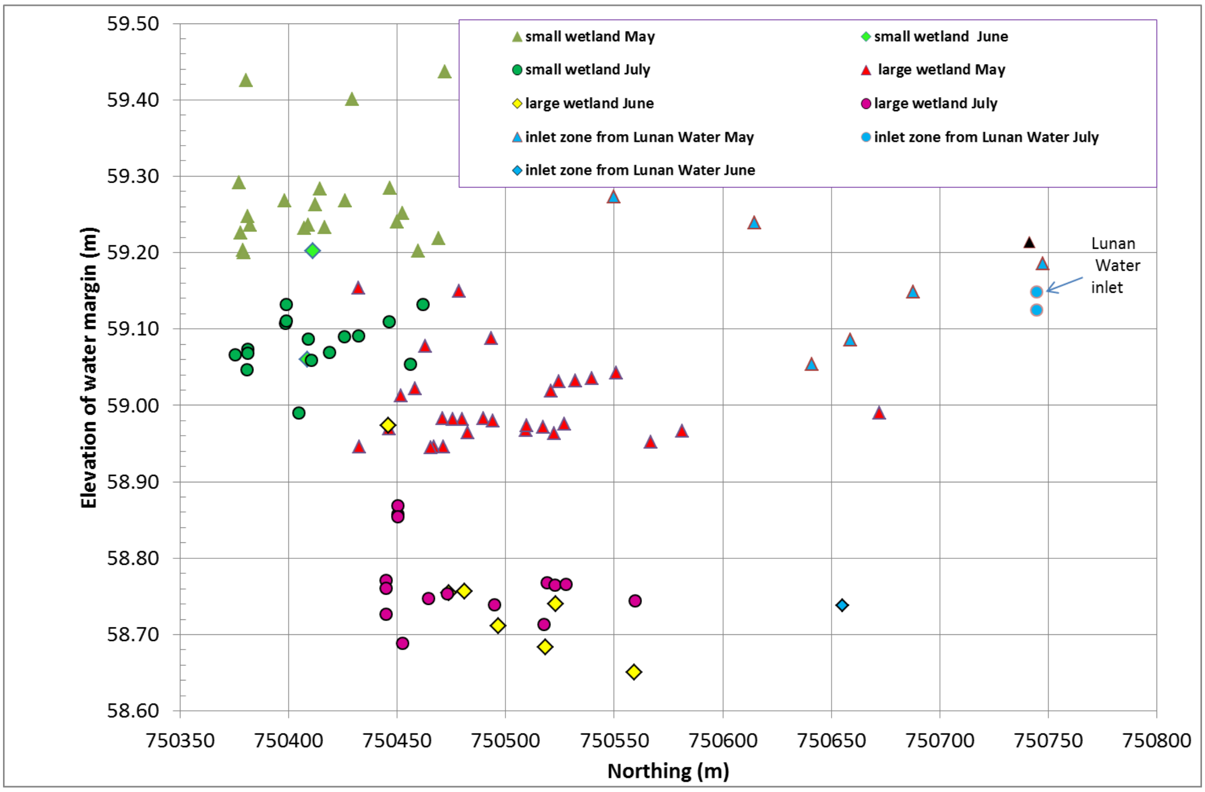



**Figure 17. Water levels at margins of the small wetland, large wetland and inlet zone from the Lunan Water at Chapel Mires, measured in May 2015 (return gate at Milldens closed), June 2015 (gate open) and July 2015 (gate closed).**

3.2.3 Potential for managing flows into Chapel Mires.

The question then arises, to what extent can flows into Chapel Mires be managed by the existing or additional weir gates at Milldens. To investigate this, we undertook weir gate changes and estimates of flows under low flow conditions, on two occasions:

A. 21-27 July 2016.

Both the return gate to the Lunan Water and the gate supplying the Milldens lade were set to open on 21 July. Discharge measurements were made on 26/27 July as follows:

(a) On 26th July with both gates open (discharge measured 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 measured at both Milldens gates);

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

Finally both the gates at Milldens were re-opened.

