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Lunan Water downstream of Mildens

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Development of hydraulic management options for the upper Lunan Water,

Angus, Scotland.

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Acknowledgments

I would like to thank my office coworkers, who were patients when I screamed at my computer. My tutor for showing me the beautiful places around Scotland and keeping me on the right tracks during the internship. I will also remember the other students in the James Hutton Institute for all the moments we spend together.

I cannot forget my engees teachers who guide me along the three years and make this happened, and certainly not all my friends who kept me sane and happy during these long months oversee.

My last word is for the red bar, who win numerous arguments between me and it before I get rid of it.

Abstract

Development of hydraulic management options for the upper Lunan Water.

The study of new management methods for the upstream part of Lunan Water is a problem that the James Hutton Institute has been interested in since before 2012. The objective is to find a solution for flood and low water management that allows preservation of wetlands connected to the river. Several proposals had already been modeled on a first model, but this one did not take into account the impacts of the structures on flood dynamics.

The objective of this internship was to realize a second hydraulic model, on a wider perimeter and to perform simulations using floods measured on the basin during the last ten years. The model served as a test bar to test the probable behavior during floods of management proposals previously tested in continuous mode. These are the results that will be presented here.

Lunan Water is a Lowlands river, with a particular geography, combining Lochs and highly anthropized parts, related to agriculture or ancient communication networks. The modifications of this watercourse, especially on the downstream part, are those which allow a management without intervening heavily in the river but have made the models complex and moderately unstable.

Some of the tested facilities allow a priori to fulfill several of the objectives of these management plans, with varying efficiencies. The two proposals, which are a priori effective in flood management, do not have the same costs and the same capacity to be accepted by local residents.

Résumé

Développement d'options de gestion hydraulique pour la partie supérieure de la Lunan Water

L'étude de nouvelles méthodes de gestion de la partie amont de la Lunan Water est un problème auquel le James Hutton Institute s'est intéressé depuis avant 2012. L'objectif étant de trouver une solution de gestion des crues et des étiages qui permet la préservation des zones humides connectées à la rivière. Plusieurs propositions avaient déjà été modélisées sur un premier modèle, cependant celui-ci ne rendait pas compte des impacts des ouvrages sur les dynamiques de crues.

L'objectif de ce stage était de réaliser un second modèle hydraulique, sur un périmètre plus large et de réaliser des simulations utilisant des crues mesurées sur le bassin lors des dix dernières années. Le modèle a servi de barre d'essais pour tester le comportement probable lors de crues des propositions de gestion testées auparavant en régime continu. Ce sont ces résultats qui seront présentés ici.

La Lunan Water est une rivière des Lowlands, possédant une géographie particulière, combinant des Lochs et des parties fortement anthropisées, liées a l'agricultures ou d'anciens réseaux de communication. Les modifications de ce cours d'eau, particulièrement sur la partie aval, sont celle qui permettent une gestion sans intervenir lourdement dans la rivière mais ont rendu les modèles complexes et modérément instables.

Certains des aménagements testes permettent a priori de remplir plusieurs des objectifs de ces plans de gestions, avec des efficacités variables. Les deux propositions a priori efficaces dans la gestion des inondations n'ont cependant pas les mêmes couts et la même capacité à être acceptées par les riverains.

Contents

Abbreviations and list of figures

DTM : Digital Terrain model, raster used in GIS software to get elevations data

ETP : Evapotranspiration, used here to design the Potential evapotranspiration

HEC-RAS : Hydrologic Engineering Centres, River Analysis System

SEPA : Scottish Environment Protection Agency

I. Introduction

The upper Lunan Water catchment is the target of efforts from various local actors to improve the management of the river and the lochs in it. The main focused area are the sediments transportation from the fields, the nutrients loads from the lochs in autumn and the flooding management. There is already existing schemes and projects to reduce the sediments loads from the fields. 5meeting on implementing SUDS on the Lunan Water 22/03/19)(SUDS sustainable drainage measures) the nutriment load is monitored by the James Hutton Institute, to study the impact of eutrophic water inputs on the Chapel Mires Wetland. The flooding risk is not classified as important in this part of the river according to the SEPA and the Angus council (Angus Council, Strategic flood risk assessment). The requirement from the Angus Council however ask for a preservation of a road bridge, in order to maintain the traffic capacity and avoid regular deviation.

The mains feature of the catchment in hydraulics terms are nearly all located after the lochs and before the Mildens houses. This part is also the part with the most numerous channel modifications that can be seen since 1970 [Compton survey]. The position of the division in two channels have been moved and a third channel is now disconnected. This area is also the entry of the Chapel Mires wetland and the pace where all the hydraulic management proposals took places.

The objective of the internship was the evaluation of the utility and the efficiency of theses proposals using a more complete model than the one used in (Vinten, 2019). The results will be used in the meetings with all the partners to help people to choose a resilient and efficient solution to deal with the flood risks. The model was built and executed using the HEC-RAS software. The proposals were submitted by my tutor, comporting a modification of the common lade inlet on a very short section, a modification of the gates and of the existing spillway and the installation of a tilting weir on a new spillway.

The results were mostly similar to those obtained by A. Vinten with his model and steady states flow simulations. However, the unsteady states simulations shown the precise behavior of the flows going in and out of the Chapel Mires wetland during floods events and gave a more precise image of the backwater influences during a flow and for a gate opening. The simulations result also show the efficiency of a tilting weir if positioned on a right place. The other working modification, in terms of flood control, is the modification of the existing spillway.

In this report you will find a description of the catchment, a presentation of the hydrologic and hydraulic models used. Then every proposition is described and the impact of each of the analyzed propositions. All the proposed scenarios have been suggested by A. Vinten and discussed with him.

II. Catchment description

1. General overview

The Lunan Water catchment is a lowland catchment in the east of the Scotland, located between Dundee and Aberdeen. The Lunan water spring is on the east side of the Burg of Forfar. The Lunan Water is influenced by a large number of wetlands and lochs in the early stages.

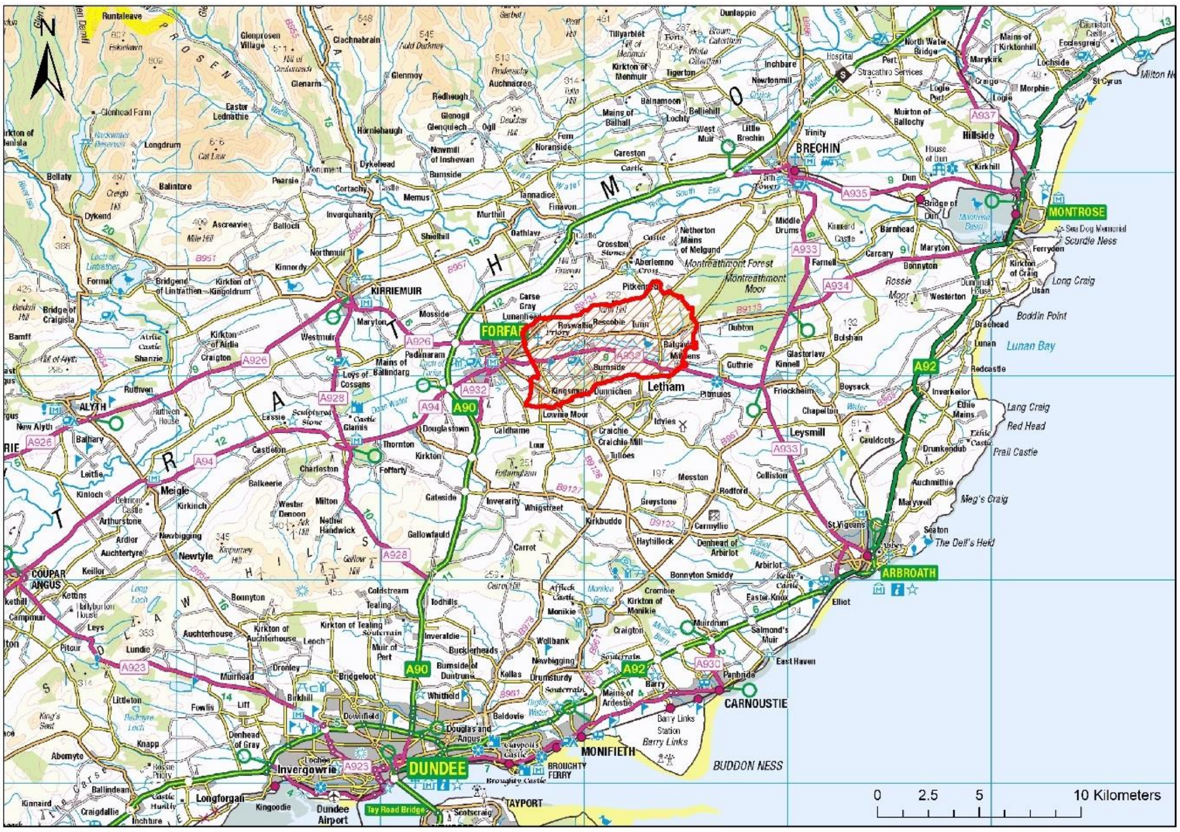


Figure 1 : Placement of the studied catchment on a large scale, the bottom map is a road map from the ordinance survey

The Lunan Water is a short and low river when compared to rivers from nearby catchment (rivers Isla and South Esk). There are only a few urban areas along the Lunan Water or the Lunan tributaries. The two urban areas along the rivers are Friockheim for the Lunan and Letham along the Vinny Water. The lack of inhabitants along the river explain why there is no big plan to improve the flood control on the Lunan Water. According to the SEPA (Scottish Environment Protection Agency) the potential vulnerable area is located on the Vinny water only, with a main point in Letham.

The James Hutton Institute have monitored the Upper part of the Lunan catchment since at least 2007, date of early flow and rain recordings. The initials interest was mostly focused on sediment transportation and deposit and nutrients transport along the river and the wetlands, compared to the groundwater input. The different actors (council, SEPA, Wildlife trust and James Hutton institute) are monitoring the implementation of Rural Sustainable Drainage Measures in the catchment to improve the efficiency of anti-erosion tools for the lowland agricultural catchments.

The Lunan Catchment area is mostly covered with arable lands, with important slopes in the fields for the upper part of the catchment, leading to sediment transportation during rain event.

The area of interest for the model was not the whole Lunan Water catchment but only the upper part of It, the part above Guthrie and Friockheim. The main points of interest are the Chapel Mires wetland, the different channels upstream of Mildens and the Lochs. The Angus Council added one point of interest, a road bridge at the junction between the Burnside burn and the Lunan Water.

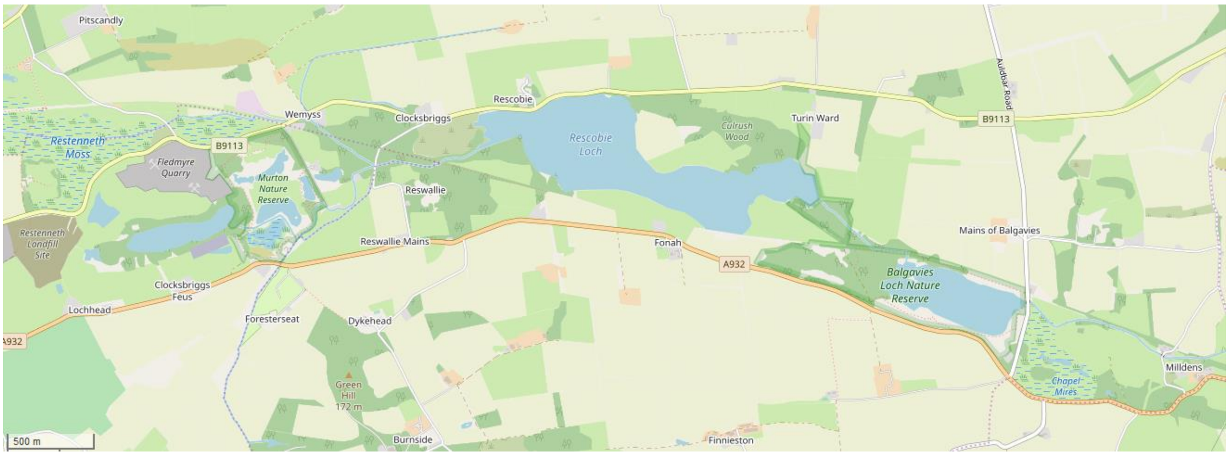


Figure 2 : part of the Lunan Water catchment modelled in the Hec-Ras model, image from openstreetmap.com. ©OpenStreetMap contributors

The five major naturals elements who impact the Lunan Water upstream part are visible. The Rescobie Loch, the Balgavies Loch located on the main channel give a significant inertia to the system. The Restenneth Moss, a wetland surrounding the Lunan Water course before the junction with the Burnside Burn, and the Murton reserve ponds help to withstand the low flow times. And finally, the Chapel Mires wetland can be seen as a storage area on the hydraulic view. Chapel Mires is not only a small wetland who store a part of floods event but also a particular and precious wetland. The Chapel Mires particularity an explanation of it monitoring by the James Hutton Institute is it mesotrophic characteristics, with the lochs classed as eutrophic bodies. (Vinten 2012)

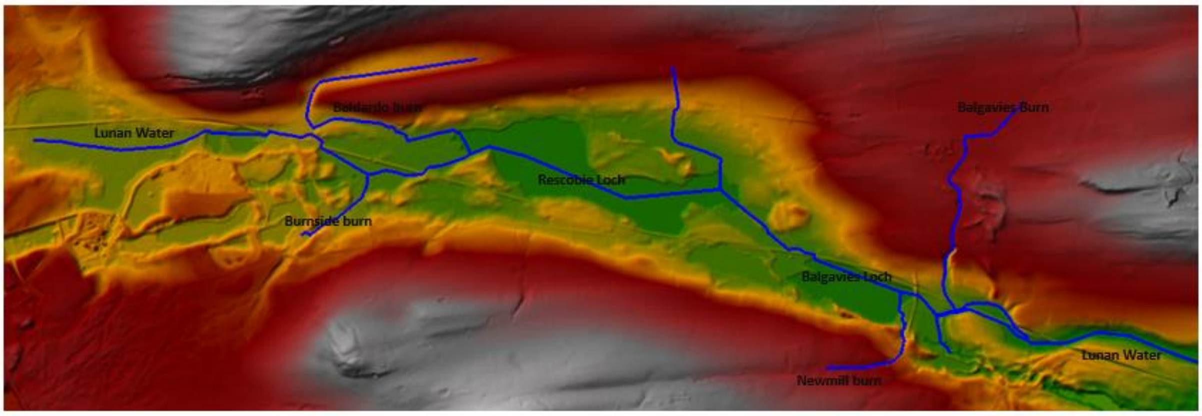


Figure 3 : rivers modelled in the Hec-Ras model of the upstream part of the Lunan Water, similar extend than figure 2

The hydraulic model cover the sector showed in the figure 2, but without modelling the murton reserve ponds. The lochs has been counted as larges rivers without more precise definition of the geometry than a setting of the average depth for the whole section. The geometry for the lower part of the model is based on a field visit and a survey conducted by Mr Compton (local farmer) in the 70.

2. Hydrology of the catchment

The Lunan Water catchment is on the east coast of Scotland, with an important gradient of rainfall between the mountains and the coast. As an illustration of this gradient, the mean annual rainfall for a small catchment (7km²) on the north-west border of the Lunan catchment (Hatton, Lemno burn) is about 824mm (years 2005-2015, grid rainfall). The mean annual rainfall for the Baldardo burn catchment (2.4 km²) on the north of the Rescobie Loch (Wemyss, Baldardo burn) is only 794mm. Theses rain values are estimated rain for grids of 1km², based on radar measures.

The average annual rain for the years 2005-2015 is above the average for the years since 1961, but without a significant trend in the timeseries.

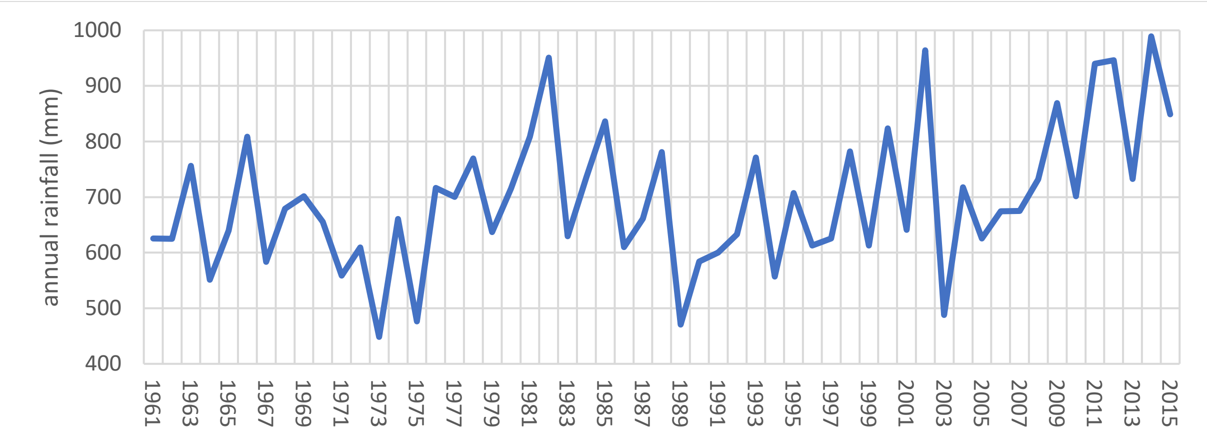


Figure 4 : annual rainfall on the Baldardo Burn catchment, years 1961-2015, data from the UK weather office, data obtained from I. Pohle.

To correct the incertitudes related to the Radar measurement, who generally underestimate the rain, we can use a rain gauge exploited by the institute near Balgavies Loch. This rain gauge is a rain intensity measure place in the field, 200 meters north-east of the Balgavies loch inlet.

Tableau 1 : annual rainfall in the raingauge near Balgavies Loch (mm)

Balgavies Rain gauge		
Years	Annual rainfall	Days recorded
2008	808.20	343
2009	877.05	365
2010	791.94	365
2011	1071.36	365
2012	1136.45	325
2013	784.51	345
2014	1087.76	365
2015	918.52	365
2016	869.62	354
2017	492.62	346
average	883.80	354

The rain measure from the gauge or the radar measure are different enough to question the quality of the previous hydrologic models' calibrations. Furthermore, the question of which rain dataset to use is more crucial with this gap. The radar data is the only one who represent the rain gradient in the catchment, but it underestimates the rain by 5 to 10 percent.

Tableau 2 : Table of Rainfall, flow and ETP (mm) for the Balgavies Burn catchment.

	Rainfall	Flow	ETP
2008	742	515	605
2009	867	480	610
2010	703	353	586
2011	933	486	608
2012	939	561	594
2013	719	391	595
2014	971	480	623
2015	833	405	599

For the above table, the rain is extracted from the estimated rainfall based on radar measurement, the flow values from the sonar gauge located at Westerton, on the Burnside burn and the ETP was calculated by I. Pohle with the Thornwaite formula.

None of the hydrologic balances calculations was near zero or positive for all the years covered with flow and rain values, and the ground water leakage wasn't event counted. The problem can come from a sensible overestimation of the ETP from the Thornwaite formula or coming from an underestimation of the catchments area due to underground transfers. The overestimation of the ETP is suspected to be the main problem.

The ground water influence was investigated by Birkel, *et al* in 2010, using stables isotopes of oxygen and hydrogen (Birkel, 2010). He mentions that the Lunan upper catchments are losing between 25% and 50% of the water to the ground water and a regional aquifer. Considering the geology of the catchment and the observations, this result is not a surprise but will increase the difficulty to get an accurate and right hydrological model for the catchment.

On an additional note Birkel use ETP values 30% lower than the ones obtained with the Thornwaite formula. The rain values and flow values are coherent with the records used in during this work. See the table with hydrology balance and geologic description of the catchments used by Birkel in annex.

3. Hydraulics of the catchment

Considering the hydraulics properties of the catchment there is two major points, the general geometry of the reaches and the hydraulics structures along the Lunan Water.

The geometries can be divided in three distinct types, the reach from the fields on the sides of the Lunan Water, the central part with the loch and flat bed levels, and the part between Balgavies loch and Mildens.

The first type of geometry concerns the following reach: Burnside burn, Balgavies burn, Newmill burn, Nethermuir ditch and Baldardo burn. These burns are very small channels, with a lot of obstacles and an irregular but important slope. They are also characterized by an important elevation difference between the bed level and the top of the banks. Theses reaches has also been modified by the farmers to optimize the field geometry.

Figure 5 : Newmill burn, 200 meters upstream of Balgavies loch, photography taken from upstream. Personal photography.

Figure 6 : Burnside Burn, near Murton reserve, photography taken from upstream, personal photography.

Theses rivers are difficult to model, because of a very small channel, very low flows and a succession of subcritical and supercritical flows. The modelling problem related to this type of river is not critical for the model, since those rivers aren't essentials for the modelling of the Lunan water. They could be replaced by laterals inflows in the model.

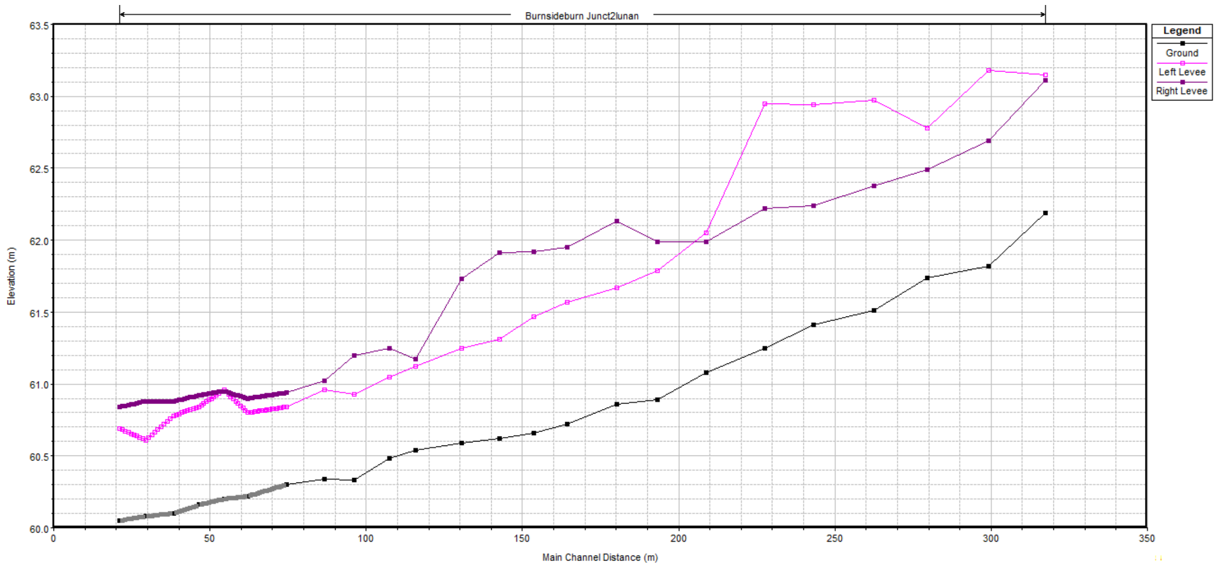


Figure 7 : Profile of the Burnside reach in the Hec-Ras model.

The profile plot before is the modeling of the Burnside reach, using the levees to force the flow in the channel and not in the nearby fields who can be below the riverbed elevation. The general slope of the river is near 1% in the upstream parts with a riverbed 80cm below the banks.

The second group or rivers is the Lunan water upstream of the Rescobie loch, between the two lochs and 100 meters after Balgavies Loch. The Lunan water in these places is a slow and flat river, going through very flat semi-humid areas. There are also a few channels without clear origin or output.

These places were not well rendered by the DTM, and are difficult to measure manually, mostly because of rough terrain and a very dense vegetation cover. This type of area give a large extension fields for the floods, reducing the impact for downstream inhabitants and structures.

Figure 8 : Lunan water 200 meters downstream of the junction with the Burnside Burn, personal photography

The channels here are very flat, sandy and the water levels, when visiting (19 feb 2019), was always close from the top banks. The channel geometry can move with every medium flood, considering than half of the sand deposit were fixed by logs blocked in the channel or in roots systems.

The last sector concerns the division of the Lunan in two parallel channels downstream of the Balgavies Loch. The lunan going out of the loch is partly deviated to the right by a stone spillway just before the Chapel Mires wetland. When following the flow, the part of the river going straight became the Common lade. The diverted flow will keep the Lunan name. The common lade will continue on a nearly strait line, with a flat bed level, except for a sediment deposit upstream of a bridge and the junction with Balgavies burn. This sediment deposit, located at a cattle drinking point, increase the riverbed by 30 cm, and therefore, is a probable key point to understand the flow partition between the Lunan channel and the Common Lade.

The common lade end with a pair of guillotine wooden gates. The left gate lead to a small channel designed as Mill Lade. The mill lade is the old water course for the mill at Mildens. The second gate, named return gate, open the way to a discharge in the Lunan Water. The gates are operated by the two farmers owning the nearby fields. These gates are an essential feature to control the loch levels and the discharge rate of Balgavies loch. Some parameters of theses gates can even generate negative flows in Common Lade during early stage of floods events.

