WATER LEVELS AND FLOWS IN THE UPPER LUNAN WATER

A hydrological-hydraulic modelling approach to management and decision support

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1. Executive Summary

A. The “Water for all” project has aimed to develop a multi-disciplinary science case for adaptive management of flows, water levels and flow routing to/from high nature value wetlands in the Upper Lunan Water, a lowland catchment in Scotland. The forecasting tool we have developed provides live information for catchment management planners, farmers and local stakeholders. For example, the tool highlights the development of logjam-driven high water levels in the lochs and also forecasts water levels for 5 days from the present. This could be developed into an alerting tool to aid adaptive management in the future.

B. A key element has been the development of a hydrological-hydraulic model of the upper Lunan Water as an aid to management and scenario analysis especially with respect to hydraulic structures. A simple project-developed hydrological model of the loch inflows was combined with a hydraulic model drawn up using HEC-RAS 5.0.7 and forecast information from the UK Meteorological Office. Catchment area multipliers, groundwater and stream roughness (Manning) coefficients were key calibration issues. Following calibration, modelling efficiency (estimated by Nash-Sutcliffe statistics) exceeded 70% in most cases. Key modelling inputs include the capture of real time and forecast rainfall, simulation of inflows, the geometric structure of the stream network and its floodplain, and the structure and management of existing and potential hydraulic structures. The hydraulic structures include a proposed tilting weir, to relieve water levels in a mill lade, as a means to lower upstream loch water levels in flood conditions and divert polluting event waters from sensitive wetlands (Chapel Mires). Outputs of the model include dynamic loch water levels and flow routing, presented on a live webpage. This provides better working knowledge of catchment behaviour and forecast-based simulations of potential high or low flow situations.

C. Following calibration and validation, the model was used to assess scenarios of management of existing and potential hydraulic structures and dredging/vegetation removal. Significant dredging and hence lowering of the common lade channel invert, was found to give a lowering of the base level of Balgavies and Rescobie Lochs, providing a delay in flood peak water levels (by a few hours) and some decrease in the event maximum loch levels (by a few cm); It would be difficult to achieve further significant reduction of Balgavies Loch (or Rescobie Loch) levels during event conditions, through installation of a tilting weir on the mill lade. However, the tilting weir option would increase the potential for diverting flow down the common lade and away from the reach of the river which feeds into Chapel Mires, giving potential mitigation of flow of polluting, sediment rich event waters into the ecologically sensitive Chapel Mires.

D. The tilting weir option would require ongoing active management, which may be difficult to achieve, so our recommendations include a more passive option, namely re-instatement of a blocked off engineered spillway downstream of the current earth based spillway, which would achieve some of the functions of a tilting weir for protection of Chapel Mires. We also recommend managed vegetation removal and local dredging upstream of a cattle track culvert on the common lade. All these aim to minimise inflow of the pollutant-rich leading edge of storm event waters into Chapel Mires. In addition, improved recording of actions taken in the catchment, including weir gate and vegetation management, and ongoing monitoring of water levels and vegetation would be desirable.

E. Note that acceptance, in principle, of a proposed action to restore the blocked spillway d/s of Bagavies Loch, shown in Figure 11, was given by riparian owners and Nature Scotland on the 31st March 2021.

2. Introduction and objectives

Strategies for sustainable water resources management require integration of hydrological, ecological and socio-economic considerations. The “Water for all” project has sought to develop a multi-disciplinary science case for adaptive management of water levels and flows in the Lunan Water, a lowland catchment in Scotland. [1] described how local water demands of arable agriculture and protection from flood risk needed also to balance conservation needs of lowland mesotrophic wetlands. Hydro-ecological assessment focused on the outlet zone of Balgavies Loch, where the Lunan Water discharges into a partially confined common channel (lade). This lade controls water delivery to a mill or returning to the river, controlled by an existing engineered gated weir, and water also flows from the river into to its lateral floodplain wetlands (Chapel Mires) via a non-engineered spillage zone, which replaces a now-blocked engineered spillway. The ecological value of these wetlands may be vulnerable due to ingress of sediment and nutrients from the river[2, 3]. A key part of this process has been the development of a hydrological-hydraulic model of the upper Lunan Water and the operation of this outlet zone. The aim of the modelling is to generate a time series of historic, real-time and forecast based surface water and ground water flows and water levels in the upper Lunan Water catchment, whose area is defined by the surface water outlet at Milldens bridge (Grid Reference NO 354526 750566). These could then be used to provide triggers or other guidance for hydraulic management.

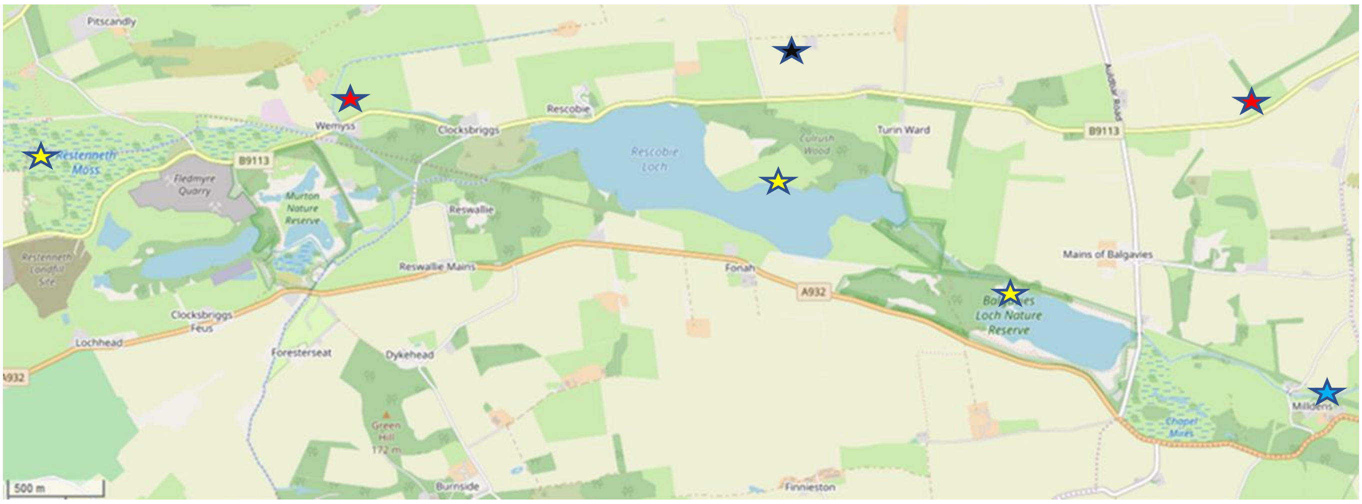


Figure 1. Core area of upper Lunan Water, showing the main standing waters and catchment outlet at Milldens★). Stream gauging (★) and loch water level monitoring stations (★), and raingauge (★) are also shown. **Raingauge at** NO 53056 51304. Figure from [4].

With these goals in mind, Table 1 summarises the modelling objectives, data inputs, modelling procedures and outputs of the combined hydrological/hydraulic model described in the following section.

Measured and/or modelled flows (for forecasting) are used as input data to a conceptualised hydraulic model, formulated in HECRAS 5.0.7, simulating water levels and flows for the various water bodies making up the catchment. The purpose of this combined model is to:

(a) Identify potential ways in which management of current or alternative hydraulic structures and channels could be adapted to improve delivery of water ecosystem services across the various drivers in the catchment, associated with low flows, high flows and flow routing to/from high nature value mesotrophic wetlands.
(b) Provide a better working knowledge of the catchment behaviour for catchment management planners, farmers and local stakeholders.
(c) Provide forecast-based alerts of potential high or low flow situations that could be mitigated by adaptive management.

Table 1. a. Summary of objectives and data requirements for development of hydrological/hydraulic model

		Hydrological/hydraulic model of upper Lunan Water			
Objectives					
O1	1. To analyse impacts of weather/inflow on water levels, flood risk, low flows and water routing in the catchment.				
O2	2. To explore impact of existing/potential hydraulic management options on water levels and water routing.				
O3	3. To provide a live service forecasting future water levels based on Met.Office 5d forecasts and showing past levels				
O4	4. To develop an alerting system for stakeholders using 1 and 2 (not in RDF).				
Input data					
	Geographic information (GIS)				
CAT		Catchment topography, areas and boundaries			
NET		Stream network			
SLW		Soil, land and water cover			
GEO		Superficial geology			
CROSS		Inflow stream, main channel and flood plain cross section and invert elevations above sea level			
	Catchment hydrology (CAT)				
R15T		Raingauge (15 minute, telemetered)			
WEST15T		Westerton stream stage (15 minute, telemetered) and stage-discharge relationship			
WEM15M		Wemyss stream stage (15 minute, collected monthly) and stage-discharge relationship			
REST15M		Restenneth Moss stage (15 minute, collected monthly)			
RESC15M		Rescobie loch stage (15 minute, collected monthly)			
BAL15T,BAL15M		Balgavies Loch stage (15 minute, telemetered OR collected monthly)			
LOCHOUT		Balgavies Loch outlet stage-discharge			
	Forecast data Met. Office (UKV)				
FORE	1D,2D,3D,4D,5D	hourly to T+48 and then 3 hourly to T+120			
T		Instantaneous temperature (for ET estimation)			
NRAD		Net radiation (for ET estimation)			
	Simple Hydrological Model (SHM - developed for this project)				
STORIN		Initial storage in 2 storage pools		$S_{\text{init\_hill}}$	$S_{\text{init\_field}}$
STORTHRESH		Pool storage above which flow to streams occurs for 2 storage pools		$S_{\text{thresh\_hill}}$	$S_{\text{thresh\_field}}$
STOREL		Two coefficients for release of water to streams for each of 2 pools		$K_{\text{1,2\_hill}}$	$K_{\text{1,2\_field}}$
GWLEAK		Leakage rate to groundwater for 2 storage pools		$K_{\text{3\_hill}}$	$K_{\text{3\_field}}$
AREAS		Three hydrological areas (hill, field, direct)	$A_{\text{R\_hill}}$	$A_{\text{R\_field}}$	$A_{\text{R\_direct}}$
	Hydraulic model (HECRAS)				
INFLOW		Inflow stream and loch direct input points; area multipliers and minimum flows			
MANNING		Inflow stream, main channel and flood plain Manning roughness coefficients			
STRUCTURE		Hydraulic structure geometry (weirs, culverts, gates etc) and their management			
TSTEP		Timesteps for solving flow equations			
COEFF		Hydraulic modelling assumptions (weir coefficents, methods of solution of flow equations etc)			
MANAG		Hydraulic structure management (GATE OPENING, DREDGING)			
Output data					
INF	Inflows to HECRAS				
HIST	Historic water levels and flow routing				
LIVE	Live water levels and flow routing				
FUT	Forecast water levels and flow routing				
NS	Nash-Sutcliffe stats comparing simulations with observations				

b. Summary of modelling process

Objective	Catchment structure	Weather	Inflow hydrology	Hydraulics	Calibration/ Validation	Management Scenarios	Output Simulations
	GIS	**CAT**	**CAT**	**HECRAS**	**CAT**		
O1,O2	*CAT*	*R15T*	*WEST15T*	*INFLOW*	*RESC15M*		1. Balgavies and Rescobie Loch levels 2. flow routing d/s Balgavies Loch
	NET		*WEM15M*	*MANNING*	*BAL15T,BAL15M*		
	SLW			*STRUCTURE*	*LOCHOUT*		
	GEO			*TSTEP*	*Nash sutcliffe stats*		
	CROSS			*COEFF*			
				MANAG			
	GIS	**UKV**	**SHM**	**HECRAS**	**CAT**	HECRAS	
O3, O4	*CAT*	FORE	*STORIN*	*INFLOW*	*RESC15M*	*MANAG*	
	NET	T	*STORTHRESH*	*MANNING*	*BAL15T,BAL15M*		
	SLW		*STOREL*	*STRUCTURE*	*LOCHOUT*		
	GEO		*GWLEAK*	*TSTEP*	*Nash sutcliffe stats*		
	CROSS		*AREAS*	*COEFF*			

3. Monitored water balance of upper Lunan catchment.

Feeder streams

The surface water catchment areas for the upper Lunan catchment have been separated, for water balance purposes, into the areas used for the hydraulic modelling, which are shown in Figure 2. The areas (Table 2) of each of these sub-catchments were used to scale measured and modelled flows from ***monitored sub-catchments*** where flow and water quality monitoring take place (see Figure 1). These are the Balgavies Burn sub-catchment, at Westerton (A=4.4 km^2), which generates real time stage and flow data and the Baldardo Burn sub-catchment at Wemyss (A=2.4km^2), which generates water level data from a baro-diver collected monthly.

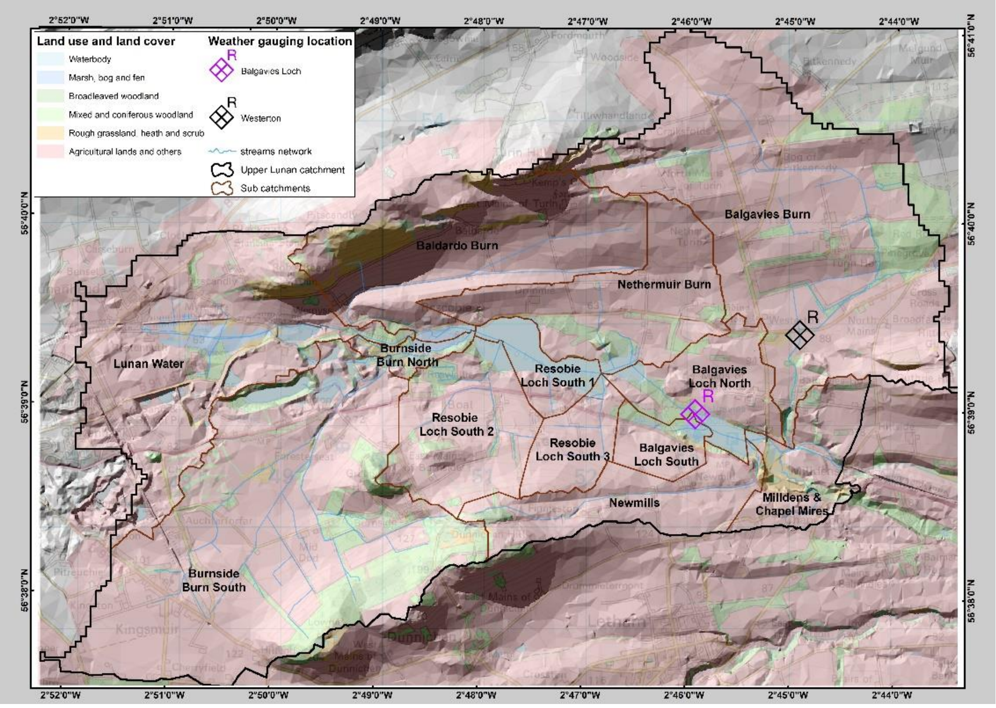


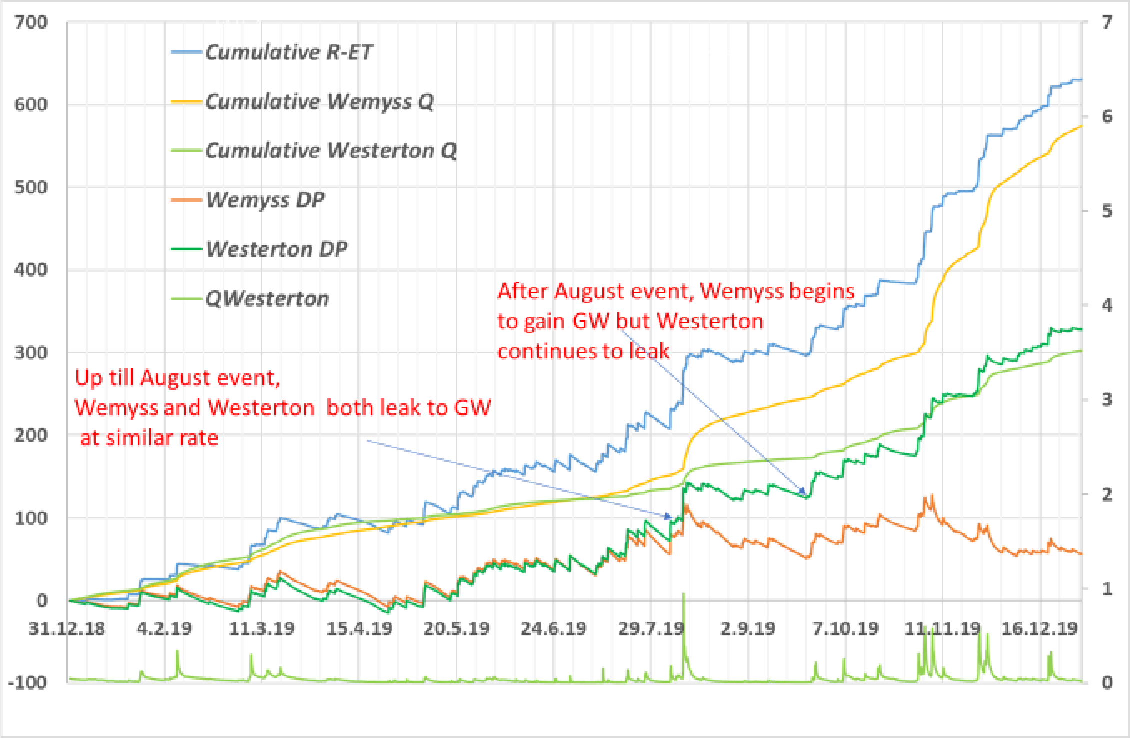
FIGURE 2. SUBCATCHMENTS OF UPPER LUNAN WATER USED IN HYDROLOGICAL-HYDRAULIC MODELLING.

Table 2. Sub-catchment areas

Name of subcatchment	Hydraulic model input area (km^2)
Baldardo Burn (flow monitored at Westerton, A=2.4 km^2)	3.60
Lunan Water	4.41
Burnside Burn South	7.57
Newmills	1.53
Balgavies Loch South	0.50
Balgavies Loch North	1.26
Nethermuir Burn	2.23
Rescobie Loch South 1	0.55
Rescobie Loch South 2	1.83
Rescobie Loch South 3	0.72
Burnside Burn North	0.25
Lunan at exit of Balgavies Loch	*23.40*
Balgavies Burn (flow monitored at Westerton, A=4.4 km^2)	7.01
Milldens and Chapel Mires	1.13
Lunan Water at Milldens	*32.58*

Rainfall is also recorded in real-time at Balgavies Farm, and water levels are recorded at Rescobie Loch (using a baro diver, which replaced a telemetered logger lost in a flood event) and Balgavies Loch in real-time, using a telemetered (Frog) logger. Some datalogging of water levels has also occurred at Restenneth Moss and upstream of Milldens weir (NO 54059 50827). More details of the monitoring set up [5], and of the hydraulics [1], [4] are provided elsewhere.

The freely drained nature of many of the soils in this area means that there is not a closed water balance for either of the monitored sub-catchment streams, and there is potential for them to either lose water to deep groundwater (as noted by [6]), or in some circumstances, to gain water from long term groundwater storage underneath the hillslopes above the stream. Figure 3 for example shows (a) closed water balance for Jan-May, (b) net loss of water to deep groundwater (May-Aug), followed by (c) return to net loss to groundwater for the Balgavies Burn subcatchment at Westerton, (d) zero loss or net gain from groundwater for the Baldardo Burn at Wemyss.



Up till August event, Wemyss and Westerton both leak to GW at similar rate

After August event, Wemyss begins to gain GW but Westerton continues to leak

Other years with large events (eg 2015/6) show similar pattern...

FIGURE 3 EXAMPLE OF CUMULATIVE ELEMENTS OF MONITORED SUB-CATCHMENT WATER BALANCES FOR 2019. Y1 AXIS IN MM, Y2 AXIS (Q WESTERTON) IN CUMECS. R=RAINFALL, ET=EVAPOTRANSPIRATION, DP = DEEP PERCOLATION, ESTIMATED BY DIFFERENCE BETWEEN R-ET AND Q.

Estimation of outflow from Balgavies Loch

We have collected time series data of observed stage for Balgavies Loch since 2014 using both data logging divers and telemetered real time Frog loggers. We made estimates of the outflow from Balgavies Loch from this loch stage time series and a stage discharge relationship at the outlet. This was based on (a) several stage-discharge points and (b) hydraulic modelling, with three assumptions about the Manning roughness coefficient (n) of the Sluggish Section reach (see Figure 11 below) which carries Lunan Water flow downstream of Balgavies Loch (n=0.02, 0.035 or 0.05). The HECRAS hydraulic model (see section 4) enables us to generate a modelled stage-discharge relationship for any point in the surface water network. At the outlet to Balgavies Loch the stage-discharge relationship (Q_{loch} vs H_{loch}) depends strongly on Manning's n for the reach immediately downstream (and to a much lesser extent on the position of the weir gates at Milldens weir). See Figure 4, based on simulations of flow during March -May 2020.

The comparison with the limited number of measured stage-discharge points shows a good fit for n=0.05 with the exception of the point obtained in March 2017, when vegetation coverage/autumn leaf fall in the stream might be expected to be at a minimum. Some winter scouring of sediment from the stream bed may also have occurred, leading to less roughness or increased channel capacity. The low flow points were obtained during July-Sep 2016.