B. 27-29 September 2016.

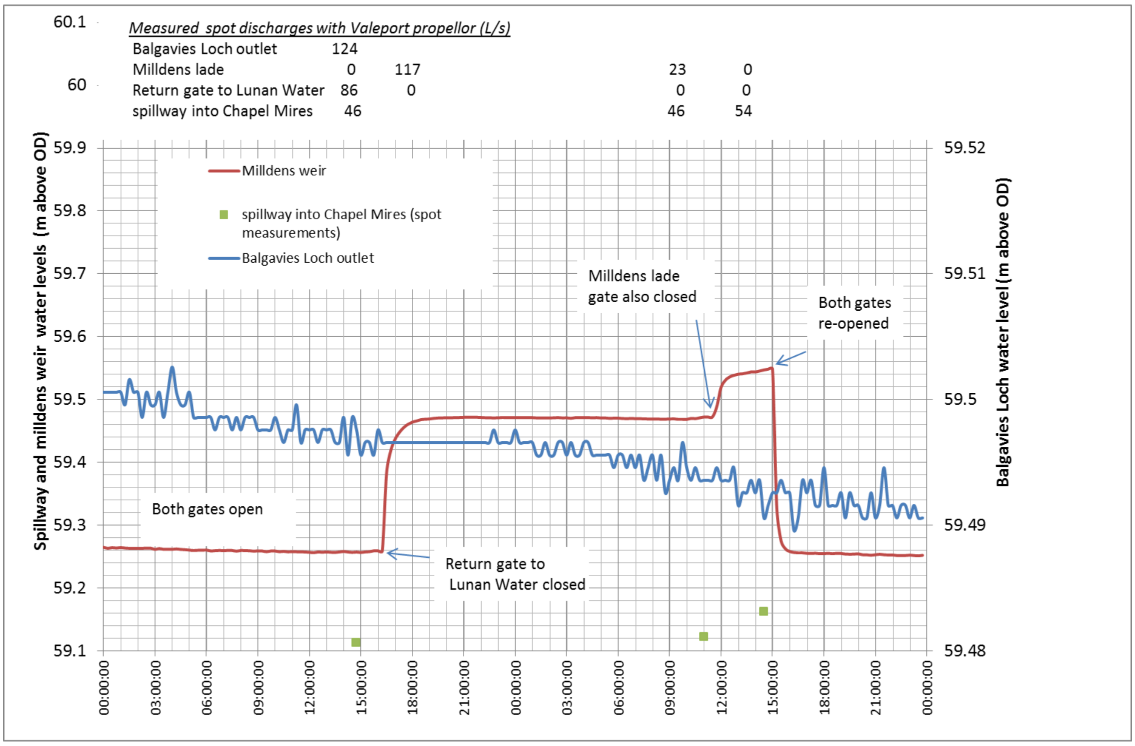
At the beginning of this period, the return gate to Lunan Water was closed and the Milldens lade gate was open. On 27 September at 14.30 the Milldens Lade gate was also closed. At 16.30 both gates were opened. Discharge measurements were made on 27/28 September as follows:

(a) On 27th September with Milldens Lade gate open and return gate closed (discharge measured at outlet to Balgavies Loch, spillway to Chapel Mires and Milldens lade gate);
(b) On 27th September 1.5 hours after closing the Milldens lade gate (discharge was measured at the spillway to Chapel Mires);
(c) On 28th September ((discharge measured at outlet to Balgavies Loch, spillway to Chapel Mires, return gate and Milldens lade gate);
(d) On 10th October before and after opening return gate (discharge measured at spillway to Chapel Mires only).