The Lunan channel, starting at the lateral stone spillway, is at first a rectangular channel with no slope and heading to the Chapel Mires entrance. The connexion with Chapel Mires is done by a flow path coming from the right of the Lunan. In the model this part of the Lunan will be named “Lunan deviation”. After the Chapel Mires entrance, the Lunan start becoming larger and sloppier. The channel start looking like it’s counterpart (Common Lade) but with an increasing difference in river elevations. This difference will go up to 1.25 meters at the gates.

Figure 9 : photography of the Common lade (left) and Lunan (right) upstream of the Balgavies burn junction. Personal images

The pictures above have been taken on the from the same place, on the central levee, at approximately the middle of the Common Lade channel length. At this time the return gate was set at less than 10cm and the mill gate was an open top flow.

The hydraulics properties of the catchment are also highly related to the bridges, gates and spillways build along the Lunan.

The first obstacle, along the Lunan from the spring, is the road bridge, the one the Angus Council ask to preserve. This bridge is a two-arch bridge, located at the junction of three water courses. This bridge is full of sediments and working at reduced capacities. The rivers coming to the bridge, on the photography are: the Lunan on the left, the Burnside burn on the middle and right. The middle part come from the Murton reserve and a deviation of a part of the Burnside burn before Murton cottage. The water is very deep (1 meter) at the entrance of the bridge but less than forty centimeters at the outlet.

Figure 10 : road bridge upstream of Rescobie loch, personal photography

After this the Lunan Water will pass three times under an old railway line (now disarmed). The railway line act as an impressive levee of four meters, with only one way to pass under. The arch to go under the line are all different, with a very large opening for the outlet of Balgavies Loch and before Rescobie Loch to a long 2.1 meters wide and 2 meters high tunnel.

The next structures are the two bridges seen at the figure 9. These two bridges don’t have a sensible impact during low or medium flows. However, the bridge in the Lunan is a bit undermentioned to let pass an important flood. This bridge was built with three wastewater concrete pipes and the rest was filled with stones and cement.

The last structures are the twin gates in the end of Common Lade. These gates are vertical gates with a manual control on the top. The entrance of each gate is a stone triangular channel with a flat stone inlet at 59.0 m.

Figure 11 : gates in Common Lade from upstream, photography by A. Vinten

The gates were overtopped during the floods resulting of the storm Frank. The water level was high enough to reach the opening mechanism of the gates.

The modelling of all of these structures is described further in the report

III. Modelling

Why a new hydraulic model

There were an existing hec-ras model of the Lunan water, in the same area, however, the existing model was rather small and very schematic. It was built in Hec-Ras using topographic measurements in the field, and since had a poor density of initial cross-sections and had to rely massively on interpolated cross-sections for the unknown areas or to work with great gaps between cross sections. In addition, this initial model was built for the steady state only and not for an unsteady state simulation, which meant it is not adapted to model gate movements and flood dynamics.

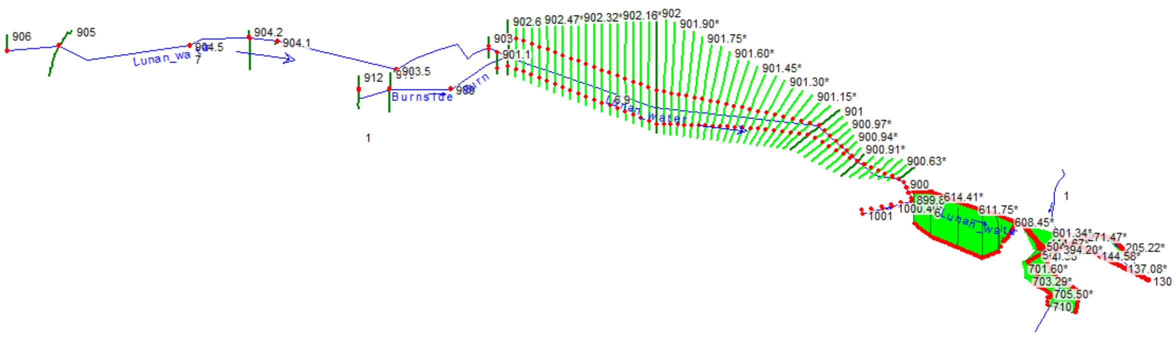


Figure 12 : View of the geometry of one of the models used for the steady state simulation by A. Vinten

The geometry above was one of the geometries used in (Vinten, 2019) for steady states analysis of the different proposals for improvement of the flood management and nutrients management.

In order to model more precisely the floods dynamics and the effect of hydraulics management on the system, a new model was built. It was designed to include a more accurate description of the two Lochs, the road bridge (in the end of Burnside burn) and the mill lade channel.

And to correct the lack of data from topographic measurements, the altimetric measurement were based on DTM from the Scottish government Remote sensing platform. Theses information's are available under the Open government license for public sector information. The DTM resolution is one pixel per 1m². [https://remotesensingdata.gov.scot/products?collections=scotland-gov/lidar/phase-1/dsm]

The new model allowed us to measure more precisely the impact of static hydraulics structures or dynamics installations to improve the efficiency of flood and flow control.

1. Hydrology

The hydraulic model needed a flow or a water level value for each input reaches. For each of these reaches, we had the information's that can be extracted from a DTM, and pluviometry data. However, two of the reach are monitored since 2007, giving us, partial flow data. The two flow timeseries isn't enough to make the hydraulic model working, we needed more inputs, but there are enough to calibrate a hydrologic model, along with a gauge outside of the catchment.

In order to set up a hydrologic model we gathered information's from nearby flow gauges. Four flow gauges have been used to calibrate hydraulics models. Three of the gauges are located on the model area or nearby and operated by the James Hutton Institute. The last one is a SEPA gauging station located downstream on the Lunan Water.

In order to get flow values for ungauged basin we could use several methods. From empirical formulas to determine the peak flow for a raining event for small catchment, to regional formulas based on existing flow values and regionals coefficients, or expending a hydrologic model calibrated on the few gauges available.

A regional formula is generally used to model one flood event with a know frequency on a close and similar basin. These methods are generally use for 10 years return time floods, with regional coefficient predetermined. However, if there is more than one gauged basin nearby, the coefficient can be calculated, for a more precise result, from these nearby catchments.

Formulas like the rational formula, using the slope, the area and a concentration time in addition of the rain value, are designed to give peak flow values. We still can recreate a flood hydrograph from the peak value, but we cannot recreate a full timeseries with medium and low flow values. And since the goal is not only the flood protection but also the behavior during common times, we didn't use these formulas.

The two other solutions, an extension of the parameters from a hydrologic model or using a regional formula have been tested. For the modelling we used the modified regional formula. The efficiency criteria were similar for the Regional formula calibration and the previous models used on the catchment, and greater than the first results obtained with the GR4J model.

Two models have been tested, the GR4J model and a modification of a regional formula. The modified regional formula has been used to test the early stages of the model, taking advantage of the quick parametrization and adaptability of the formula. The development described later on this text was created when we needed to model more than one event. The GR4J model was chose for its simplicity and the fact that we didn't need to install any package of software to make it run. The GR4J model was an alternative to the TUW model, used by I.Pohle, and already calibrated for some of the sub catchments of the Lunan. However, the calibration process using the TUW model took more than 30 hours and the calibrations results for the Wemyss and Westerton catchment had a Nash between 70 and 60 which is similar to those obtained with the regional formula.

A. GR4J model

The fist model used was the GR4J from Irstea. The GR4J model is a conceptual hydrological model using a daily timestep. This model uses two inputs, the rain and the potential evapotranspiration, to generate a daily flow. The model uses a first reservoir to store a part of the rain and build two hydrographs. The two hydrographs are builds combining a calibration parameter, a part of the rain and the result of the percolation from the production reservoir. One of the two hydrograph will be modified by a function related to the exchanges with the groundwater. The other hydrograph will go to another reservoir. The routing reservoir is modified by one of the calibration parameters and the function conditioning the groundwater exchange. The final flow value is the addition of the routing reservoir draining and the flow from the first hydrograph, after modification for ground water.

This model has been chosen because of its adaptability and quick parametrization time. The other argument was it’s just an excel file easy to use when the inputs are csv. files with various configurations for headings. It was also previously used by me, reducing the time required to understand how it work.

The model only requires three timeseries, daily values for rain, evapotranspiration and runoff, (in cumsec or mm/day). The flow timeseries can have some missing values without generating problems. The other timeseries has to be exempt of missing values. The calibration was made using the first years and the validation is axed on the year 2010. Once calibrated and valid, the model can be transferred to nearby catchment, by copy pasting the parameters and giving the rain and evaporation timeseries.

The calibrations process using portions of datasets given by Ina gave Nash values around 0.45

Tableau 3 : calibration and validation result for half of the dataset with the GR4J model

Catchment	Nash value calibration	Nash value validation	X1	X2	X3	X4
Westerton	0.426	61.5	134.94	0.66	12.80	0.50
Wemyss	0.394	68.1	3.69	-9.89	107.44	0.50
Hatton	0.598	24.1	4.52	-15.01	26.21	0.50

Table for calibration results covering 17/08/2007 to 20/09/2009 (years after 2011 were suspicious because of an error in the rain dates in the first half of 2011) the validation window end in 01/01/2011.

The GR4J model used was the version of Perrin et al., 2003, downloaded from the Irstea website (https://webgr.irstea.fr/modeles/journalier-gr4j-2/). Better results have been obtained, after with new, datasets, without duplicates and longer times for calibration and validation. However, the choice was already made in favor of the regional transposition. For Prospective scenarios I recommend using either the GR4J model or the TUW model, with a generalization of the parameters to the different catchments.

B. Regional transposition

The regional formula, like the one mentioned in Culdworth, is also set to model a singular flood event with a certain frequency of apparition. However, the formula can be twisted if we get an apparition frequency for each entry in the initial timeseries and generate a set of parameters for each of these frequencies. The initial hypothesis is that the "b" coefficient is dependent of only the catchments and the frequency of the flow values.

Global form of the formula: $Q_1(Fi) * {A_1}^b = Q_2(Fi) * {A_2}^b$

In order to determinate a "b" coefficient we needed to get flow values of the same apparition frequency. So, we generate bijective relations between flow values and the frequency. The first problem was to find a bijective law accurate enough in the set of definition ([0 : 0,5]x[0 : 10]). The first try wasn't successful, so I had to do a transformation on the frequencies. The matching has been done between the flow and the logarithm of the inverse of the frequency.

The flow values were quite well reproduced using the frequency of their apparition to model them, and we managed to get a good representation of the frequency of apparition using the flow value. After this stage, we were able to determinate a apparition frequency with only the measured flow value, and then determinate the b coefficient for same frequency flows.

The full process is described in annex along with the graphic representations of the fittings between calculated frequency and empirical frequency and the B coefficient curves obtained.

The log transformation give us the opportunity to fit a polynomial function in the graph (Q , -ln(F)), that can be easily inverted. After the inversion we only need to verify the correlation between the flow calculated from the frequency and from the initial timeseries. The correlation is excellent except for the six to ten highest flow, which are all located around the first days of January 2016, in other words: the storm frank runoff. These results are coherent with the expectations of storm frank floods being more than a decennial flooding and are expected to be under-estimated because of an over-estimation of the apparition frequency.

Then with a common frequency, we calculated b coefficients for each frequency, and try to fit a relation bonding b coefficients and frequencies values. However, the "forms" of the b coefficients doesn't make much sense, so we also tested the mean value of all the b values. The choice of the flow dataset for modeling the flow and the choice of the b coefficient have been done by testing every combination of b calculation method and flow selected as reference.

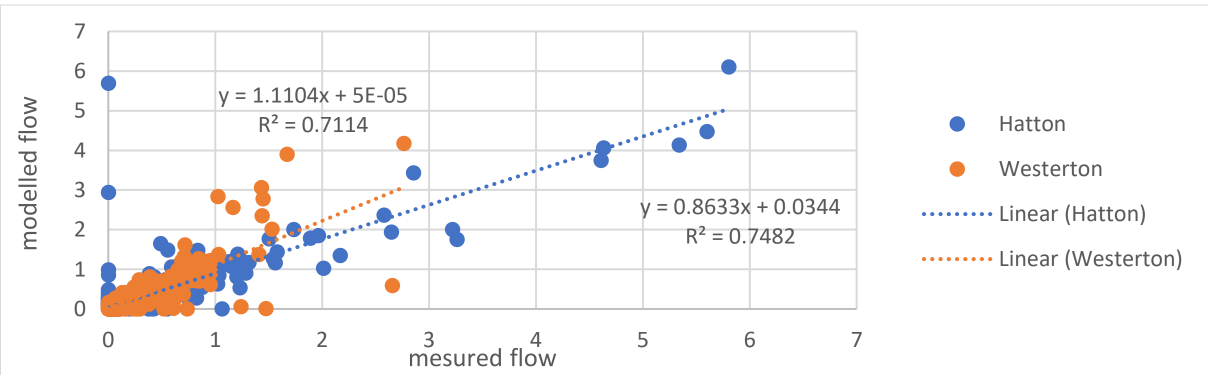


Figure 13 : result of the modelled flow against the measured flow in Wemyss and Westerton catchment, using the Wemyss catchment as origin and a b coefficient fixed at 1.288

The selection has been done by graphic lectures in the first place, then by calculating a Nash efficiency criteria for the last remaining combinations.

The best results have been obtained using the Wemyss flow timeseries and a constant b coefficient. When in the set of Q values used to establish all the functions the Nash efficiency criteria for the Hatton and Westerton catchments were 0.886 and 0.617 but 0.725 and 0.610 if the whole dataset is exploited.

Tableau 4 : Nash values for validation of the modified regional formula on the Hatton and Westerton catchment

Catchment	Hatton	Westerton
Nash (in the limits of the functions)	0.886	0.617
Nash (whole dataset)	0.725	0.610

The Regional formula was chosen because it was the more practical and nimble solution. With this solution we generate quickly new inputs for new sub-basins. The other advantage was the elimination of the ETP overestimation, and the groundwater leak were treated. The use of flow values instead rain move the problem after the exchanges with the groundwater and the evapotranspiration.

2. Hydraulics

The hydraulic model used was done using the Hec-Ras software from the US Army Corps of Engineers. This software allows to make one dimensional steady and unsteady state flow modelling. It can also do two-dimensional flow calculation and sediment transportations computations, but theses capacities were not used here. The version used to build the model was the 5.0.6., we noticed than the ulterior version require more information's in the lateral structures description to run.

The software can be downloaded in the US Army Corps of Engineers website by everybody, and the documentation is provided on the same page.

The model was used with unsteady flows only on mixed flow regimes. The steady flow simulations were already done by A. Vinten and the results presented in (Vinten 2019).

The chapter following describe the steps and tools used to create the model

A. How this model was built

The GIS

The GIS was the base of the new hydraulics model. It contains a more accurate description of the river path, allowing us to use the DTM to automatically import distances and elevations into the cross sections and generate names for cross-section. All of these are permitted though an ArcGIS extension: HEC-GeoRAS

Steps used to extract the GIS information and export them to the RAS model were :

1. identification of the different information sources for the digitalization of the river paths and areas of interest, such as aerial photography, DTMs, topographic maps and rivers layers from the SDE database. (Note the DTM are mandatory).

2. rivers digitalization, with one vector per reach, with only one reach between two junctions (a junction is a confluence or a division of the river). With this operation the rivers lengths were be set.

3. creation of the flow paths, river path flow, left overbank flow and right overbank flow for each reach. These flow paths will be used for distances calculations between cross sections.

4. cross-section digitalization. drawn from left to right and with no overlapping.

With all of this done, we had a file with georeferenced rivers and cross sections, including altimetric data from the DTM. The only problem come from the DTM characteristics; it cannot penetrate water and consider the water level as the bed level.

5. correction of the rivers channels geometry. This needed firstly the operation of a river burning on the DTM (mainly to see the channel path and having a rough approximation, then doing a finer modification of cross section in the Hec-Ras geometry editor.

6. export to a format that Hec-Ras can read, you will also need to export the DTM as a TIN. (Triangular irregular network, representing the surface morphology)

For all the pre-cited operation I recommend reading "HEC-GeoRAS GIS Tools for Support of HEC-RAS Using ArcGIS User ' s Manual" for more information on the detail of procedures and actions needed.

In order to keep the correct distances, importing the grid reference system from the TIN is crucial.

With all these operations we had a complete, georeferenced and fairly accurate geometry for the hydraulic model.

Corrections of cross sections

As mentioned before, the cross sections were inaccurate, especially in the flat parts of the landscape and for the lochs. The problem comes from the DTM characteristics, the laser used cannot penetrate water, and therefore, doesn't give us a correct bathymetry but the water surface elevation. The river burning process on the DTM to lower the altimetric values of the "river bed" wasn't a great success. The two main problems coming from the lack of non-remotely measured data in large portions of the Lunan Water and, the ratio between the river reach widths and the resolution of the DTM.

With almost no measurement on the parts upstream of Balgavies loch, and no reasonable possibility to make some, the width and the deepening of the burn process was mainly done by guesswork. This operation allows us to see the river trench in cross-sections and have reasonable values for width of river reaches. However, the problems related to the DTM were still present, and we had numerous and sharp elevation variations in the bed level of the different rivers reaches.

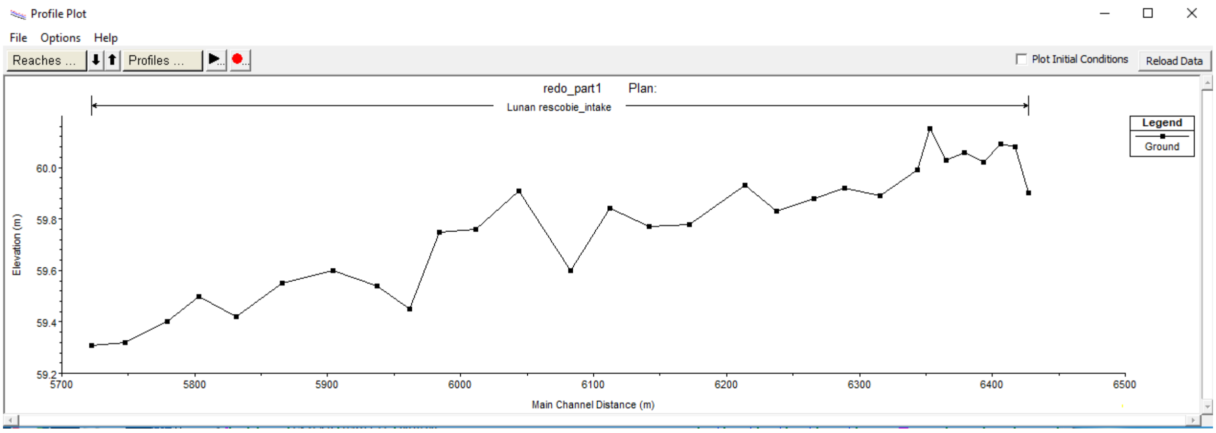


Figure 14 : reach profile just after import from the GIS, reach depicted: Lunan - Rescobie Intake

As shown in the previous plot, the bed level is quite variable, and theses variations created numerical instability, forcing numerous and unrealistic critical flows. In order to have a stable model we smoothed the bed level, accordingly with the Addy and Vinten measured points (see annex) and set interpolated cross-sections. Each place where interpolated cross-sections were placed was an area generating instability in the early stages of the model. The source of most of these instabilities was the backwater solution/first iteration transitions.

We also deleted some rivers and reaches which were too difficult to stabilize and not very significant for the final objective. For example, the Lunan Water between Mildens and Friockleim was removed, as well as the Vinny Water. The head and the connexion of the Burnside burn with the Murton reserve was also removed because it was a succession of subcritical flow and supercritical flow. The upper part of Baldardo Burn and Balgavies Burn were deleted to correct similar problems.

After solving the problems of bed level topography, the problem was to force the water flow in the river channel. The first and major solution was using the "levee" tool. The right and left levees points were put just next to the bank of the channel, on or just below the ground, to avoid impact on flood extension. For some sectors, mainly when the railway structures are near the river, ineffective flow area were used.

Finally, in some particular places, near Chapel Mires, I was forced to adjust the flood plain elevation to match with the bank stations. It was the only way to make the water go in the channel during the simulation. The levee tool was not suitable for this location because due to the particular configuration of the site, the backwater solutions set an initial water level above the bank stations in the upstream part of the reach, and the iterative solution set a water level below the banks stations, so the difference of water surface and water speed was too big for Hec-Ras to converge.

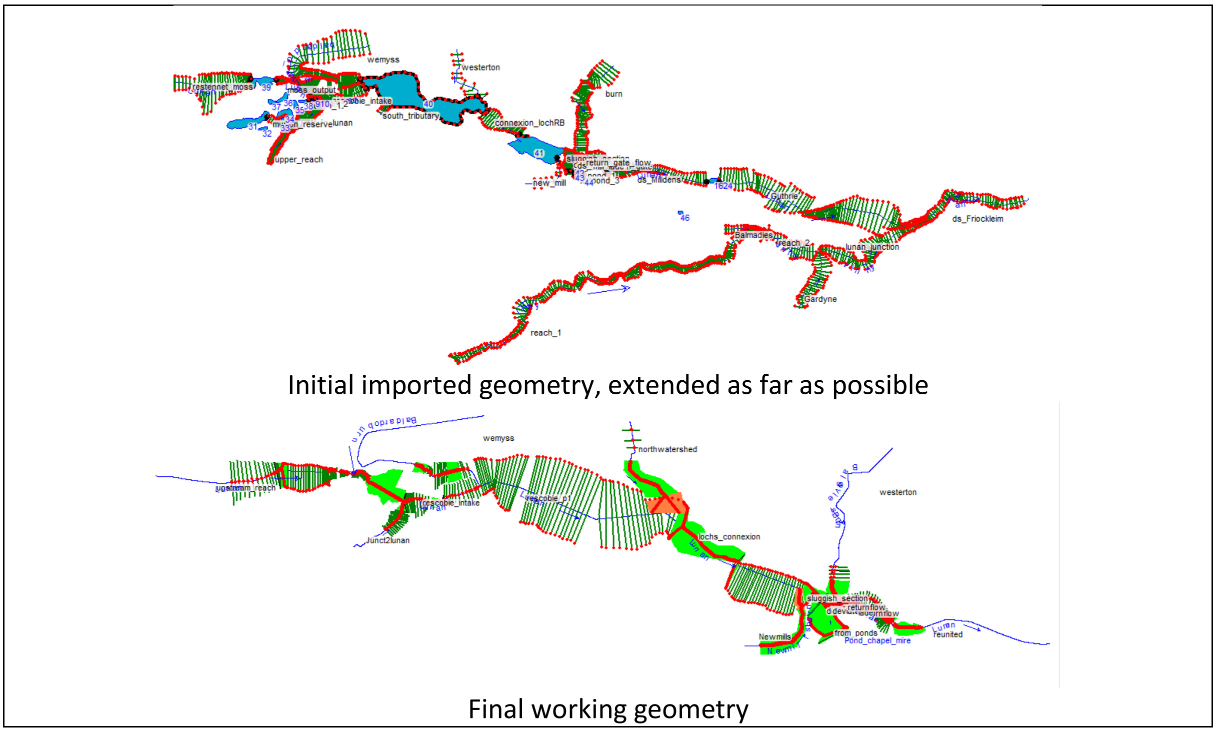


Figure 15 : Evolution of the project extend from start to working state

As shown above, the final form of the geometry is far less extended than the initial drawing. The reasons behind the reduction are summarized above, but not in detail. The part about the Vinny water and the Lunan between Milldens and Friockheim had the only goal to study the impact of the modifications for downstream areas. However, it can easily be done with an hydrographs study at the end of Milldens bridge. Moreover, the modeling of the Lochs with storage areas has been omitted following the difficulties to stabilize the model, even if the storage areas weren't the main causes, and following the choices of (Shelley, 2015).

This modification was the root of a major remodification of the whole model. The problem here appears only when we started to explore medium and low flow simulations, in order to calibrate the model. With low flow simulations, it was clear than the deviation of the lunan to the south channel was allowing too much water to go in this direction. This situation was acceptable and realistic in case of high flow but not during normal flow times. And the reduction of the water section generated new instability problems. These problems were solved by modifying methods of calculations in a few junctions, adding new cross sections near junctions and correcting the channel geometry between the two lochs.

With all these modifications the model was able to withstand every flow input except Storm Franck flows. However, it cannot start on low flows and need to be set on timesteps below 1 sec to pass any quick flood which may appear during a low flow period (a slow growth of flow value can still be done with the 1 sec timestep).

Importation of existing hydraulic structures

After the initial cross-section corrections, the main hydraulic structures had to be modelled. Only those suspected to have impact on the hydraulic behavior were modelled. The hydraulics structures modelled are : the road bridge upstream of Rescobie Loch (A), the rail bridge before Rescobie Loch (B), which has a stone channel at the entrance and a 90° turn with the natural direction of the river, the bridge at the Balgavies Loch entrance (C), the two bridges near the end of Balgavies Burn (D & E) and the Gates complex with the spillway (F).