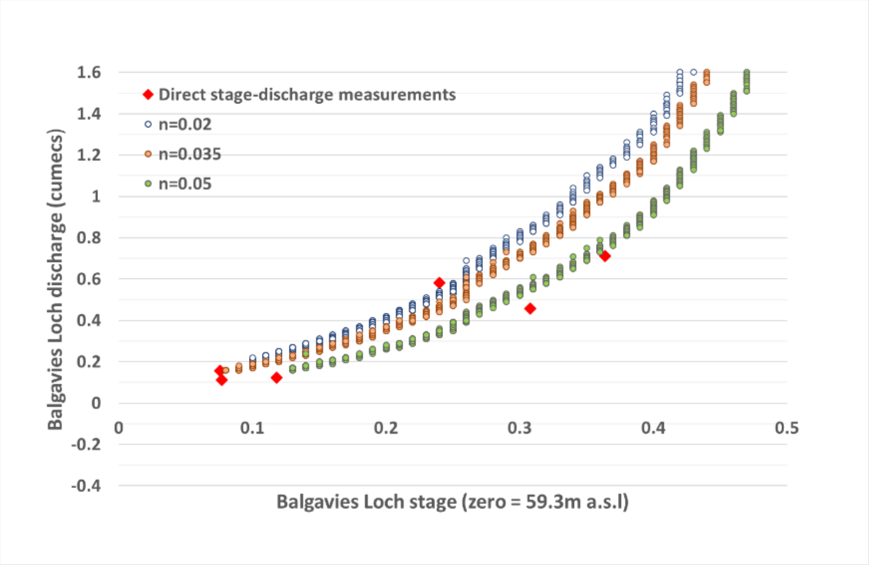


FIGURE 4 HECRAS MODELLED STAGE-DISCHARGE AT BALGAVIES LOCH EXIT AS A FUNCTION OF MANNING COEFFICIENT OF THE REACH IMMEDIATELY DOWNSTREAM (NAMED "SLUGGISH SECTION") AND DIRECT MEASUREMENTS OF STAGE-DISCHARGE MADE BETWEEN 2017 AND 2020

Figure 5 shows estimates of cumulative flow from Balgavies Loch for 2019 based on two potential values of Manning's n immediately downstream of the Loch.

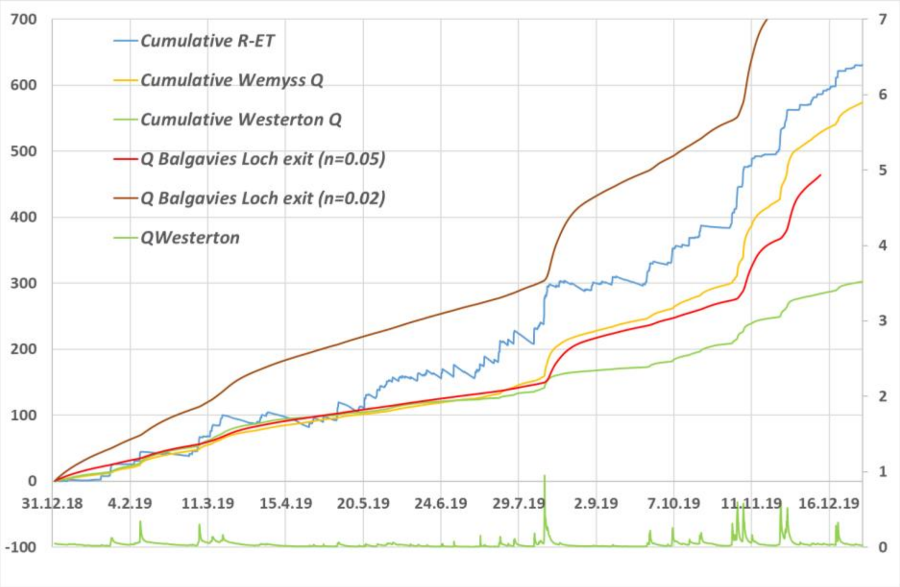


FIGURE 5 ESTIMATED CUMULATIVE FLOW FOR 2019 FROM BALGAVIES LOCH BASED ON TWO ASSUMPTIONS ABOUT MANNING'S N IMMEDIATELY DOWNSTREAM OF THE LOCH (N=0.02 OR 0.05). NOTE THAT A LOGJAM IN THE LUNAN WATER D/S OF BALGAVIES LOCH EXIT STARTED IN DEC 2019, SO THE LOCH WATER LEVELS ARE NOT RELIABLE PREDICTORS OF FLOW DURING THIS PERIOD, TILL JAN 2021, WHEN THE LOGJAM WAS CLEARED.

Depending on which value of n is chosen, the upper Lunan Water catchment may be considered as showing a net gain or net loss of groundwater relative to rainfall input and evapotranspiration losses, but for both of the two values for n we see a gain from local groundwater at Balgavies Loch outlet, compared to the area scaled flow from Westerton on the Balgavies Burn. The Wemyss flow matches the low (n=0.02) estimate of Balgavies Loch outflow quite well, but this still represents a net leakage of groundwater for the whole catchment, relative to the estimated input of R-ET. Given the presence of the geological sill near the outlet of Balgavies Loch (see below) we think it likely that the outflow at Balgavies Loch may represent a point at which a complete water balance is achieved.

4. Model conceptualisation

Hydrogeology of upper Lunan catchment.

Box 1 summarises a hydrogeological assessment of Restenneth Moss and Rescobie and Balgavies Loch, drawn from [7] . Based on this information we should expect that SE of the anticline bedrock geology may contribute some upward flow of water; however NE of the anticline it may not. Flow in the superficial deposits will be mainly SE and the presence of the volcanic lava flow in the solid geology below Balgavies Loch may lead to most of the superficial groundwater flow supplying surface water flows at or upstream of the outlet to Balgavies Loch. Overall we might expect the water balance for surface water to account for >90% of R-ET, but that there could be significant lag in the appearance of groundwater contribution to the surface water flows.

For this reason, we propose for calibration of the hydraulic model that it makes sense to use the Wemyss time series for the hydrological inputs, allocated initially on an area basis across the catchment, but then allocate a proportion of this flow to an array of lagged time series of Wemyss flows scaled to 1 km^2 of catchment, Q(m,n), with lag m and averaging period n, both varying from 1d to 8d. In addition, we propose to set a minimum flow input into the whole catchment of Q_{base} = 0.06 cumecs, to represent minimum flow from groundwater. The proportion of flow which is lagged, the amount of lagging and the minimum flow would be part of the calibration process. The exception to this is the Balgavies Burn itself, which feeds into the system below the Lochs, which can be based on observations from the Westerton flow station, after area correction. It might also be appropriate to vary the total area contributing to the water balance, as the underlying geology might lead to some loss or gain of groundwater from inside/outside the topographic catchment area.

Box 1. Summary of comments about Restenneth Moss and Rescobie and Balgavies Loch hydrogeology.

Location: SW Corner 347280,750570; NE Corner 353790, 752255

Superficial deposits. High ground along North and South of the valley is underlain by glacial till. In the base of the valley lie extensive fluvioglacial and gravel deposits. Alluvium overlies much of the centre of the valley, including the area under the Lochs. These is a mixed sequence of sand, gravel, silt and clay, occasionally with pockets of thin beds of soft, compressible peat. These deposits are at least 4 to 6 m up to 10m thick. Groundwater flow will be eastwards, with components from N and S toward the centre of the valley. Water levels at <3m deep.

Water flowing from this superficial aquifer may recharge the bedrock aquifer (see below). However, the catchment areas for these two aquifers are different.

Bedrock Geology. Sedimentary rocks of the Dundee Flagstone Formation (lower Devonian). The line of the Sidlaw anticline may run SW to NE through the area. To the NW rocks will dip to NW, to the SE, they will dip SE. Likely to have moderately high transmissivity (100m^2/d). Much of the groundwater flow associated with fractures, and direction controlled by dip of the beds (ie NW on the NW side of the anticline, SE on the SE side). It may contribute to maintaining superficial deposit groundwater flow in summer and autumn. There is not likely to be direct hydraulic contact with the surface water in the lochs.

Beneath Balgavies Loch, volcanic andesites and basalts formed from lava flows are present, likely dipping SE, with low transmittivity to water.

Conceptualisation of hydrology.

Figure 6a shows a conceptual N/S cross section from Turin Hill to Finnieston Hill showing the main features relevant to the hydrogeology. Figure 6b shows a conceptual E/W cross section from Restenneth Moss to Milldens.

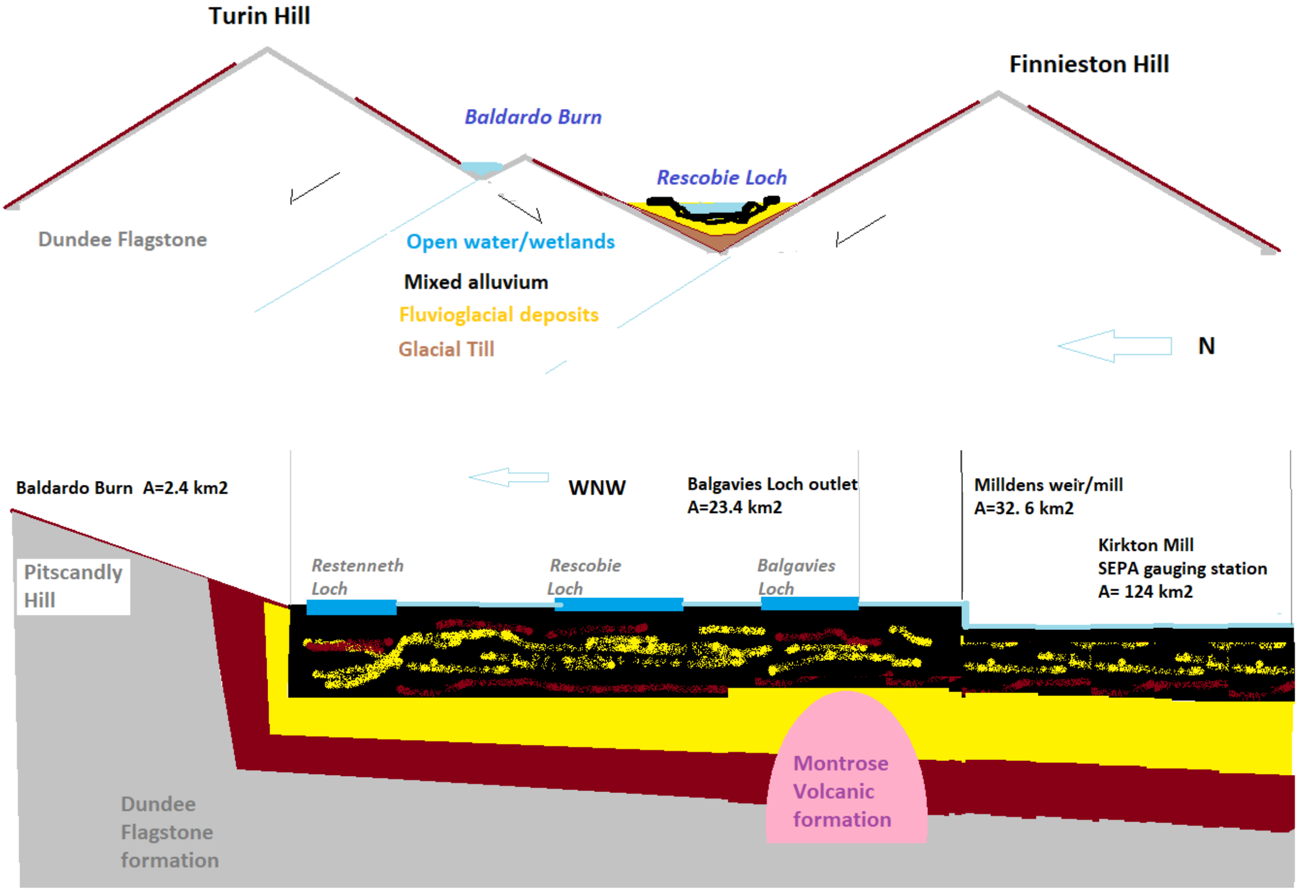


FIGURE 6. (A) A CONCEPTUAL N/S CROSS SECTION FROM TURIN HILL TO FINNIESTON HILL SHOWING THE MAIN FEATURES RELEVANT TO THE HYDROGEOLOGY. (B) A CONCEPTUAL E/W CROSS SECTION FROM RESTENNETH MOSS TO MILLDENS.

EW cross section.png

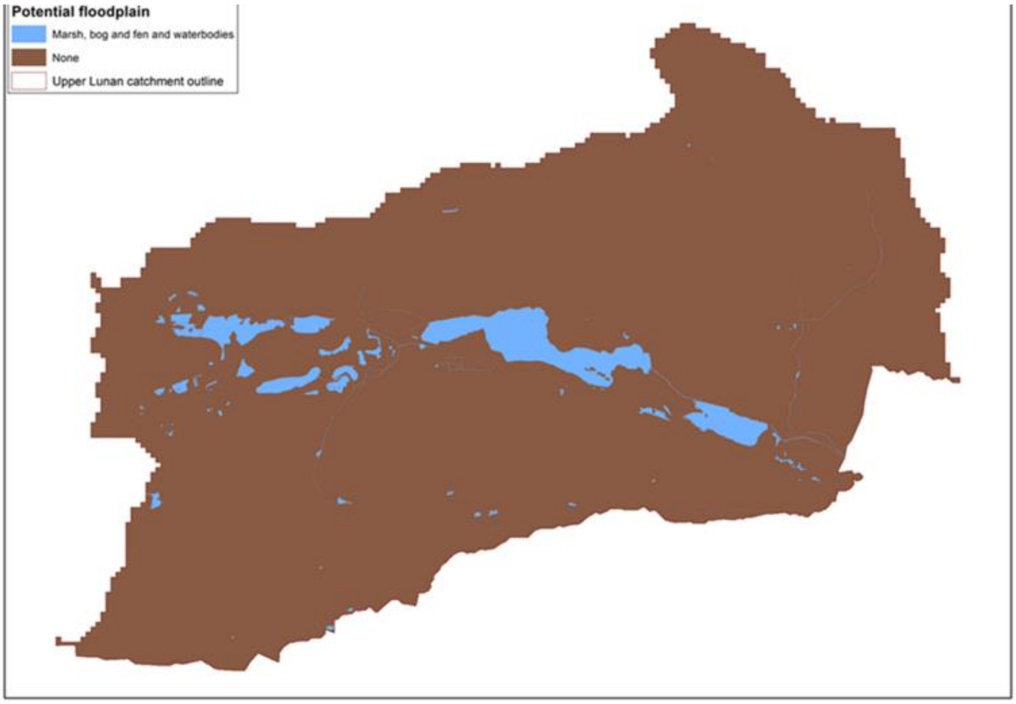


FIGURE 7 AREA OF WETLAND SOILS AND OPEN WATER IN THE UPPER LUNAN, AMOUNTING TO 1.3 KM^2.

Bearing in mind our aim is to generate a useful management tool for predicting high and low water levels and flow routing, we need to strike a balance between complexity and simplicity. [4] attempted to hydraulically model the feeder streams into the lochs, using HECRAS linked to topographic information on the flood plain of these streams. The resulting hydraulic model runs successfully in HECRAS, but requires a short time step, and the model often crashes due to numerical instability under event or low flow conditions. This is not surprising given the very complex surface water network that characterises the upper Lunan Water upstream of Rescobie Loch (see Figures 2 and 7).

An alternative approach is to model the feeder streams as direct inputs into the lochs and calibrate the hydraulic model to achieve a reasonable fit to the water levels in Rescobie Loch (and Balgavies Loch, though levels in Balgavies Loch are less critical to flood risk). The water level in Rescobie Loch is the main water level output we are interested in obtaining from simulations, as this is a simple indicator of risk of flooding in the upper catchment and of the impact of management of hydraulic control structures and channel management on flood risk.

HECRAS model of hydraulics of unsteady flows in upper Lunan catchment

The Hydrologic Engineering Center's (CEIWR-HEC) River Analysis System hydraulic modelling tool HEC-RAS 5.0.7 [8] was used to model the response of water levels in the lochs to inflows and hydraulic management of structures in the upper Lunan water system. This software allows the user to perform unsteady flow calculations. Detailed description of the characterisation and schematisation of the upper Lunan Water are provided in other publications, particularly [1] and [4], see also here: The key elements of the hydraulic model inputted to HECRAS are as follows:

Geometric data

This consists of a series of elevation cross sections of the modelled river reaches and their connections, including their floodplains. It also includes specification of the dimensions and hydraulic characteristics of bridges, culverts, weirs and other hydraulic structures. For each channel segment and its associated banks and flood plains, Manning roughness coefficients for the main channels and overbank areas are specified. An example of this characterisation including the feeder streams into Rescobie and Balgavies Lochs used by [4] is shown in Figure 8a.

The starting point for these cross sections was [1] but this was enhanced and modified by[4]. For this report, we have further simplified this representation by feeding input streams directly into Rescobie or Balgavies Lochs (Figure 8b), made some modifications to channel cross sections to improve stability at high and low flows, and re-parameterised the cross sections at the outlet to Balgavies Loch to better represent the outlet culvert and the "sluggish section" reach below the outlet culvert. This is because model instability issues were occurring in the upper Lunan inflow stream modelling, meaning we would have needed to run the model with impractically short time steps, for some periods. These would have been unknown prior to forecasting runs, which need to be done reliably. We have also adjusted the Manning coefficients for key reaches.

Figure 9 shows an example of simulated transformation of stream inflows during flow through the upper Lunan wetlands upstream of Rescobie Loch, using the description of Figure 8a, compared with a range of possible averaging methods for flows entering the lochs directly. This example suggests that transforming modelled or measured flows to generate input data based on direct inputs to Rescobie Loch would be best done using 1d lagged moving averages rather than 12h or 2d lagged moving averages.

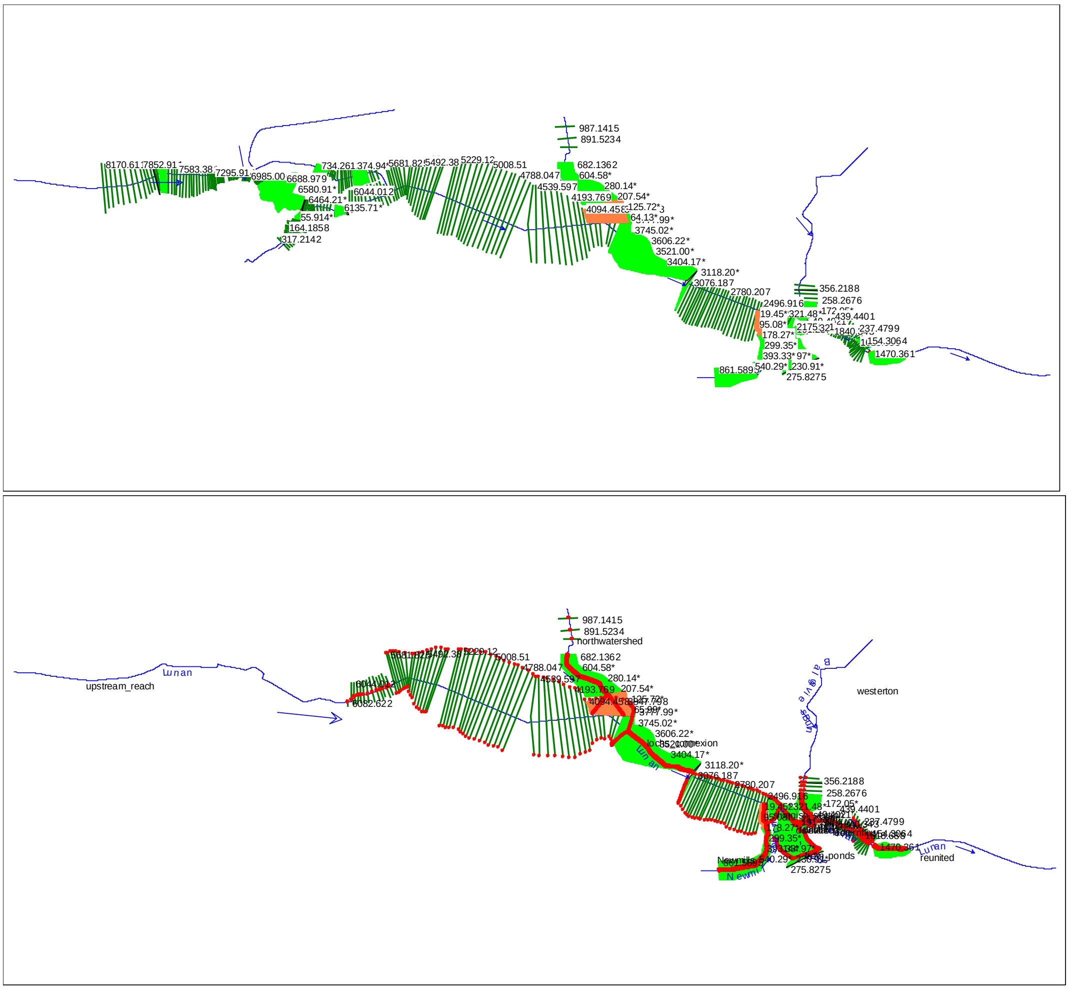


FIGURE 8. CROSS SECTION PLOTS FOR HECRAS SIMULATION OF UPPER LUNAN WATER. A. INCLUDING FEEDER STREAMS. B. SIMPLIFIED OR OMITTED FEEDER STREAMS.