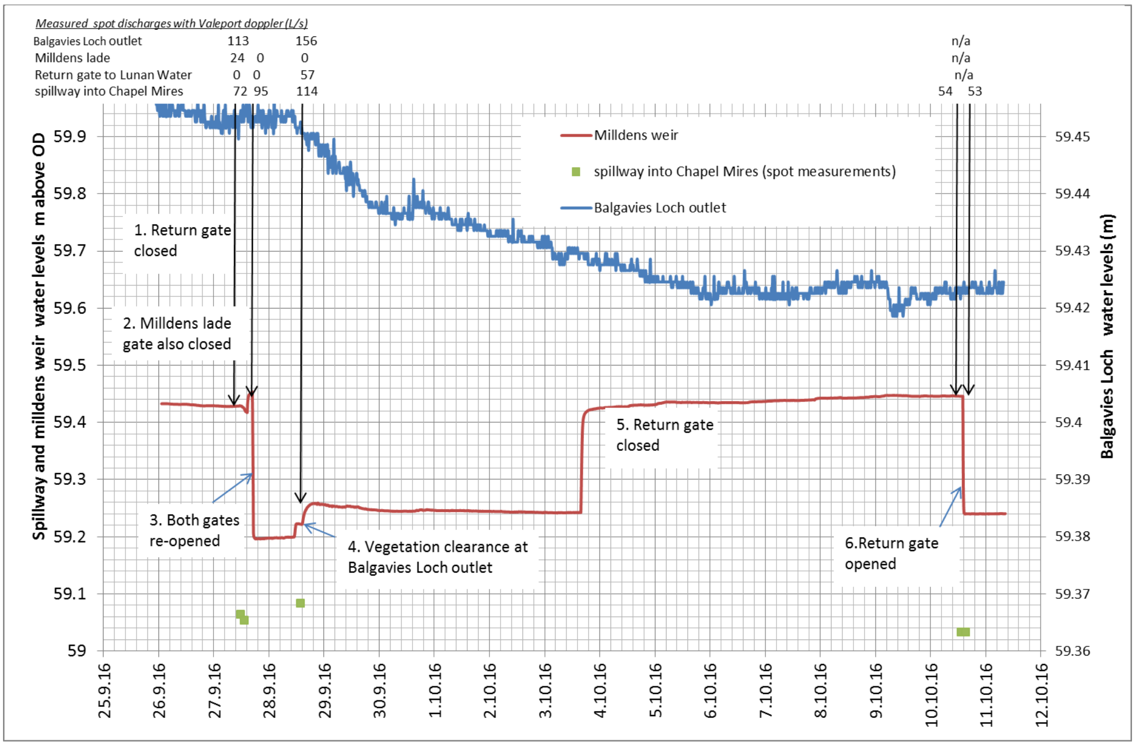
Note that the discharge measurements on 28th were influenced by the unexpected intervention field staff of the reserve in clearing vegetation from the outlet area to Balgavies Loch, leading to a large increase (ca. 40%) in discharge at the outlet. This led to a dynamic situation similar to that which would occur if a weir gate located at the outlet to the Loch were lowered.

Figure 18a and 18b show the water level recordings and discharge estimates at Chapel Mires spillway, Balgavies Loch outlet and at Milldens weir over these two periods. For the first (July 2016) period, the initial discharge through the spillway into Chapel Mires was 46 l/s. The discharge through the return gate to the Lunan Water (86 L/s) also includes a contribution from Balgavies Burn. After the return gate is closed on 26 July, the discharge to the Mill lade increased from undetectable to 117 L/s. For reasons that are unclear, the discharge to the Mill Lade decreases over night. It may be that the initial discharge reflects a larger hydraulic gradient at the Mill lade gate, because the Mill Lade was not yet full and the following morning it was. What is clear however is that neither the water level or the discharge at the Chapel Mires spillway increased due to closing the return gate only. Only when the Mill Lade gate is closed as well, does the water level (+5cm) and the discharge (from 46 to 54 L/s) at the Chapel Mires spillway increase. This demonstrates that at this water level in the Balgavies outlet, increasing the water level at Milldens Weir to above 59.47 cm leads to increased spillage of water into the Chapel Mires. This figure could be indicative as to when the weir gate should be opened in summer to prevent excess of nutrient rich loch water entering the Chapel Mires.

Continuous water level recording at Milldens weir, linked to a weir management, whether or not a new weir installation occurred, would be helpful in identifying when water levels are such that excess nutrient rich water could be prevented from entering Chapel Mires by opening the weir gate. Under the conditions observed in July 2016, this water level is around 59.47m above OD. This level was approached or exceeded during the May 2015 and July 2015 periods of gate closure when wetland margin water levels in Chapel Mires were measured (see Figures 16 and 17).