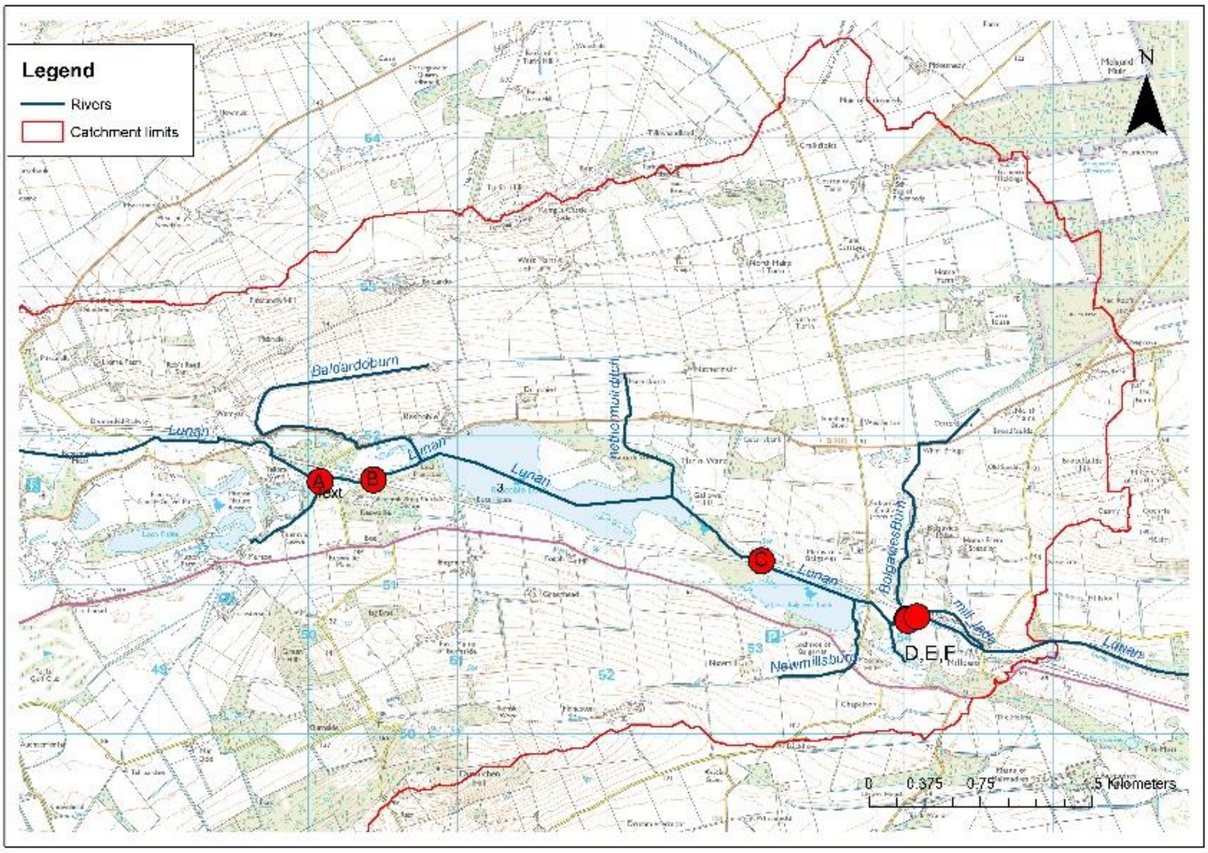


Figure 16 : position of the hydraulic structure modelled in the Hec-Ras model, large scale

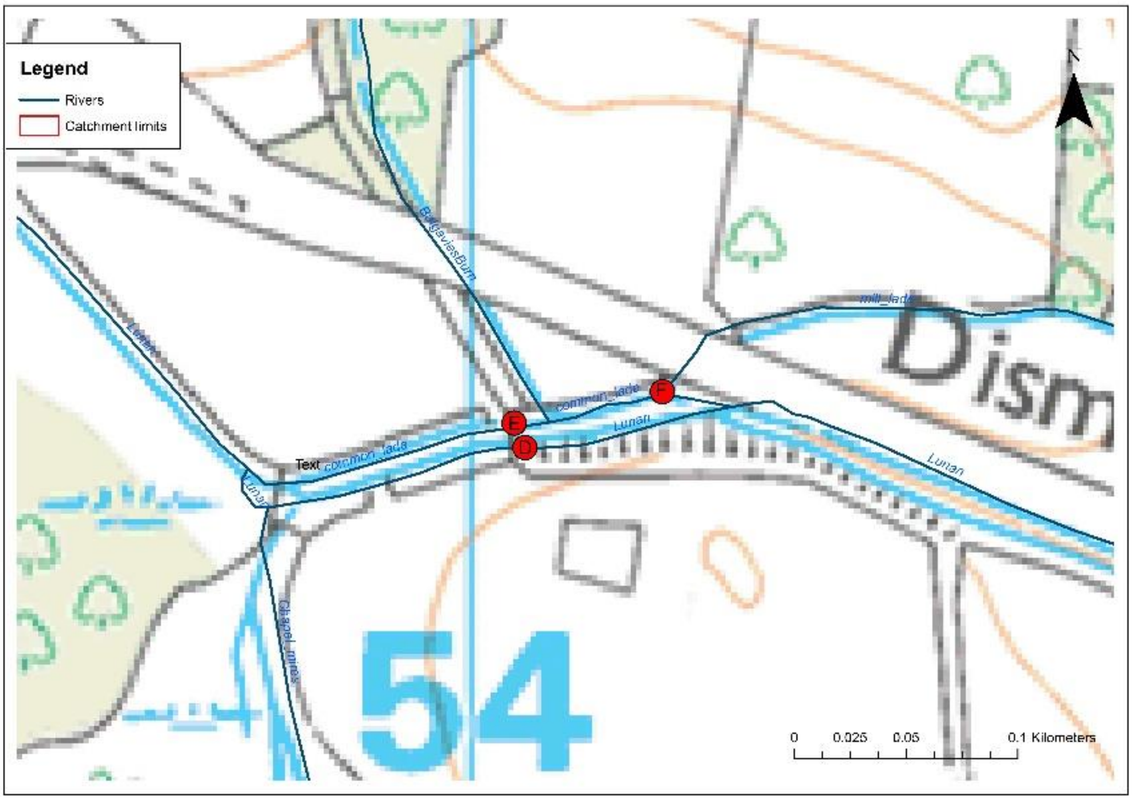


Figure 17 : position of the hydraulic structure modelled in the Hec-Ras model, small scale

Photography of each of theses structures are displayed in Annex

Each of these structures (except the gates) were measured on site with D. Riach. The gates measurements come from Andrew Vinten (pers comm), see also Vinten et al 2019

In addition a small weir was set at the end of the mill lade, to have a coarse representation of the water behavior through the mill.

The culverts on Baldardo burn, Balgavies burn and Newmill burn were not set since they don't have a big impact of the flow regulation. They can only slow down a bit the flow but we don't need an extremely precise representation of these burns.

Three bridges are missing in our model, the one in the end of Balgavies Burn, the small one over the mill lade and the one on the Lunan at mildens. The last one was initially in the model but deleted with the reduction of the modelled area.

These structures where manly built using the bridge/culvert tool and not the inline structures. The Deck is always the first built and the culverts afterward. The sediments deposits in the bridge's openings were set as obstructed elevations in some culverts to match with the field data. The options to select the type of culverts was set to the best of our understanding to match with the reality of the material and geometry.

The entrance of Balgavies loch was not constructed with the correct geometry, only the lower part of the arch is accurate. The bridge is in fact modelled as a trench in the railway embankment. This is the only one bridge without a accurate geometry parametrization. The rail bridge in "Lunan – Rescobie Intake" suffered from a glitch during a saving, giving the view below in the Hec-Ras geometry editor.

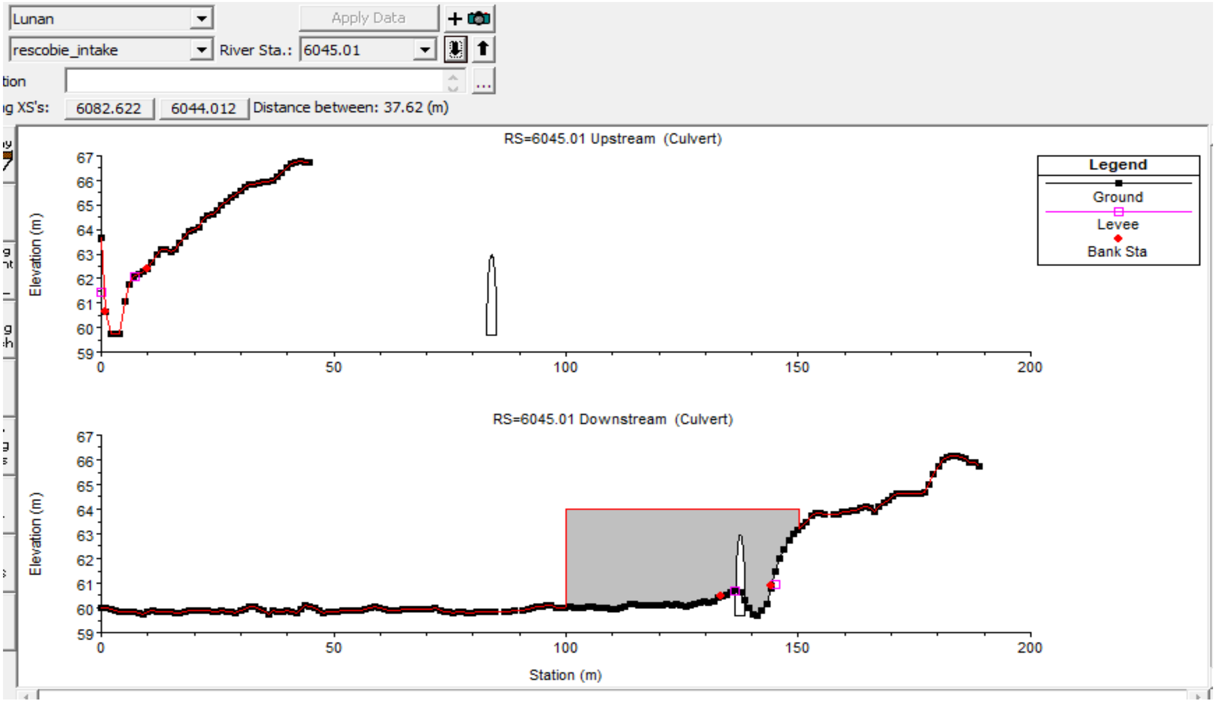


Figure 18 : Inline structure editor view of the rail bridge of Lunan – Rescobie Intake, extracted from the reference geometry

However, the moved opening seemed to work perfectly fine and any try to correct this led to a crash of the model within minutes.

Placement of non-existing hydraulic structures

Two types of non-existing structures were used in this model. The first type is to force a hydraulic behavior in some complex places like the Chapel Mires ponds and groundwater influence and the Mill at Milldens (cross sections 273 and 54.5). The other structures are here to force a flow type on a few places.

A to force flow type is placed on the upstream part of Balgavies burn. It's a very little weir placed here to force a subcritical flow on the boundary condition. It was needed due to the slope of the bed in this area which generated an alternation of super and sub-critical flows without the weir.

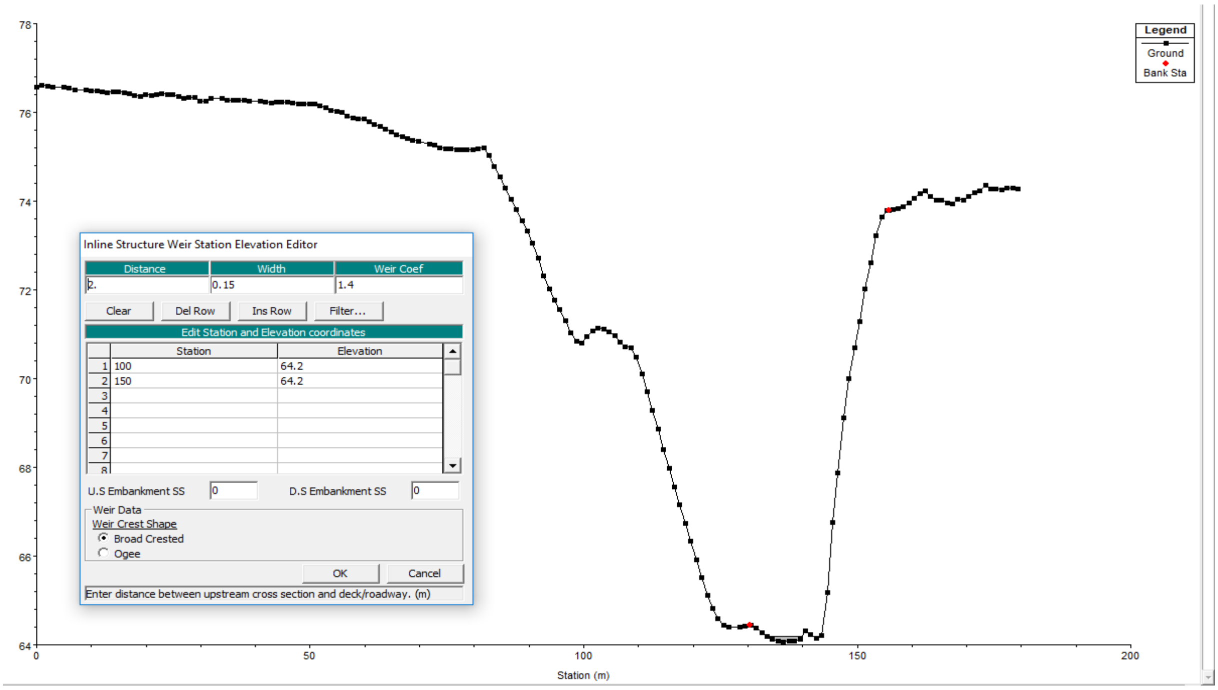


Figure 19 : front view from upstream of the weir, with the characteristics set for it. Balgavies Burn, cross section 320.

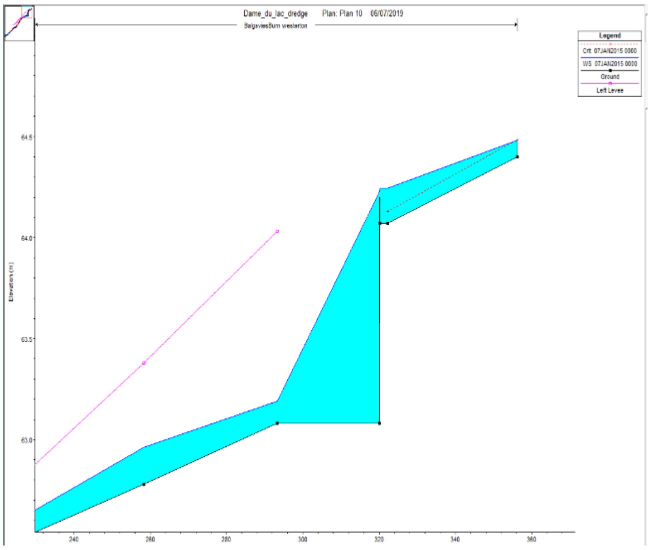


Figure 20 : extract of the profile view for the Balgavies Burn reach, water level calculated for the 7th Jan 2015 midnight. The x axis is the meters from the junction with "Common Lade"

As depicted on the two figures, the Balgavies Burn weir is here to fix the boundary condition. If present in reality, this weir will be no more than a rail sleeper in height, similar to those present in the Burnside burn.

This structure presented above has nearly no impact on the upstream flow, due to a very low capacity of storage in the two cross sections. But it allows fixing of the transition points between the two flow regimes and guarantees stability of the simulation at this point against the problems of critical flow estimation. The other solution would have been to set stage and flow boundary condition on this reach. The solution with a double condition gives us more controls about the flow but we don't have any information of the flow characteristics on this river, so a more robust and simple solution is better.

The hydraulics at the South of Chapel Mires are designed to copy the complex pond-river-groundwater interactions. The boundary condition is a stage condition set at the groundwater table level, so most of the time it will be below the water level in Chapel Mires. To avoid losing water due to this kind of condition a weir with a culvert is set. The weir is here to separate the end of the reach from the rest of the model, with a flap gate on the culvert. The flap gate is here to prevent flow going from the Lunan to the boundaries of the system and allow the groundwater refill in case of very low flow.

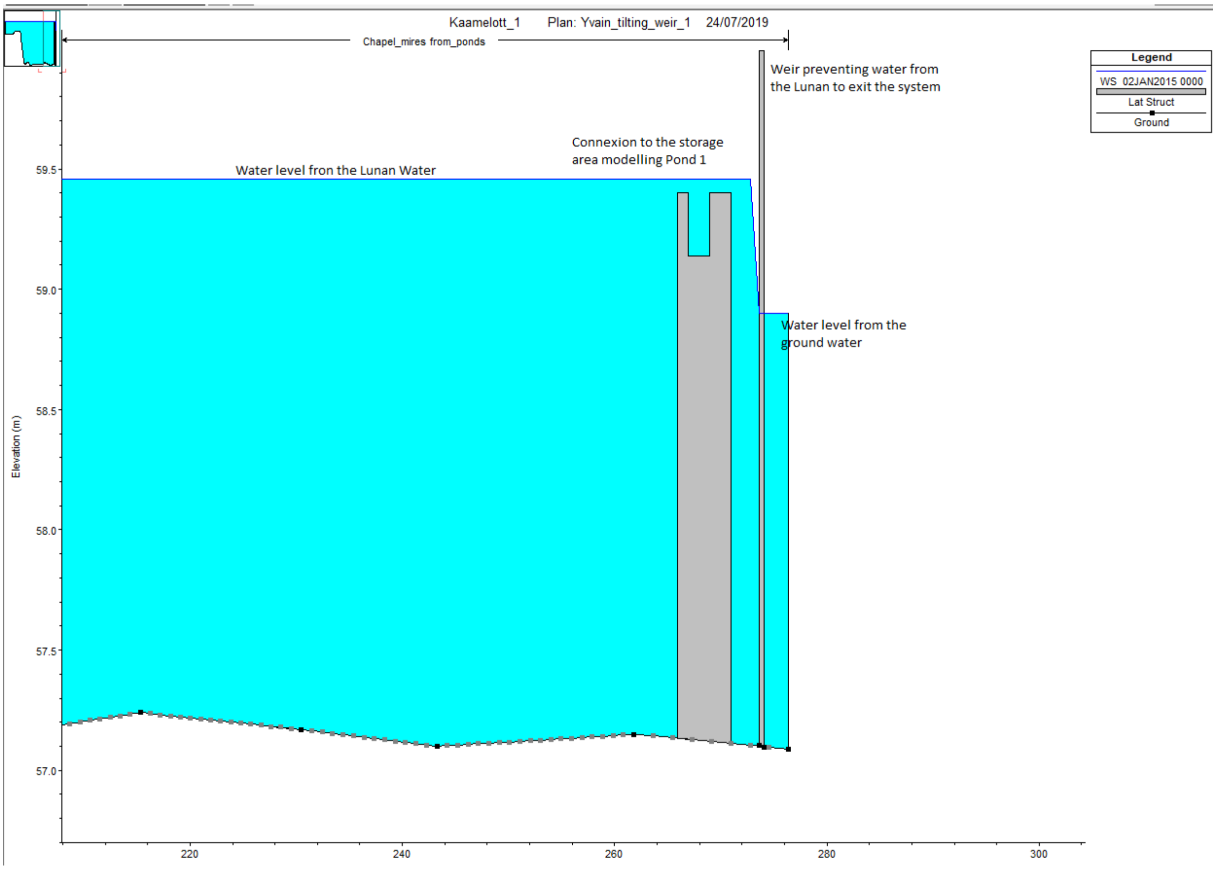
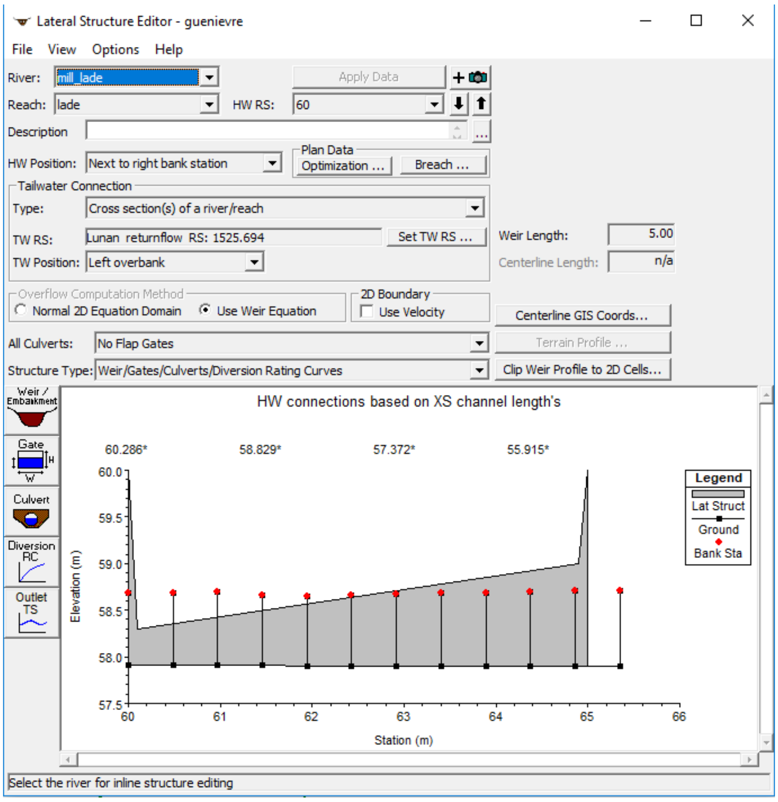


Figure 21 : profile view of the end of the Chapel Mires reach, and the hydraulics structures used to fit the real behaviour.

The Storage area is here to represent Pond 1. The connexion with the river is made using a lateral spillway, set a bit above the lowest elevation of the storage area. The spillway is set just five meters north of the blocking weir on the chapel mires reach.

The last pair of weirs are at the end of the mill lade "river", they are here to fix the flow transition in the mill. On field there is no "weir" but several small U channels that are selected by wooden gates. In the model we have a very flat section followed by a very steep one, and there are topics about problems with this type of geometry in the Hec-Ras forums. The general solution is the creation of a small weir to force the position of the point which experience the critical water level. The second is here because the fist wasn't able to play this role for very high water levels, so we set a lateral spillway near the initial weir, to reduce the water level, without modifying to much the hydraulic behavior of the river in general.



Characteristics of the "artificial" lateral spillway placed at the end of Mill Lade. The spilled water is set to be re-injected in the "lunan-deviated" course. The spillway has been built with a slope to not work at full capacity immediately and allow a bit of flooding in the nearby fields.

This spillway is not present in the field, however, the channels in the end of mill lade is a rectangular shaped stone canal with a 30 cm difference between the bank and the bed level. Overtopping flows go though the dirt slope terrain upstream of the mill and end in the Lunan.

Figure 22 : description of the lateral spillway created in the end of Mill Lade reach

Calculations options in hydraulics structures and junctions

Many parameters can be set in the structures characteristics to improve the accuracy of the model or to calibrate it. The three main parameters are the entrance and exit loss coefficients and the Manning coefficient.

Initially we wanted to use the entrance and exit coefficient as calibration tool but the impact on the global scale was not significant and the entrance loss coefficient was an important problem for the first iterations of the model. Any positive value created a step in the water level in the bridge entrance.

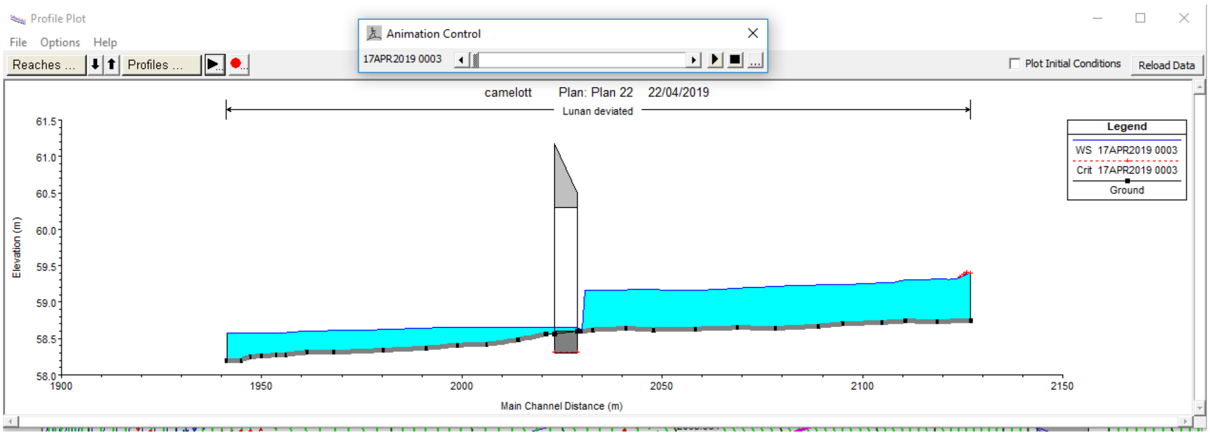


Figure 23 : illustration of initial water level step in the bridge entrance, Lunan channel, bridge labelled "D" on figure 17.

The step is not always the starting point of instability but in particular circumstances this small step can be too much for the model to converge to a stable solution. Depending of the timestep and the distance with the upstream reach the step is more or less important. To avoid any problem every entrance loss coefficient has been set to 0.