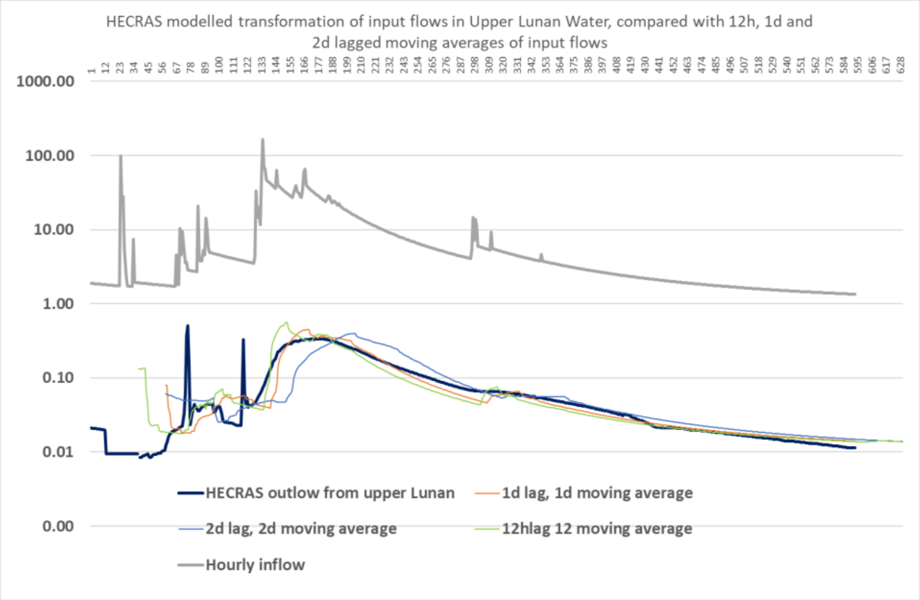


FIGURE 9. EXAMPLE OF MODEL OUTPUT FROM HECRAS OF THE UPPER LUNAN REACH USING THE FULL GEOMETRIC REPRESENTATION OF[4] (FIG 8A) , COMPARED WITH SCALED TRANSFORMATION OF MODELLED INPUT FLOWS WITH 12H, 24H AND 48H LAGS (12H, 24H, AND 48H MOVING AVERAGES OF LAGGED FLOWS, RESPECTIVELY). UNITS ON X AXIS ARE IN HOURS FROM 00:00 ON 4 AUGUST 2019.

However, it should be born in mind that some inflow (e.g. from roads, and direct input to surface water) may be better modelled with shorter lags, and other flows (e.g. from groundwater) with longer lags. There is a considerable amount of open water, roads, farmyards etc in the catchment, which will have little storage time and will not be affected much by the development of soil moisture deficits in summer. This area amounts to 1.3 km^2 (6% of the total catchment area at Balgavies Loch exit). This area has therefore been modelled using hourly inflow of excess rainfall (R-ETa), to the Lochs with a small, nominal maximum soil moisture deficit of -5mm moderating the runoff in these areas. This flow needs to be added to flows generated by the Wemyss stream inputs as the Wemyss sub-catchment used for calibrating input flows across the whole catchment has < 1% surface water and roads. It is particularly important to include such contributory areas during summer storm events, when upland soils across the catchment have a significant antecedent moisture deficit.

Manning values for the geometry used at the start of the calibration process are summarised in Table 3.

Reach	Manning main channel	Manning overbank
Lunan upstream	0.020	0.05
Loch connexion	0.015	0.05
Sluggish section	0.030	0.07
Lunan downstream	0.020	0.05
Common Lade	0.020	0.05
Lochs	0.010	0.05
Other	0.020	0.05
Plan on database	Plan 66	

Table 3. Summary of Manning values for default geometry for simplified upper Lunan cross sections.

Inflow data

The inflow at the start of each input channel (whether a direct input to the lochs or a stream reach), was specified as a flow time series. Table 4 summarises the default inflow allocation used at the start of the calibration process. The multiplier factors can be thought of as effective contributory catchment areas in km^2. Note the direct input area of 1.3 km^2, which we model as input at River Station (RS) 5337 with flow having a lag of 1h (Rescobie Loch South 1). Other inputs have 1d lag, and 1h, 1d or 4d smoothing periods.

Table 4. Default inflow data allocation to the Lochs and core reaches of the Lunan Water and the common lade.

RS receiving inflow	Name	Multiplier	Smoothing	lag	Wemyss or Westerton	Minimum flow	Hydraulically modelled or direct input to lochs
734.2	Baldardo Burn	0.0			Wemyss	0.001	Direct
6082	Lunan Water	2.0	1d	1d	Wemyss	0.030	Direct
317.2	Burnside Burn 1	0.0			Wemyss	0.001	Direct
5681	Burnside Burn 2	5.0	1d	1d	Wemyss	0.001	Direct
5337.2	Rescobie Loch South 1	1.3	1h	none	excess rainfall	0.001	Direct
4704.1	Rescobie Loch South 2	5.0	1h	1d	Wemyss	0.001	Direct
4239.6	Rescobie Loch South 3	5.0	4d	1d	Wemyss	0.001	Direct
987.1	Nethermuir Burn	0.1	1d	1d	Wemyss	0.001	Direct
861.5	Newmills	0.1	1d	1d	Wemyss	0.001	Direct
3000.8	Balgavies Loch 1	2.0	4d	1d	Wemyss	0.001	Direct
2802.3	Balgavies Loch 2	2.0	1d	1d	Wemyss	0.001	Direct
2577	Balgavies Loch 3	2.0	1h	1d	Wemyss	0.030	Direct
356.2	Balgavies Burn	7.0	1d	1d	Westerton	0.005	Hydraulically modelled
2177	Milldens and Chapel Mires	1.1	1d	1d	Wemyss	0.001	Direct
		32.65					

We estimated the goodness of fit using the Nash-Sutcliffe statistic [9] comparing observed and modelled water levels in both Rescobie and Balgavies Lochs. Values for the event in Aug 2019 were 0.68 and 0.79 respectively. For comparison, the simulations using the default geometry of the full upper Lunan input streams in [4] and the mean of Wemyss and Westerton flows, were 0.39 and 0.41. We then explored the impact of changing the inflow multipliers, the time lags, the averaging period, and the Manning coefficients in key parts of the system, on the Nash-Sutcliffe goodness of fit of model output to observations of Loch water levels.

This was a complex process, partly because of the equifinality problem associated with highly parameterised models, and also because of the uncertainty about input data such as inflows, especially from groundwater. In addition, model runs were prone to instability problems dependent on timestep used, so achieving smooth and reliable running (vital for real time and forecast mode modelling) was a time-consuming process. Our approach was to use stepwise changes in the above data sets and parameters, to try to approach as good a fit as possible, for one storm event, that in August 2019, and then compare (and, if necessary, modify the calibration) based on the results for other events, such as early November 2019. The main parameters we modified in this process were:

1. The area multipliers defining the catchment area of inflows (from 31.4 to 35.6 km^2)
2. The lag and smoothing assumptions (from direct hourly input to an 8d lag with 8d moving average)
3. The Manning coefficients, especially for the key reach controlling loch water levels, downstream of Balgavies Loch exit (sluggish section reach, which includes a 50m culverted exit to Balgavies Loch) (from 0.02 to 0.05)
4. The stream invert level, especially that between Rescobie Loch and Balgavies Loch (Loch connexion reach) (inverts used in [4] report to 0.2m lower inverts)

Table 5 summarises this stepwise process, showing a gradually improving Nash-Sutcliffe test for the water levels in the two lochs, and some comments. Table 6 shows a summary of the Nash-Sutcliffe coefficients for different hydrological event periods from Aug 2019 to October 2020.

A key step in improved calibration for low flows, was lowering the invert level in the reach connecting Rescobie and Balgavies Loch, as it proved impossible to achieve good simulations of Rescobie Loch at low water levels without doing this. This modification was based on only one field measured cross section, because of access difficulties and poor operation of RTK satellite signals in the dense riparian woodland between the two lochs.[4] did not use any field data for this section, rather relying on topographic map interpretation, and this generates an invert level which would seem to be about 0.2m too high for this reach. Another key step was using the Manning coefficient of the outlet reach of Balgavies Loch as a calibration parameter to fit to observed Balgavies Loch outflow data (see Figure 4).

Plan 83 gave a greatly improved fit for the August 2019 event (used for the main calibration process in Table 5), but it overpredicted the peaks for the larger events in November-Dec 2019 and October 2020. As these peaks are events of primary interest, because they generate Rescobie Loch water levels in excess of 60m above sea level, the level at which Rescobie Loch carpark begins to flood) it is important that these are well represented. In order to do this, we compromised on the Aug 2019 fit, and explored modifying (a) the total area of inflow (b) the Manning coefficient of the outflow of Balgavies Loch. Results are shown in Figure 10.

This process (Plan 83 modified to plan 84 by reducing the flow multiplier, Plan 83 modified to plan 85 by changing the Manning coefficient in the outflow reach of Balgavies Loch) shows that the larger peaks can better be simulated with assumptions of lower input areas but the smaller peaks are better simulated with lower Manning coefficients at Balgavies Loch outlet. This group of 3 plans (83-85) also provided the basis for sensitivity and uncertainty analysis.

The sensitivity of the higher peak levels (>60m in Rescobie Loch) to changes in the catchment area are of the order of 0.03 m per 1km^2 change in catchment area and 0.005m per 0.01 change in Manning coefficient, so calibration to achieve correct values for the higher peaks is probably best done by changing the multipliers used for inflows, or the distribution of lags and averaging times on input flows. However, we should also bear in mind that these calibration datasets are subject to considerable spatial and temporal variation and uncertainty, such as:

a. Variation in rainfall, evapotranspiration and hydrological response to rainfall across the catchment;
b. Unknown groundwater inputs to the lochs which may be influenced by long lag processes;
c. Seasonal variation in Manning coefficient associated with vegetation, sediment accumulation and removal, and in channel management works, including existing existing weir gate opening/closing management.

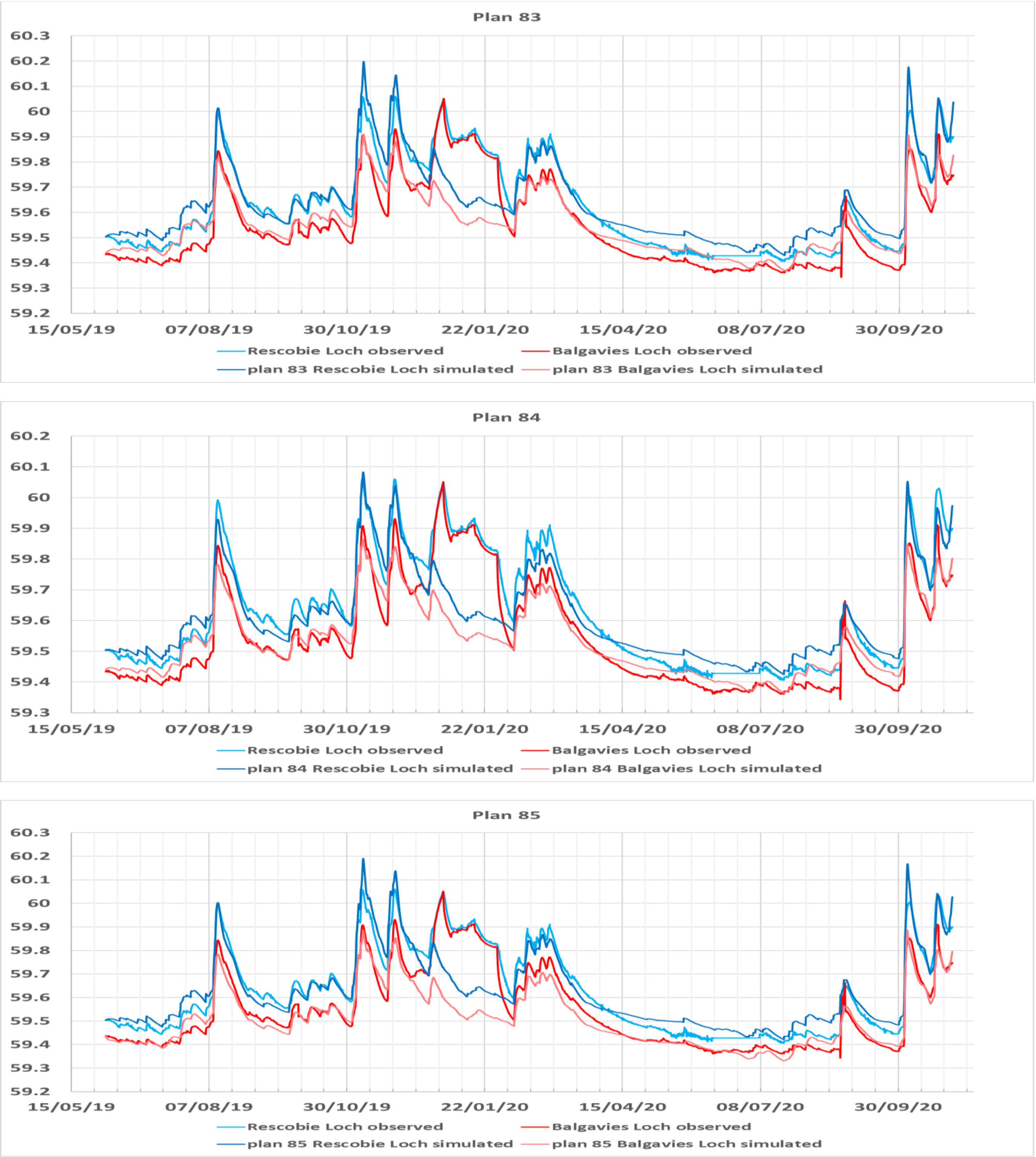


FIGURE 10. SIMULATED AND OBSERVED WATER LEVELS IN RESCOBIE AND BALGAVIES LOCHS UNDER 3 SETS OF MODEL CONDITIONS. NOTE THAT A LOGJAM IN THE LUNAN WATER DOWNSTREAM OF BALGAVIES LOCH OCCURRED DURING DEC 2019 TO JAN 2020, LEADING TO MUCH HIGHER WATER LEVELS THAN SIMULATED.

Table 5. Summary of stepwise improvements in fit of simulated loch water levels to observations during Aug 2019 event, by modification of HECRAS parameters and input data.

	Aug-Sep 2019 event Nash Sutcliffe coefficients			Nash-Sutcliffe	
HECRAS Plan number	Sequential Geometry changes	Sequential Flow changes	Overall upper Lunan area multiplier km2	Rescobie	Balgavies
61	Trenkmann report, but using simplified default table of Manning values (Table 1) and updated cross sections for Balgavies Loch exit	Direct input of flows into Rescobie Loch, Westerton/Wemyss mean inflows, mix of lags	34.3	0.67	0.12
66	See above	Wemyss measured flows only, default table of flows(see Table 2)	34.3	0.92	0.57
67	n=0.02 for all non-loch channels	see above	34.3	0.92	0.08
68	n=0.02 for all non-loch reaches, except n=0.04 for sluggish section reach (downstream of Balgavies Loch)	see above	34.3	0.91	0.88
69	n=0.07 for overbank flows	see above	34.3	0.91	0.88
70	as above	Subtract 3km2 from upper Lunan 1d flow	31.3	0.92	0.78
72	n=0.035 for sluggish section	8d instead of 4d lags 34.4 km2 flow	34.3	0.93	0.77
73	as above	31.4 km2 flow	31.3	0.84	0.60
75	as above	All input 1d, excess rainfall on 1.3km2	32.6	0.85	0.63
77	as above	4d lags instead of 8d, 35.6 km2 flow, excess rainfall corrected for SMD on 1.3 km2	35.6	0.93	0.81
78	as above	excess rainfall-direct SMD on 1.3 km2	35.6	0.92	0.83
79	lowered connexion reach invert by 20cm, n=0.05 for sluggish section	min flows 0.04 cumecs to Rescobie	35.6	0.91	0.84
83		5 km2 of 8d lag, 1.3 km2 of direct input, 10km2 of 1d lag, 5 km2 of 1h lag into rescobie Loch	35.6	0.95	0.90
84		reduced total flow to 31.6 (4km2 off 1d flows to Rescobie)	31.6	0.88	0.92
85	n=0.035 for sluggish section	5 km2 8d, 1.3 km2 direct input, 10 km2 1d, 5 km2 1h into Rescobie Loch	35.6	0.94	0.89

Table 6. summary of Nash-Sutcliffe coefficients for modelling of water levels in Rescobie and Balgavies Lochs for hydrological event periods from Aug 2019-Oct 2020

		Rescobie	Rescobie	Rescobie	Balgavies	Balgavies	Balgavies
from	to	Plan 85	Plan 84	Plan 83	Plan 85	Plan 84	Plan 83
01/08/2019	30/09/2019	0.94	0.88	0.96	0.88	0.92	0.92
30/09/2019	28/10/2019	0.73	0.35	0.76	0.78	0.37	0.16
28/10/2019	23/11/2019	0.89	0.96	0.86	0.93	0.81	0.77
23/11/2019	17/12/2019	0.81	0.82	0.78	0.51	0.41	0.62
17/12/2019	08/01/2020	-0.08	-0.08	-0.10	-0.08	-0.10	-0.12
08/01/2020	05/02/2020	-0.09	-0.08	-0.10	-0.12	-0.15	-0.18
05/02/2020	01/03/2020	0.88	0.69	0.96	0.68	0.82	0.96
01/03/2020	17/07/2020	0.84	0.83	0.79	0.89	0.89	0.82
17/07/2020	14/08/2020	0.23	0.24	0.18	0.37	0.21	0.15
14/08/2020	27/09/2020	0.46	0.47	0.36	0.67	0.33	0.26
27/09/2020	29/10/2020	0.94	0.91	0.92	0.93	0.91	0.90

The variation in rainfall across the catchment will be dealt with during the section on the use of forecasting of rainfall across the catchment (section 8). Forecasting also requires a model to simulate stream inflows based on excess rainfall, which will also be dealt with in section 8.

For now, to explore the impact of management of hydraulic structures and channel dredging, we designated plan 85 as the default calibration, as this was the best fit taking all events between Aug 2019 and October 2020 into account, and also uses a compromise Manning coefficient for the Balgavies Loch outlet which best fits the range of observations of stage-discharge for the Loch outlet (n=0.035). This choice of default was also influenced by the pragmatic consideration that reducing the flow multiplier/catchment area to 31.4 km^2 (as for plan 84) also leads to instability in some low flow model simulations, if the Manning coefficient is reduced to n=0.02. This would therefore have needed a much shorter timestep for simulations, inconvenient for sensitivity and scenario analysis. For risk analysis, it also makes sense to modestly overpredict the risk of high water levels, in the context of forecasting and risk reduction.

For best simulation of peak November 2019 levels in Rescobie Loch, which is important for the forecasting element of the work, it is better to use Plan 84, as although this does a less good job over the whole range of levels in the simulation period of interest (June 2019-Nov 2020), for the peak levels in Nov 2019, it does a better job that plan 85. Both have been considered as potential default options for the forecasting section of the work in section 8.

Hydraulic structures

Hydraulic structure input data, which form part of the geometry and unsteady flow file structures in HECRAS, has been outlined in detail in [4]. The unsteady flow input to HECRAS also specifies management of hydraulic structures and initial conditions throughout the stream network, which can be set in a time-specific manner.

The main hydraulic structures of interest are (see also Figure 11):

A. The return gate (RET) from the common lade reach 2 to the Lunan Water which has an invert level of 59.1m and width of 0.9m. This is modelled as a broad-crested weir (coefficient 0.67) with a sill invert and closed top.
B. The gate to the mill lade (MILL) from the common lade reach 2. This has the same structure and coefficients as RET.
C. The existing high flow spillway on the common lade reach 2 (HFS). This has a width of 3m and is modelled as a broad-crested weir (coefficient 0.67) with a sill invert at 59.6m asl (above sea level).
D. Potential tilting weir in the location of the HFS on the common lade reach 2 (TIW2) but with adjustable invert from 59.1 to 59.6m asl Note that in the dredging options discussed below, the minimum invert can be lowered to 58.5m.
E. Potential tilting weir on the common lade, reach 1 (TIW1) but with adjustable invert from 59.1 to 59.6m asl. The rate of opening, and water level trigger for opening or closing the tilting weir can be varied and can be triggered remotely in response to changing water levels. Note that in the dredging options discussed below, the minimum invert can be lowered to 58.5m.
F. The two culverts supporting which a cattle track/ footpath over the common lade (invert 59.0) and the Lunan Water (invert 58.3m).

Note that when the proposed tilting weir (at either proposed position) is in the closed position, the system operates as currently occurring. The rate of opening or closing, and water level trigger for opening or closing either of the tilting weirs can be varied and can be triggered remotely in response to changing water levels.

In addition, there are a number of bridges and culverts in the system. These are described in [4]. The culverted exit to Balgavies Loch has been updated to a square-walled cross section channel 6m wide, with invert level at the loch outlet of 59.03m asl.

For calibration, the default distance between the invert and the closed top of the RET and MILL weirs was set at 0.4m, although there are periods during low flow summers, when the invert is raised, or the gate opening is reduced to a much lower value, which we have taken as a 0.1m opening with invert at 59.1m. This change has little effect on upstream water levels, but it does affect flow routing to some extent.