(a) 26-27 July 2016




(b)27 Sept to 10 October 2016

**Figure 18. Details of water level measurements and flow estimates following weir gate changes. (a) using the Valeport propeller flow meter made at Balgavies Loch outlet, 26-27 July 2016. (b) using Valeport Doppler flow meter 27 September – 10 October 2016.**

### *3.3 Impacts of irrigation abstraction*

3.3.1 Lunan Water low flows

The total maximum permitted abstraction in the Lunan Water catchment for 2013 was 3,399,015 $m^3$. This figure is well in excess of regulatory requirements and is the main reason for downgrading the ecological status of the Lunan Water. The distribution of maximum abstraction volumes across the catchment is shown in Figure 19 as a function of $Q_{95}$.

According to positive abstraction returns, the amounts of water abstraction in 2011 (19,691 $m^3$) and 2012 (zero $m^3$) were very low as they were very wet years (highest and second highest annual $Q_{95}$ figures for the 1983-2012 period, respectively). However in 2013, a relatively dry year (10$^{th}$ lowest annual $Q_{95}$ figures for the 1983-2012 period) the total recorded abstraction was 204,252 $m^3$/year including those farms downstream of Kirkton Mill. This is probably an underestimate, as only 23 out of 73 licence locations gave positive water use returns. The other sites had either a zero entry, a "no data entered" entry or were not available (N/A) on the actual abstractions dataset, although present on the license dataset.

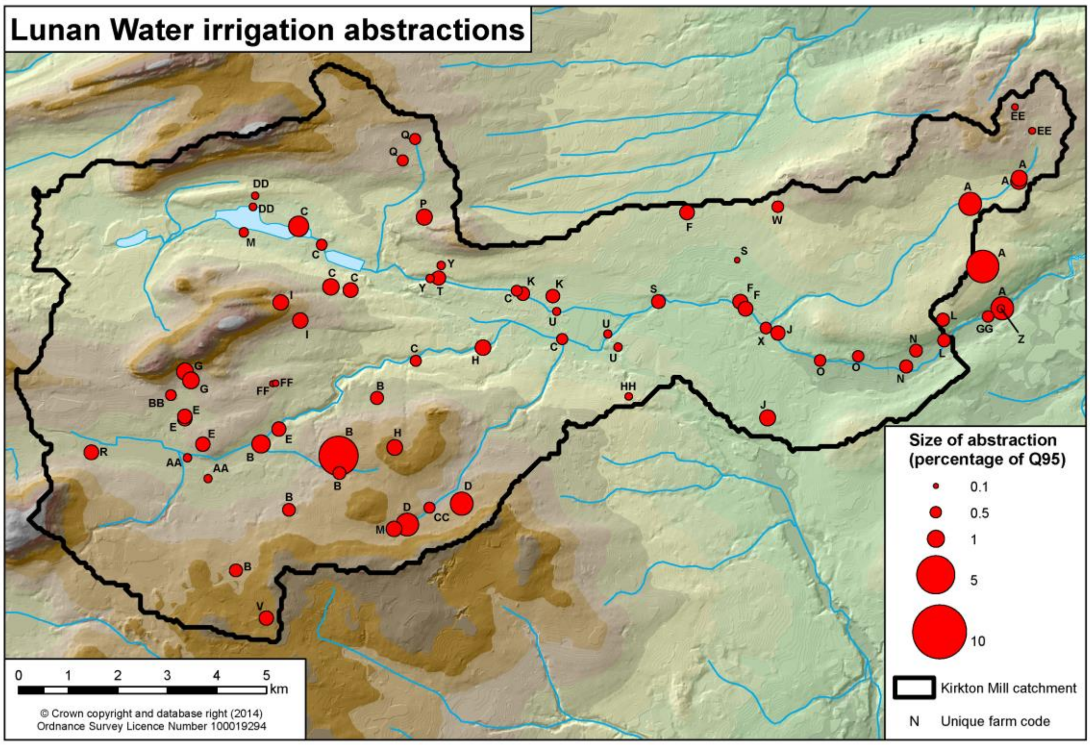



**Figure 19. Maximum abstraction rates permitted on abstraction licences as a percentage of Q95. Letters indicate licence holder.**

The outcome of the regulatory test for various assumptions about the abstraction rates is shown in Table 4.