Flaws in the modelling conception

There are two types of problems related to the initial conception of the model, those related to the exploratory scenario, and those linked with a lack of planification in the cross-section placement. There is also one place that is needed in the description of the current system, but it is a problem in one of the tested hydraulic configurations.

The most important problem in the interpretation of result is located on Chapel Mires. The problem comes from the contradiction between the instructions in the cross-sections draw, the dispositions of the Chapel Mires wetland. The cross sections must be draw perpendicularly to the flows paths in order to get the right distances between the different cross-sections. However, the potentials laterals flow paths during a flood in Chapel Mires would have forced us to make very complex cross-sections to make sure that no cross-section crossed two ponds. The simplicity of the cross-sections and the respect of the angle with the flow paths have been set as the main criteria.

This decision has created another water path in the Chapel Mires wetland, going through the different ponds as well as going in the natural channel. This is not a problem except if the goal is to use the model to study the distribution of nutrients in this wetland.

The second major flaw is the decision to set the return flow as a channel in the Hec-Ras model. As a channel in the model we cannot set a null flow for this channel. The main consequence is the impossibility to fully close the return gate. This problem cannot be corrected due to the differences of names and cross-sections references in the “common lade” and “mill lade” channels.

The “Lunan-deviation” and “Lunan-deviated” include the same kind of flaw. In some of the propositions the spillway to chapel mires is moved to the previous position. But we cannot move the junction ending the “Lunan-sluggish section” and cannot close the existing spillway to open a new one. The only solution is to create a weir and a gate on “Lunan-deviation” and a lateral spillway on “Common Lade -reach 1”. This has to be done to explore the effect of moving the existing spillway to it’s old place, a little bit downstream.

Unsteady flow files and inputs

The unsteady flow data has been based on the flow dataset from the Wemyss and Westerton gauges. The flow value for each input have been determined with a geographical relationship based on the recommendation of Cudworth (1989) , however, the exponent has been modified to get the best results.

The law used is the following one:

$$Q_i = Q_w * \frac{Aw^{1.2887}}{Ai^{1.2887}}$$

Were Qi is the flow we want to model, Qw the flow value at the Wemyss gauge, Aw the area of the Wemyss catchment, Ai the area of the modelled catchment and 1.2887 the coefficient bi.

The 1.2887 is the center of mass of the three bi(Fi) curves, it have been tested along with bi(Fi) curves and the three centers of mass. A better coefficient was discovered after by accident, but it was too late to redo every simulation with the new flow values. Coefficient that should have been used is 1.01

For a precise description of the creation of the flow values see [Model - Hydrology]

Numerous flow files have been used on the model, most of them cannot be seen on the final models. On those that cannot be seen but were used we have some portions of the existing flow files, a few typical hydrograms, including a flat flow, an exponentially decreasing and a exponentially increasing one. These have been used to test the limits of early phases of the model. These experiment lead to the division in two sub catchments for Burnside burn, Newmill burn and Nethermuir ditch. Along with a maximal flow boundary for some reaches, this test allows to determinate the minimal flow for each reach. These limitations

Three files are in the final model. Two files are a reduction of the whole flow dataset, covering the dates between October 2013 and December 2017. The first one is an hourly timestep, translated from the initial hourly flow from Wemyss with the general formula. The second one cover the same time window but on a daily timestep. The third file is a representation of the daily flow since 2008.

Unsteady calculations options and tolerances

First of all, the model is not stable enough to tolerate a start at every date. And depending on the value and variation the flow value some timestep can lead to a crash. Moreover, the mixed flow option and the increasing of the number of iterations before stopping is a necessity.

If only a small window of time is simulated, a constant computation interval in (2, 1, or 0.5 sec), with the mixed flow option selected (m factor at 4, default value) and the maximum number of iterations lifted to 40 is enough to run the model.

However, running more than a month can be tricky or very long with this method. In this case I recommend using the advanced Timestep controls and adjust the time step by a time series. The Courant methodology is useless, since the instability is related to flow variations, and not flow values or velocity values.

For example, the timestep division for 2015 have been set as show below (fig 24).

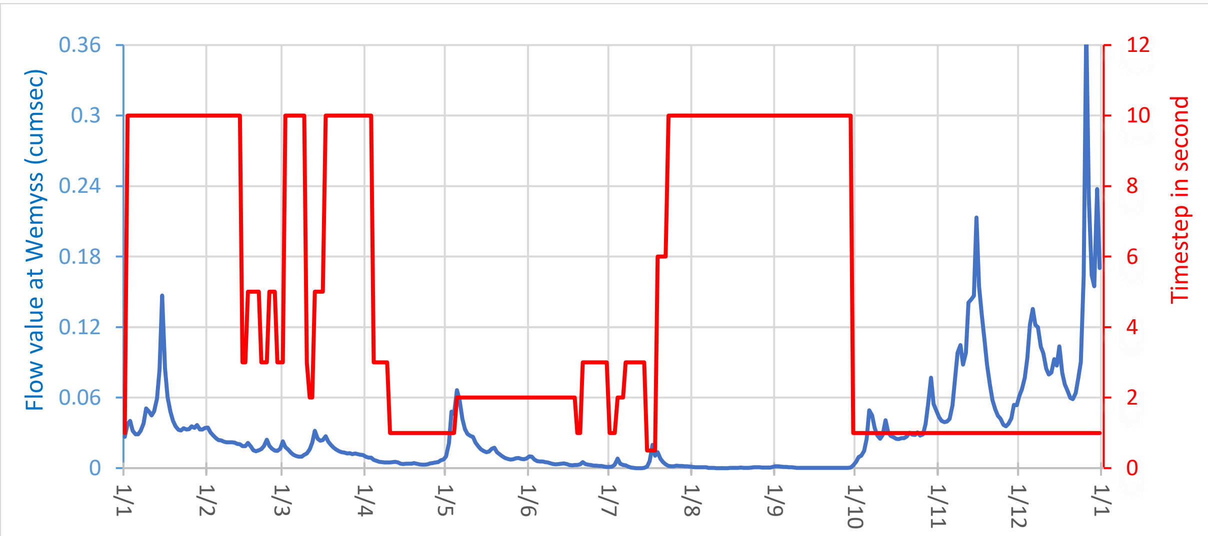


Figure 24 : Plot of the reference flow values and the calculation timesteps used for the simulation of 2015

Below a flow value (approx. 0.03 cubic meters per second for the reference flow) any variation of the flow can be a problem for the model. This explains why there are so many variations in the first half of the year but not in the end.

B. Calibration strategy

The calibration has been done using the water level time series in Rescobie Loch and Balgavies Loch, the water level in Common Lade has also been used but in a less importance.

The calibration has been done using only the 2014 values by modifying the roughness factor in the different channels and overbanks. The roughness factor is the same for an entire reach, excepted for the sluggish section and the cross-sections in the lochs. The roughness factor was initially set at 0.033, a common book value for natural channels with a sandy riverbed.

Using only theses three references points, with the different photography to confirm the choices made and to avoid major errors lead to a quite good representation of the part upstream of Balgavies loch and on the immediate downstream reach. However, the calibration on the lower part of the model, "Lunan-return flow" "Lunan-reunited" and "mill-lade" cannot be considered as accurate, for this I need some water level data on low flows and not only one photography taken during the Storm Franck event.

The Manning coefficient, (roughness factor), table is show below (table 5). These coefficients are between 0.01667 and 0.1. The choice of the coefficients is highly dependent of the channel width, if the channel smallest width is too big the Manning coefficient must be artificially increased.

Tableau 5 : Manning coefficients in the different reaches of the model.

Reach	Manning values in the river channel
Baldardo Burn	0.05
Balgavies Burn	0.025
Burnside Burn	0.025
Chapel Mires	0.05
Common Lade	0.04
Mill Lade	0.05
Nethermuir ditch	0.1
Newmill Burn	0.05
Return gate channel	0.05
Lunan - Upstream reach	0.1, 0.028, 0.05
Lunan - Rescobie intake	0.02
Lunan - loch connexion	0.01667
Lunan - Sluggish section	0.09, 0.022
Lunan - deviation	0.0435
Lunan - Deviated	0.04
Lunan - Return Flow	0.05
Lunan - reunited	0.1

The Calibration was not pushed to far due to the sensibility of the model, the small numbers of calibrations points and the difficulty to parameter a calculation. The model, as previously mentioned, is very sensitive to timestep adjustments, and those timesteps has to be selected given the flows in every reach. The timesteps selections is mostly done by running and failing simulations, and a full year simulation took about 40 hours to run, with 15 hours variations following the scenario and the computer used.

C. Validation results

The validation has been done on two points of the Lunan, during a whole year. The third point (On the common Lade) was too dependent on the gate openings, which at times were uncertain, to be used.

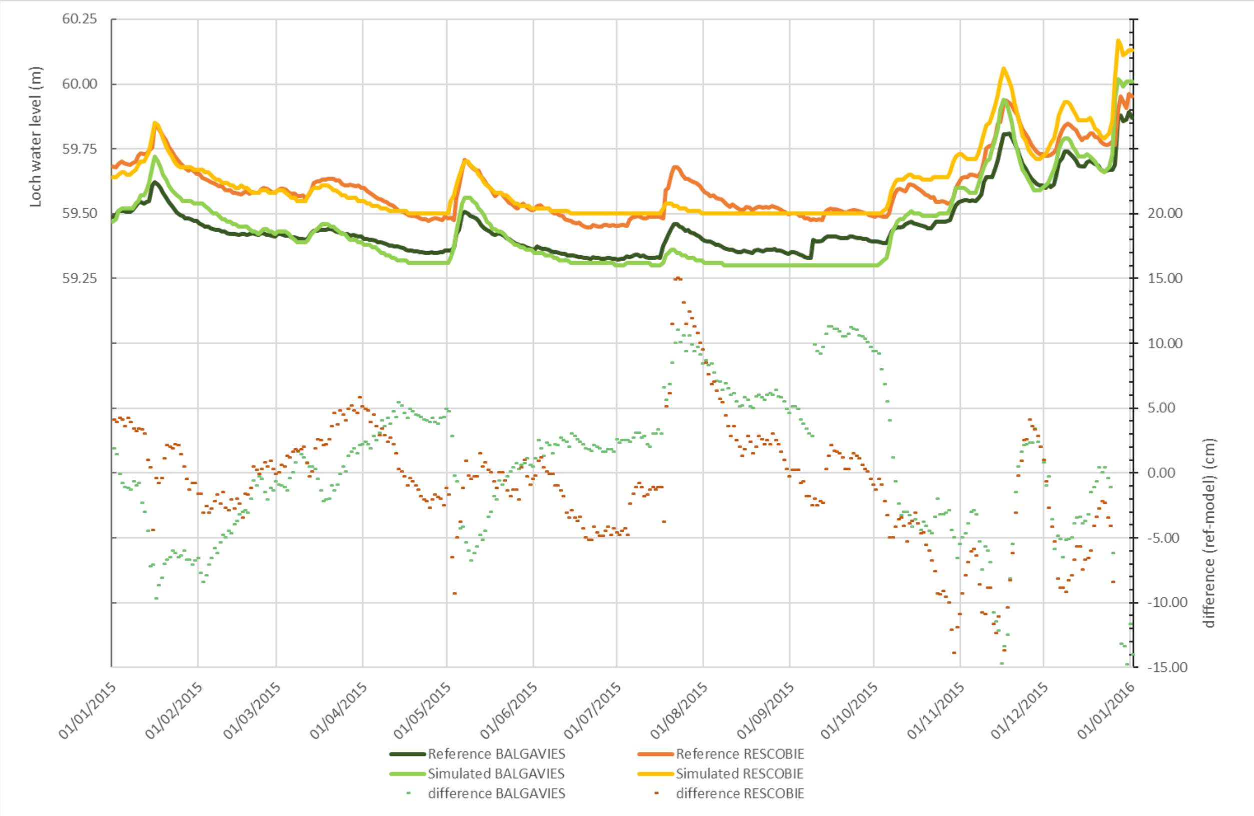


Figure 25 : plot of the measured (reference) and calculated (simulated) water levels in Balgavies and Rescobie Loch in 2015

The figure above is a graphical representation of the measured and modelled water levels for Balgavies and Rescobie Lochs. The dotted lines show the difference between the measured and the modelled approximation in centimetres. For Rescobie Loch the calibration is pretty good excepted at the end of the year and for the event in mid-July. In Balgavies Loch the model seems to exaggerate the extreme events. The peak flows are overestimated, and the low ones are underestimated.

The systematic overestimation of the water level after mid-October is certainly caused by an overestimation of the input flow values, which is quite probable since we only used a one-point data to build the flow time series. If there were macrophytes beds in the channel the modelled water level would also have been below the measured water level.

The other problem is the time window between June and early October. The calculated water level is flat, related to the artificial limited flow values and the event of mid-end July wasn't well recorded by the Wemyss sensor. However, I don't have a good explanation on why the water level is quite underestimated on Balgavies Loch and not so much in Rescobie Loch. I think it's a ground water influence because the other causes are improbable. It cannot be a modification of the channel roughness coefficient related to macrophytes beds growth, as they will not have disappeared before the November floods. The hypothesis of a sediment deposit isn't more tenable, at this time the soil is covered with grown plants, and the deposit will not have been totally washed out by the flow increase of mid-October.

Tableau 6 : stats about the validation of the Hec-Ras model

	Balgavies Loch	Rescobie Loch
average difference (cm)	0.45	-1.17
Max difference (cm)	25.3	26.8
Correlation coefficient r^2	0.929	0.863
Nash-Sutcliffe coefficient E	0.786	0.774

As shown in the table 6, the average difference between the model and the reality is quite acceptable given the problems described in the previous paragraphs. The two calculated efficiency criteria describe the model as acceptable for modelling the water levels in the two Lochs, despite the errors with the flow values during summer.

D. Sensitivity analysis

I couldn't test all the factors that can influence the model and its results mostly because it's time consuming and because I cannot automatize the modelling process and the extraction of results. The impact of the channel geometry sensitivity for the Common lade or Lunan deviation channels were planned but not done.

The sensitivity of the roughness factor has been tested with a 10% variation on the validation period. A variation on the channel minimal elevation or width cannot be done effectively. However, some variations of the sediment deposit elevation on the Common lade have been tested. I could have tested the impact of the Chapel Mires Spillway "Lunan-Deviation" geometry modifications on the flow partition but this is a very sensitive place and a modification in this area can easily lead directly to a crash at the first iteration loop.

For information, if the Manning-Strickler formula is used and the other parameters set as constant (slope, wet perimeter, food surface) an increment of ten percent of the Manning coefficient must reduce the flow capacity of the channel by 9.1%, the opposite modification lead to an increase of 11% of the flow capacity.

The variation of the roughness factor by 10% didn't generate variation of the water levels in the calibration and validation points during floods. This might be the result of the great extension of the water over the banks in the downstream rivers. If the banks of the Lunan between the lochs and Chapel Mires is submerged, the flow balance between Common Lade and the Lunan is in favor of the Lunan, meaning a less influence of the roughness factor due to larger channel downstream in the Lunan. Moreover, the flow values in the Common lade is quite insensitive to small variation of the Manning but highly sensitives to the gate opening.

The increasing if the roughness factor generate a slight increase of the filling speed of the lochs, and the opposite modification gave the opposite result. This could be explained by considering the general geometry and the place of the points used for the calibration. The points used are Lochs, with more than one input reach each and only one output. Also, the roughness coefficient will have a greater impact if the river goes through a small channel than a bigger one. Since the two inputs for Balgavies

Loch come from several small channel, there are more impacted by the roughness modification than the output, who go through a unique larger channel.

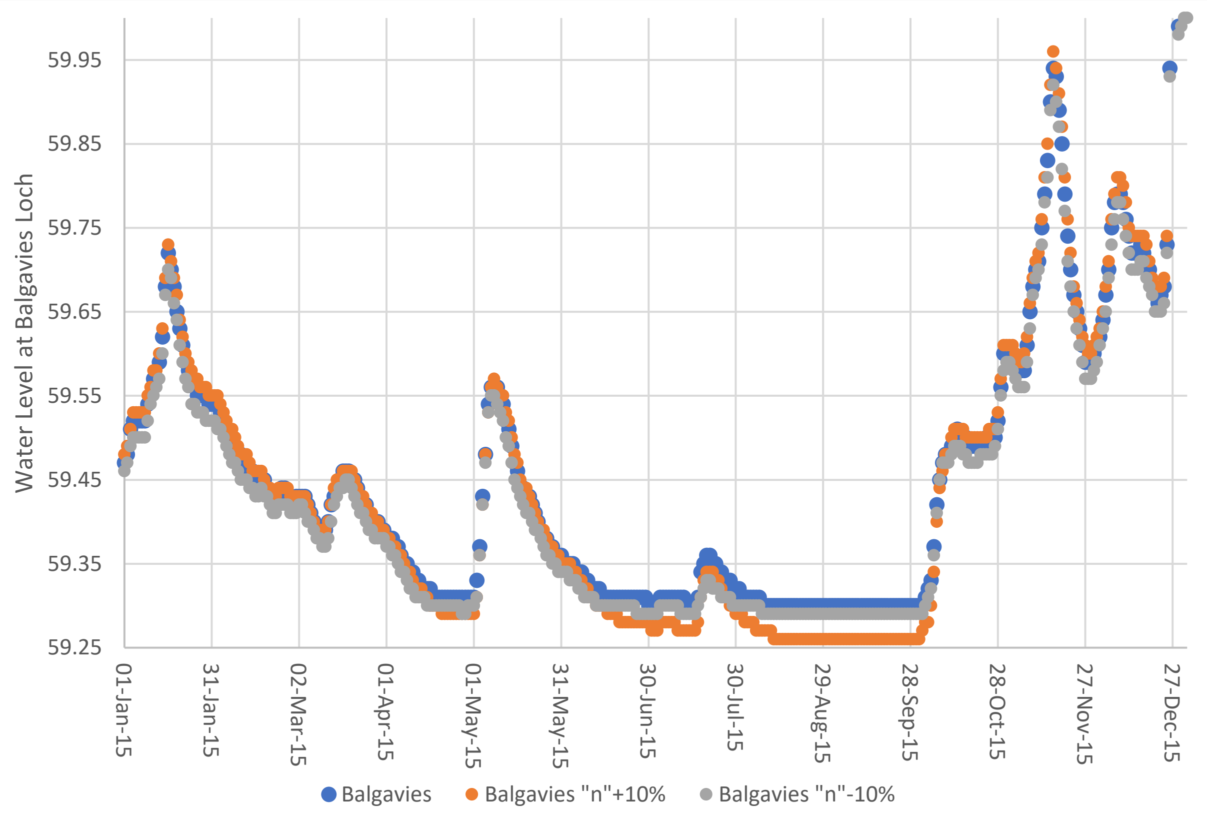


Figure 26 : impact if a modification of the Manning coefficient (n) by ten percent for all the rivers on the Balgavies Loch water level

The impact of the sensibility test was the most important during the summer period, with very low flows in all the system. During this time, the hydraulic structures haven't any impact on the flow repartition, the roughness factor and the geometry are the only influences. So during low flows the model is very sensitive to Manning coefficient modification. Moreover, modifying in the both directions give the same kind of evolution on the water levels. This similar evolution is a key point to explain why the calibration process was so difficult for this model during low flows.

The calibration done in two points was quite accurate, but we cannot be sure of getting of the right values for the right reasons. To guaranty this, we need to be sure of the geometry between the Lochs, and a record of the gates opening more precise than a binary timeseries.

The model is sensible to roughness coefficient modifications during low flow configurations. The floods peak water levels aren't influenced by small variations of the Manning coefficients. The flood hydrograph shape is more impacted, with and evolution coming from the dendritic geometry of the river system.

E. Equifinality problems

During the calibration process we focused on the Rescobie and Balgavies Lochs water levels, mainly by playing with the Manning coefficients in the upstream and downstream reaches. We were at a point we needed to increase the water level in Balgavies Loch during low flows, and the increase has to be done by modifying the downstream reach. But event when the Manning coefficient in the channel was set to 0.5 in the Lunan channel between the Common lade start and the Chapel Mires entrance the water level stay too low. The problem didn't come from the Common lade parametrization, at this time the part between the spillway to Chapel Mires and Balgavies Burn was seeing negative flows. The Lunan channel had a too great flow capacity.

The problem was coming from the DTM and the automatic placement of the river in the cross section when there are no levees. The DTM was inaccurate in this place, giving to the right overbank lower elevation than the channel bed level. The water was mostly going over the overbanks than in the channel, and since the "channel" in the overbank was way larger than the river channel, the impact of the Manning modification was much smaller than expected.

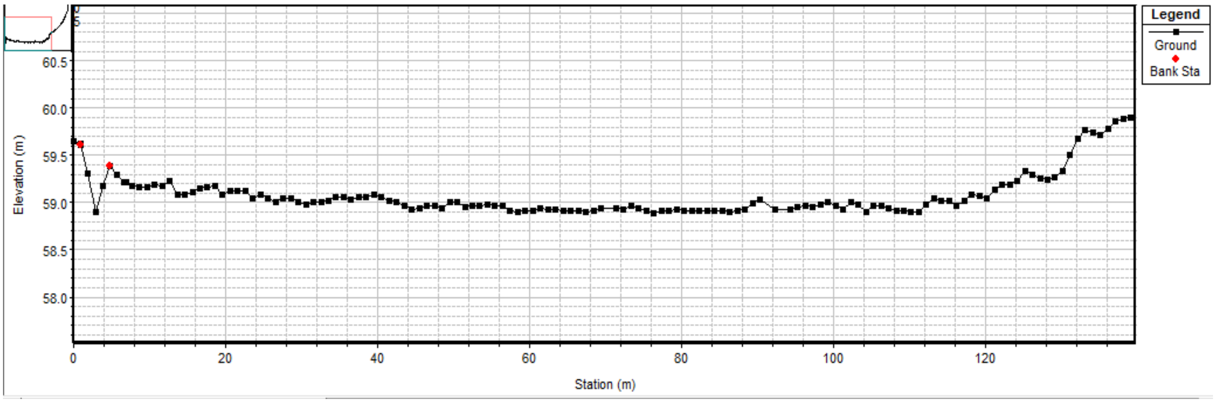


Figure 27 : Lunan Deviated second cross section (3 meters downstream of the spillway), initial geometry

Since the overbank is usually wet or submerged during winter floods, the problem was not clearly visible during the first part of the calibration, who used the December 2014 month. During this month, having water at 59.4m or 59.5m in the spillway and in the

This part of the model is the most sensitive part and placing levees points at the banks weren't working. To solve the problem, we had to artificially fill the overbanks up to the bank station elevation and modifying the channel geometry who was slightly inaccurate. The initial shape was triangular, from the DTM resolution and the channel width. The channel is 2 meters wide and the DTM had a 1 m² resolution, so the bed level was only one point if the cross section cut the pixel by the diagonal.

Due to the sensitivity of this reach the correction process was very long, we had to make sure that every modification was stable for every flow encounter in the chronicle.

A similar problem was detected in Burnside Burn, in the downstream part of the reach, in Sluggish section (the lunan between Balgavies Loch and Common Lade) and in the reach connecting the two Lochs. The sluggish section was easy to correct because we had measures points previously done in this area. For the two other we didn't have information about the correct elevation or channel geometry, the vegetation was too dense to do a manual check after the winter and there was no historical data. In these points there is a compromise between the channel modification and the Manning coefficient. Neither of them can be seen as exact but the combination of the two gave a acceptable result at the reach scale.

F. Results extraction

The results extracted from the different simulations come from the “Profile Output table – Standard Table 1”. Theses tables show for each cross section and each profile the water surface elevation, the Flow value, some information about energy, and information about the wet area and the top width of the channel. The result tables were stored and analyzed in excel files.

Exploiting these tables is more efficient than using the maps exports to show calibration results, to look for relations between water levels and flows. Hec-Ras allows extraction of a table of 24 600 lines at the same time, which correspond to 45 profiles for every non-interpolated cross-section.