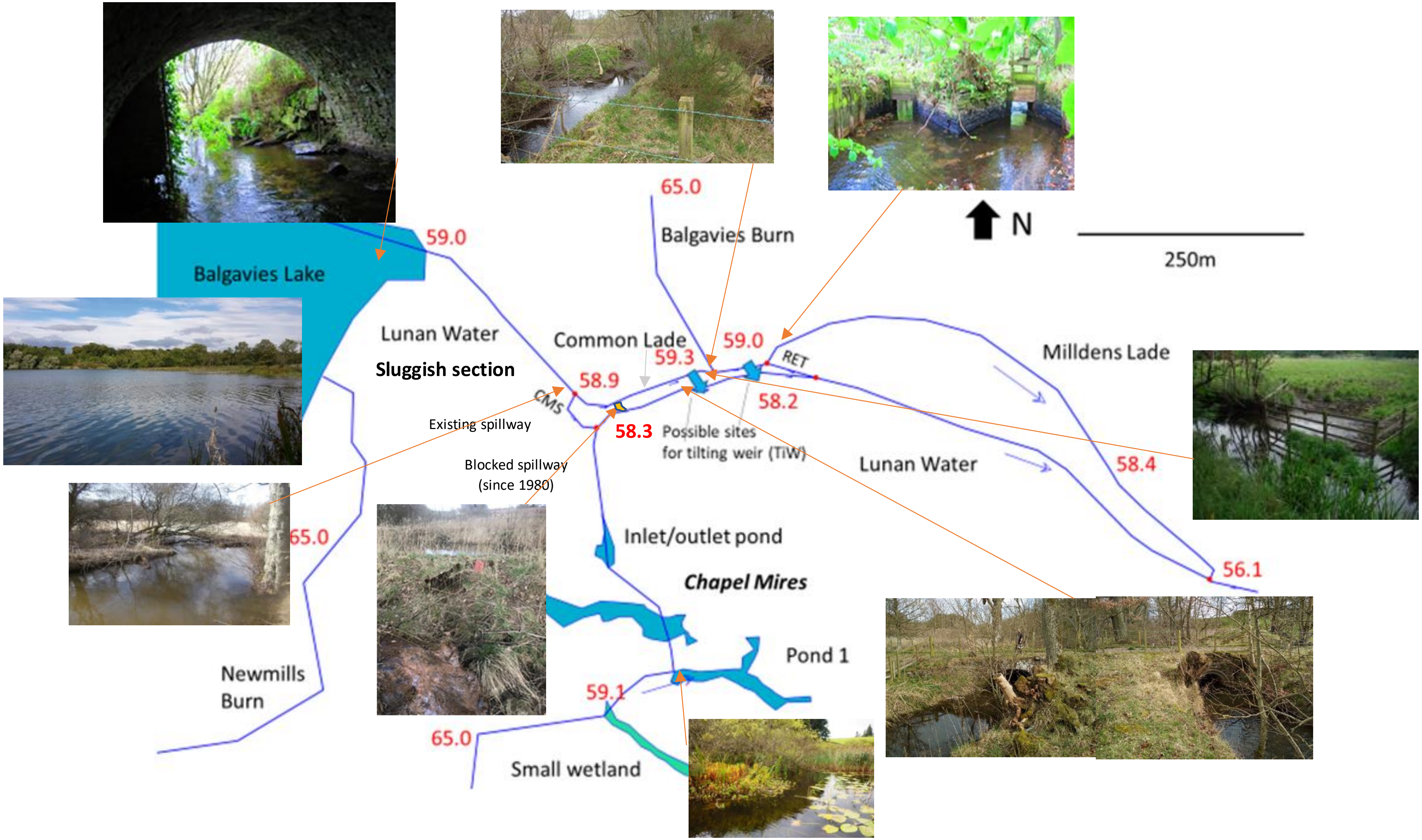
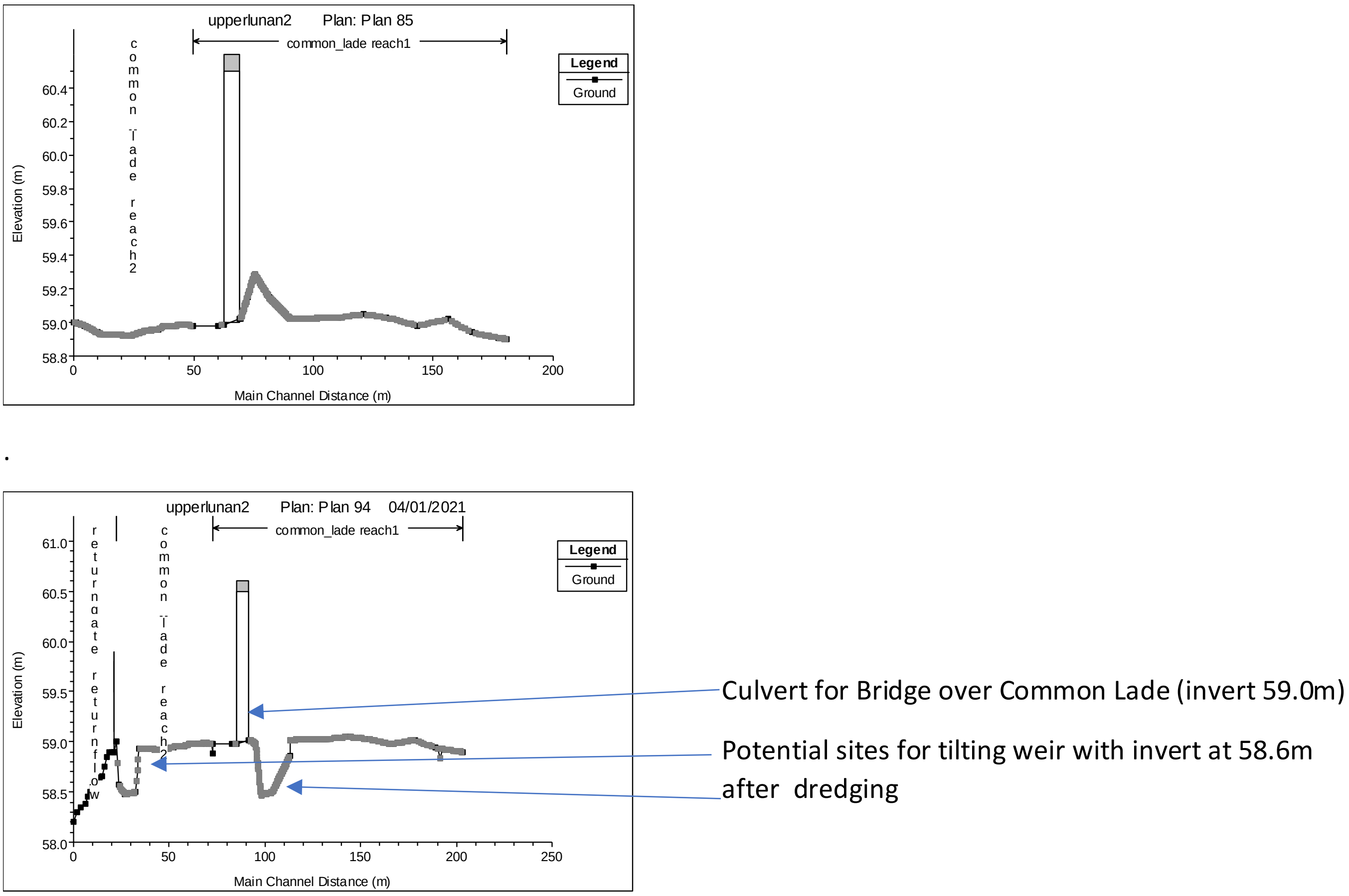


Figure 11 Outlet structures of Balgavies Loch/Lunan Water. Bed levels shown in red in m above sea level. RET=return gate from common lade to Lunan Water; CMS = Existing Chapel Mires spillway; TiW1, TiW2 = possible sites for installation of tilting weir to manage flow routing and upstream water levels.

Dredging

The field survey [1] showed a build-up of sediment in the common lade reach 1 to an invert level of 59.3m u/s of the bridge culvert which is located just upstream of the confluence of Balgavies Burn and the common lade. The first step in any dredging scenario analysis was to remove this build-up, giving the lade a constant invert bed level of 59.0. The second step was to lower the invert level of the common lade, to promote better flow through this channel. This in itself could enhance flow and lower event water levels upstream. It also could give the potential for further lowering of the weir invert for the tilting weir options. In the default set up, these cannot be lower than the minimum bed level of 59.0m in the common lade. By dredging all or part of the lade by 0.5m, the tilting weir would have a much larger range of potential action.

As a first step in this approach, we just dredged the region around the proposed tilting weir in reach 2, to allow a minimum invert of 58.6m. We then also did the same thing in reach 1, to allow installation and operation of a tilting weir in this reach, just upstream of the culvert at the downstream end of reach 1 (Figure 12). Finally, we dredged the whole of reaches 1 and 2 and lowered the culvert invert on reach 1 of the common lade to 58.5 m to maximise the potential for flows from upstream passing through the common lade and over an operational tilting weir.



Culvert for Bridge over Common Lade (invert 59.0m)

Potential sites for tilting weir with invert at 58.6m after dredging

FIGURE 12 A. CONTROL AND B. DREDGING SCENARIO FOR COMMON LADE IN FLOW ROUTING AND WATER LEVEL ANALYSIS.

5. Scenarios of hydraulic management

Impact of tilting weir operation

The effect of operation of either TIW1 or TIW2 on upstream stage in Balgavies Loch was small (a few centimetres), under the default conditions of Plan 85. However, the flow routing was influenced much more, with more water flowing down the common lade, and much less down the Lunan Water, when TIW1 was operating (a 37% reduction in the volume of the event flow from 1 to 23 Nov 2019). The effect of TIW2 on flow routing was much smaller (8% reduction in the same event flow). See Figure 13. The extent of the flow diversion was greater for larger events.

Impact of dredging

The field surveying [1] for common lade reach 1 showed a build up of sediment to an invert level of 59.3m u/s of a bridge culvert which is located just upstream of the confluence of Balgavies Burn and the common lade. The first step in dredging scenario analysis was to remove this buildup, giving the lade a near-constant invert bed level of 59.0m. This did have a small effect on water levels upstream and flow diversion.

The second step was to lower the channel invert in a section of either reach 1 or reach 2 to 58.5m. This was to allow a tilting weir to have an invert level that was 0.5m lower than was possible with a bed level of 59.0m. The effect of this dredging alone was to divert more of the Nov 2019 event water into the common lade (about 10% for dredging of reach 1 or 8% for dredging of reach 2). These actions had a small effect on peak water levels in Balgavies Loch (-10mm for dredging of reach 1, -16mm for dredging of reach 2). The dredging of reach 1 also led to a lower loch level at low flows when the impact of the common lade on drainage from the loch was not counteracted by the flows entering from Balgavies Burn. This had the effect of delaying the onset of the water level peaks in the Lochs during storm events.

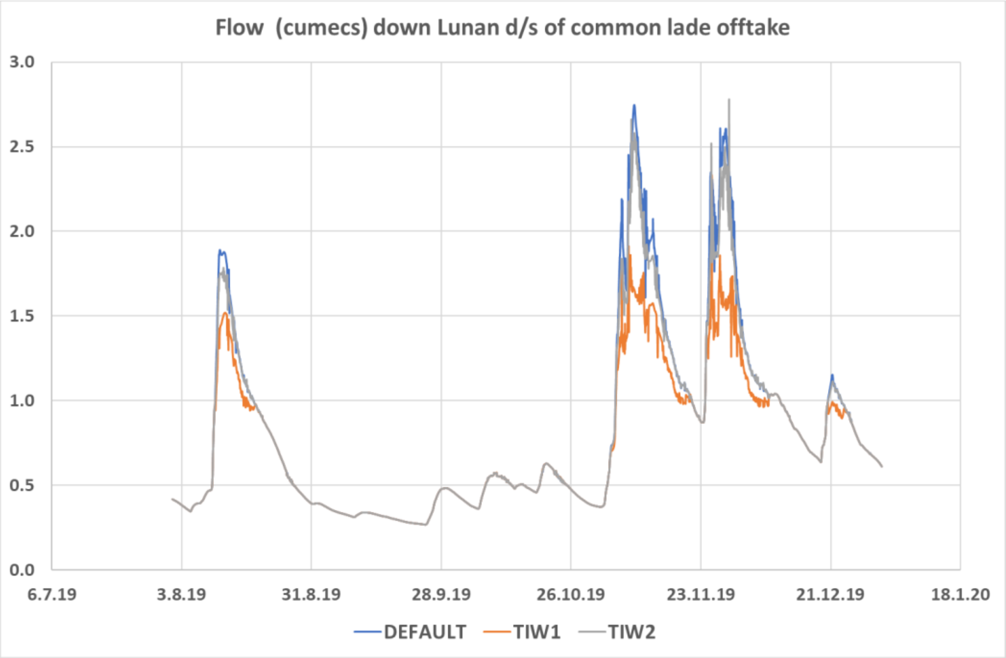


FIGURE 13 FLOW AT RS 2148.368 (LUNAN DEVIATION REACH) UNDER DEFAULT (PLAN 85) CONDITIONS AND WITH TILTING WEIR OPERATING EITHER IN REACH 1 OF COMMON LADE (TIW1) OR REACH 2 OF COMMON LADE (TIW2).

Impact of combination of dredging and tilting weir operation.

One of the objectives of dredging the common lade to a bed level of 58.5m was to explore the impact of installing a tilting weir with a lower invert (minimum level 58.5m) than would be possible with the existing channel (minimum level 59.0m). A combination of dredging and tilting weir with an invert at 58.5m had very little additional effect on Balgavies Loch Levels and in the case of a tilting weir on reach 1, this actually counteracted the effect of dredging on loch levels slightly, so that peak levels only went down by 6mm instead of 12mm, probably due to the backwater effect.

However, the effect of the combination of dredging and a tilting weir on routing of flows was greater. There was an increase in the diversion of flow from the Lunan Water to the common lade by a further 5% for TIW1 to 42% and a further 12% to 20% for TIW2. There is uncertainty about the additional impact, however, because of instability in model outputs associated with operating the tilting weir. See Figure 15.

A series of alternative dredging/tilting weir operation strategies was then explored, using the event which peaked on 9 Nov 2019. Table 7 summarises the results, showing the reduction in the maximum water level in Balgavies Loch that resulted from these strategies, and also the effect on the excess flow peak between 1 Nov and 23 Nov, flowing in the Lunan Deviation reach of the Lunan Water. This is the reach that directly connects with the Chapel Mires, so is most relevant to the potential contamination of Chapel Mires with sediment and nutrient rich storm water. Figure 14 shows the timeseries of Loch water levels and Lunan Deviation flows as well.

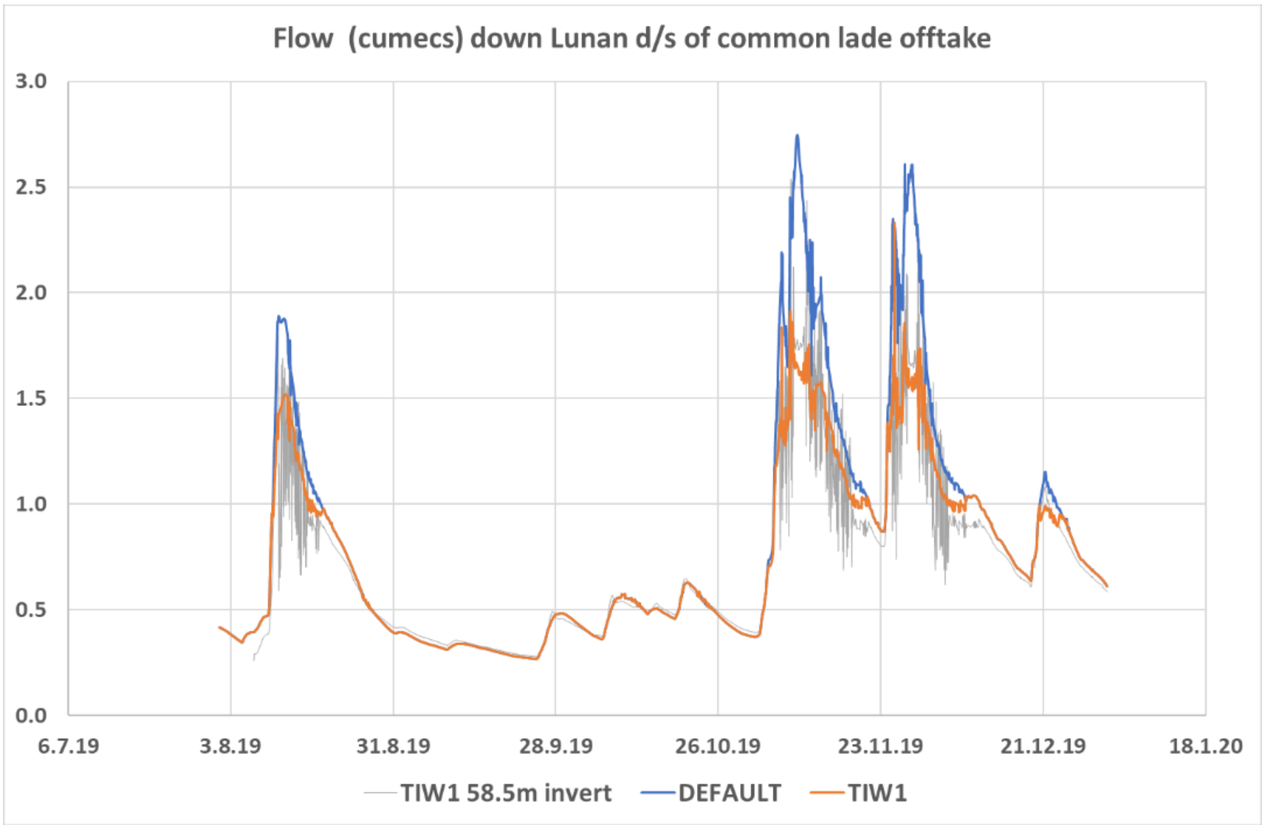


FIGURE 14 FLOW AT RS 2148.368 (LUNAN DEVIATION REACH) UNDER DEFAULT (PLAN 85) CONDITIONS AND WITH TILTING WEIR OPERATING IN REACH 1 OF COMMON LADE BEFORE (TIW1) OR AFTER DREDGING OF COMMON LADE TO 58.5M (TIW1 58.5M INVERT). NOTE THAT THE INVERT OF THE TILTING WEIR IS IN THIS CASE ALSO LOWERED TO 58.5M.

These results confirm the rather small impact of modifying hydraulic structure management on upstream water levels also observed by [4], at least in the short term, but the much larger potential for diverting high flow away from the Lunan Deviation reach, which connects with the Chapel Mires wetland. **This could be deemed valuable for protecting the wetlands from sediment and nutrient enrichment.** Note the tendency for instability in flow simulations, especially where the tilting weir is in operation. The complex nature of the flow in the section including Balgavies Burn and Lunan Water inputs, and the several hydraulic structures in operation in this area, make this unsurprising, but the instabilities appear to be self-compensating to some extent. Further work to remove these will require a rather open-ended commitment of modelling time, which cannot be justified at present.