This also shows the discharge which would just give compliance with the regulatory standards for low flows. These results show that all the sub-catchments clearly fail the low flow regulatory standard (10% of $Q_{95}$) for abstraction if the licenced amount is abstracted. They also show marginal non-compliance for the assumptions based on actual abstraction rates, except for the Gighty Burn. If we take the 2013 dataset (a dry year in which irrigation was widely used) the excess of water use over use that would be compliant with regulation is 19,404m$^3$ over the whole Lunan catchment. This analysis shows that there is a long term pressure for abstraction of water at low flows, which could be alleviated if more water were available from upstream under these conditions, removing the need to restrict irrigation.

**Table 4. Abstraction rates in 2013 (a dry year) as a function of the long term (1983-2012) $Q_{95}$ values for different subcatchments of the lunan Water , making various assumptions about abstraction.**

| | *Gighty* | *Lunan u/s of Vinny* | *Vinny* | *Lunan u/s of Gighty* | *Kirkton Mill* | *Lunan u/s Inverkeilor* |
|---|---|---|---|---|---|---|
| *long term $Q_{95}$ (1983-2012) m$^3$/s* | 0.022 | 0.055 | 0.084 | 0.158 | 0.195 | 0.197 |
| *Irrigation abstraction according to positive actual returns* | 16,161 | 58,850 | 85,094 | 163,473 | 193,364 | 204,252 |
| *Actual annual abstraction which just achieves compliance with 10% standard for daily flows* | 20,826 | 51,671 | 79,156 | 147,754 | 182,921 | 184,849 |
| Maximum percentage of long term $Q_{95}$ abstracted at daily flows <$Q_{95}$, for various assumptions: | | | | | | |
| *A. Assuming irrigation as per positive actual returns* | 7.8% | 11.4% | 10.8% | 11.1% | 10.6% | 11.0% |
| *B. "no data returned" licences assumed to be abstracting at 19.7% of licenced amount* | 7.8% | 19.3% | 15.2% | 17.2% | 17.0% | 17.7% |
| *C. Assuming irrigation as per maximum abstraction on licence* | 118.6% | 121.8% | 198.7% | 166.4% | 162.8% | 183.9% |

3.3.2 Economic impact of alleviating restrictions on irrigation at low flows

What is the impact of alleviating flow-restricted irrigation abstraction on the economic returns for potatoes in the catchment? Crabtree et al (2002) evaluated the economic impact of irrigation abstraction controls associated with low flows for two rivers in south-eastern Scotland; the West Peffer and Tyne River catchments. Using their data, we have estimated the mean difference in gross margins and water use for potato growing under scenarios where irrigation is restricted by 90%ile flow regulation, and where there is no such restriction (Table 5). Over a ten year period, the loss in gross margin when restrictions occurred were £609k and £276k for the two catchments. The decrease in water use was 86.1 and 81.1ML respectively. These give marginal costs of restricted water use of £7.1 and £3.4/m$^3$ respectively. The West Peffer Burn probably represents an extreme case of catchment water stress, as it has minimal upland headwaters, but the Tyne is more typical of many of the rivers on the east coast of Scotland, which have significant headwaters. The Lunan Water has limited headwaters compared to the Tyne, and an average of 488 ha of irrigated ware potatoes, so probably lies between the two documented cases. On the basis of a marginal benefit of water use of around £5/m³, managing flows to deliver a 10% increase in availability of water above

**Table 5. Estimated marginal cost of water use restriction in two catchments in Eastern Scotland. Mean of 1989-1998 data. Based on data from: Crabtree et al. (2002).**

| *Catchment* | | *West Peffer* | | *Tyne* | |
|---|---|---|---|---|---|
| *irrigation restriction* | | *none* | *Q< 90%ile* | *none* | *Q< 90%ile* |
| *Yield* | *t/ha* | 64.2 | 58.3 | 66 | 62.1 |
| *total area* | *ha* | 380 | 380 | 373 | 373 |
| *unirrigated* | *ha* | 0 | 92 | 0 | 0 |
| *irrigation applied* | *mm* | 103 | 106 | 118 | 96 |
| *margin over irrigation* | *£/ha* | 8368 | 6765 | 9102 | 8363 |
| *water use* | *m³/catchment* | 391,400 | 305,280 | 440,140 | 359,013 |
| *margin £* | *£/catchment* | 3,179,840 | 2,570,700 | 3,395,046 | 3,119,399 |
| *marginal value of water at Q=90%ile* | *£/m³* | 7.07 | | 3.4 | |

currently compliant water use (19,000m³) would deliver a catchment benefit for irrigators of £95k per year for a dry year. The 2013 $Q_{95}$ value is on the 32%ile of the long term rankings for April-September flows (i.e. 32 years in 100 are drier than this). One can therefore expect similar benefits or greater in 32% of years, or at least £30k/year economic return in the long term.