Profile Output Table - Standard Table 1

File Options Std. Tables Locations Help

HEC-RAS Plan: Plan 10 | Reload Data

River	Reach	River Sta	Profile	Q Total (m3/s)	Min Ch El (m)	W.S. Elev (m)	E.G. Elev (m)	E.G. Slope (m/m)	Vel Chnl (m/s)	Flow Area (m2)	Top Width (m)	Froude # Chl	Crit W.S. (m)
Baldardoburn	wemyss	197.331	25NOV2015 0000	0.0368	58.60	59.79	59.79	0.000000	0.00	83.52	42.64	0.00	
Baldardoburn	wemyss	197.331	26NOV2015 0000	0.0352	58.60	59.76	59.76	0.000000	0.00	82.43	42.48	0.00	
Baldardoburn	wemyss	197.331	27NOV2015 0000	0.0370	58.60	59.74	59.74	0.000000	0.00	81.60	42.36	0.00	
Baldardoburn	wemyss	197.331	28NOV2015 0000	0.0413	58.60	59.73	59.73	0.000000	0.00	81.09	42.28	0.00	
Baldardoburn	wemyss	197.331	29NOV2015 0000	0.0520	58.60	59.73	59.73	0.000000	0.00	81.05	42.27	0.00	
Baldardoburn	wemyss	197.331	30NOV2015 0000	0.0525	58.60	59.74	59.74	0.000000	0.00	81.32	42.32	0.00	
Baldardoburn	wemyss	197.331	01DEC2015 0000	0.0592	58.60	59.75	59.75	0.000000	0.00	81.70	42.37	0.00	
Baldardoburn	wemyss	197.331	02DEC2015 0000	0.0656	58.60	59.76	59.76	0.000000	0.00	82.33	42.47	0.00	
Baldardoburn	wemyss	197.331	03DEC2015 0000	0.0758	58.60	59.78	59.78	0.000000	0.00	83.18	42.59	0.00	
Baldardoburn	wemyss	197.331	04DEC2015 0000	0.0913	58.60	59.81	59.81	0.000000	0.00	84.48	42.79	0.00	
Baldardoburn	wemyss	197.331	05DEC2015 0000	0.1191	58.60	59.86	59.86	0.000000	0.00	86.58	45.42	0.00	
Baldardoburn	wemyss	197.331	06DEC2015 0000	0.1320	58.60	59.92	59.92	0.000000	0.00	89.32	47.27	0.00	
Baldardoburn	wemyss	197.331	07DEC2015 0000	0.1190	58.60	59.96	59.96	0.000000	0.00	91.37	48.45	0.00	

Figure 28 : view of the output tables saved in excel documents

It take about one hour to parametrize the extraction and copy the whole year, with a point every day, to excel. The time is mostly consumed by copying the data set from the profile output table. The extraction to txt files is not quicker and requires more intervention afterwards. Furthermore, I recommend deleting or moving the “Crit W.S.” column, this column could show empty cells that can lead excel to move to the left the rest of the values, disconnecting the values from headers.

The extraction to excel files allows a comparison of the different scenarios or the impact of different settings of the gates or hydraulics structures. The extraction will also be used to search for relatiosn between flows in certain reaches and water levels in the monitored points. Theses relations will allow quick estimations of the flow values rather than launching a long simulation for the first approach.

IV. Modelling of the proposed modifications

The first test was a dredging of the common lade, to rectify the sediment deposit near the cattle drinking point upstream of the bridge. This deposit is suspected to reduce the flow capacity of the common lade and increasing the water level at the Chapel mires Spillway.

Depending on the impact of the dredging different propositions will be tested.

If the dredging is seen as a notable modification of the hydraulic behavior of the Lunan downstream of Balgavies Loch, then a modification of the return gate inlet elevation is tested. And eventually a modification of the base elevation of the dirt spillway. If the dredging isn't efficient, the plan is to add a tilting weir on a new lateral spillway, and to test different inlet elevation and longitudinal position.

The dredging will improve the common lade flow capacity, especially during low flows, by reducing the water level needed in the end of Sluggish section for generating a flow in common lade. It should also increase the influence of the gates openings in the loch levels.

The modification of the inlet of the gates is seen as a way to improve the evacuation of the flood peak by lowering a bit the water level in the Common lade reach. However, the lowering of the inlet of the "return gate" gate will probably increase the days of low flows in the lunan water by increasing the draining speed in the lochs. The impact of the gate opening modifications may not be enough to correct this.

The modification of the actual spillway will make it more effective. If the inlet of the spillway is lowered smaller floods events will make the spillway work, and this may reduce the frequency of flooding in the bridge near Murton reserve.

A modification consisting of increasing the length of the spillway may not be as efficient as expected since the length of a spillway may, above a certain value, not influence the spilled flow value. So different strategies will be tested, trying to increase the legth of the spillway, or creating more spillways along the Common Lade.

The last solution, including a tilting weir will allow to store the water during the flood decrease to release it later to days of restrictions dues to low flows. The problems will be the increase of maintenance efforts and the potential command complexity to make. The tilting weir will need an input from the weather forecast to make sure that it won't increase the water level just before a flood event.

1. Dredging of the Common Lade

As previously mentioned, the small elevation at the cattle drinking point on the common lade is suspected to be the element increasing the flow in the Chapel Mires. The dredging process involved will be the removal of this deposit, lowering the channel bed level from 59.30 to 59.0 just upstream of the bridge. The dredging operation can be easily done, but to avoid quick return of it, the cattle drinking point has to be modified to avoid disturbance of the bed by the cows.

The expected results of this scenario are that the dredging will only increase the channel capacity for low and medium flows. For larger flow, the geometry difference will not significantly matter, in term of flow section and energy loss. However, the improvement may still be enough to reduce the flood occurrence in the road bridge near Murton Reserve. The bridge is one of the main objectives of the planned modifications.

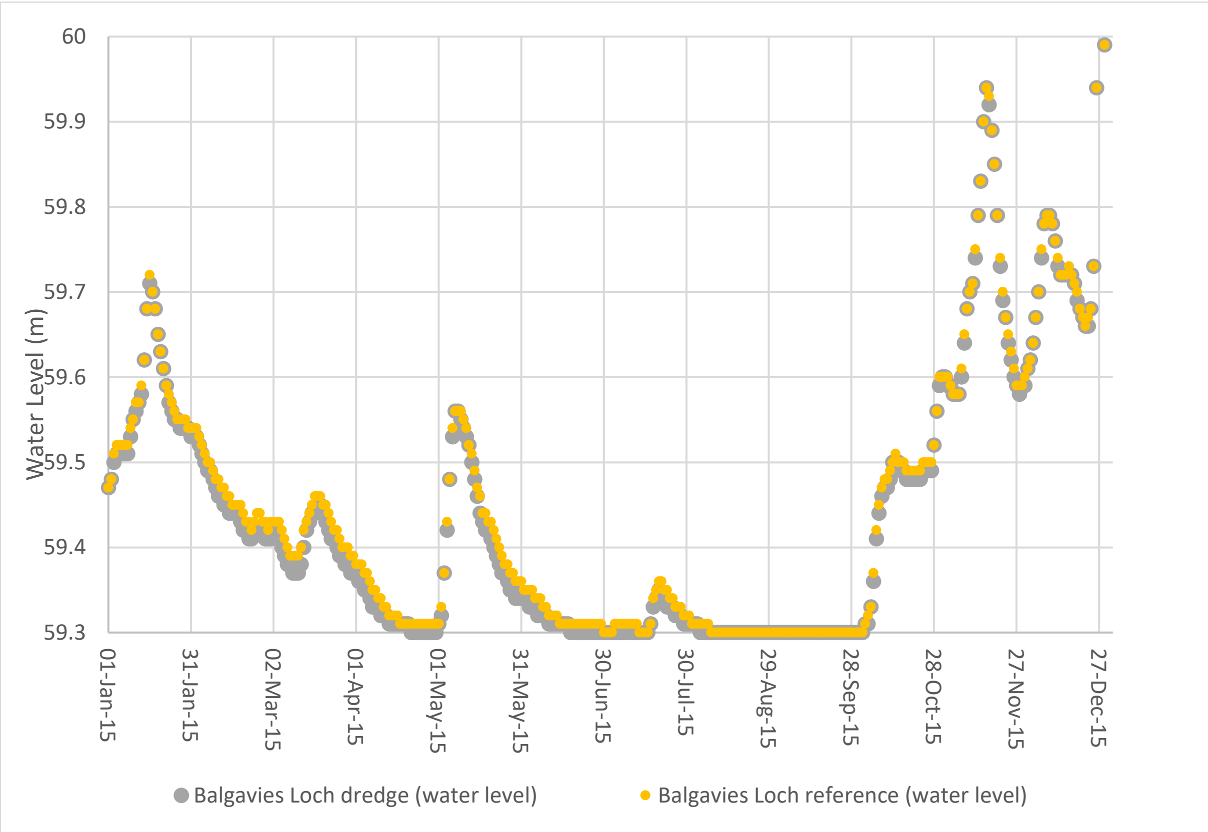


Figure 29 : comparison of water levels from the dredge and reference scenario, with the return gate set with an opening at 0.5 m

The dredging of the common lade near the Balgavies burn junction with common lade allow a very little reduction of the water level in the Lochs, as show above. The gain is around 1cm in average and can go up to 2cm during flood regression. Considering theses elements, the dredging cannot seen as a flood reduction tool, but it could still be a useful tool for increasing the effect of further devices or modifications in the common lade to do flood control, flow partitioning and maybe low flow control.

The impact on the flow values in the upstream course is non-significant, which is predictable considering the impact in term of water level. However, the impact on the flow partition is quite

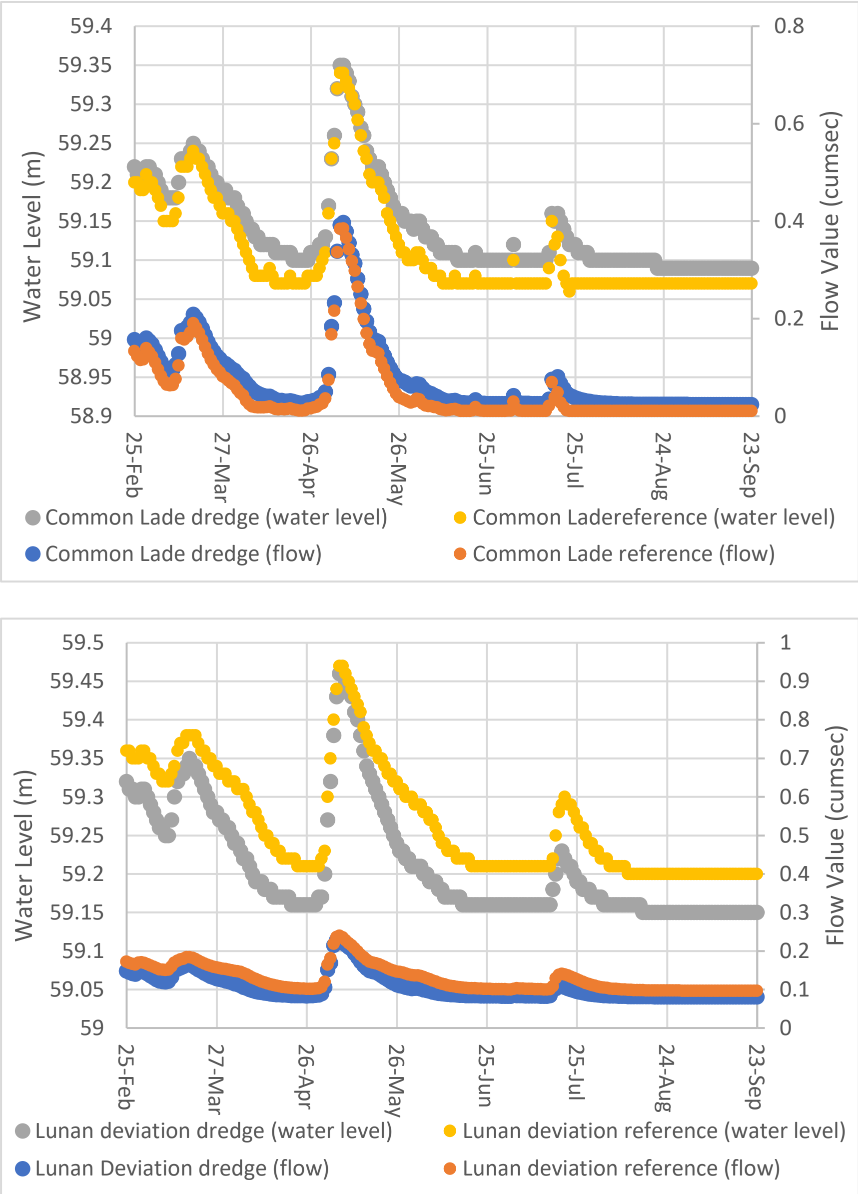


Figure 30 : plot of the stage and flow values for Common lade and Lunan Deviation for the reference and dredges geometry

important as show in the graphs (fig 30). The dredging doesn't modify the high flow situation but generate an enough water level increase in the common to play with the gates or to install a tilting weir with a more efficient way.

The flow division between the Lunan and the Common lade is greatly impacted during low flows by the removal of the sediment deposit. The difference in terms of flow values is important, with a maximal difference of 30 l/s. However, the increase of the water level in the Common lade is an indication of greater capacity to manage the Loch with only the existing gates, by completely closing the gates. Closing the gates cannot be done with this model.

The second test was the impact of the gate opening values on the water level in Balgavies loch. The impact of the gate opening on the lochs levels is important in order to deal with flooding's of the road bridge.

During low flows the gate opening seems to have no effect, this can only be caused by the fact that the return gate event at 0.15 cm is an open channel. During high flows the gain can be quite significant with a gain of 10cm in November floods. However, this difference is the same than the one done in the initial configuration. The management of the floods with the existing gates in not improved by the

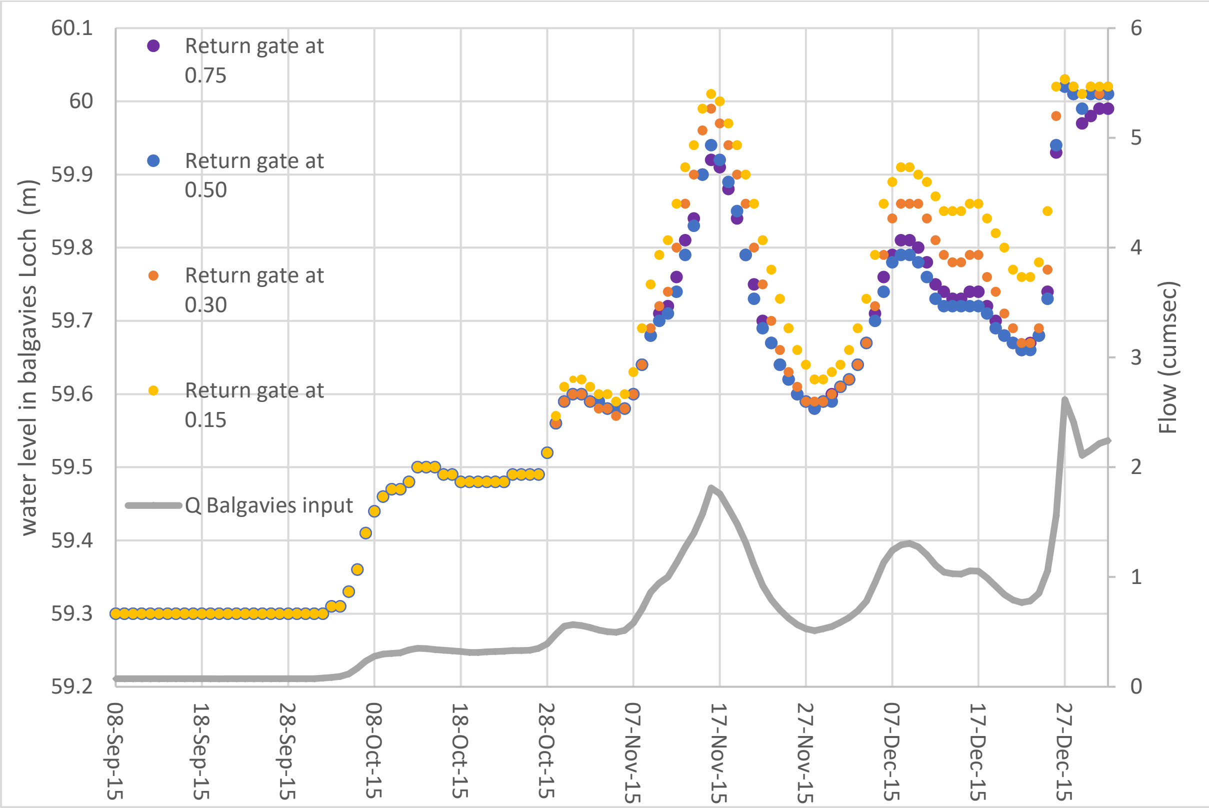


Figure 31 : impact of the different openings in the return gate on the Balgavies Loch level

To conclude on the Dredging process alone, the dredging alone doesn't give a significant improvement for the flood control but give lower water level in the Lunan channel near Chapel Mires. The lower water level means a lesser influence of the river in the wetland. This situation can, following the gates settings, lead to a partial draining of the wetland or the reducing of the nutriment load from the river.

Given the results obtained by erasing the sediment deposit upstream of the Balgavies burn input in common lade and the cost of this intervention, the erasing of this deposit will be kept in all further exploration scenarios.

2. Gate (return gate) modification

This have been planned to improve the effect of the dredging of Common Lade to evacuate more water to the Lunan lower channel and reduce flooding in the fields upstream located upstream of Mildens. The inlet of the return gate will be lowered to 58.8 instead of 59.0. Given the previously seen impact of the gates opening on the water levels in the lochs, lowering the gate inlet will probably increase the flow capacity of the Common Lade. If the flow capacity of the common lade is increased, the water levels in the lochs will decrease a bit, reducing the flood frequency for the road bridge.

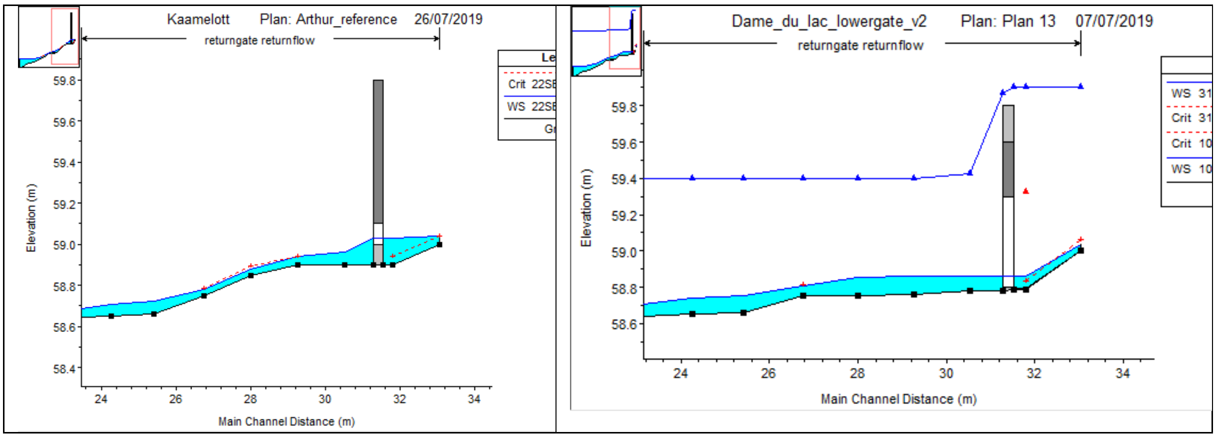


Figure 32 : profile of the return flow channel before and after the gate inlet modification

The lowering of the gate was mean to generate a supercritical behavior for greater flow by increasing the slope of the reach. However, it seems inefficient, the water level reduction in the lochs is only 2 mm greater than what can be obtain with the dredging only. A study of the Common lade show that the limiting factor is the geometry of the channel just upstream of the gates.

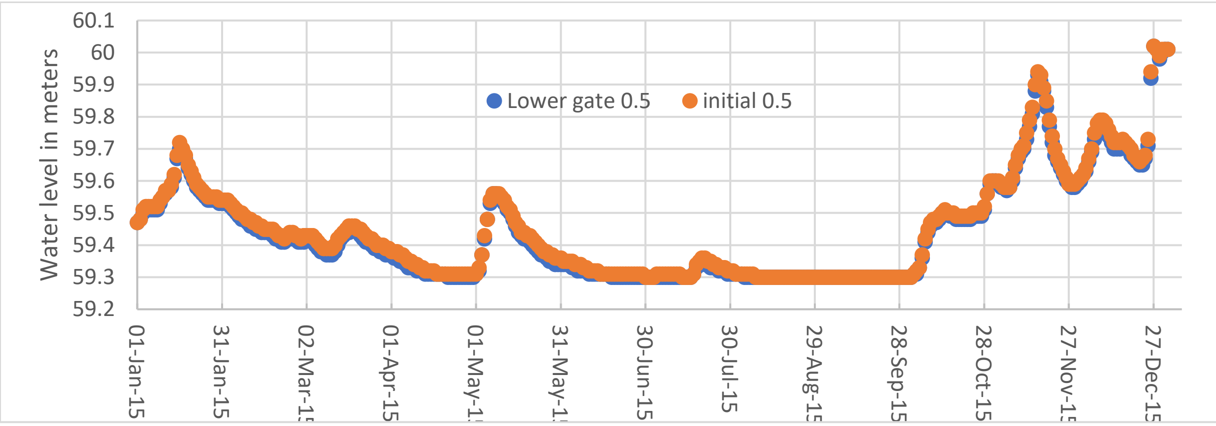


Figure 33 : impact of modifying the return gate inlet in the Balgavies Loch water level

Lowering the gates inlet without modifying the channel geometry in the area will not generate an improvement in flood control or in the flow repartition between the Lunan and the common lade. However, it will modify the flow repartition between the return gate channel and the Mill lade, reducing the flow in the second channel.

Modifying the gates is a heavy investment compared to the previous and next proposition, with a situation where the river needs to be dried to make the modifications. The modification of the gates will only preserve the fields along mill lade from moderate floods.

3. Common lade Spillway modification

Modifying the return gate geometry to increase the flow capacity of the Common Lade had a less than expected efficiency due to the geometry just upstream of the gates. But modifying the existing spillway allow to use the previous problem as an advantage. The previous limiting geometry, with forced the high water level, may increase the efficiency of the spillway. This solution has the advantage of being easy to present to the local actors, with a low investment cost and a low technicity. This solution will also avoid increasing the maintenance cost of the installation.

The modelled modification was a lowered spillway. Lowering the spillway will also allow the spillway to work earlier or more frequently. The inlet level has been selected to be above the low flows levels but low enough to have an impact on common floods. The level is set to have an impact since the water level on Rescobie loch is above 59.70m. This level has been chosen because if the water level in Rescobie loch is above 59.8m the bridge upstream became to be submerged. Acting before the critical water level will allow to increase the storage capacity of the lochs by draining them before the event.

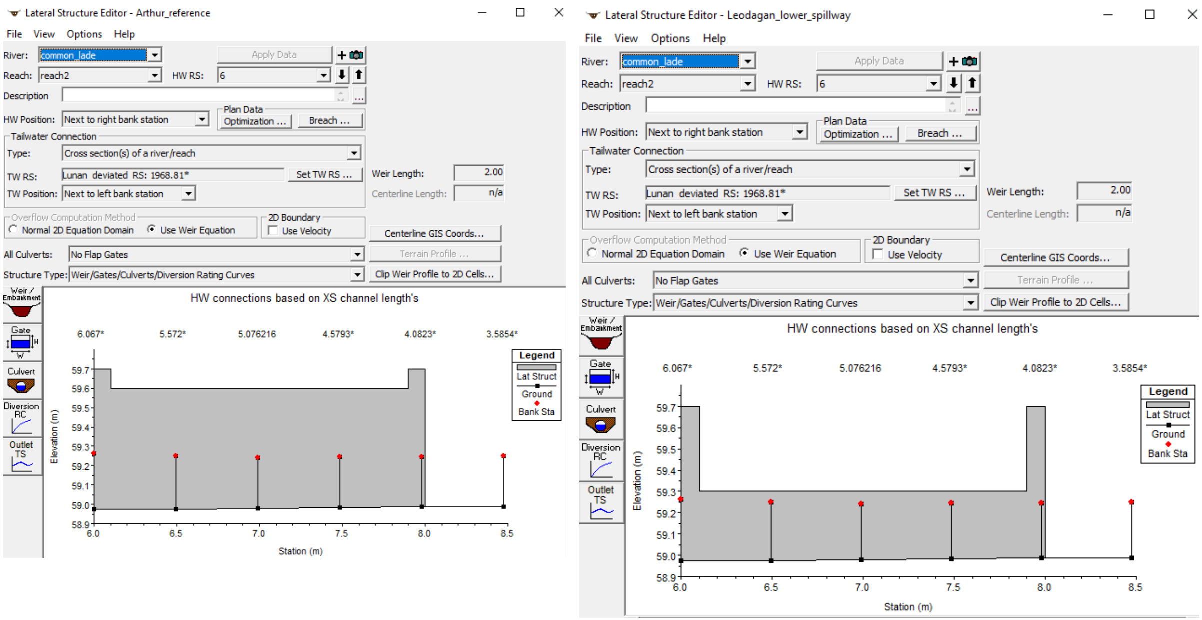


Figure 34 : description of the modification of the lateral spillway in Common Lade

As planned, the lowered spillway, along with the dredging of the common lade, had an impact on the water levels in Balgavies and Rescobie Loch. However, the impact is far less important than expected. The maximal gain in water level in Balgavies Loch was only 3 cm. The gain cannot be higher due to the water level in the discharge channel and backwater effect.