Table 7. Impact of a range of dredging and tilting weir operation scenarios on peak water levels in Balgavies Loch in Nov 2019 and reduction in event flow through Lunan Deviation reach during 1-23 Nov 2019. Table of scenario

Name	Summary	Scenario Description	Plan	Balgavies Loch peak maximum on 9 Nov 2019 (m)	m reduction in loch peak level	% reduction of event flow in deviation reach of Lunan Water over period of 1 Nov - 23 Nov
A	Default	Default (flow max = 2.74 cumecs on 9 Nov 2019)	85	59.884	0.000	0%
B	Dredge 59	Dredge of common lade (CL) to 59.0m	91	59.878	0.006	10%
C	B+TIW1	Tilting weir on CL reach 1 (TIW1) operating to invert of 59.0m	2	59.879	0.005	37%
D	B+TIW2	TIW2 operating to invert of 59.0m	1	59.872	0.012	8%
E	CL2 Dredge 58.5	Dredge CL2 around TIW2 to 58.5m, but TIW2 closed	38	59.878	0.006	10%
F	E+TIW2 58.5	Dredge CL2 around TIW2 to 58.5m, TIW2 operating to 58.5	92	59.872	0.012	20%
G	CL1 Dredge 58.5	Dredge CL1 around TIW1 but TIW1 closed	93	59.874	0.010	12%
H	G+TIW1 58.5	Dredge CL1 around TIW1 to 58.5; TIW1 operating to 58.5m	94	59.874	0.010	42%
J	Culvert 58.5	Lowered bridge culvert to invert of 58.5m no TW	96	59.881	0.003	7%
K	J+TIW2 58.5	Lowered bridge culvert to invert of 58.5m TiW 2	97	59.870	0.014	30%
L	J+TIW1 58.5	Lowered bridge culvert to invert of 58.5m TiW1	98	59.884	0.000	22%
M	G+TIW1 59.0	Bridge culvert at 59.0m; Dredge CL1 around TIW1; TIW1 operating to 59.0 m	99	59.882	0.002	42%

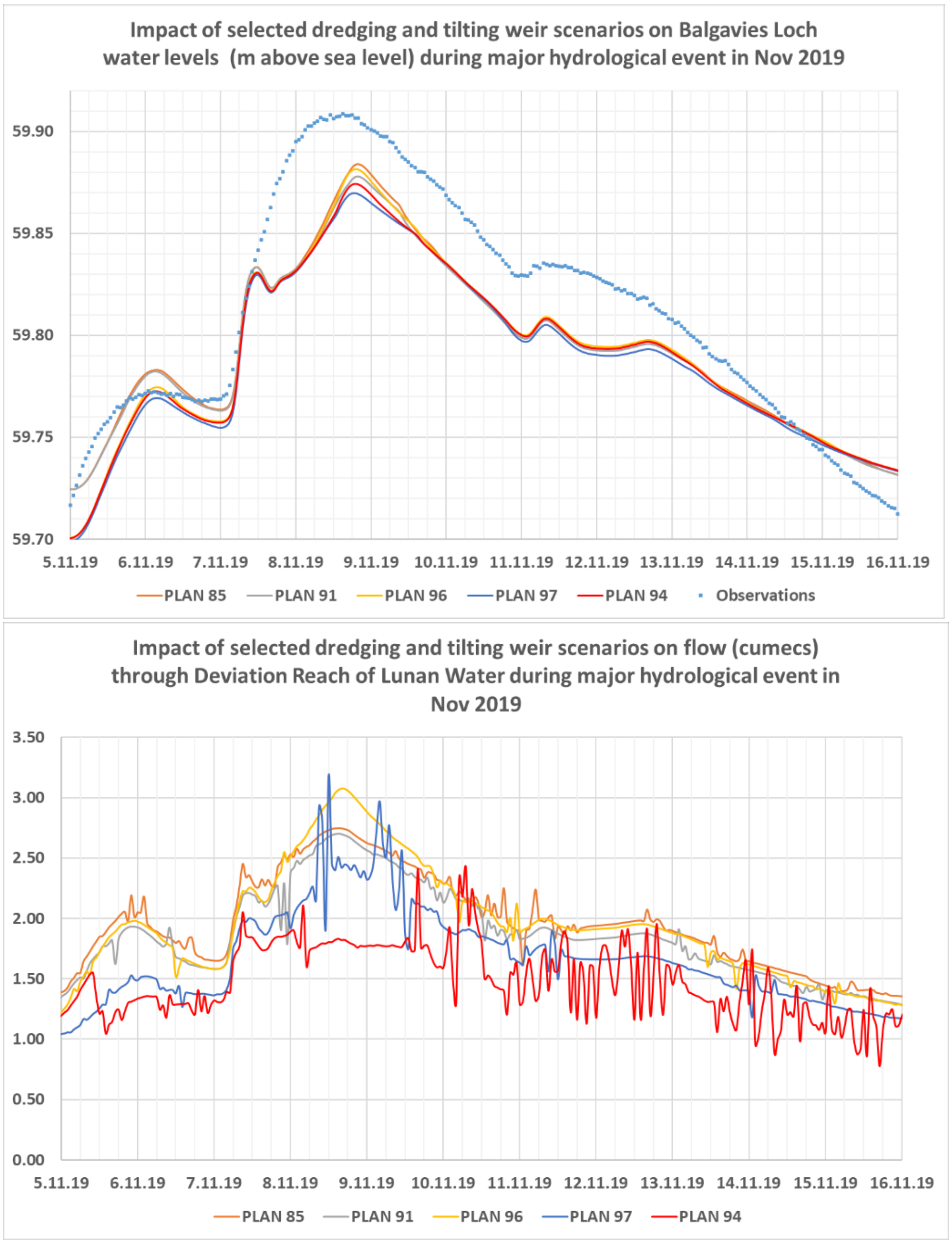


Figure 15 Impact of selected dredging and tilting weir scenarios on a. Balgavies Loch water levels (m above sea level) b. flow (cumecs) through Deviation reach of Lunan Water during major hydrological event in Nov 2019.

6. Discussion and recommendations for hydraulic management

The above scenario analysis shows that:

a. Significant dredging and hence lowering of the common lade channel invert, would give a lowering of the base level of Balgavies and Rescobie Lochs, facilitating a delay in flood peak water levels (by a few hours) and some decrease in the maximum level (by a few cm).

b. It would be difficult to achieve further significant reduction of Balgavies Loch (or Rescobie Loch) levels during event conditions, through installation of a tilting weir, even when operating with minimum level of 58.5m asl and/or lowering of the culvert in reach 1 of the common lade. The main reasons for this relatively low impact of enhanced hydraulic management on loch water levels were:
    - the relatively high Manning coefficient in the sluggish section reach, at the outlet to the Balgavies Loch (n=0.035). Any measures that decrease this coefficient (and it probably varies through the year), are to be welcomed for relieving upstream water levels;
    - The inflow of Balgavies Burn just downstream at the junction between Reach 1 and Reach 2 of the common Lade. If the culvert on reach 1 of the common lade were to be lowered, then a tilting weir on reach 1 would receive a lot more of the water from Balgavies Burn, than would be the case otherwise without this lowering, reducing the tilting weir's capacity to receive flows from upstream.
    - The backwater effect, which means that sending water over a weir can lead to enhanced water levels upstream.

c. The limited impact on Balgavies Loch water level (up to – 1.4cm) could be achieved most effectively if the TIW2 option is chosen, ie locating hydraulic controls in the region of the existing high flow spillway on reach 2 of the common lade. Similar, or slightly larger impacts on Rescobie Loch were found.

d. However, the tilting weir option (especially TiW1) increased the potential for diverting flow down the common lade and away from the Lunan deviation reach of the river. The most effective means to divert flow in this way would be a combination of dredging around the zone immediately upstream of the culvert in reach 1 of the common lade, to 58.5m and instllation of a tilting weir that operates to open to a minimum invert of 58.5m. This gave a reduction of peak flows for the Nov 9 event of 42% Table 5, Plan 94). This is considered a desirable management to reduce the transport of sediment and nutrient rich water into Chapel Mires during storm events. Previous work [1] has shown the large gradient in water quality and plant trophic status across the Chapel Mires, which indicates the importance of dynamics of flooding of this area on ecological conservation.

Our recommendations are therefore:

A. Vegetation removal in the common lade reach 1 and in the sluggish section reach at the outlet of Balgavies loch (below the road culvert) should be practiced as regularly as possible to decrease the Manning coefficent in these reaches (see Figure 16) and make the hydraulic management on the common lade more effective. This should include vegetation in the overbank containing walls at the outlet of the culvert.

B. Dredging should be carried out in the region immediately upstream of the culvert on reach 1 of the common lade. This would have a significant impact on the stage-discharge relationship for water exiting Balgavies Loch, especially at low flows (see Figure 16). This means there would be more capacity to store water in the lochs, during the leading edge of hydrological events, delaying the water level peak and also reducing this peak by a few cm for events giving a high risk of flooding (see Figure 17);

C. 1. A fixed or tilting weir could be installed in the common lade reach 1 upstream of the bridge culvert, with an adjustable invert level which is as low is as practical, ideally as low as 58.5m above sea level.
2. The current existing spillage point from the common lade into the Lunan Water is not an engineered structure but a breach in the earth wall of the common lade. The bed level of this spillage zone (CMS) is 58.9m above sea level. Note that a little upstream of the proposed optimal site for the proposed fixed or tilting weir, there is a blocked off engineered broad crested spillway (OS ref 353927 750747) – see Figure 11, [4] Annex 4 and [1] supplementary information - which we understand was blocked about 50 years ago, before the time of the 1980 restoration of the Milldens water mill and weir (T.Sampson, pers.comm). An alternative to installing a new hydraulic structure would therefore be to re-open the existing blocked

spillway. The bed level of the Lunan Water d/s of this blocked spillway is 58.3m asl. This could be done in several ways:

i. simply lowering the river bank to an agreed level at this point, to link up with the redundant blocked spillway base. This could be done with or without blocking the existing CMS spillway;
ii. Installing a wooden sleeper on the blocked spillway at an agreed elevation somewhere between 58.5 and 59.0m to act as a more robust spillway, while minimising further erosion of the earth bank and the existing (but currently redundant) spillway base;
iii. Installing a fixed gated structure or weir on the blocked spillway, similar to the mill lade and return gates on the common lade reach 2 - see figure 11;
iv. Installing a tilting weir at the site of the blocked spillway, instead of immediately upstream of the culverted bridge.
v. Status Quo. Continuation of "benign neglect" of the existing spillage zone of the Lunan Water, with flow continuing over the top of the earth bank of the common Lade.

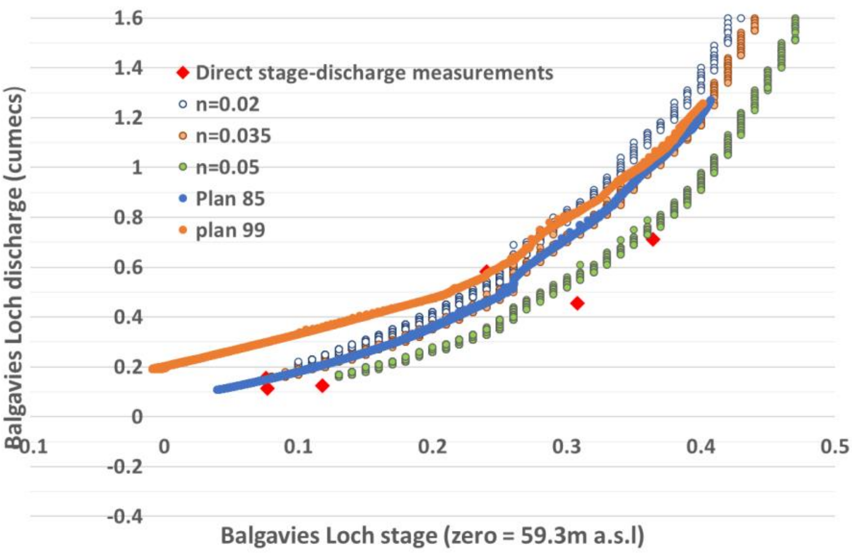


FIGURE 16 STAGE DISCHARGE RELATIONS FOR THE OUTLET OF BALGAVIES LOCH. IMPACT OF CHANGING MANNING N FOR THE SLUGGISH SECTION REACH JUST DOWN STREAM OF THE LOCH, AND OF IMPLEMENTING DREDGING IN THE COMMON LADE REACH 1 (PLAN 85 = DEFAULT; PLAN 99 = COMMON LADE REACH 1 DREDGED TO 58.5M JUST UPSTREAM OF BRIDGE CULVERT. NOTE THAT THE PLAN 99 ALSO INCLUDES A TIW1 OPERATING TO AN INVERT OF 59.0M AT HIGH FLOWS, BUT THIS DOES NOT INFLUENCE THE STAGE DISCHARGE ON THE OUTLET TO THE LOCH, ONLY THE DIVERSION OF FLOW INTO THE COMMON LADE AND AWAY FROM THE LUNAN AT HIGH FLOWS.

In all of cases C2ii, C2iii and C2iv, the options exists to allow the existing earth bank spillway (CMS in Figure 11) to operate, or to close it off. The former option seems more in keeping with river restoration principles.

Of the options proposed in recommendation C, we suggest the option C2ii would be the most practical and acceptable to all stakeholders, if it were accompanied by observations of performance leading potentially to modification of the sleeper invert level. Option C1 is likely to require considerable cost for installation, operation and maintenance, as would option C2iv. Option C2i would be the most "natural" of the options, including the status quo (Option C2v). As the blocked spillway is already engineered, with a stone base, this would constitute restoring the situation to as near to natural as is feasible on a lowland river of this kind, which has been engineered to provide water power for centuries. Option C2iii may not be acceptable under River Restoration legislation about hydraulic structures.

This option (C2ii) is also likely to reduce the build up of sediment and instream vegetation immediately upstream, which currently has the effect of increasing the effective Manning coefficient. It would be the option requiring the least active management, with the exception of C2v, the status quo.

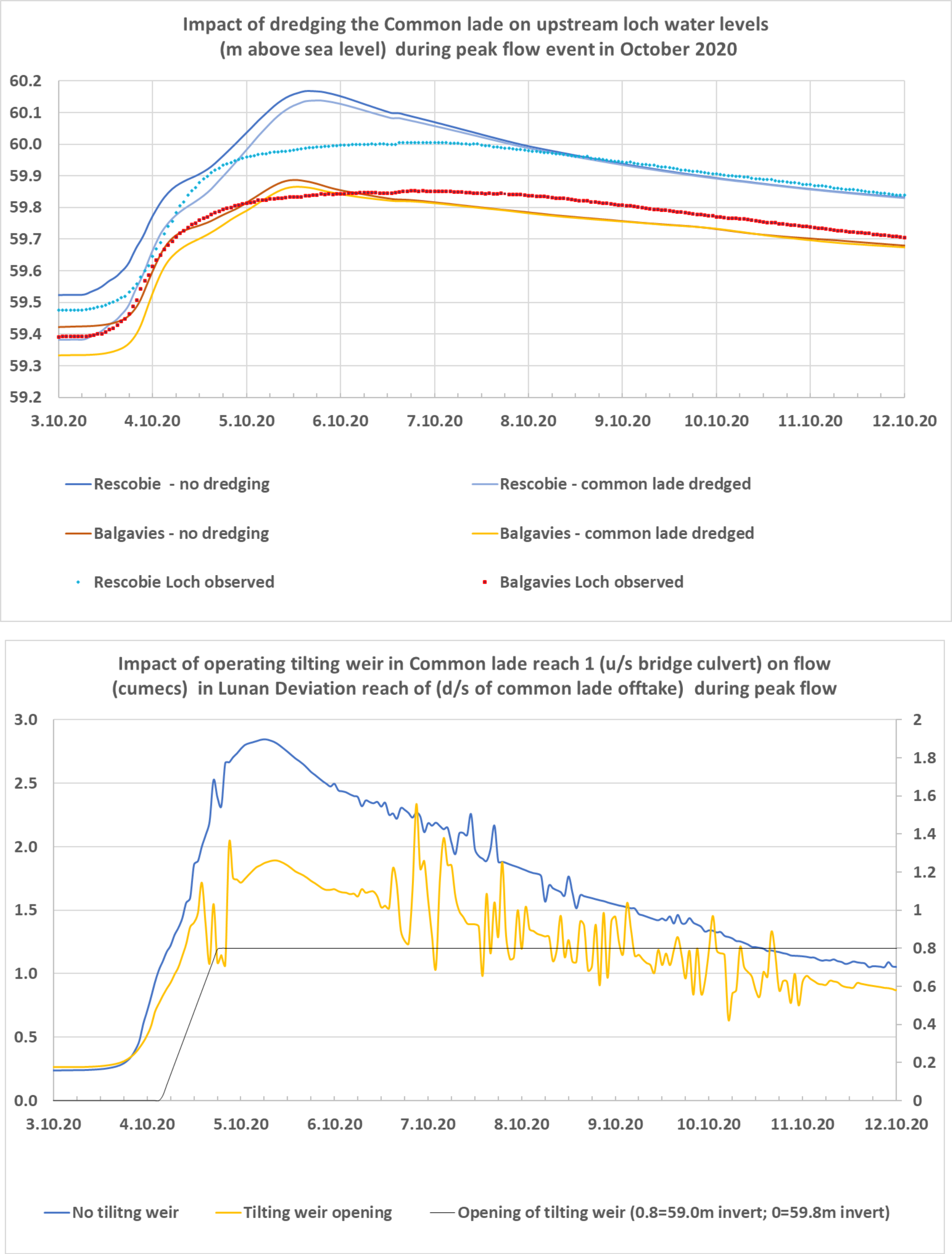


Figure 17 Influence of (a) dredging common lade on loch water levels and of (b) operation of tilting weir upstream of bridge culvert on Common Lade on diversion of flow away from Deviation Reaxh of Lunan Water d/s of common lade offtake.

7. Forecasting tool for water levels and flows in the upper Lunan

A further stage in facilitating the improvement of hydraulic management on the upper Lunan Water was to develop a forecasting tool, based on the HECRAS model calibration described above. This involved developing a rainfall-runoff model calibrated for the sub-catchments where discharge has been observed. The output of this model, driven by spatially distributed rainfall and evapotranspiration 5d forecasts from the Meteorological Office, was then fed into the above HECRAS calibration to deliver forecasted water levels.

Stream flows are currently monitored at 3 different locations in the Lunan Water catchment: (i) at Kirkton Mill, which represents the boundary of the whole of the Lunan Water catchment; (ii) at Baldardo Burn, a small tributary in the upper Lunan, which feeds into the Rescobie Loch and represents the sub-catchment of Wemyss; and (iii) at Balgavies Burn, a small tributary which feeds into the main stem of the Lunan Water just downstream of the Balgavies Loch and which represents the sub-catchment of Westerton.

In this section, a hydrological model will be described and calibrated for Wemyss and Westerton sub-catchments. The calibrated models will subsequently be scaled and used to simulate the stream flows for the other sub-catchments in the Upper Lunan that feed into the hydraulic model.

Water balance

The long-term water balances (2009-2019) for the entire Lunan catchment (Kirkton Mill) as well as for the sub-catchments of the Baldardo Burn (Wemyss) and the Balgavies Burn (Westerton) are summarised in Table 8. In this period, the annual average rainfall and runoff at Kirkton Mill were around 885 mm and 470 mm, respectively, meaning that the annual loss from the entire catchment due to actual evapotranspiration (AET) (and other losses) was about 415 mm. The average potential evapotranspiration (PET) has been estimated to be just under 500 mm/yr using the model of [10], which only requires temperature and radiation as input. This suggests that the ratio of actual to potential evapotranspiration is around 0.8.

Table 8. Water balance summary for the whole of Lunan and the sub-catchments for the Baldardo and Balgavies Burns in the upper Lunan catchment.

	Lunan Water at Kirkton Mill	**Wemyss (Baldardo Burn)**	**Westerton (Balgavies Burn)**
Catchment area [km^2]	124	2.4	4.4
Mean annual rainfall [mm]	885		
Mean annual PET [mm]	491		
Mean annual runoff [mm]	472	433	162
Mean annual loss [mm]	413	452	723
Mean flow [m^3/s]	1.88	0.033	0.021
Flow Q95 [m^3/s]	0.30	0.002	5.4e-5
Flow Q50 [m^3/s]	1.04	0.017	0.007
Flow Q10 [m^3/s]	4.18	0.067	0.044

The average annual runoff for Wemyss and Westerton are 433 mm and 162 mm, respectively. The average annual loss from these two sub-catchments are therefore about 450 mm and 720 mm, respectively. The loss from Wemyss is similar to Kirkton Mill and can therefore largely be explained by evapotranspiration (i.e. the ratio of actual to potential evapotranspiration is around 0.9). However, as noted above, the loss from Westerton is much larger than PET, which suggest that there is a loss from this catchment via deep groundwater (or other sources). It is also possible that the (effective) size of the catchment for Westerton has been overestimated, and/or that the rating curve for Balgavies Burn is underestimating the discharge. Three different stage-discharge rating curves have been developed for the Balgavies Burn. The most recent rating curve (2018/19) has been used here for the water balance calculations and the hydrological modelling. However, this rating curve is consistently estimating lower flows compared to the previously developed rating curves for Westerton, as shown in Figure 18. Although this could just reflect a true change in the stage-discharge relationship at Westerton over time, it does suggest that the observed flows are likely to be associated with significant uncertainty. Storm Frank (2005/6) may have been influential as well.

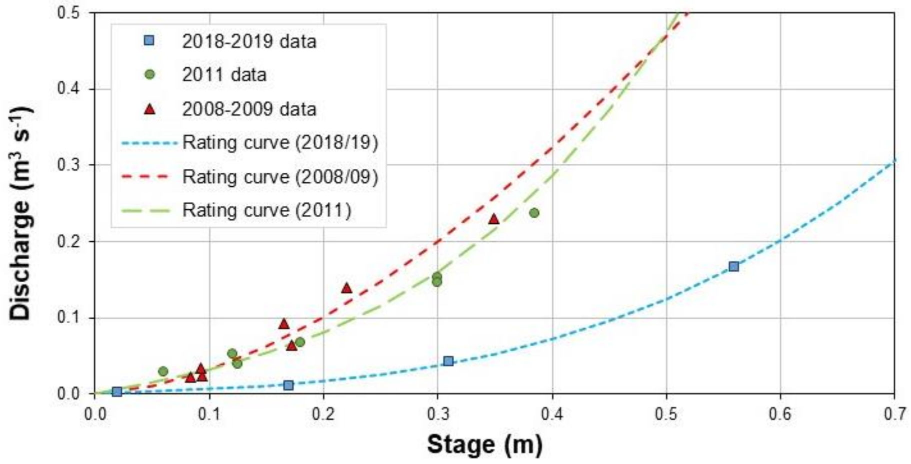


FIGURE 18. RATING CURVES FOR WESTERTON

The rainfall data are also associated with uncertainty and may vary spatially within the catchment. Daily rainfall data are available from Kirkton Mill from 1961-2017. As part of this project, rainfall has also been measured hourly in Lunan near Balgavies Loch since 2009. A comparison of the rainfall records from these two stations between 2009-2017 shows that while the rainfall pattern is generally very similar, the average annual rainfall at Kirkton Mill was 928 mm and 879 mm near Balgavies Loch. The estimated evapotranspiration is also associated with uncertainty. Here, the simple model by [10] was used, but other more detailed ways of estimating evapotranspiration exist such as Penman-Monteith [11].