## 4. Discussion

The three key elements of water ecosystem services management we are considering are:

a. Potential for generation of extra storage capacity in the Balgavies and Rescobie lochs and surrounding wetlands, to accommodate winter flood storage. This could be achieved by attaining a lower base level in the Lochs at the end of the dry summer/early autumn period.

b. Potential for managing water inputs into Chapel Mires to reduce loading of nutrients from the upstream lochs when they release high concentrations of P in late summer. This could be achieved by diverting such nutrient rich flows away from the Chapel Mires spillway and into the Milldens lade and return flow further downstream.

c. Potential for more timely delivery of suitable flows to downstream users of the Lunan Water at low flows, to maintain ecological status of the river. This could be achieved by storing of water in early summer in the Lochs so that the necessary supplies of water for maintaining ecological flows and protecting interests of marginal wetland ecology, irrigators etc. could be met.

4.1. Potential for generation of extra flood storage capacity in the Balgavies and Rescobie lochs.
The model simulations demonstrate clearly the potential for lower winter water levels in the Lochs as a result of the proposed new tilting weir and associated management regime. Structurally, it may be difficult to operate the proposed weir in partially open mode during extreme flows, when the head of water at Milldens was up to 59.8m above OD (See Figure 20). Therefore it would be best if the proposed management regime allowed it to operate in fully open (H=58.8m) or fully closed (H=59.6m) under such conditions. Otherwise it needs to be managed so that the depth of water over the weir lip does not exceed 300mm. Further work is now needed to develop scenarios of management and their impacts on downstream flows and loch water levels and to make economic and ecological assessments of the impacts of these changes.

The impact on long term flood risk at $Q_{01}$ or above, downstream is thought to be slight, because those areas most at risk of flooding have an input from a catchment area about 6 times that of the upper Lunan Water. However more work with longer term datasets is needed to confirm this point.

**Figure 20. Impact of Storm Frank, January 2016 on upper Lunan Water (a)Fishing boat house and car park at Rescobie Loch ($H_L$≅60.0m) (b) Existing weir gates at Milldens ($H_w$ ≅ 59.8m).**

4.2. Potential for managing water inputs to Chapel Mires.
We think it likely that the bed level of a tilting weir gate should be at least 20cm below the existing return gate bed level (ie < 58.8m) for upstream discharge into Chapel Mires to be markedly reduced. If the gate was set much lower than this, at low flows there may be potential for flow to Chapel Mires from the river to be cut off completely. This may be desirable for periods in late summer/autumn when P levels in the water from the Lochs are high. They have been observed to reach >100 ug/L Total P, and such concentrations are likely to enhance the risk of eutrophication of the wetland vegetation, favouring for example S28 (*Phalaris*) over S27 (*Carex*) communities (Figure 21). A tendency for more of the former, nutrient, tolerant *Phalaris* in areas of the Chapel Mires close to the river has been observed. However care would need to be taken that the weir level were set higher for most of the rest of the year. By limiting release of water for downstream alleviation of low flows only to July and August, and continuing this low level regime into the later summer and autumn to prevent nutrient enriched water entering, we may still be able to improve the condition of the mesotrophic wetlands.

**Figure 21. Chapel Mires wetlands. (a) small wetland (b) large wetland.**

Further work to establish the relationship between ground and surface water inputs to the wetlands, the nutrient inputs associated with these, and the response of the existing Chapel Mires vegetation mosaic to these inputs, is now needed.