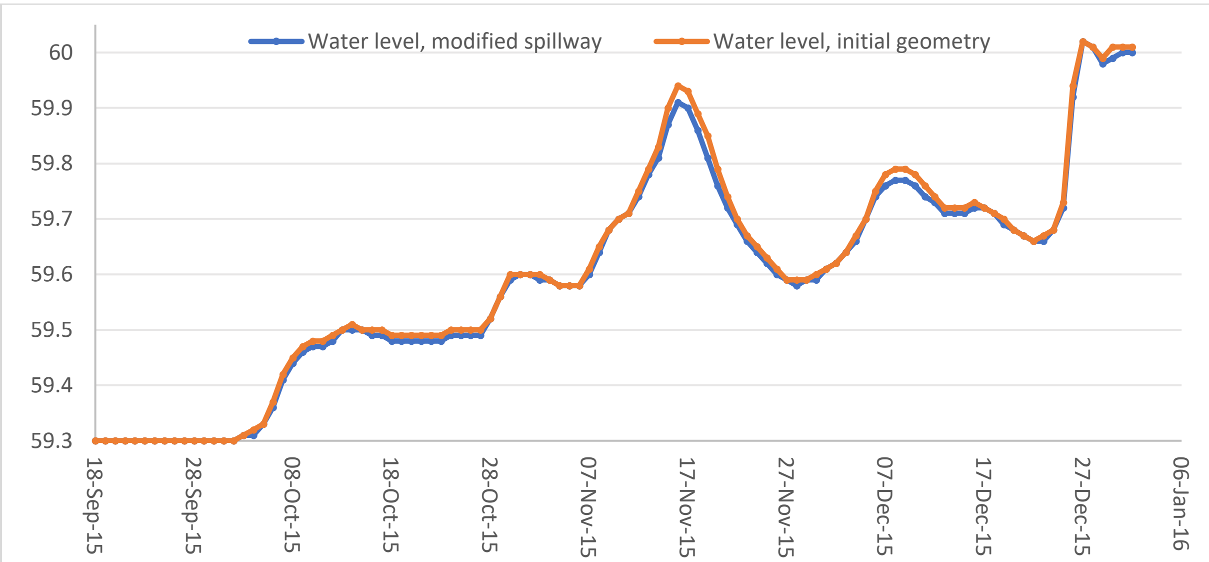


Figure 35 : influence of the modification of the existing spillway on the Balgavies Loch water level

The reduction of the spillway inlet doesn't give a modification of the water level for the targeted floods, the water level in the lochs doesn't change before the water level in Rescobie Loch reach 59.9m. The modified spillway will only improve the situation when the bridge is already flooded. Furthermore, the improving of the flood management will disappear with exceptional flows like the consequences of the Storm Frank.

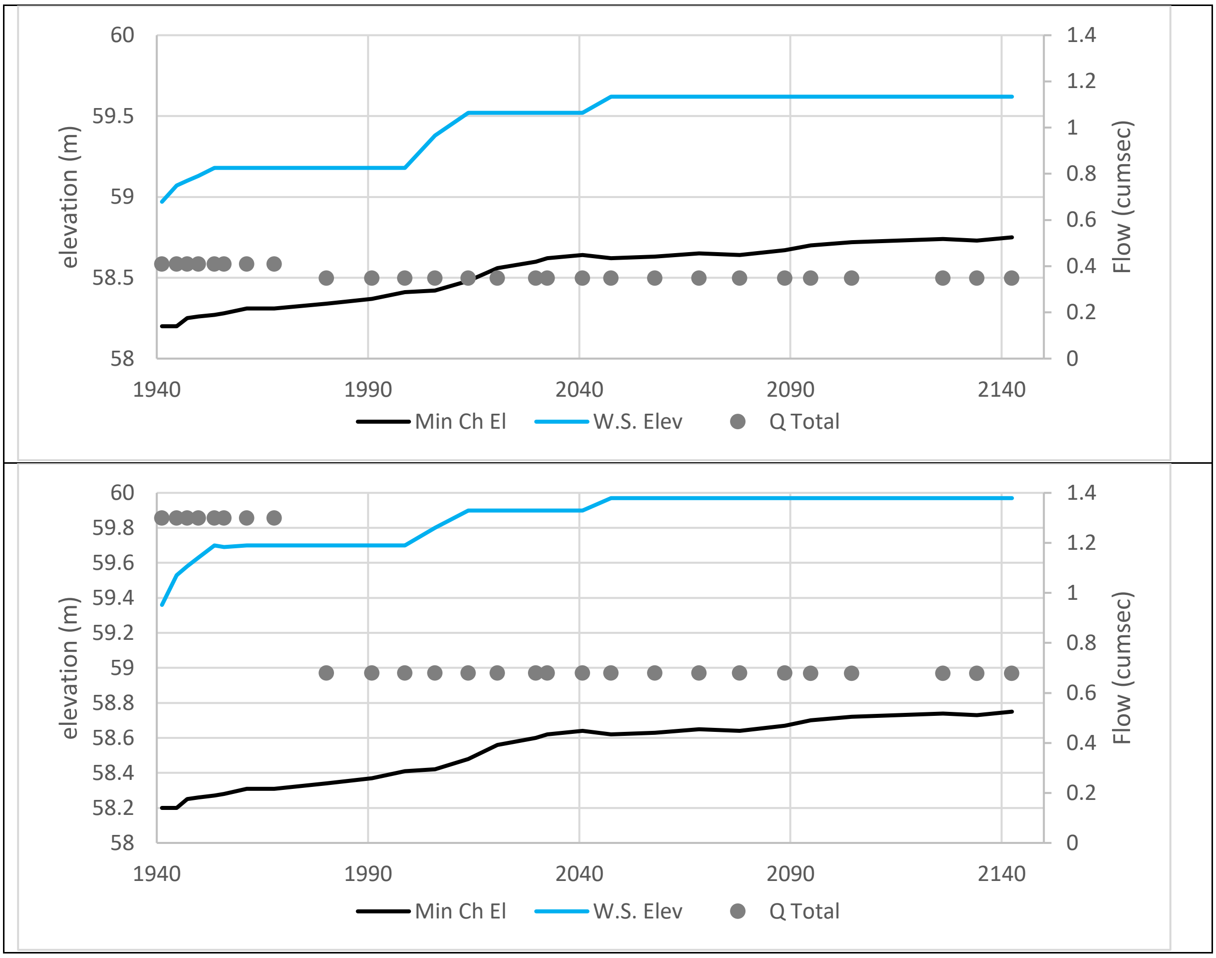


Figure 36 : profiles of the Lunan Deviated channel on the 24 and 29 December with the modified spillway

The brutal increasing of the flow value within the channel mark the place of the discharge point of the spillway.

Lowering the spillway will increase the discharge rate of the system by 100 l/s during medium floods, without starting a strong backwater effect. The last figure indicates than event submerged the spillway increase the discharge of the system. The backwater effect in this scenario is not strong enough to worsen the situation during the peak flows. The increase of the water level upstream of Mildens is not a problem excepted maybe for the Chapel Mires nutrient balance. This part of the Lunan is inhabited and during this type of events the fields are already flooded.

A modification of the existing spillway is a working solution to improve the flood control in the system. The modelled solution is not enough to protect the bridge upstream of Rescobie Loch, or to reduce the flooding occurrence in the farmers' fields near Mildens but there is no negative effect and a variation of this solution were the spillway is wider can be easily tested with probable goods results.

4. Adding of a spillway with a tilting weir

A tilting weir is a motorized weir with an adjustable level, moving around an axis placed across the stream in the bed level. A tilting weir can be completely erased if fully open of show a vertical wall if closed. This solution will need a monitoring of the Loch levels and of the weather prediction, with a remote or on-site control.

Theses solutions are the only ones needing a constant monitoring and a planned gestion to move them. A tilting weir is a mobile weir, moving around an axis placed in the perpendicular of the stream in the bed level. A tilting weir can be completely erased if fully open of show a vertical wall if closed.

Theses weirs are modelized as an overflow open-top gates in Hec-Ras, meaning than we don't model the sloping part of the weirs. The other solution was to have a "user defined curves" for parametrization. However, theses curves require a more deep knowing of the behavior of these type of gates. For theses we needed the physicals or empirical equations that describe the behavior of a tilting weir, analyzing them and simplified them for the studied case. This strategy was more time consuming, more hazardous and may not improve significatively the model quality.

Two placements have been tested, following an intuition about the capacity of the discharge channel to accept the incoming flow without nullified the effect with a downstream influence. The first proposition is to put the tilting weir in the upstream part of the Common Lade, discharging just after the Chapel Mires junction. Both solutions were made with a 4 meters wide gates, leading to more visible effects if effective.

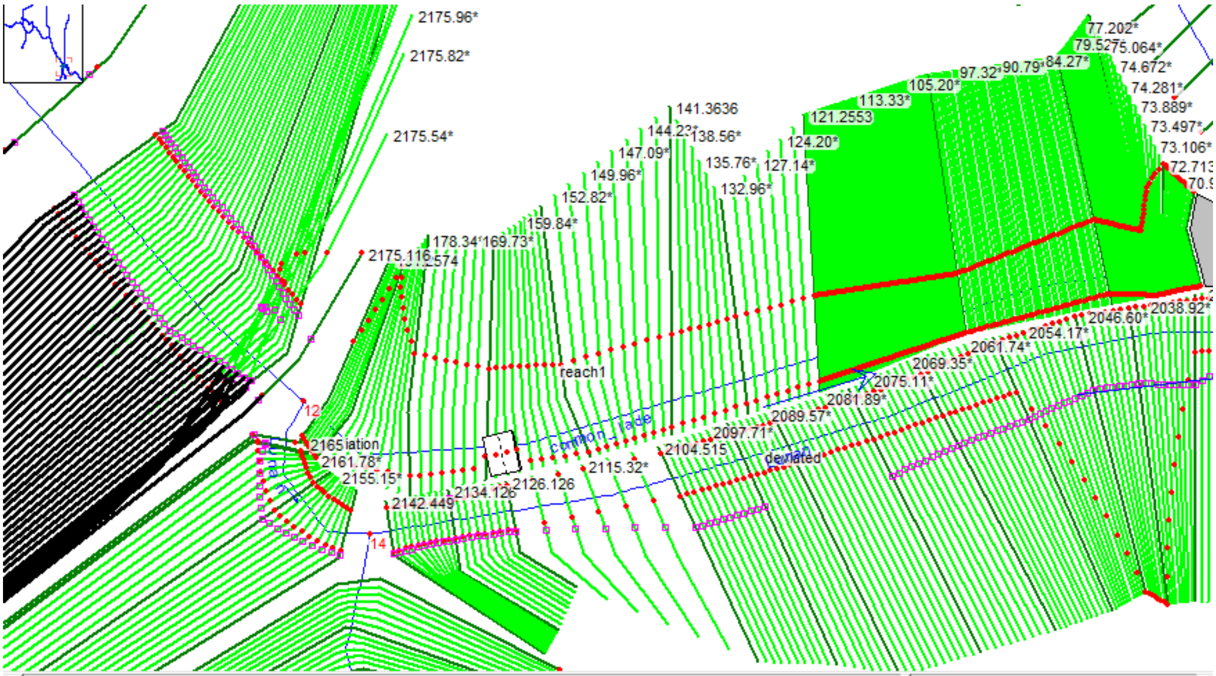
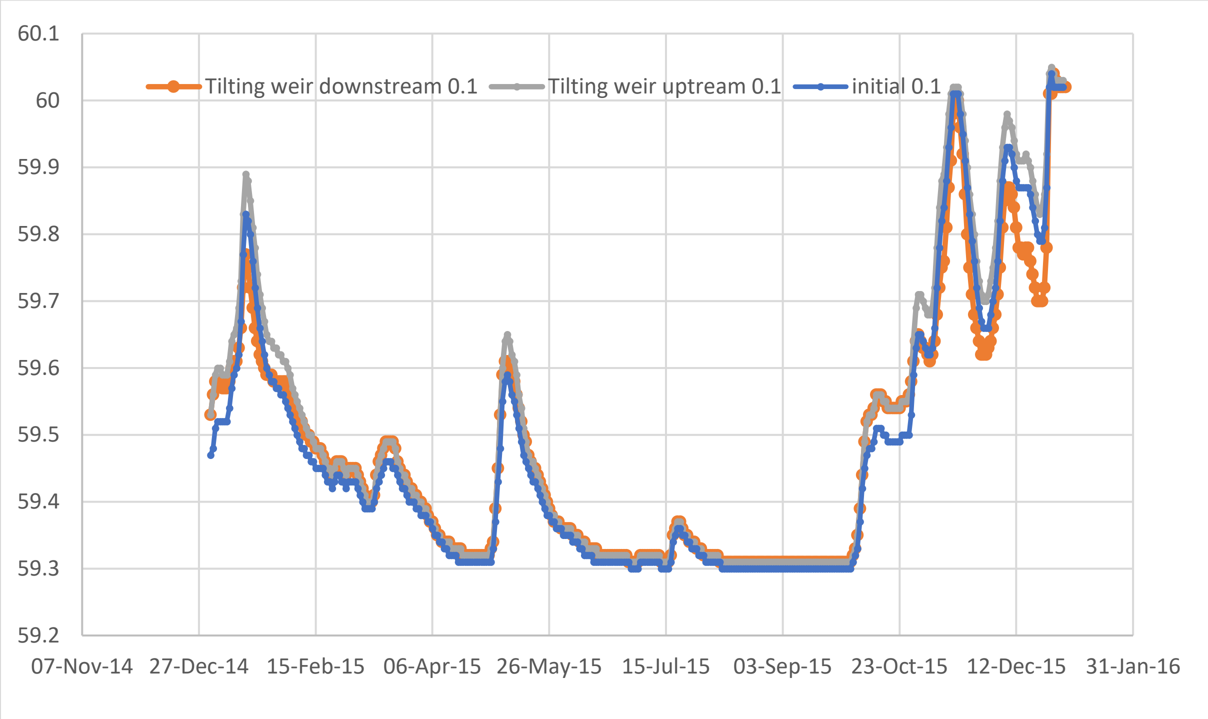


Figure 37 : view of the positioning of the tilting weir, placed on the upstream part of the Common Lade

The second possibility tested was to place the tilting weir just after the input from Balgavies Burn, to place the discharge after the energy losses next to the bridge in Lunan Deviation. The idea was to take advantage of the energy difference between the Common lade, buffed by Balgavies burn, and the Lunan deviated, lowered by the bridge surroundings.

The gates have been parametrized to open if the level in Rescobie loch is above 59.75m and close if the level is below 59.65m. Such a parametrization was expected to reduce the floods of the road bridge upstream of Rescobie loch and preserve the lochs from quicker discharge than the current sittuation.



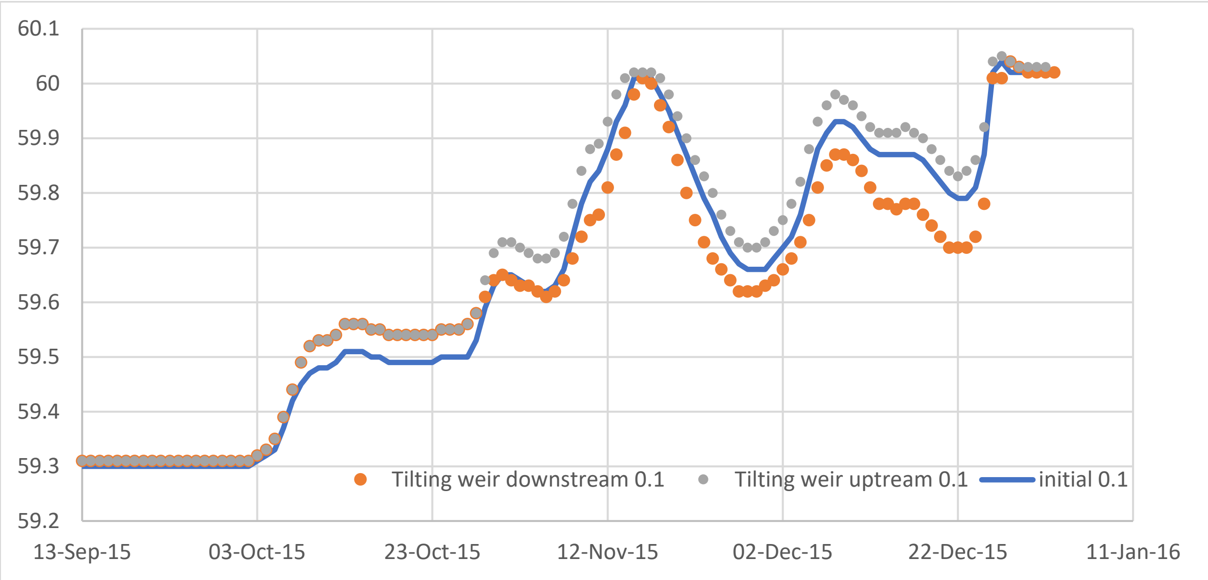


Figure 38 : Water levels in Balgavies Loch for initial geometry and the two scenarios for the tilting weirs

The simulations results have shown strong backwaters effects, especially with the “upstream solution”. With the opening of the tilting weir, the water level in the discharge channel studently rise to a level close to the one in Common Lade. The elevation of the water level in the Lunan channel lead to a rising water level in the head of the Lunan Deviation Reach, leading to a new water partitioning between the Lunan and the common lade and rising levels upstream of the partition plan. This backwater effect can be a major problem or an inconsequent one.

The placement of the gate is a great deal as seen on the plot above. If the connexion between the two reaches is made before the bridge, the backwater effect is too strong during the peak flow of the floods, leading to an increasing of the water levels upstream in the lochs and flooding of the road bridge more frequently. The second solution, with the gate/weir placed after the bridges and the energy loss in the Lunan channel, also generate backwater effect but for much smaller window of flow values. The backwater effects are reduced to medium-low flows and erased from highs flows. This modification made the tilting weir viable and efficient. The downstream tilting weir increase the water levels in the lochs when there is no risk, lower it for common floods and erase himself during important floods, avoiding worsening the situation for the upstream sectors.

The tilting weir, coupled with a removal of the small sediment deposit in Common Lade upstream of the bridge, is the most efficient of all the analyzed solutions for flood control. This also allow a little gain in the repartition of high flows away from Chapel Mires. The tilting weir, during the first part of the flood, reduce the amount of water going into the Chapel Mires wetland and, when the backwater effect became too strong, gave the same result as the current system. The dredging only solution gave a lower amount of water in the wetland during all the flood. The difference of efficiency between the two only depend of the nutriment loads during floods events.

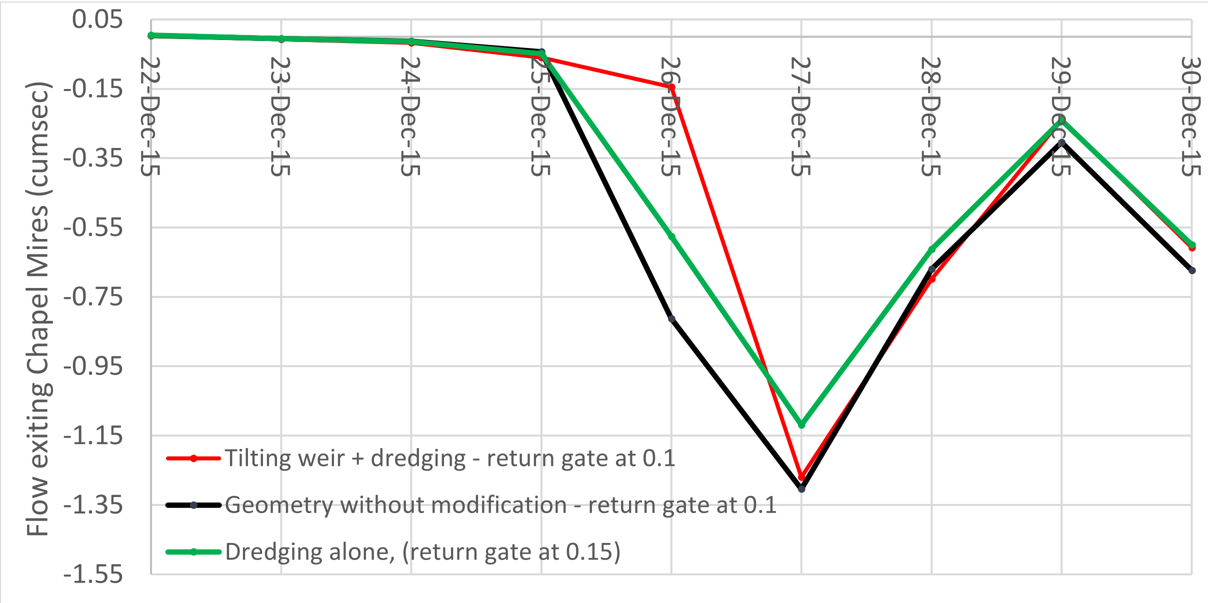


Figure 39 : evolution of the flow going into the Chapel Mires wetland during the floods of the 27th December 2015 for the reference and two proposed solutions.

The effect of the tilting weir on flows though Chapel Mires are more important than the one obtained with the dredging of Common Lade only, due to the backwater effects but they are enough to have an impact on the sediment and nutriment load. This analysis is valid for high flows, presents in autumns, and showing the highest load un nutriments.

5. Other observations

With the backwater phenomenon analysis, it appears than the geometry of the Lunan – Deviated channel was crucial in the flood management strategies. In order to increase the discharge of the system, widening some part of this channel, not the submerged parts but the upper part of the trench will improve the flow speed. In the figure 21 we can clearly see three steps without relation with the bed level for two of them. In this case the acceleration of the flow, or the sudden lowering of the water level is related to the geometry. Widening the channel section just before the third step (around cross section 1960) can lead to a lower water level on the upstream part of the reach. And this because of the characteristics of the sub-critical flow type always presents in this channel.

However, this type of modification can significantly worsen the impact of the floods downstream, increasing booth the volume and peak flow value of the flood downstream. With inhabitants just downstream of this reach, living in a floodable location **I recommend to NOT doing that.**

V. results

1. Observations and scenarios results

The upper part of the Lunan Water is heavily impacted by the geometry of in the output of the Sluggish section. The Common lade, without slope, but with a sediment deposit increasing the bed level and two gates in its end, is the channel which control the water levels in the upstream part during low and mediums flows. The study of the initial/reference geometry shown the great influence of the gates opening over the water level in the lochs. The difference in water levels can be higher than ten centimeters between closed and fully open gates. A flood management tool is already existing for the smaller floods. Operating the gates before the rain to drain the loch will also slightly reduce the flood impact by allowing more storage in the Lochs.

It was shown than the sediment deposit doesn’t have a significant influence on the water levels upstream but determine the flow partition between the Common Lade and the Lunan channel. The removal of this element will also increase the efficiency of every hydraulic structure placed on the Common Lade.

The modification of the inlet of the “return gate” gate will not grant any advantage to the flood management or the flow repartition between Common Lade and Lunan water. The modification of the gate will only change the flow repartition between the Mill Lade and the return flow channel. This solution will have an important initial cost and will not improve the flood control capacities.

The modification of the existing spillway, by lowering its inlet, will slightly reduce the water levels upstream during floods. The importance of the effect is reduced by the size of the spillway, which show a less than 1m² section for commons floods. However, the results are showing that another modification of the spillway, by increasing its length, may have good chances to produce a more effective flood control. This hypothesis is backed by the results of the modelling of the spillway incorporating a tilting weir. The backwater effect induced by the flow diverted in the Lunan is not strong enough to worsen the situation upstream.

The creation of a new spillway built with a tilting weir can be a great or a very bad idea. The backwater effects can be very strong depending on the position of the discharge on the Lunan channel. For the test on the upstream position, the effect was so strong that it worsened the situation for the upstream parts of the Lunan, instead of increasing the discharge values. For other positioning on the Common Lade, the backwater effects can be limited. The tilting weir can give a significant improvement in term of water level in the upstream parts. The second solution also preserve the Chapel Mires area from the early stage of floods, heavily loaded with sediments and nutriments.

The Lunan channel running parallel of Common lade as also been identified as one of the great influences in the flood behavior of the system, conditioning the impact of the backwater effects and the discharge speed.

2. Recommendations

The model accuracy is not guaranteed in some part, essentially due to the geometry that cannot be checked. There is an important need to check the geometry of the channel between the Rescobie and Balgavies Loch. The geometry in this part of the river is the main reason of the difference between the two lochs water levels.

The Second important point to improve the model will be the extension of the model further downstream, in order to have an estimation of the gains and losses the flood management solutions studied here will impacted the houses at Mildens. The protection of the houses wasn't in the objectives of this modelling, but the definitive solution shouldn't make them more vulnerable to floods events.

VI. Conclusion

The model objective was to model with a better accuracy and a better representation of the floods dynamics of the Lunan upper catchment. Once this part done the model was used to model the impact of proposed solutions to improve the flood control in the Lunan Catchment. Along with the flood controls were demands about helping to preserve the Chapel Mires wetland in a mesotrophic state and reducing the numbers of days with water abstraction restrictions.

The model was calibrated and validated using the water level recording gauges in Balgavies Loch entrance and in Rescobie Loch outlet. The calibration of the model was done by modifying the Manning coefficients of the rivers and overbanks rivers by rivers, with internals subdivisions for some of them.

The hydrologic modelling needed to extrapolate flow values at every boundaries of the hydraulic model was based on a regional formula. This formula use the flow values in one gauged catchment to determinate the flow at nearby catchments. The Wemyss gauge was used as reference and the formula was calibrated using the Westerton and Hatton gauges.

The modelling of the different proposed management options showed the best efficiency in terms of flood control with one of tilting weir proposition. To improve the nutriment partition between the Lunan channel and the Chapel Mires a tilting weir is efficient but not as efficient as the dredging solution alone. The lowering of the gate inlet doesn’t lead anywhere, showing no positive nor negative impact on the system in its globality.