Figure 19 shows the monthly values of net rainfall (rainfall – AET), runoff and loss/gain for Wemyss and Westerton, respectively. It is assumed that the ratio of actual to potential evapotranspiration is 0.9. Note that a positive loss/gain value means that the runoff is lower than the estimated net rainfall and hence suggests that the catchment is losing water (eg to deep groundwater). A negative loss/gain value on the other hand suggests that the catchment is gaining water from another source.

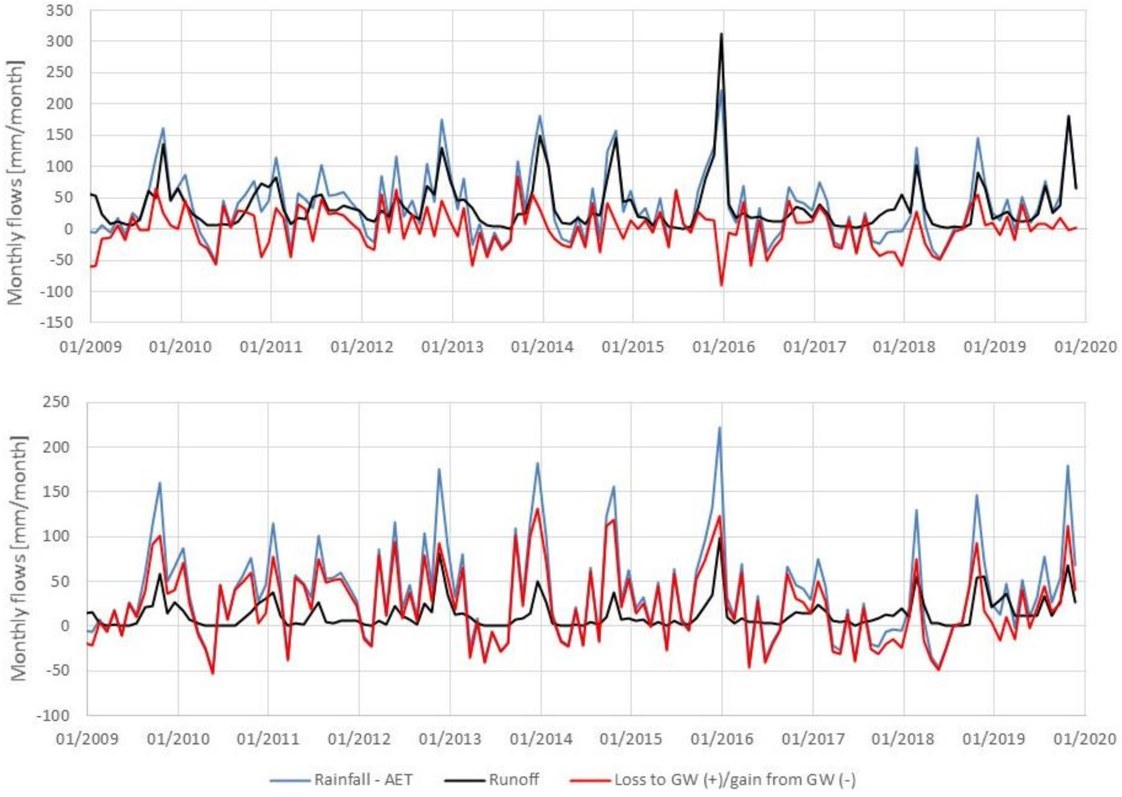


FIGURE 19. MONTHLY NET RAINFALL (RAINFALL – AET), RUNOFF AND LOSS/GAIN FOR WEMYSS (TOP) AND WESTERTON (BOTTOM), RESPECTIVELY. A NEGATIVE VALUE OF THE LOSS/GAIN (RED CURVE) MEANS THAT RUNOFF IS HIGHER THAN THE ESTIMATED NET RAINFALL AND HENCE SUGGESTS THAT THE CATCHMENT IS GAINING WATER FROM ANOTHER SOURCE. A POSITIVE VALUE OF THE LOSS/GAIN (RED CURVE) MEANS THAT RUNOFF IS LOWER THAN THE ESTIMATED NET RAINFALL AND HENCE SUGGESTS THAT THE CATCHMENT IS LOSING WATER.

Figure 19 shows that the flow at Wemyss is closely linked to the difference in rainfall and evapotranspiration. A previous study based on isotope analysis suggested that water can be lost from the Wemyss catchment via deep groundwater. However, as noted in section 2 (see Figure 4), there may be inflow of water from groundwater storage in this catchment following large events. For Westerton, the relationship between net rainfall (blue curve) and runoff (black curve) appears to be less pronounced. Westerton has a large unaccounted flow component (ie loss), which is assumed to be a loss to deep groundwater.

The water balance considerations above suggest that the hydrological model needs to be able to account for losses to, and possibly gains from, groundwater. To do this, a simple hydrological model has been developed, which is described in the following section.

Hydrological model description

The catchment is divided into three "compartments", each of which contribute to the river discharge Q. The compartments are:

1. "Hill" compartment
2. "Field" compartment
3. "Direct input" compartment

The river discharge Q [mm/hr] is calculated as:

$$Q = A_{R\_hill}Q_{hill} + A_{R\_field}Q_{field} + A_{R\_direct}Q_{direct} \tag{1}$$

where Q_{hill}, Q_{field} and Q_{direct} are the flow contributions [mm/hr] from the hill, field and direct input compartments, respectively, and A_{R_hill}, A_{R_field} and A_{R_direct} are the areas of the hill, field and direct input compartments relative to the total (sub) catchment area, respectively. Note that all flows are expressed per unit area and hence are given in units of mm. The water balances for the different compartments are here modelled numerically using an hourly time step.

The water balance modelling is illustrated in Figure 20. The hill and field compartments are assumed to consist of two connected reservoirs: an upper soil reservoir and a lower subsoil reservoir. The direct flow compartment is assumed to consist only of an upper soil reservoir.

The inflow to the upper soil reservoir is the effective rainfall J_0 [mm/hr], i.e. the difference between rainfall P [mm/hr], and actual evapotranspiration AET [mm/hr]:

$$J_0 = P - AET \tag{2}$$

The water storage in the upper soil reservoir is expressed as Soil Moisture Deficit (SMD) [mm]:

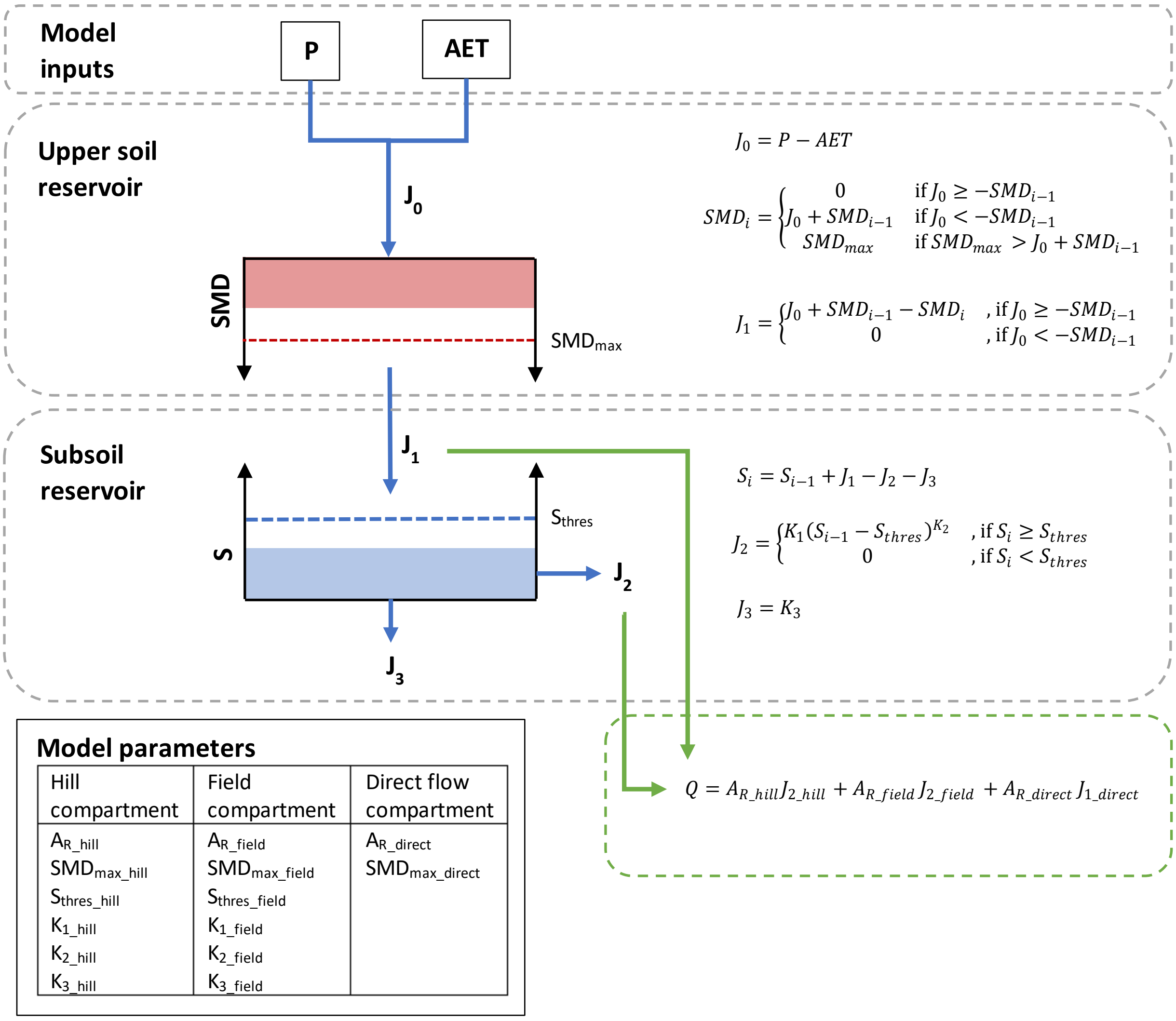
$$SMD_i = \begin{cases} 0 & \text{if } J_0 \geq -SMD_{i-1} \\ J_0 + SMD_{i-1} & \text{if } J_0 < -SMD_{i-1} \\ SMD_{max} & \text{if } SMD_{max} > J_0 + SMD_{i-1} \end{cases} \tag{3}$$

The soil moisture deficit will increase (i.e. become more negative) when AET exceeds P. A lower limit of SMD (SMD_{max}) is specified for each compartment. For the modelling here, the lower SMD limit has arbitrarily been set to SMD_{max_direct} = -5 mm for the direct flow compartment and to SMD_{max_hill} = SMD_{max_field} = -150 mm for the hill and field compartments.

Water will leave the upper soil reservoir at rate J_1 [mm/hr] if the effective rainfall is positive and SMD is 0, i.e.:

$$J_1 = \begin{cases} J_0 + SMD_{i-1} - SMD_i & \text{, if } J_0 \geq -SMD_{i-1} \\ 0 & \text{, if } J_0 < -SMD_{i-1} \end{cases} \tag{4}$$

For the direct flow compartment, the water leaving the upper soil reservoir, J_{1_direct}, is assumed to enter directly into the river (J_{1_direct} = $Q_{\_direct}$). For the hill and field compartments, the water leaving the upper soil reservoir is assumed to infiltrate to a lower subsoil reservoir, as illustrated in Figure 20.



Hill compartment	Field compartment	Direct flow compartment
A_{R_hill} SMD_{max_hill} S_{thres_hill} K_{1_hill} K_{2_hill} K_{3_hill}	A_{R_field} SMD_{max_field} S_{thres_field} K_{1_field} K_{2_field} K_{3_field}	A_{R_direct} SMD_{max_direct}

FIGURE 20. CONCEPTUAL HYDROLOGICAL MODEL

The subsoil reservoir water storage S [mm] is calculated as:

$$S_i = S_{i-1} + J_1 - J_2 - J_3 \tag{5}$$

where J_2 [mm/hr] is the flow that leaves the subsoil reservoir and enters the river (i.e. $J_{2\_hill} = Q_{hill}$ and $J_{2\_field} = Q_{field}$), J_3 [mm/hr] is a deep leakage term that is lost from the catchment. J_2 is assumed to be a nonlinear function of the subsoil reservoir storage:

$$J_2 = \begin{cases} K_1(S_{i-1} - S_{thres})^{K_2} & \text{, if } S_i \geq S_{thres} \\ 0 & \text{, if } S_i < S_{thres} \end{cases} \tag{6}$$

The parameter K_1 is a measure of how easily water is released from the storage S once the water level in this storage is above S_{thres}. K_1 is in this way similar to a hydraulic conductivity in Darcy's law. It should be noted that $1/K_1$ is typically referred to as the residence time. At low values of K_1, the water level will build up in the storage S (above S_{thres}) until a head difference is reached that is large enough to balance the inflows and outflows.

The exponent parameter K_2 determines whether the release of water from storage S is linear (K_2=1) or non-linear ($K_2 \neq 1$) once the water level in the store exceeds S_{thres}. When $0 < S_i - S_{thres} < 1$, more water is released from the store when $K_2 < 1$ resulting in a slower build-up of water in the storage, while the opposite is true when $S_i - S_{thres} > 1$.

The deep leakage loss from the subsoil reservoir J_3 is assumed to be constant:

$$J_3 = K_3 \tag{7}$$

Based on the equations above, the total discharge is calculated as follows:

$$Q = A_{R\_hill}J_{2\_hill} + A_{R\_field}J_{2\_field} + A_{R\_direct}J_{1\_direct} \qquad (8)$$

Note that the direct flow component does not include a subsoil reservoir and hence is based on J_1.

The flow model has been coded in R.

Model analysis and scenarios

A few simple modelling scenarios have been carried out to explore the effect of the different model parameters on the simulated flows and storages. All simulations below have been carried out for a single compartment.

Scenario 1. AET>P (falling limb): Following a long, wet period it is assumed that both P and AET are constant and AET>P. This means $J_1=0$ while SMD will become increasingly negative. The water storage S will in this case decline as follows:

$$S_i = S_{i-1} - K_1(S_{i-1} - S_{max})^{K_2} - J_3$$

or

$$\frac{dS}{dt} = -K_1(S - S_{max})^{K_2} - J_3$$

If the initial water storage at is S_{ini} ($S_{ini}>S_{max}$) and $K_2=1$ (i.e. linear release), the water content S and the outflow J_2 from the S will decline exponentially at a first-order rate equal to K_1:

$$S(t) = S_{max} - \frac{J_3}{K_1} + \left(S_{ini} - S_{max} + \frac{J_3}{K_1}\right) \exp{(-K_1 \mathrm{t})}$$

and

$$J_2(t) = K_1\left(S_{ini} - S_{max} + \frac{J_3}{K_1}\right) \exp{(-K_1 t)} - J_3$$

This means that if we plot the falling limbs of the river discharge, these should according to the model display an exponential decline. However, it should be noted that this will only be the case if $K_2=1$ and river discharge was modelled using a single compartment. The model simulates the river discharge as the sum of three compartments, so even if $K_2=1$ for both the hill and the field compartment, the sum will not necessarily display an exponential decline.

Figure 21 shows how the outflow J_2 and storage from a single compartment will decline for different values of K_1 and K_2. The figure demonstrates how the decline in outflows deviates from the exponential decline when K_2 is different from 1.

Scenario 2. P> AET following dry period (rising limb): If both P and AET are constant and P>AET following a dry period, then the delay in response seen in the river discharge should reflect the build-up in SMD and losses from S during the dry period. Once S reaches S_{max}, the outflow J_2 from the storage S will increase depending on the values of K_1 and K_2.

$$\frac{dS}{dt} = J_1 - K_1(S - S_{max})^{K_2} - J_3$$

If $K_2=1$ (i.e. linear release), the water content S and the outflow J_2 from the S will increase as follows:

$$S(t) = S_{max} + \frac{(J_1 - J_3)}{K_1}(1 - \exp{(-K_1 \mathrm{t})})$$

and

$$J_2(t) = (J_1 - J_3)(1 - \exp{(-K_1 \mathrm{t})})$$

Note that if the wet period continues indefinitely, all flows and storages will eventually reach a steady state situation, where:

$$J_{2,steady} = J_1 - J_3$$

$$S_{steady} = \left(\frac{J_1 - J_3}{K_1}\right)^{1/K_2} + S_{max}$$

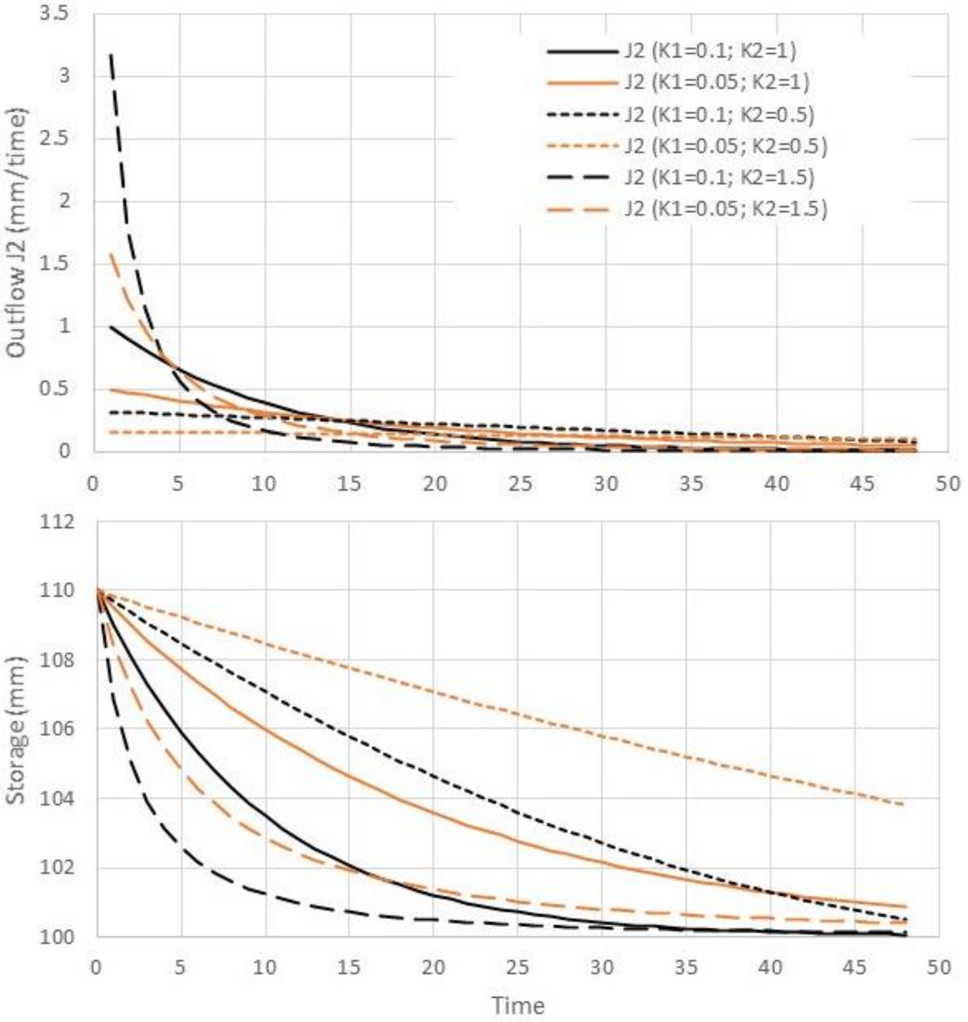


FIGURE 21. MODEL SIMULATION OF OUTFLOW (J_2) AND STORAGE (S) DURING 'FALLING LIMB' FOR DIFFERENT VALUES OF K_1 AND K_2. FOR THE SIMULATIONS, THE INITIAL WATER STORAGE IS 110 MM, S_{MAX} IS 100 MM, K_3=0 AND J_1=0 MM.

Figure 22 shows how the outflow J_2 and storage from a single compartment will increase for different values of K_1 and K_2 during a wet period following a dry period. The figure illustrates how the outflow from the compartment does not start until the water storage reaches S_{max} (after about 16 hrs). It also shows that a steady-state situation will be reach quicker for higher values of K_1 (i.e. lower residence times in S) and K_2.