4.3. Potential for low flow management.

The area of ware and seed potatoes which could potentially need irrigation is around 2000ha. We can consider the demand for water in terms of the frequency with which flows are lower than Q95, leading to potential restriction of irrigation by SEPA. Figure 20 shows the number of years out of 10 in which a given number of days when Q<Q95 occurs at the Kirkton Mill SEPA gauging station, in July and August, using records from 1981-2015. Also shown is the situation in which an additional 30L/s of Balgavies loch water is released for these months. So for example, 3 years in 10, the number of days in August with Q<Q95 would be reduced from 12 days to 3 days if the additional loch water were released.

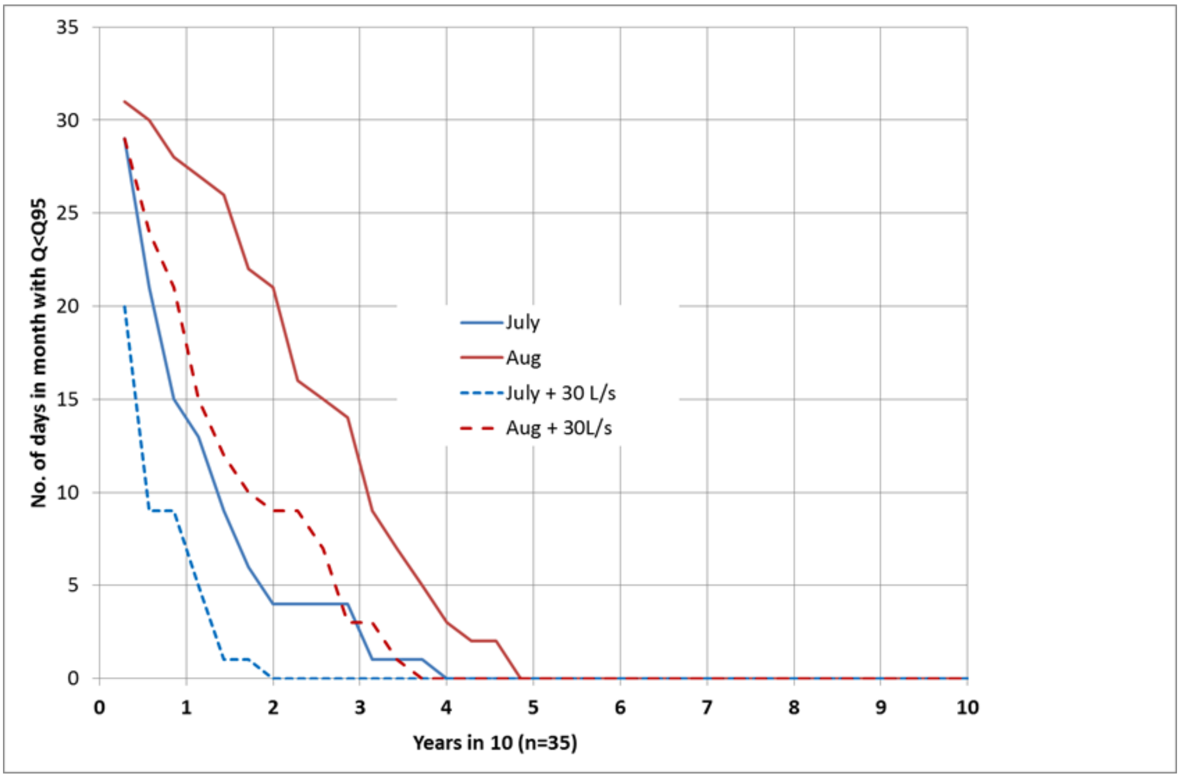



**Figure 22. Number of years out of 10 with which a given number of days when Q<Q95 occurs at the Kirkton Mill SEPA gauging station, in July and August, using records from 1981-2015. Also shown is the situation if an additional 30L/s of Balgavies loch water could be released for a month.**

Can the current, unmodified weir gates be used to manage timely delivery of extra flow to the Lunan Water at low flows? The evidence of the experiments done in summer 2016 is that they cannot. When the return gate was closed or opened, there was very little response in the rate of decline of Loch Water levels unless water levels were high. This can be compared to the situation when the vegetation clearance at the outlet of the Loch was cleared, which led to an increase in the rate of level decline from 3mm/d to 10mm/d for a period of 2 days, with discharge increasing by 43 L/s.