Other managements options, without need of constant monitoring were useful for flood management or for flood partition, in a lesser importance. The mofication of the spillway lower a bit water level upstream during floods. The dredging alone, doesn’t change anything in term of flood, but influence the Chapel Mires flow values.

All of the tested solutions didn’t give any significant improvement of the low flows management, the solution with the tilting weir placed downstream however show capacity to store a bit of water in the loch during flow regression. This element effect be increased with a good management of the Common Lade gates.

The tilting weir is the most efficient structure according to the simulations done with Hec-Ras, but it will be very costly to set and maintain. The fixed structures like a modification of the current spillway, despite lower gain will probably be easiest promote to other actors of the project and to the farmers who own the lands.

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Annexes

Annex 1 : Table of the catchment geology and hydrology used by Birkel,

Annex 2 : Description of the process behind the modification of the Regional Formula

Annex 3 : Supporting information from Vinten et al 2019.

Annex 4 : Cross section data from the previous model, data coming from Vinten, Addy and Compton

Annex 5 : bridges description

Annex 6 : maps of the end of the catchment by OpenStreetMap, google map and the hydraulic model.

Annex 7 : Hec-Ras model geometry overview

Annex 8 : translation of Introduction and Conclusion

Annex 1 : Table of the catchment geology and hydrology used by Birkel,

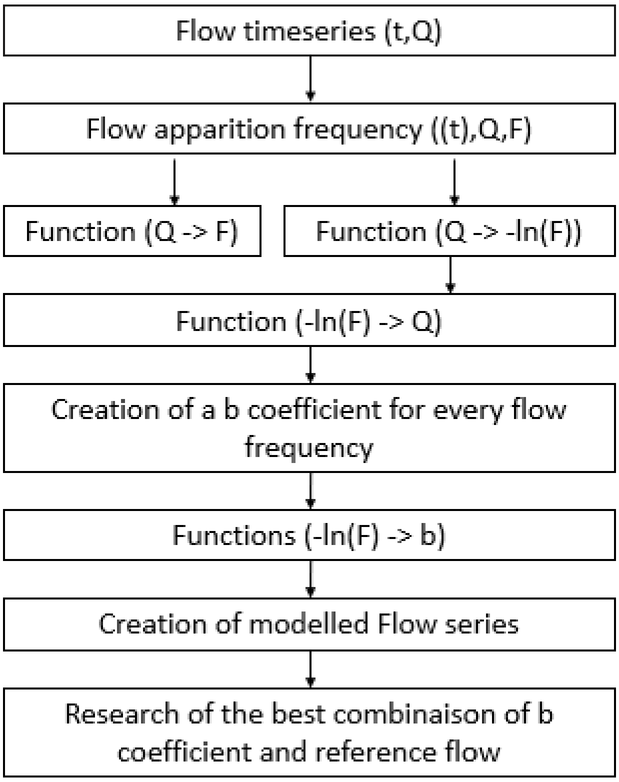
Basic descriptors (hydrology, topography, geology, soils, landcover and soils) of the Lunan catchment at Kirkton Mill (KM) and the headwater sub-catchment Wemyss.

	Kirkton mill (km)	Wemyss
Area (km^2)	122	2.3
Hydrology (2008/09)		
Precipitation ($mm\ a^{-1}$)	854[a]	831[b]
Runoff ($mm\ a^{-1}$)	450	268
Evaporation ($mm\ a^{-1}$)	404[c]	401[d]
Topography		
Mean elevation (m.a.s.l.)	96.6	134.7
Min. elevation (m.a.s.l.)	1	66
Max. elevation (m.a.s.l.)	250.9	250.9
Mean slope (°)	2.9	8.8
Max. slope (°)	45	45
Drainage density (km/km^2)	0.83	0.76
Bedrock geology		
Lower old red sandstone (%)	74.3	100
Upper old red sandstone (%)	1.4	–
Andesitic and basaltic lavas (%)	24.3	–
Superficial geology		
Till (Diamicton) (%)	79.3	100
Glacial sands and gravel (%)	17.2	–
Alluvium (clay, silt, sand) (%)	0.7	–
Raised marine deposits (sand, gravel) (%)	2.8	–
Landcover		
Forest (%)	8.4	8.8
Agriculture (%)	81.6	86.9
Heather (%)	0.9	–
Urban (%)	9.1	4.3
Soils		
Humus iron podzol (%)	41.7	100
Peat (%)	1.2	–
Brown forest soil (%)	9	–
Noncalcerous gley (%)	3.7	–
Mineral alluvial soil (%)	11.9	–
Brown forest soil with gleying (%)	32.5	–
Water bodies		
Lochs (lakes)	2 (0.73%)	–

[a] Inverse distance interpolated catchment average precipitation based on five stations.
[b] Single rain gauge measurement closest to the Wemyss sub-catchment.
[c] Water balance evapotranspiration estimate for 2008/09.
[d] Land use adjusted Penman–Monteith evapotranspiration estimate for 2008/09.

Table extracted from Birket et al, 2011

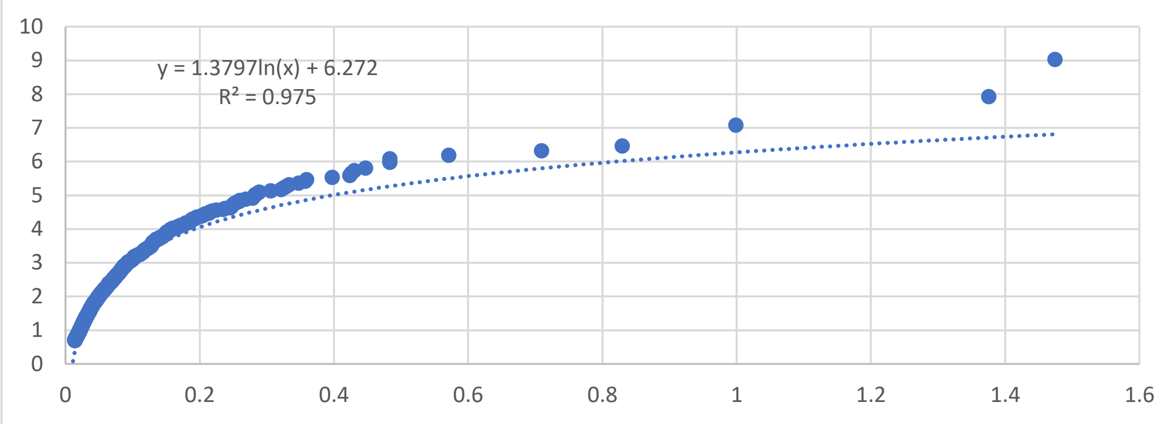
Annex 2 : Description of the process behind the modification of the Regional Formula



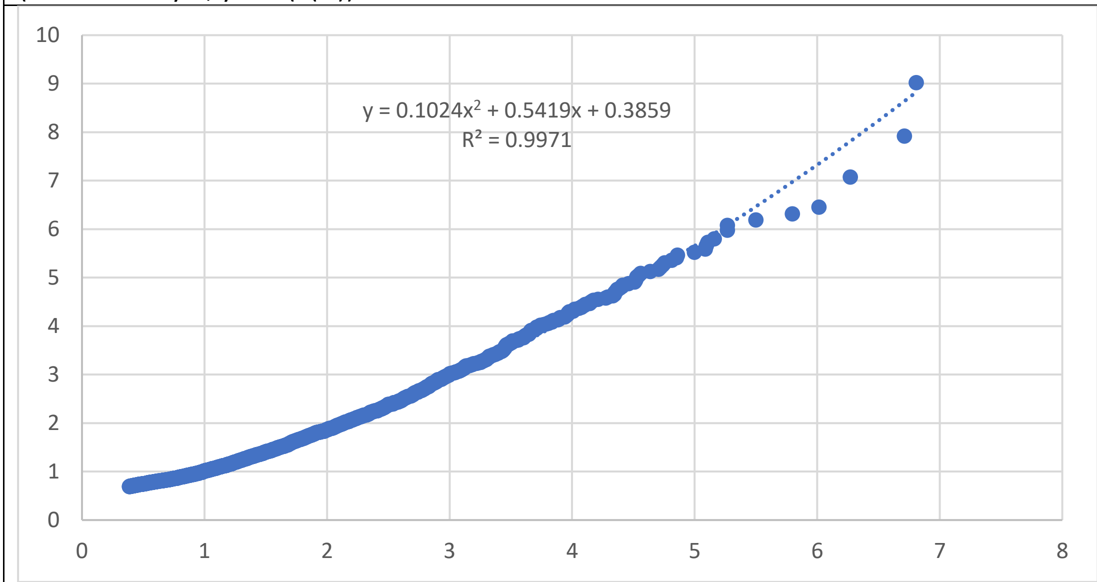
To get correct values for the b coefficients we needed to find which flow get the same apparition frequency. To do it we linked the Flow values to their frequency values to be able with just a frequency, to determine the flow values for the three catchments. Or to do the opposite. The basic hypothesis was “ the b coefficient is dependent of the appearance frequency of the flood”. So we searched a relation between Q, F and b. However, a fixed b coefficient gave better results than a moving one.

The difference between the formula used here and the one describes in (Cudworth 1989), is that the one used here wasn’t based on peak flow. We created a frequency for every flow value, disregarding of the influence between two consecutives days. The frequency when doing this became biased but if we don’t try to compare it to frequency used in floods classification, we can sort it out.

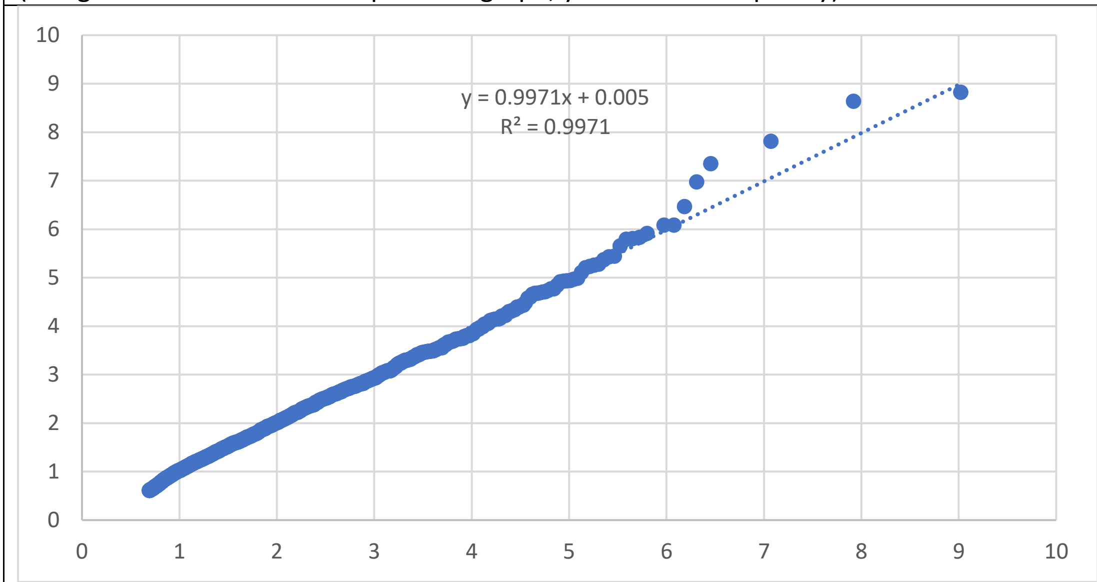
On the next page there is the plots used to determine the functions between frequency and flow values and the coincidence between frequency calculated by sorting the flow values and frequency calculated by successive operations on flow values.



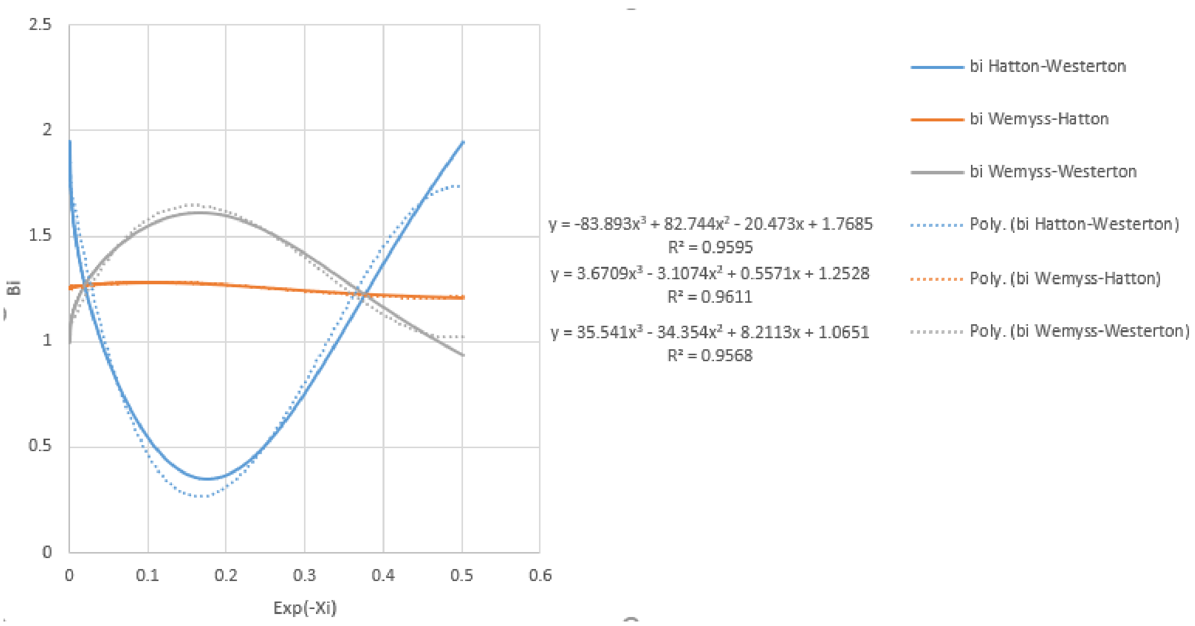
Plot of the modified apparition frequency against the measured flow value
(x=Q at wemyss, y= -ln(F(Q))



Plot of the function of the flow discovered on the previous plot and the modified frequency
(x=log function of Q fitted on previous graph, y= modified frequency)

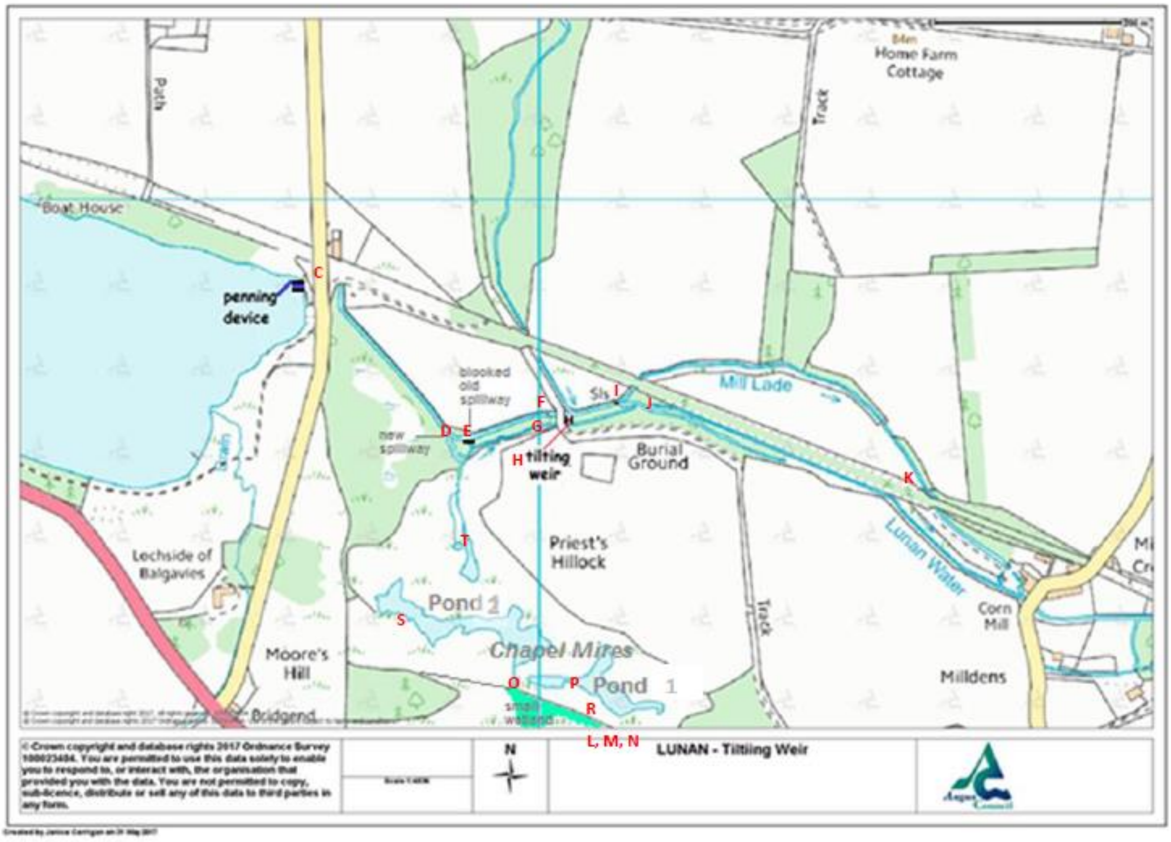


Plot of the initial modified frequency against the frequency calculated with the flow values
(x=f'(Q wemyss) , y= modified frequency)



B coefficients curves when functions of the flow frequency.

Annex 3 : Supporting information from Vinten et al 2019.



A. Rescobie Lake Boathouse after storm Frank, Jan 2016 (not on map below).
B. Balgavies Lake, looking north east towards outlet, Sept 2017.
C. Outlet of Balgavies Lake into Common Lade (chainage =0m).
D. Chapel Mires spillway of Lunan Water from Common lade with Balgavies Lake level at HL=59.7m
E. Wider section of Common lade with sediment accumulation on bend just upstream of blocked spillway (chainage = 270m)
F. Cattle drinking area u/s cattle bridge on Common Lade, chainage 374m in summer 2017.
G. Debris dam u/s cattle bridge on Common Lade
H. Proposed site of tilting weir at chainage 381m (see arrows). Note Balgavies Burn coming into Common Lade (on left) and the tailwater channel (Lunan Water d/s of Chapel Mires) on the right. Looking east from cattle bridge.
I. Milldens weir gates looking d/s (left hand gate leads to mill lade, right hand gate returns to Lunan Water)
J. Milldens weir at chainage 674m looking from u/s in spate.Note Lunan Water (tailwater channel) in background, Common Lade in middle, and return flow to Lunan water from Common lade and offtake to Milldens lade (in foreground).
K. Milldens Lade in March 2018 upstream of bridge at chainage 838m.

L. S27a Carex wetland on southern edge of Chapel Mires in summer 2017, looking west
M. S27a Carex wetland on southern edge of Chapel Mires in March 2018, looking west
N. Carex (S27a/W9) wetland, Chapel Mires in June 2017
O. Culverted embankment between S27a wetland (on left) and channel to Ponds 1 and 2 (on right). Looking west.
P. View of the Chapel Mires Pond 1 after the high flooding event in Jan 2016.
Q. Utricularia vulgaris agg. collected from Pond 1
R. Pond 1 looking north east
S. South-western margin of Pond 2, Lysimachia thyrisiflora in foreground
T. Inlet pond from eastern shore

Photography and maps by A. Vinten

Annex 4 : Cross section data from the previous model, coming from Vinten ,Addy and Compton

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

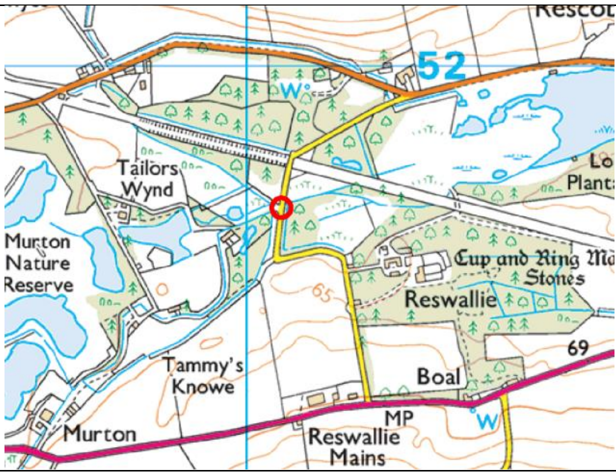
Surveyor & date	Vinten, 2015		Addy 2017		Addy 2017		Vinten 2015		Addy 2017		Addy 2017		Addy 2017		Addy 2017	
Chainage of upstream reach (m)	5			12		33		9		24		71	1	4		3
Cum. Chainage from Balgavies Loch outlet (m)	225			232		265		274		298		369	370	374		381
LHB Easting	353883			353897		353918		353927		353947		354015	354015	354015		354035
LHB Northing	750775			750768		750743		750747		750759		750777	750777	750777		750782
crosssection no.	20.1			20		19		18		17		16	15.9	15.8		15,78
Description of cross section	Lateral outflow through Chapel Mires spillway		downstream of Chapel Mires spillway (part of X2)		wide, vegetated section (X3)		at barrier to old spillway into Lunan Water		just d/s of bend (X4)		just u/s of bridge/culvert (lade part of X5)		4m culvert		just d/s of bridge/culvert u/s of BB (copy of X7)	
	CMS spillway		distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)
	0.00	61.00	0.00	59.91	0.00	59.34	0.00	61.00	0.00	60.37	0.00	60.08	0.00	61.00	0.00	60.19
	0.01	58.90	1.02	59.94	0.37	58.78	0.00	59.16	1.18	60.16	1.34	59.87	0.10	58.98	1.10	60.26
	2.69	58.90	2.05	59.97	1.04	58.79	0.00	58.90	2.28	60.16	3.04	59.71	3.40	58.98	2.41	60.47
	2.70	61.00	3.22	59.99	2.20	58.85	0.65	58.81	3.38	60.23	4.57	59.57	3.50	61.00	2.76	60.42
			4.15	59.82	3.06	58.82	1.49	58.80	4.43	60.11	5.29	59.72			4.12	59.95
			5.01	59.72	4.06	58.77	2.58	58.78	5.07	59.82	6.61	59.54			4.53	59.43
			5.53	59.42	4.50	58.88	3.61	58.83	5.50	59.34	7.62	59.66			5.16	59.14
			6.16	58.85	4.87	59.08	4.48	58.84	5.69	59.10	7.96	59.61			5.32	59.10
			6.27	59.08	5.12	59.37	5.35	58.89	6.71	58.87	8.56	59.46			5.75	58.93
			6.34	59.02	6.08	59.77	5.44	59.16	8.69	58.51	9.37	59.36			6.45	58.80
			6.37	58.97	7.35	59.78	5.44	59.88	9.45	58.83	9.83	59.32			7.20	58.59
			6.73	59.04					9.99	59.12	10.65	59.31			7.84	58.70
			6.83	58.80					10.44	59.57	11.12	59.32			8.43	58.72
			7.10	59.22					11.59	59.81	11.51	59.45			8.18	58.88
			11.01	59.45					12.53	59.76	11.57	59.56			8.94	59.09
			12.08	59.43					13.56	59.83	11.77	60.36			9.96	60.88
			13.35	59.41					14.90	59.99	12.38	60.894				
											13.17	60.842				
											14.47	60.764				
											15.41	60.862				
											16.45	60.873				

Surveyor & date		Addy 2017		Addy 2017	Addy 2017		Compton 1978		Addy 2017		Compton 1978		mpton 1978	
Chainage of upstream reach (m)	8		3	1		13	46			1	1		1	
Cum. Chainage from Balgavies Loch outlet (m)	376		380	381		394	440			441	442		443	
LHB Easting	354035		354035	354035		354049	354097			354049	354097		354097	
LHB Northing	750782		750782	750782		750780	750802			750780	750802		750802	
crosssection no.	15.1		15	7.1		7	6.8			6.75	6.74		6.73	
Description of cross section	Proposed tilting weir lateral outflow just d/s of bridge	just u/s of BB (copy of X7)		Balgavies Burn tributary inflow	d/s of bridge and BB inlet(X7)		Lateral Return flow weir to Lunan Water		copy of of X7		start of Inline weir gate to Milldens lade		end of Inline weir gate to Milldens lade	
		distance from LHB (m)	bed elevation (m)		distance from LHB (m)	bed elevation (m)	distance (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)
		0.00	60.19		0.00	60.19	0.00	61.00	0.00	60.19	0.00	61.00	0.00	61.00
		1.10	60.26		1.10	60.26	0.01	59.04	1.10	60.26	0.01	59.04	0.01	59.04
		2.41	60.47		2.41	60.47	0.90	59.04	2.41	60.47	0.90	59.04	0.90	59.04
		2.76	60.42		2.76	60.42	0.91	61.00	2.76	60.42	0.91	61.00	0.91	61.00
		4.12	59.95		4.12	59.95			4.12	59.95				
		4.53	59.43		4.53	59.43			4.53	59.43				
		5.16	59.14		5.16	59.14			5.16	59.14				
		5.32	59.10		5.32	59.10			5.32	59.10				
		5.75	58.93		5.75	58.93			5.75	58.93				
		6.45	58.80		6.45	58.80			6.45	58.80				
		7.20	58.59		7.20	58.59			7.20	58.59				
		7.84	58.70		7.84	58.70			7.84	58.70				
		8.43	58.72		8.43	58.72			8.43	58.72				
		8.18	58.88		8.18	58.88			8.18	58.88				
		8.94	59.09		8.94	59.09			8.94	59.09				
		9.96	60.88		9.96	60.88			9.96	60.88				

Surveyor & date	Vinten 2015		Vinten 2015		Vinten 2015		Addy 2017		Compton 1978		Compton 1978	
Chainage of upstream reach (m)		1		10		11		359		174		187
Cum. Chainage from Balgavies Loch outlet (m)		444		454		466		825		999		1186
LHB Easting		354097		354102		354111		354400		354521		
LHB Northing		750802		750811		750818		750710		750585		
crosssection no.		6		5		4		3		2		1
Description of cross section	Start of Milldens lade		u/s railway culvert going N		d/s railway culvert going N		just u/s of railway culvert going S (X8)		Outlet from Mill		Mill bridge	
	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)	distance from LHB (m)	bed elevation (m)
	0.00	61.00	0.00	60.82	0.00	60.79	0.00	60.18	0.00	60.09	0.00	56.41
	0.01	60.19	0.01	60.19	0.01	60.16	0.01	59.55	0.01	59.46	0.40	56.21
	0.28	59.59	0.28	59.59	0.28	59.56	0.28	58.95	0.28	58.86	0.80	56.11
	0.84	59.48	0.84	59.48	0.84	59.45	0.84	58.84	0.84	58.75	1.20	56.10
	1.00	59.45	1.00	59.45	1.00	59.42	1.00	58.81	1.00	58.72	1.60	56.43
	1.36	59.07	1.36	59.07	1.36	59.04	1.36	58.43	1.36	58.34	2.00	56.13
	1.82	59.06	1.82	59.06	1.82	59.03	1.82	58.42	1.82	58.33	2.40	56.19
	1.90	59.04	1.90	59.04	1.90	59.01	1.90	58.40	1.90	58.31	2.80	56.21
	2.55	59.14	2.55	59.14	2.55	59.11	2.55	58.50	2.55	58.41	3.20	56.26
	3.04	59.11	3.04	59.11	3.04	59.08	3.04	58.47	3.04	58.38	3.60	56.34
	3.46	59.29	3.46	59.29	3.46	59.26	3.46	58.65	3.46	58.56	4.00	56.46
	3.54	59.49	3.54	59.49	3.54	59.46	3.54	58.85	3.54	58.76		
	3.67	59.59	3.67	59.59	3.67	59.56	3.67	58.95	3.67	58.86		
	4.02	59.77	4.02	59.77	4.02	59.74	4.02	59.13	4.02	59.04		
	4.29	59.78	4.29	59.78	4.29	59.75	4.29	59.14	4.29	59.05		
	5.11	61.00	5.11	59.82	5.11	59.79	5.11	59.18	5.11	59.09		
							5.86	59.136				
							6.02	59.066				
							6.83	58.974				
							8.02	58.845				
							8.64	58.555				
							9.59	58.38				

These cross sections were used during the river burning process and to check the final geometry in the model.