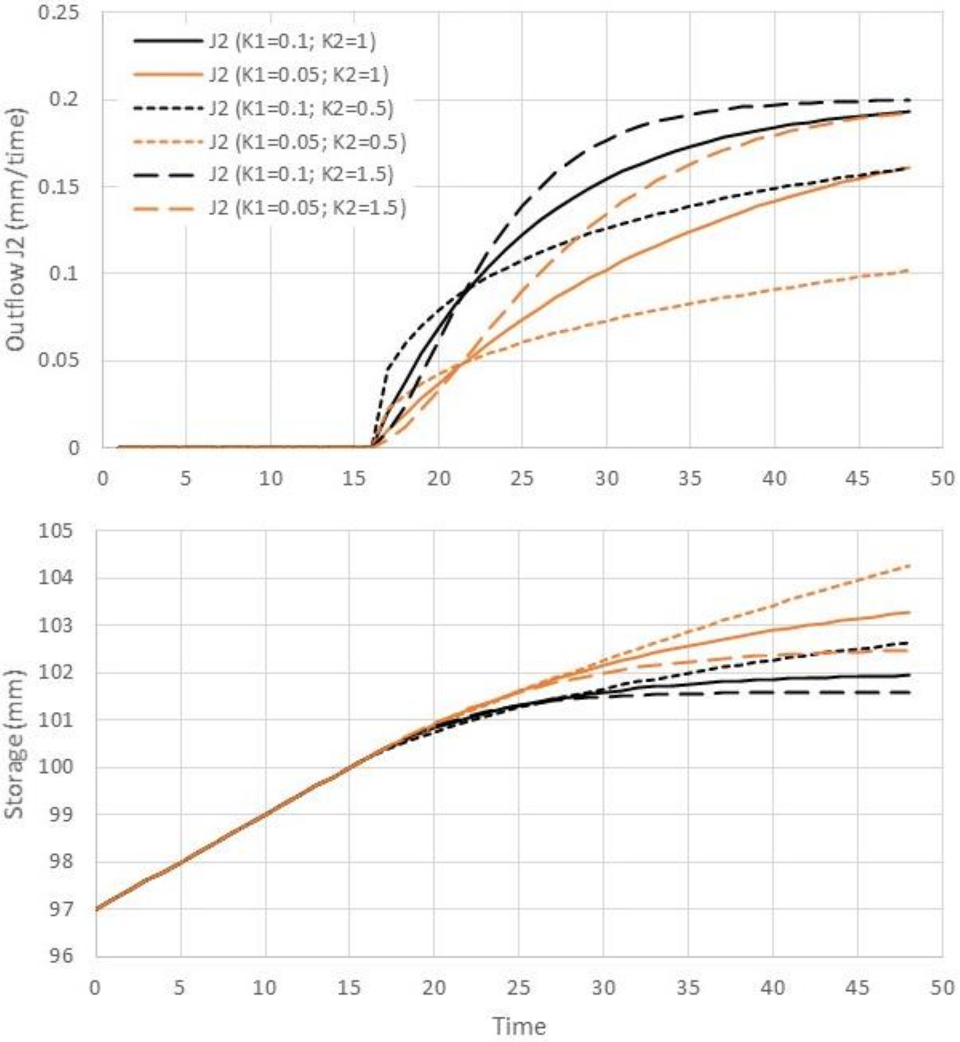


FIGURE 22. MODEL SIMULATION OF OUTFLOW (J_2) AND STORAGE (S) DURING 'RISING LIMB' FOR DIFFERENT VALUES OF K_1 AND K_2. FOR THE SIMULATIONS, THE INITIAL WATER STORAGE IS 97 MM, S_{MAX} IS 100 MM, K_3=0 AND J_1=0.2 MM.

Model calibration

The hydrological model has been set up for Wemyss and Westerton, and calibrated with the observed hourly data from 2019-2020. The Nash-Sutcliffe efficiency coefficient was used as the main objective function for the calibration, but we also take into account the total water balance between observed and modelled flows, the maximum flows and the replenishment of subsoil deficits in autumn as the SMD declines to near zero.

Figure 23 shows (a) the results for the whole modelled period from 1/1/2019-15/11/2020, (b)for the calibration period of the model (1/8/2019-1/12/2019) for Wemyss, and (c) for the validation period (1/9/2020-1/11/2020). Figure 24 shows the same plots for Westerton. Table 12 gives coefficients and Nash Sutcliffe statistics and water balance for these periods.

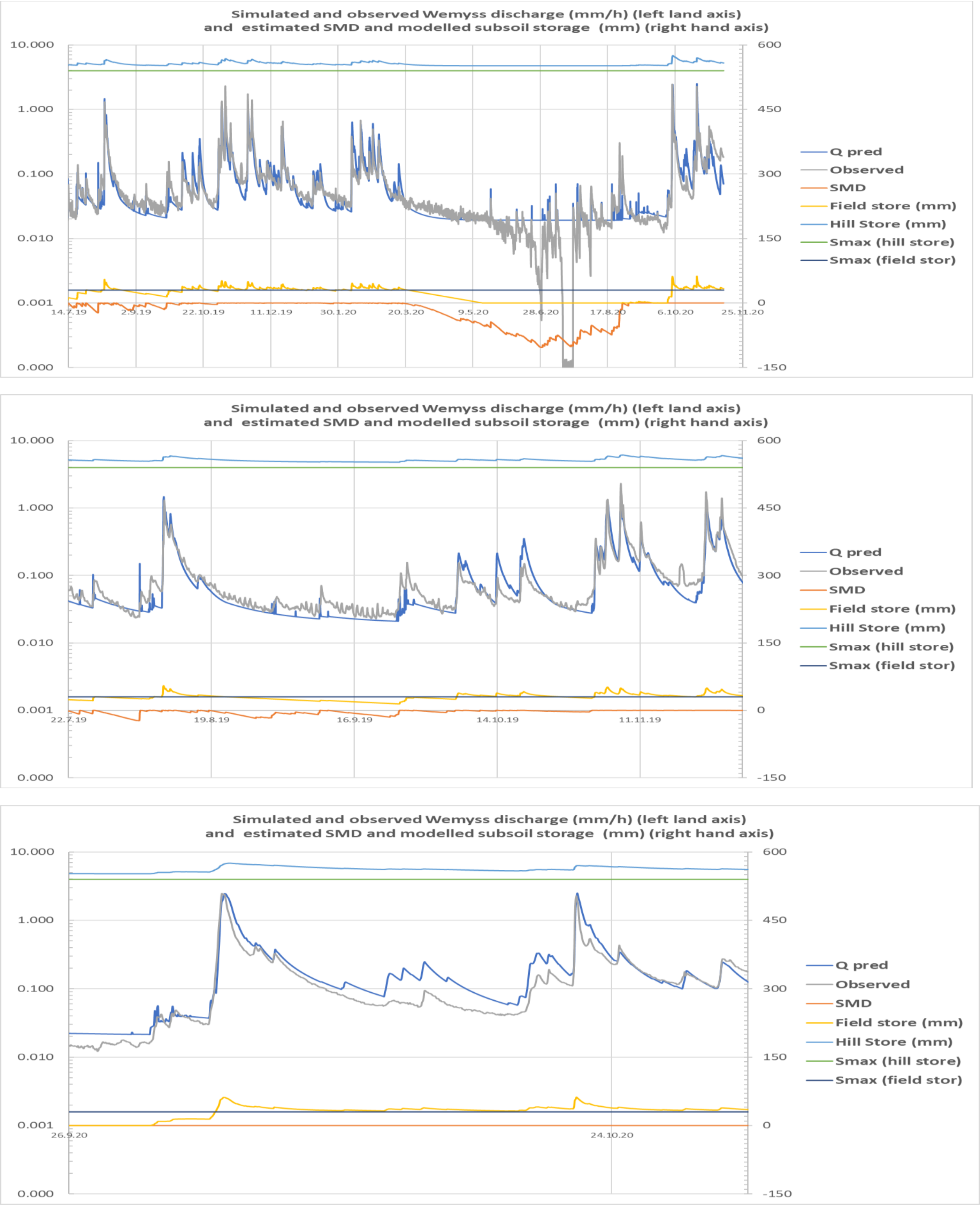


Figure 23 Simulated and observed hourly flows at Wemyss. (a) the results for the whole modelled period from 1/1/2019-15/11/2020, (b)for the calibration period of the model (1/8/2019-1/12/2019) for Wemyss, and (c) for the validation period (1/9/2020-1/11/2020).

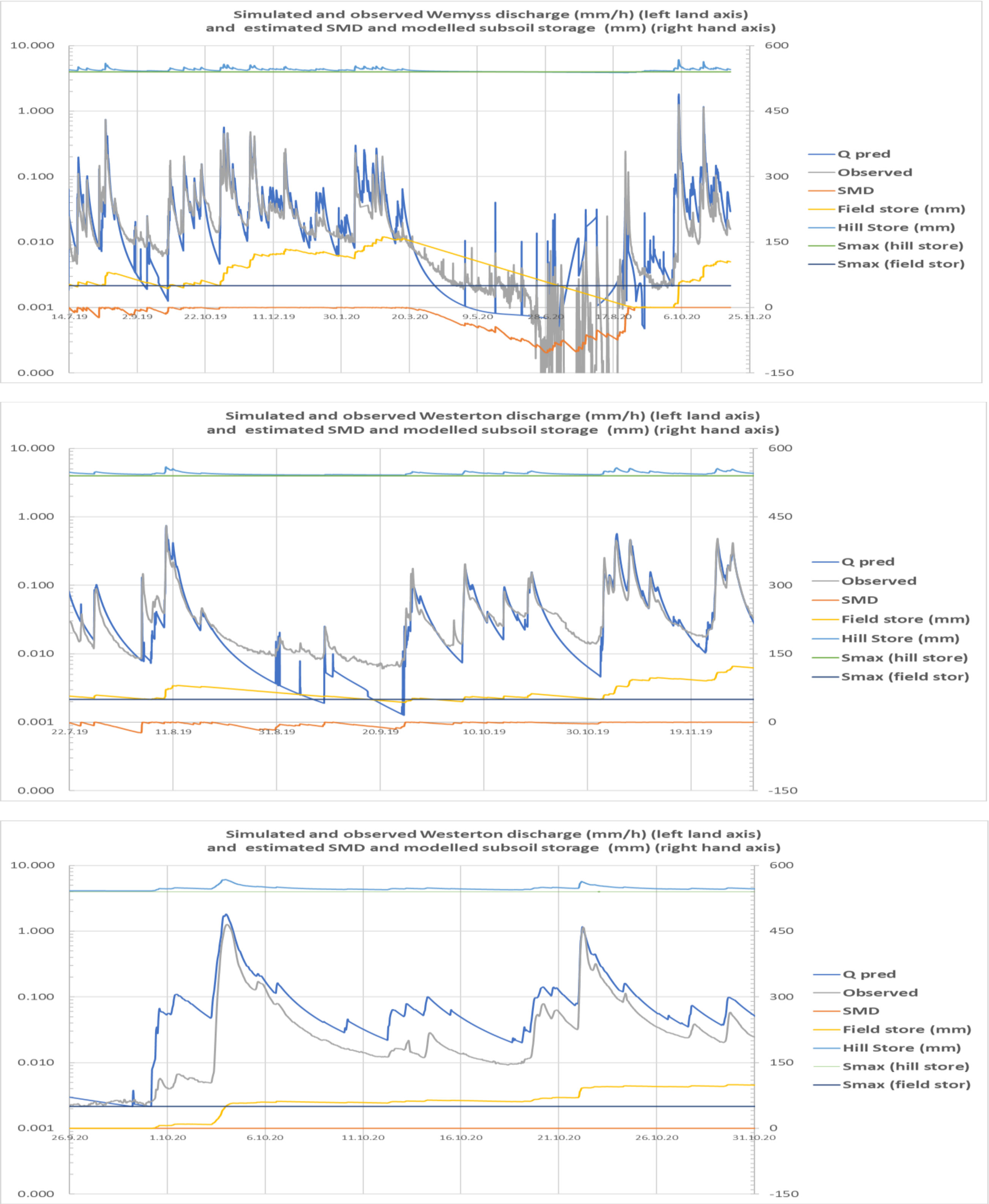


Figure 24. Simulated and observed hourly flows at Westerton. (a) the results for the whole modelled period from 1/1/2019-15/11/2020, (b)for the calibration period of the model (1/8/2019-1/12/2019) for Westerton, and (c) for the validation period (1/9/2020-1/11/2020).

Table 9. Parameter values and modelling statistics for simple hydrological model of flows at Wemyss and Westerton for use in forecasting water levels and flows in Upper Lunan Water with HECRAS hydraulic model.

Parameter		**Wemyss**	**Westerton**
A_{R_hill}		0.24	0.44
S_{max_hill}		540	540
K_{1_hill}		0.0006	0.001
K_{2_hill}		2	2.5
K_{3_hill}		-0.08	0.002
A_{R_field}		0.75	0.55
S_{max_field}		30	50
K_{1_field}		0.003	0.001
K_{2_field}		2	0.1
K_{3_field}		0.03	0.07
A_{R_direct}		0.01	0.01
Nash Sutcliffe statistic	Calibration Period (1/8 – 1/12/2019)	0.79	0.87
	Whole period (1/8/2019 – 1/11/2020)	0.77	0.76
	Validation Period (1/9/2020-1/11/2020)	0.77	0.75
Water Balance Pred/Obs	Calibration Period (1/8 – 1/12/2019)	0.92	1.02
	Whole period (1/8/2019 – 1/11/2020)	1.07	1.27
	Validation Period (1/9/2020-1/11/2020)	1.25	1.69

8. Forecasting of water levels and flows

Capture of forecast rainfall data

A major objective of this project was to use the calibrated hydrological model for forecasting the input stream discharges and use these forecasted flows as input for the hydraulic model, thereby providing a live service for forecasting water levels and flooding risk in the Upper Lunan and an alerting tool for active management of flow routing.

To do this, the hydrological model is run using weather forecast data from the Met office's UK Atmospheric Hi-Res Model (UKV model), which is a post-processed regional downscaled configuration of the Unified Model, covering all of the UK and Ireland. The UKV model resolution is 0.018 degrees (approximately 2 km), and it is run every 3 hours (i.e., 8 times per day). Each forecast data file contains hourly forecast data covering the period T+0 to T+48 hours and then becomes 3-hourly from T+48 to T+54 (extended to T+120 for the model runs done at 3am and 3pm UTC) for the following variables: 1.5m temperature; 1.5m dew point; 1.5m visibility; 1.5m fog probability; 1.5 m relative humidity; 10m wind speed; 10m wind direction; mean sea level pressure; total precipitation accumulation; total precipitation rate; snow fraction; and surface (skin) temp. The UKV model projection is OS National Grid which has been encoded in GRIB2 format as transverse Mercator.

For the modelling of the river discharge, only the forecasted air temperature and rainfall accumulation are needed. The loading and processing of the UKV model projection files and the subsequent flow forecasting have been automated in R as follows:

1. *Run hydrological model with "historical" weather data*: Historical/live weather data up until present day are recorded from a gauge in the Lunan catchment and are accessed from the *Timeview Telemetry* site. These data are loaded, processed and used as input for the flow model to calculate the river discharges and water balances up until present day. This step is needed to determine the initial state values (i.e., SMD and soil storage S) for the forecast modelling.
2. *Load and process UKV model data*: The UKV projection file from 3pm (chosen because it covers a 5-day period into the future) on a given day is loaded from a Met Office ftp server and the relevant weather forecast data are then extracted from the grid cells covering the Lunan catchment (see Figure 25). The actual evapotranspiration (AET) rates are calculated using the forecasted temperature data and the model by [10]. Finally, the area-weighted rainfall and AET are calculated for each sub-catchment in the Upper Lunan.
3. *Run model with forecasted weather data*: The forecasted rainfall and AET data are used as input for the hydrological model (and with initial states as determined in step 1) to calculate the 5-day forecast of the river discharges in Wemyss and Westerton. The forecasted flows are saved and later used as input for the hydraulic model.

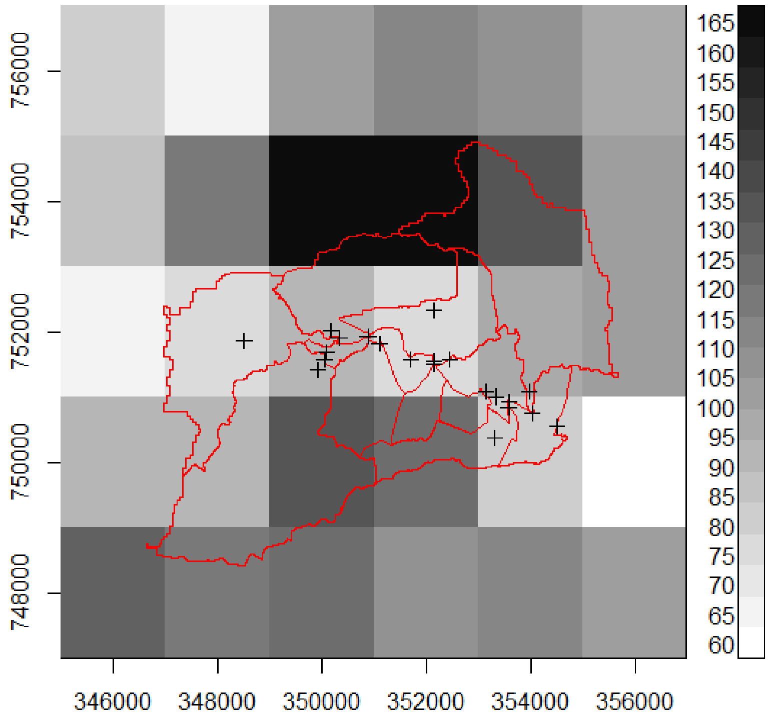


FIGURE 25. ***MAP SHOWING THE UKV MODEL TOPOGRAPHY GRID AND THE UPPER LUNAN SUB-CATCHMENTS.***

Comparison of forecast and observed water levels and flows

The forecasting element of the model is an important objective of the work. This could enable management decisions to be made, particularly based on the alert level for Rescobie Loch. To assess the performance of the combined hydrological-hydraulic model, we have two comparisons left to make:

A. HECRAS simulations of water levels in Rescobie and Balgavies Loch using (a) observed flows (we have used plan 84 simulations - see Table 4 – as this gives the best fit to high water levels at Rescobie Loch) (b) simulated Wemyss and Westerton Flows for Aug 2019-Oct 2020 using observed rainfall (ie from the raingauge in the catchment).

B. HECRAS simulations of water levels in Rescobie and Balgavies Loch using (a) Met. Office rainfall forecast to generate flows, (b) Catchment raingauge rainfall forecast, (c) Observed flows at Wemyss and Westerton. This comparison can only be done for a hydrological event period when we have an archive of Met. Office rainfall, namely Dec 2020.

Comparison of simulated water levels using observed flows and hydrological model flows.

Table 10 shows the Nash-Sutcliffe statistics comparing simulated and observed water levels in the two lochs, for the same periods as used in Table 4. Two options for the area multiplier (35.6 or 31.6 km^2), and two options for the source of inflow estimation (observations or hydrological forecast model) for the HECRAS simulations are shown.

Table 10. Comparison of statistics for simulation of Rescobie and Balgavies levels using hydrological forecasting model to simulate Wemyss and Westerton flows (Plan 03 and Plan 04) or simulations using observed Wemyss and Westerton flows (Plan 85 and Plan 84). Plan 03 and Plan 85 assume a 10% higher area multiplier (35.6km^2) than Plan 84 and Plan 03. a. Nash-Sutcliffe statistics comparing observed vs modelled water levels. Colour code: red for >0.7.b. Peak water levels for 3 storm events in 2019-2020. Colour code ranks observed and simulated results for each Loch and event, red high,yellow middle, green low.

a.		Rescobie	Rescobie	Rescobie	Rescobie	Balgavies	Balgavies	Balgavies	Balgavies
from	to	Plan 85	Plan 03	Plan 84	Plan 04	Plan 85	Plan 03	Plan 84	Plan 04
Overall multiplier (km2)		35.6	35.6	31.6	31.6	35.6	35.6	31.6	31.6
Observed or hydro model inflows		Observed	Modelled	Observed	Modelled	Observed	Modelled	Observed	Modelled
01/08/2019	30/09/2019	0.94	0.80	0.88	0.61	0.88	0.70	0.92	0.48
30/09/2019	28/10/2019	0.73	0.40	0.35	0.45	0.78	0.38	0.37	0.43
28/10/2019	23/11/2019	0.89	0.89	0.96	0.93	0.93	0.90	0.81	0.83
23/11/2019	17/12/2019	0.81	0.83	0.82	0.62	0.51	0.43	0.41	0.30
17/12/2019	08/01/2020	-0.08	-0.08	-0.08	-0.06	-0.08	-0.09	-0.10	-0.08
08/01/2020	05/02/2020	-0.09	-0.03	-0.08	-0.03	-0.12	-0.08	-0.15	-0.07
05/02/2020	01/03/2020	0.88	0.73	0.69	0.87	0.68	0.85	0.82	0.84
01/03/2020	17/07/2020	0.84	0.77	0.83	0.76	0.89	0.84	0.89	0.73
17/07/2020	14/08/2020	0.23	0.02	0.24	0.04	0.37	0.11	0.21	0.28
14/08/2020	27/09/2020	0.46	-1.61	0.47	-2.08	0.67	-3.80	0.33	-1.73
27/09/2020	29/10/2020	0.94	0.78	0.91	0.90	0.93	0.92	0.91	0.95

b.									
HECRAS simulation of event peak maxima (m asl)		Rescobie Plan 85	Rescobie Plan 03	Rescobie Plan 84	Rescobie Plan 04	Balgavies Plan 85	Balgavies Plan 03	Balgavies Plan 84	Balgavies Plan 04
Observed levels	12/08/2019	59.99				59.84			
HECRAS model	12/08/2019	60.00	60.09	59.93	59.99	59.78	59.82	59.78	59.79
Observed levels	08/11/2019	60.06				59.91			
HECRAS model	08/11/2019	60.19	60.16	60.08	60.07	59.88	59.86	59.87	59.83
Observed levels	06/10/2020	60.01				59.85			
HECRAS model	06/10/2020	60.17	60.32	60.05	60.18	59.89	59.98	59.85	59.95

It can be seen that for some periods a loss of predictive power is shown when the simulated Wemyss/Westerton flows are used, but particularly for periods with large events (e.g. Aug 2019, Nov 2019 and Oct 2020, there is good retention of predictive power when the hydrological model, instead of observed flows are used. The simulation of low water levels is still problematic, and of course the period when a log jam blocks flow is not simulated well by either modelling approach.