4.4. Proposed site for installation.

Where could such a release be managed? One possibility would be at the outlet to Balgavies Loch. If a manually operated weir gate were set into the existing site of the outlet eel trap to a depth of 10cm, this would generate an additional potential release from storage across the 2 lochs (an area of 78ha) of 78,000 $m^3$, which if released over 1 month, would generate an additional flow of 30 L/s. The gate would be removed at an agreed time in June-July, after the peak demand for wetland ecology in the upper catchment. The additional storage volume generated in the lochs would then also be available as flood storage in the following winter.

Addition of a tilting weir at the high flow spillway at Milldens weir, or upstream of the confluence of Balgavies Burn and the Common Lade (Figure 5), 1.5-1.8m width, with a base level of between 58.8 and 58.9m above OD is proposed as another possibility, or in combination with the first proposal. The uncertainty here is how the additional weir will affect flows into Chapel Mires at lower gate levels (see below), and how it will perform because of sediment accumulation in the mill lade. This sediment comes from the Balgavies Burn upstream. An alternative site, just upstream of the Burn inlet may be more favourable from this point of view, but consenting a new structure there will be more difficult.

As the consenting of new sites, either upstream of Balgavies Burn, or at the outlet to the Loch, may prove more difficult, it is proposed that the first step should be to seek consent for installation of a tilting weir at the current spillway after which performance can be assessed. We expect this installation to operate effectively to reduce risk of high water levels in Rescobie and Balgavies Lochs, and has potential to also deliver improved management of flows into Chapel Mires to reduce nutrient inputs in late summer, and additional flow to downstream users at low flows. In any case, the management of flows through the Milldens mill lade will be easier, because it can be operated remotely according to requirements there, meaning the return to the Lunan Water at other times is not impeded.

4.5 Next steps

We now need to:

(a) offer a summary of this report to the riparian owners for feedback and comment, along with more detailed site drawings, cost estimates and operating plans, to ensure they are content for an application for consent to SEPA to be made.

(b) identify a suitable responsible body to operate the weir, both in the short term experimental phase (3 years) and in the longer term (post 2020) if the experimental phase is successful.

(c) present this information to other stakeholders for comment. These include:

1. Regulatory agencies (SEPA and SNH) involved in the formal consenting process.
2. Riparian owners, both downstream and upstream of the proposed weir, including Scottish Wildlife Trust, who administer the management of Balgavies Loch, and Rescobie Loch Development Association, who manage the freshwater fishery.
3. Downstream irrigators to establish their demand for such improvements in water availability and flood risk mitigation. This is especially relevant now that SEPA have now demonstrated (Scott Leith, pers.comm) that the theoretical ecological impact associated with irrigation water use is actually occurring on the Lunan Water, based on a Flow Pressure Ecological Indicators tool (WFD-UKTAG, 2014).

4. National agencies including Scottish Government (RESAS) and NFUS.

A series of interviews with local stakeholders is now being undertaken by James Hutton Institute Staff. This follows on the interviews undertaken in 2014 (Rear, 2014, See slso Shortall et al., 2017). These will be followed by a survey seeking to establish willingness to participate in the scheme.

## 5. Conclusions

The analysis so far shows that:

- 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. However, closing the Lunan return gate continually, would affect the risk of flooding upstream quite strongly.

- The management regime for a proposed additional tilting weir would be the subject of negotiations, but a starting proposal is that it should be fully open Sep-Jan, closed Feb-Jun, and vary with Loch levels, delivering an additional 35 L/s during Jul-Aug. The gate would be closed if $H_L$<59.04m. This would increase the ability of the weir hydraulics to reduce flood risk upstream. For example the risk of Rescobie Loch being at bankfull at the Fishing Club Car park would be reduced from 6% to 3%. This would not significantly increase the risk of flooding downstream in the Lower Lunan Water.

- This additional tilting weir would have a beneficial ecological and economic 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 upstream Loch sediment release.
- Management of flows through the Milldens mill lade will also be easier, because it can be operated remotely according to demand there, meaning the return to the Lunan Water at other times is not impeded.

- Further consultation with localstakeholders is now being carried out.

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