Annex 5 : bridges description

Type of structure: Bridge			
Local name :		ID code :	
River :	Lunan Water	Town :	FORFAR
Coordinates		Map extract	
GB grid system	GPS	 	
X : 350075 meters Y : 751688 meters	56.6544 North 2.8160 West		
Date of construction :			

deck characteristics (meters)		
Length	Width	Elevation
12	6.25	60.34

This bridge had two semi-circular arches

	Left ach	Right arch
Bed level – top arch distance upstream	1.28 m	1.00 m
Bed level – top arch distance downstream	94 cm	54 cm
Arc maximal Width	2.3 m	2.0 m
Length of the arch	6.25 m	6.25 m

Comments

The left arch is filled up by sediments in the downstream side, on the right side the flow mainly pass by the left side of the arch, there is a 20 centimeters denivelation in the bed level between the two side of the downstream opening of the right arch.

The bed level just upstream of the bridge is way deeper than the downstream side with a lot more organic deposit and lot of methane emission when disturbed.

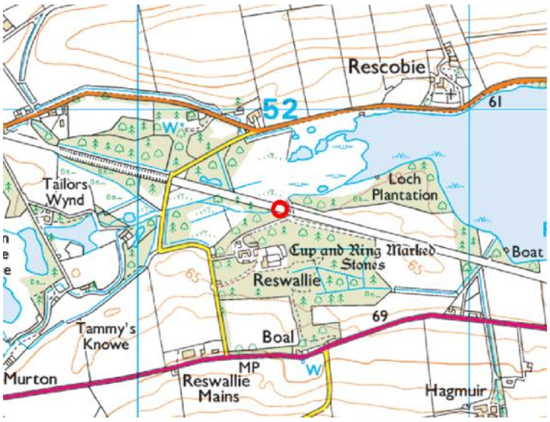
* ”left” and “right” are defined by the flow direction

Date of last modification : 02 april 2019

Photographies :

Figure 40 : view from upstream, taken on the 1st april 2019

Figure 41 : view from downstream, taken on the 1st april 2019

Type of structure: Bridge			
Local name :		ID code :	
River :	Lunan Water	Town :	
Coordinates		Map extract	
GB grid system	GPS		
X : 350434 meters Y : 751701 meters	56.6544 North 2.8098 West		
Date of construction :			

deck characteristics (meters)		
Length	Width	Elevation
	9.60	63.68

	arch
Bed level – top arch distance upstream	3.20 meters
Bed level – top arch distance downstream	3.30 meters
Arc maximal Width	2.10 meters
Length of the arch	9.60 meters

Comments

This bridge is an opening in the levee formed by an old railway track, the length of the deck is not pertinent here because the railway has the same elevation and block the water on several hundred meters.

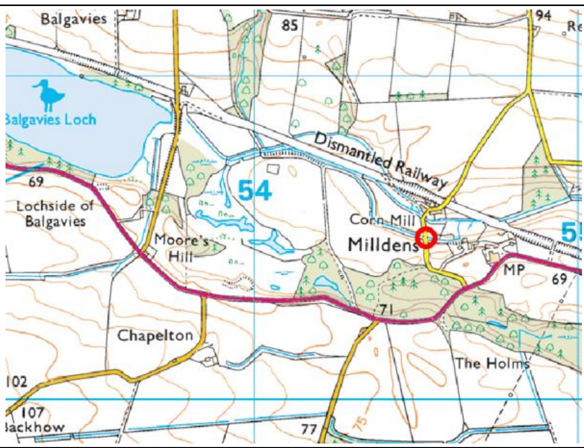
There is an rectangular channel made with stones blocks before the bridge to guide the flow in the bridge, the channel made a 90 degrees turn just upstream of the bridge, leading to an flow acceleration in the right side of the channel.

Date of last modification : 02 april 2019

Photographies :

Figure 1 : desk from the west side, taken on the 1st april 2019

Figure 2 : view from upstream with the stones channel, taken on the 1st april 2019

<table>
<tr><td colspan="4">Type of structure: Bridge</td></tr>
<tr><td>Local name :</td><td></td><td>ID code :</td><td></td></tr>
<tr><td>River :</td><td>Lunan Water</td><td>Town :</td><td></td></tr>
<tr><td colspan="2">Coordinates</td><td colspan="2">Map extract</td></tr>
<tr><td>GB grid system</td><td>GPS</td><td colspan="2" rowspan="4">
</td></tr>
<tr><td>X : 354529 meters
Y : 750501 meters</td><td>56.6447 North
2.7431 West</td></tr>
<tr><td>Date of construction :</td><td></td></tr>
<tr><td></td><td></td></tr>
</table>

deck characteristics (meters)		
Length	Width	Elevation
9.27	5.15	59.29

	arch
Bed level – top arch distance upstream	
Bed level – top arch distance downstream	2.10 meters
Arc maximal Width	4.30 meters
Length of the arch	5.15 meters

Comments

The access to the upstream part of the bridge is difficult because of dense vegetation

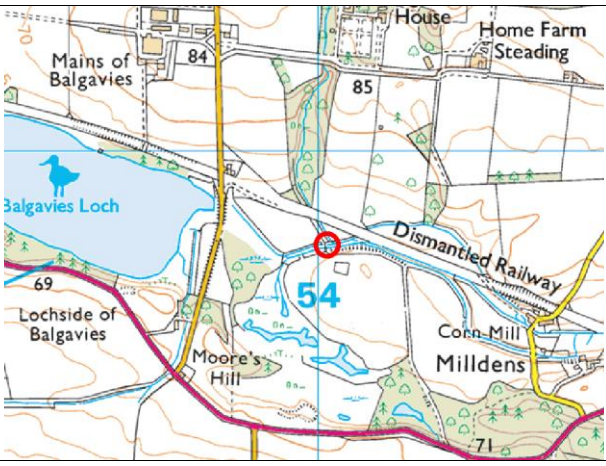
The top of the parapet is 1.55 meters above the top of the arch. (0.9 meters above the road)

the lower part of the bridge opening is set by two concrete margins and the arch start on the margins with a small distance from the edge.

Date of last modification : 02 april 2019

Photographies :

Figure 1 :view from downstream, taken on the 1st april 2019

<table>
<tr><td colspan="4">Type of structure: Bridge</td></tr>
<tr><td>Local name :</td><td></td><td>ID code :</td><td></td></tr>
<tr><td>River :</td><td>Lunan Water</td><td>Town :</td><td></td></tr>
<tr><td colspan="2">Coordinates</td><td colspan="2">Map extract</td></tr>
<tr><td>GB grid system</td><td>GPS</td><td colspan="2" rowspan="4">
</td></tr>
<tr><td>X : 354018 meters
Y : 750766 meters</td><td>56.6465 North
2.7514 West</td></tr>
<tr><td>Date of construction :</td><td></td></tr>
<tr><td></td><td></td></tr>
</table>

	deck characteristics (meters)		
	Length	Width	Elevation
North bridge		6.60	60.49
South bridge		5.80	60.49

	North bridge	South bridge
Bed level – top arch distance upstream	1.45 meters	1.60 meters
Bed level – top arch distance downstream	1.60 meters	1.70 meters
Arc maximal Width	3.30 meters	2.00 meters
Length of the arch	6.60 meters	5.80 meters

Comments

The two bridges are above the common lade (north) and the Lunan Water (south). The junction with the balgavies burn is 4 meters downstream of the bridge.

The north bridge is a semi circular arch made with stones. The south one is made with three waste water concrete pipes (2 meters diameter), there is a little gap and deviation in the junctions of the pipes.

Date of last modification : 02 april 2019

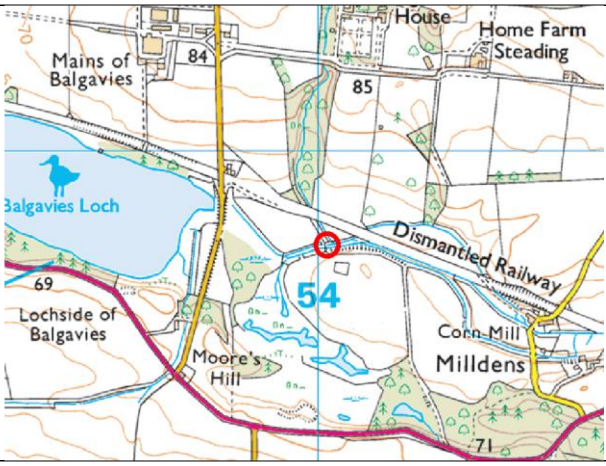
Photographies :

Figure 1 : north bridge from downstream, taken on the 1st april 2019

Figure 2 : south bridge from upstream, taken on the 1st april 2019

Figure 42 : south bridge from upstream, taken on the 1st april 2019

Figure 43 : north bridge from upstream, taken on the 1st april 2019

<table>
<tr><td colspan="4">Type of structure: Bridge</td></tr>
<tr><td>Local name :</td><td></td><td>ID code :</td><td></td></tr>
<tr><td>River :</td><td>Lunan Water</td><td>Town :</td><td></td></tr>
<tr><td colspan="2">Coordinates</td><td colspan="2">Map extract</td></tr>
<tr><td>GB grid system</td><td>GPS</td><td colspan="2" rowspan="4">
</td></tr>
<tr><td>X : 353083 meters
Y : 751142 meters</td><td>56.6496 North
2.7667 West</td></tr>
<tr><td>Date of construction :</td><td></td></tr>
<tr><td></td><td></td></tr>
</table>

deck characteristics (meters)		
Length	Width	Elevation
	6.60	62.2

Arch characteristics	
Bed level – top arch distance upstream	2.20 meters
Bed level – top arch distance downstream	
Arc maximal Width	2.20 meters
Length of the arch	

Comments

The opening is a rectangular channel on the lower half (1.1 meters) and a roman arch on the upper part. A pressure probe is located here to calculate the Balgavies loch water level.

Date of last modification : 02 april 2019

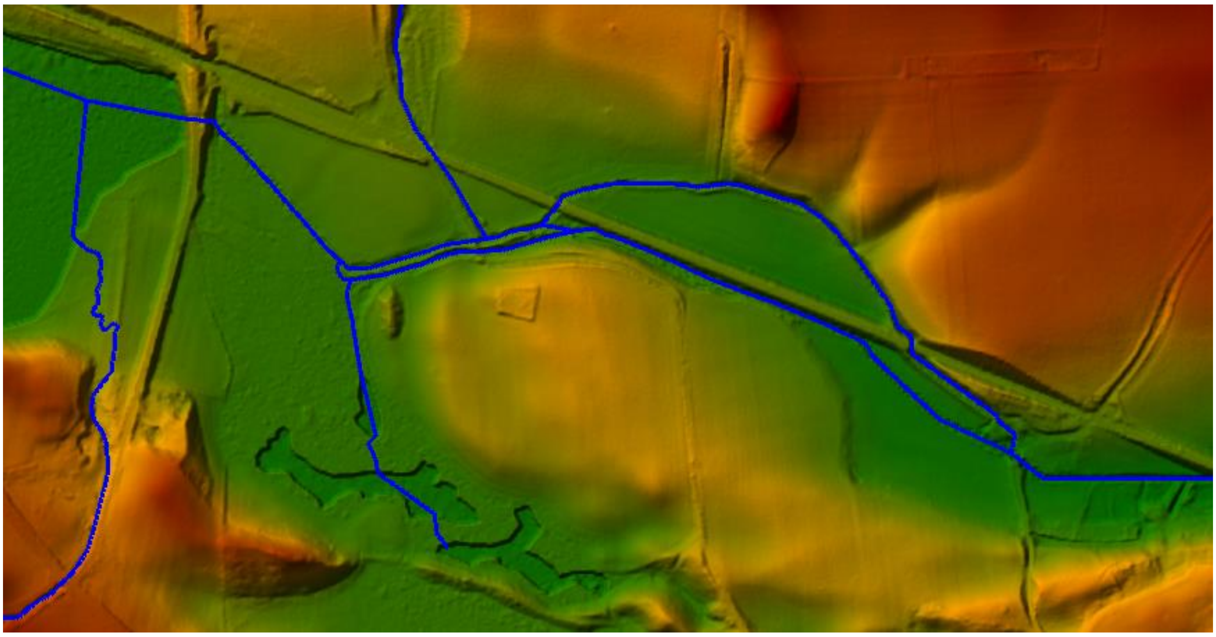
Photographies :

Figure 1 : view from upstream, taken on the 1st april 2019

Annex 6 : maps of the end of the catchment by OpenStreetMap, google map and the hydraulic model.

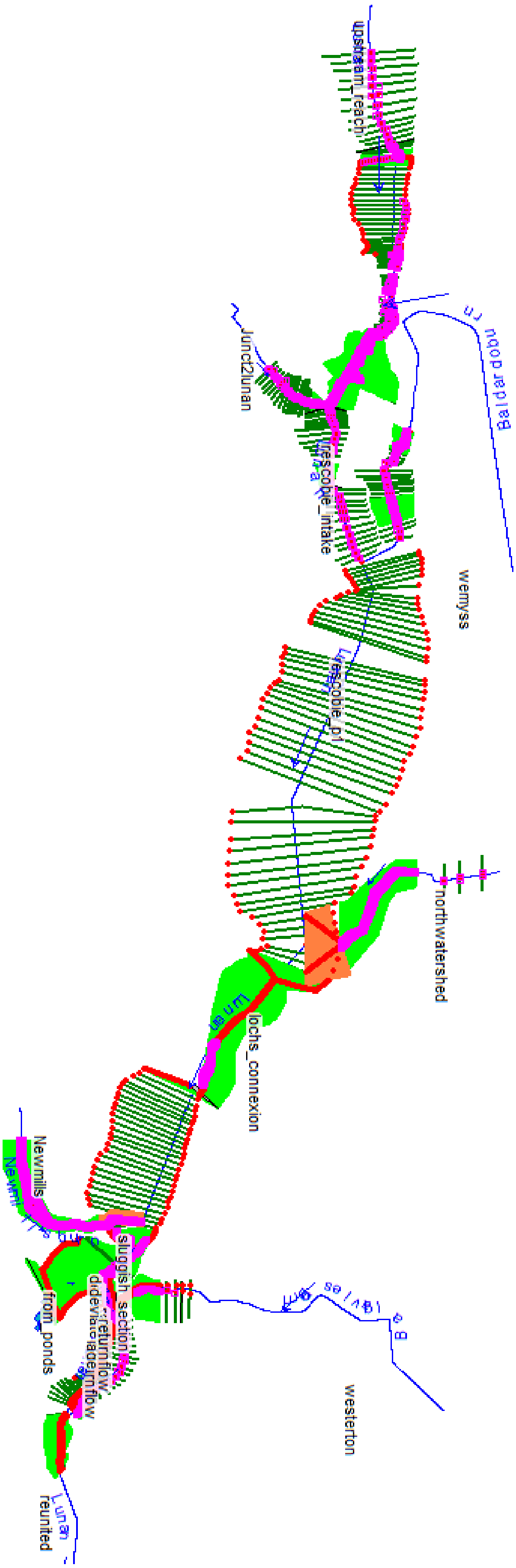
Google map extract, with the Balgavies Loch on the left and Mildens at the end of the “Mill Lade” feature

OpenStreetMap extract, same extend as above.



Rivers positioning in the Hec-Ras model, based on field visit and the Compton survey. The river positioning came from the RAS mapper incorporated in the Hec-Ras software.

Annex 7 : Hec-Ras model geometry overview



Annexe 8

Introduction

Le bassin versant supérieur de Lunan est l’objet des efforts de divers acteurs locaux pour améliorer la gestion du fleuve et de ses lochs. Les principaux domaines ciblés sont le transport des sédiments depuis les champs, les charges de nutriments provenant des lochs en automne et la gestion des inondations. Il existe déjà des programmes et des projets visant à réduire les charges de sédiments provenant des champs. Réunion sur la mise en œuvre du système SUDS sur l'eau de Lunan le 22/03/19) (mesures de drainage durable du système SUDS), la charge en éléments nutritifs est surveillée par le James Hutton Institute, afin d'étudier l'impact des apports d'eau eutrophes sur le marais de la chapelle de Mires. Selon le SEPA et le conseil Angus (Angus council, Évaluation stratégique des risques d’inondation), le risque d’inondation n’est pas considéré comme important dans cette partie de la rivière. Les exigences du conseil Angus demandent toutefois la préservation d'un pont routier, afin de maintenir la capacité de circulation et d'éviter toute déviation régulière.
Les principales caractéristiques du captage en termes d’hydraulique se situent presque toutes après les lochs et devant les maisons de Mildens. Cette partie est également celle qui contient les plus nombreuses modifications de canaux que l’on puisse observer depuis 1970 [enquête Compton]. La position de la division sur deux canaux a été déplacée et un troisième canal est maintenant déconnecté. Cette zone est également l’entrée de la zone humide de la chapelle de Mires et le rythme auquel se sont déroulées toutes les propositions de gestion hydraulique.
L'objectif du stage était d'évaluer l'utilité et l'efficacité de ces propositions en utilisant un modèle plus complet que celui utilisé dans (Vinten, 2019). Les résultats seront utilisés lors des réunions avec tous les partenaires pour aider les gens à choisir une solution résiliente et efficace pour faire face aux risques d'inondation. Le modèle a été construit et exécuté à l'aide du logiciel HEC-RAS. Les propositions ont été soumises par mon tuteur, comprenant une modification de l’entrée commune du lade sur une section très courte, une modification des portes et du déversoir existant et l’installation d’un déversoir basculant sur un nouveau déversoir.
Les résultats étaient pour la plupart similaires à ceux obtenus par A. Vinten avec son modèle et ses simulations d'écoulement à l'état d'équilibre. Cependant, les simulations sur les états instables ont montré le comportement précis des écoulements entrant et sortant des zones humides de la chapelle Mires lors d'inondations et ont donné une image plus précise des influences des marées arrière lors d'un écoulement et lors de l'ouverture d'une porte. Les résultats des simulations montrent également l’efficacité d’un déversoir basculant s’il est placé au bon endroit. L'autre modification en cours, en termes de contrôle des inondations, est la modification du déversoir existant.
Dans ce rapport, vous trouverez une description du bassin versant, une présentation des modèles hydrologiques et hydrauliques utilisés. Ensuite, chaque proposition est décrite et l’impact de chacune des propositions analysées. Tous les scénarios proposés ont été suggérés par A. Vinten et discutés avec lui.

Conclusion

L'objectif du modèle était de modéliser avec une meilleure précision et une meilleure représentation de la dynamique des inondations du bassin versant supérieur de Lunan. Une fois cette partie terminée, le modèle a été utilisé pour modéliser l’impact des solutions proposées afin d’améliorer le contrôle des inondations dans le bassin versant de Lunan. Parallèlement aux mesures de contrôle des inondations, il a été demandé d'aider à préserver la zone humide de la chapelle de Mires dans un état mésotrophe et de réduire le nombre de jours avec des restrictions de captage d'eau.

Le modèle a été étalonné et validé à l'aide des jauges d'enregistrement du niveau d'eau situées à l'entrée du lac Balgavies et à la sortie du lac Rescobie. La calibration du modèle a été réalisée en modifiant les coefficients de Manning des rivières et des rivières en amont, rivières par rivières, avec des subdivisions internes pour certaines d’entre elles.

La modélisation hydrologique nécessaire pour extrapoler les valeurs de débit à chaque limite du modèle hydraulique était basée sur une formule régionale. Cette formule utilise les valeurs de débit dans un bassin versant mesuré pour déterminer le flux dans les bassins versants voisins. La jauge Wemyss a été utilisée comme référence et la formule a été calibrée à l'aide des jauges Westerton et Hatton.

La modélisation des différentes options de gestion proposées a montré la meilleure efficacité en termes de contrôle des inondations avec une proposition de déversoir inclinable. Pour améliorer la répartition des nutriments entre le canal de Lunan et la chapelle Mires, un barrage incliné est efficace, mais pas aussi efficace que la solution de dragage seule. L’abaissement de l’entrée de grille ne mène nulle part, ne montrant aucun impact positif ou négatif sur le système dans sa globalité.

D'autres options de gestion, sans besoin de surveillance constante, étaient utiles pour la gestion des inondations ou pour la partition des inondations, mais de moindre importance. La modification du déversoir abaisse un peu le niveau d’eau en amont lors d’inondations. Le dragage seul ne change rien en termes d’inondation, mais influence les valeurs de débit de Chapel Mires.

Toutes les solutions testées n’ont apporté aucune amélioration significative de la gestion des faibles débits. La solution avec le déversoir incliné placé en aval montre toutefois la capacité de stocker un peu d’eau dans le lac lors de la régression des débits. Cet effet d’élément sera accru avec une bonne gestion des portes de la Lade Commune.

Le déversoir est la structure la plus efficace selon les simulations effectuées avec Hec-Ras, mais son installation et son entretien seront très coûteux. Les structures fixes comme une modification du déversoir actuel, malgré des gains moins importants, seront probablement les plus faciles à promouvoir auprès des autres acteurs du projet et des agriculteurs propriétaires des terres.

MEMOIRE DE FIN D'ETUDES

Diplôme : Diplôme d'ingénieur de l'ENGEES
Spécialité : Hydrosystèmes – eaux souterraines

Auteur : Rémi TRENKMANN

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Structure d'accueil : James Hutton Institute, Aberdeen site, Aberdeen, Scotland

Maître de stage : Andrew Vinten

Résumé :

Le James Hutton Institute est chargé de l'analyse des solutions techniques pour améliorer la gestion hydraulique de la partie amont de la Lunan Water. Un modèle hydraulique a donc été construit pour représenter la partie amont de la Lunan Water. Ce modèle a permis d'évaluer le fonctionnement en crue et de confirmer l'impact des solutions précédemment testées par l'Institut mais aussi de modéliser de nouvelles propositions. Ces résultats seront utilisés pour les concertations entre l'institut, le Council et les riverains.

Mots-clés :
Modèle hydraulique, Hec-Ras, Rivière d'Ecosse, Analyse d'impact, modélisation ouvrages hydrauliques, gestion de crues.

Hydraulic model, Hec-Ras, Scottish river, Impact analysis, hydraulic structures modelling, flood management.