The prediction of peak water levels (and duration of these levels) is important for forecasting risk of flooding problems. For the 3 events tabulated, Plan 84 does a good job (discrepancy of 0.1m or less), and this is retained for Plan 04 where the hydrological forecast has been used, except for the 6/10/2020 event. This discrepancy is likely due to underestimation of the Soil Moisture Deficit, wil be particularly important for the first storm event after return to field capacity. The use of the smaller multiplier (31.6 instead of 35.6km^2) helps improve the simulations for the autumn events, but the summer event in Aug 2019 is better simulated with the larger multiplier.

Given the significant uncertainties associated with many elements of calibrating the combined hydrological forecasting/HECRAS hyraulics models, the results for Plan 04, we propose, would form the basis for a live forecasting model to make available to stakeholders to aid management.

Comparison of Met.Office forecast rainfall with raingauge and measured flows.

Figure 26 shows the cumulative rainfall based on the Balgavies rain gauge, compared with 1d and 5d forecasts. Archiving of forecasts began on 21/10/2020, so there are no 5d forecasts till 26/10/2020, so Figure 26b plots begin on this date. Note that there was a very large observed event on 22 October, the magnitude of which was poorly forecast by the 1d forecast. The event on 4/12/2020 was better forecast by the 5d forecast than the 1d forecast. The event in Feb 2021 was well forecast by both the 5d and the 1d forecast. Overall, the 5d forecast underestimated rainfall by about 20%.

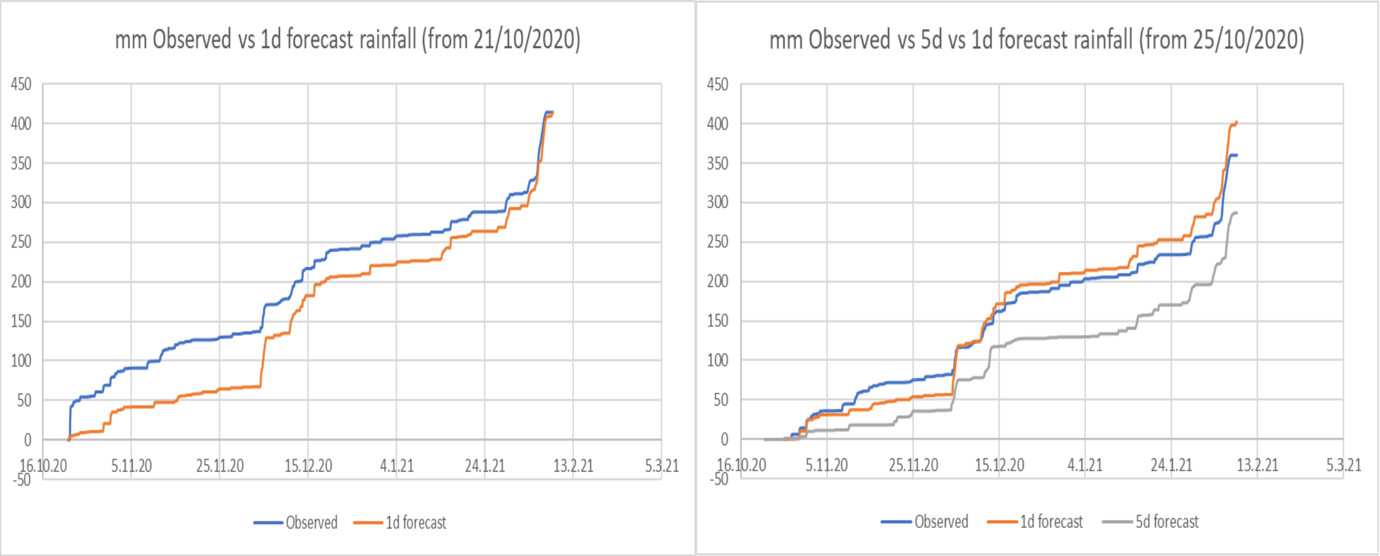


Figure 26. Cumulative rainfall during Oct 2020-Feb 2021.a. Rainfall observed by the Balgavies raingauge b. Rainfall from the 1d forecast c. Rainfall from the 5d forecast.

Computation and presentation of historical and forecast mode model results in real time.

Processes for creating streams flow and loch levels chart for webpage

The charts on the webpage show rainfall and simulated and observed Loch levels and stream flows. The processes for plotting the charts start with collecting stream levels, air temperature, rainfall and processed stream flows data from appropriate websites and computers servers. The flow data after a further processing are saved in a database which is used by HEC-RAS, a hydraulic flow simulation package to generate simulated flows and levels. Lastly the simulated flows and levels, and rainfall data are plotted to create the online charts. This processing was done using Python programming language and Matplotlib package for plotting the charts. This report briefly explains these three main steps for creating the charts for the webpage.

Data gathering

Water level and air temperature from the Westerton water data monitoring site which are transmitted to a computer server at the Institute, are picked up. Stream flow for Westerton is computed from water level using level-discharge relationship earlier established. Rainfall and Balgavies Loch level data are downloaded from the webpage. The data are then resampled with 15 minutes to one hour frequency. The Westerton and Wemyss simulated flow data, derived from processed from Met office forecast data and/or catchment raingauge data, are also picked up from where they are stored on the network computer.

Flow and level simulation

The Westerton and Wemyss hourly flows data are firstly lagged separately by 1, 2, 4 and 8 days and then moving average for 1, 2, 4 and 8 days of each are computed. These lagged data files and the hourly data files of both streams are saved into HEC-DSS, a database system for use with HEC-RAS flow simulation package.

HEC-RAS Controller, one of the Application Programming Interfaces (API) of HEC-RAS is called to run a prepared project setup on the flow data files saved as HEC-DSS. After the run, the simulated flows and levels are extracted from output file generated during the run.

Data plotting

Two groups of river variables, along with rainfall and observed Balgavies Loch levels are simulated rivers flow and level obtained from HEC-RAS run are plotted as line charts. The simulated river variables are Balgavies Loch Outlet Flow, Flow in Lunan downstream of lade and Balgavies Burn flow, and water levels at Lochs Balgavies and Rescobie. Observed Rainfall amounts are also plotted.

Historic data for the variables mentioned are calculated and plotted once whilst a similar plot for current and forecast data is done every day. These line charts are saved onto a network computer which are picked up at scheduled time to location for display in the webpage.

Figure 27 shows an example of simulations of water levels and flows of the period from 1 August 2020 to 7 Nov 2020. Note the last 5 days are based on flows simulated using the distributed Met. Office forecast of rainfall, not the observed rainfall from the catchment rain gauge. This is updated daily (not weekends) to the project website https://www.hutton.ac.uk/research/projects/payments-ecosystem-services-lessons.

Note that observed Balgavies Loch data (the blue line) is usually available live, but a battery failure on the telemetered water level logger means data are missing from 9 October 2020 to early February 2021. Note also, that work is underway to full automate the procedure.

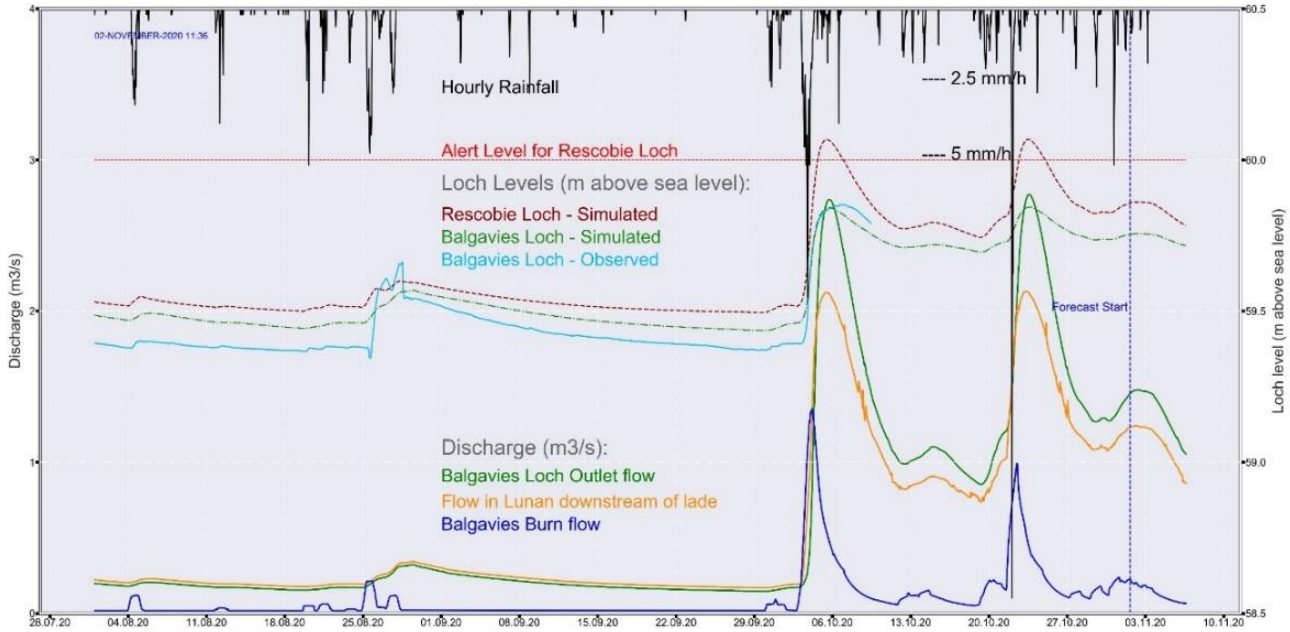


FIGURE 27. EXAMPLE OF PROJECT WEBPAGE DISPLAY SHOWING SIMULATED AND OBSERVED WATER LEVELS IN BALGAVIES AND RESCOBIE LOCH, SIMULATED FLOW IN BALGAVIES BURN, AND FORECAST WATER LEVELS AND FLOWS FOR 5 DAYS FROM PRESENT TIME.

See also: **https://www.hutton.ac.uk/research/projects/payments-ecosystem-services-lessons#**

Representing uncertainty

The model simulations depend on a large number of parameters and input data which contain significant uncertaintly. It would be very difficult to carry out rigorous uncertainty analysis across all these parameters, and a Bayesian approach is beyond the scope of the current project. However, we have identified two factors which have an influence, and whose range of potential values could be examined more closely in future, namely effective catchment area (a summary value which is proxy also for rainfall/other water balance elements), and the Manning n value for the reach immediately below the exit of Balgavies loch, the so called “sluggish section” Reach. We have determined empirical functions which describe the sensitivity of model outputs to these two values, and an example for Rescobie Loch, in the period represented in Figure 26, is shown in Figure 28. We suggest that the bounds of the modelled output show an indication of the range of likely “true” values,and put the differences between observed and simulated values into perspective. These bounds can readily be calculated without the need to run multiple model simulations, are are therefore considered useful for display on the webpage forecast. Note that the effect of the Manning coefficient is largest at lower flows, while the effect of the area multiplier is largest at high flow. The impact could be calculated separately if required.

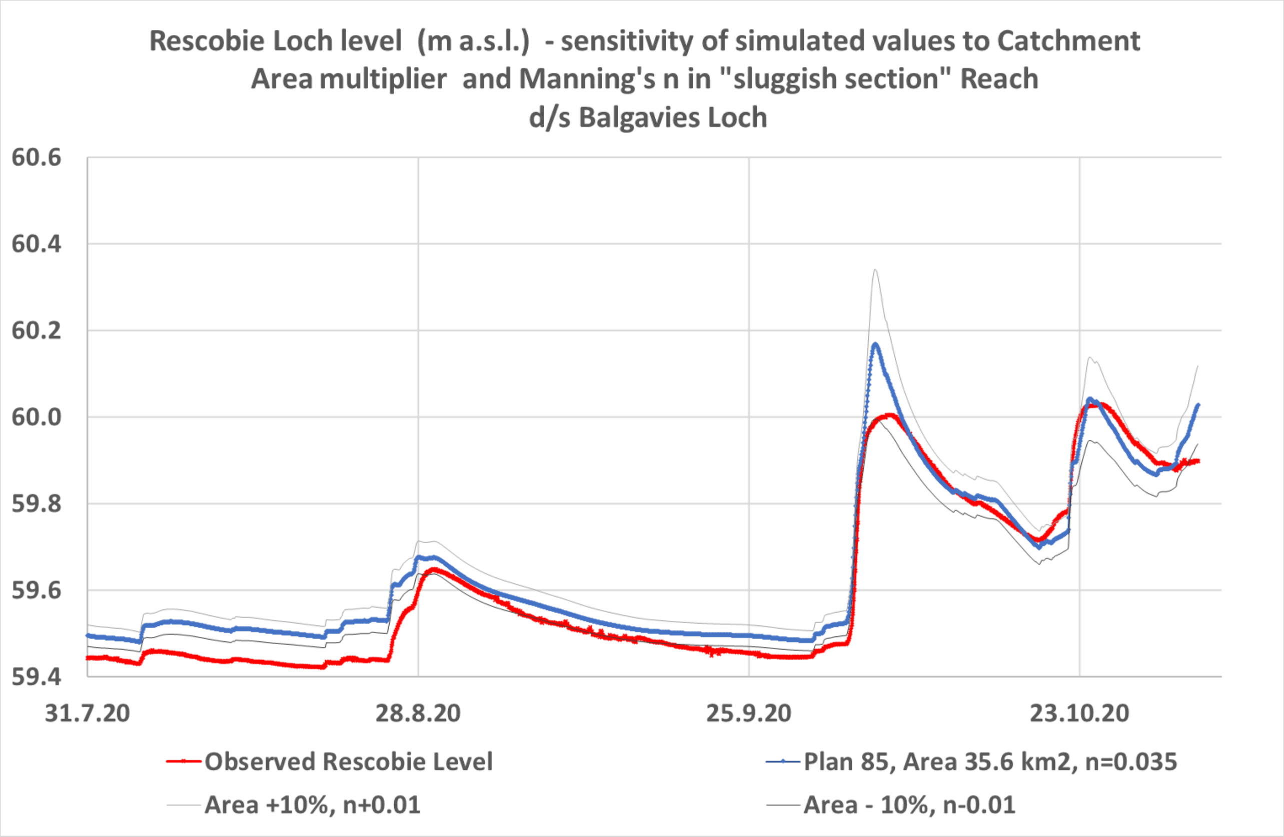


FIGURE 28. SENSITIVITY OF SIMULATED VALUES OF RESCOBIE LOCH LEVEL (M ASL) TO CATCHMENT AREA MULTIPLIER AND MANNING'S N IN "SLUGGISH SECTION" REACH (D/S BALGAVIES LOCH) IN HECRAS.

Validation of forecasting version of hydrological/hydraulic model of upper Lunan Water

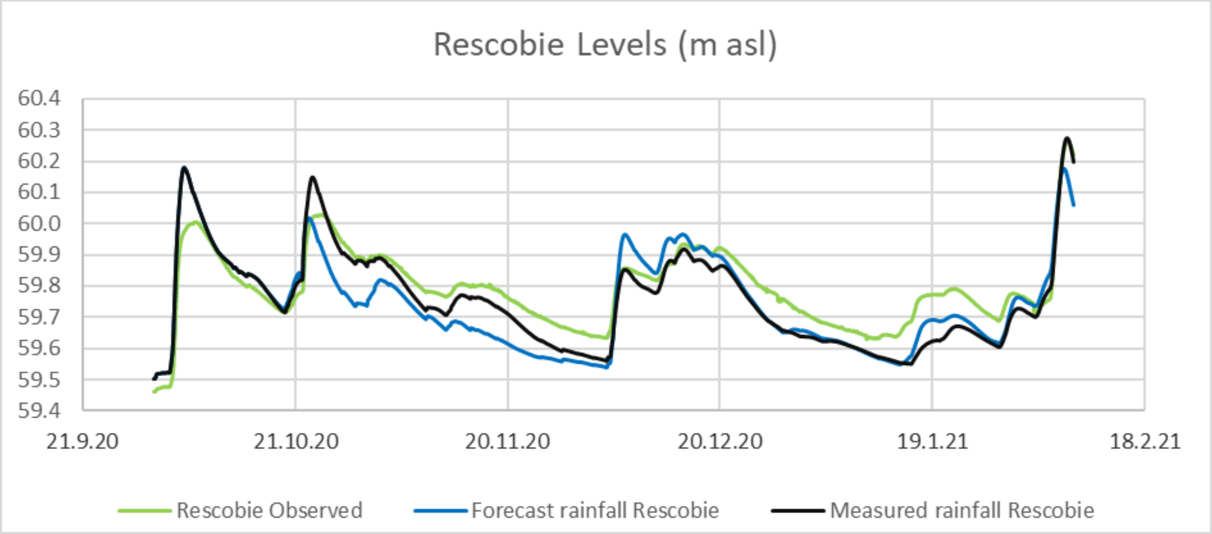
Figure 29 shows the observed water levels in Balgavies and Rescobie Lochs over Oct 2020-Feb 2021 compared with results of simulations with the hydrological model using 2 alternative assumptions:

a. **Rainfall observed by the Balgavies raingauge**
b. **Rainfall from the 1d forecast**

The Nash Sutcliffe coefficients have also been calculated and these are summarised in the Table below.

	Measured R	Measured R	1d Forecast R	1d Forecast R
	Balgavies	Rescobie	Balgavies	Rescobie
Nash-Sutcliffe	0.72	0.78	0.55	0.62

We see that some of the modelling power is lost by using the forecast rainfall, and this emphasises the value of having live site rainfall for input to any hydrological modelling exercise. Note that in this work, the live site rainfall is being used where available, so the forecasted rainfall is only needed for a maximum of 5d, so cumulative effects of using forecast data will not build up. We also see that whereas at the start of the winter, the forecasted water levels were higher than observed, for the recent February 2021 event, the observed water levels were higher, especially at Balgavies Loch. This is suggestive of higher Manning coefficients, perhaps related to higher antecedent water levels in Chapel mires. See picture of condition of the Lunan Water sluggish section reach and proximal part of Chapel Mires in February 2021 (Figure 30).



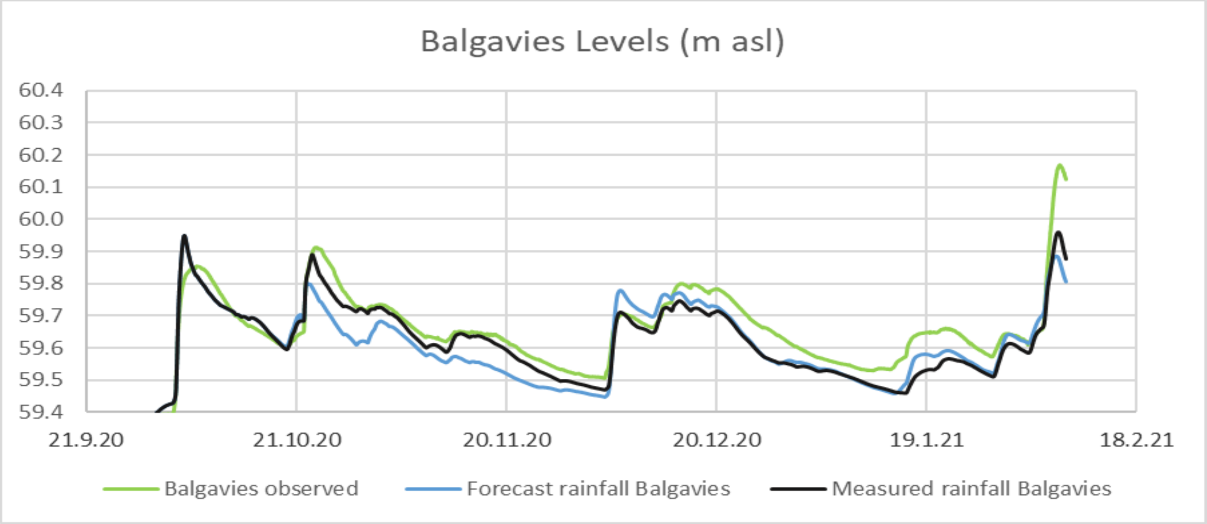


FIGURE 29. OBSERVED WATER LEVELS IN BALGAVIES AND RESCOBIE LOCHS OVER OCT 2020-FEB 2021 COMPARED WITH RESULTS OF SIMULATIONS USING THE HYDROLOGICAL MODEL USING 2 ALTERNATIVE ASSUMPTIONS: A. RAINFALL OBSERVED BY THE BALGAVIES RAINGAUGE B. RAINFALL FROM THE 1D FORECAST

FIGURE 30. LUNAN WATER SLUGGISH SECTION D/S BALGAVIES LOCH EXIT SHOWING SPILLAGE OF WATER INTO CHAPEL MIRES OVER AN EXTENDED LENGTH OF THE REACH. FEBRUARY 6TH 2021.

9. Conclusions and further work

Delivery of modelling objectives

Objective 1. To analyse impacts of weather/inflow on water levels, flood risk, low flows and water routing in the catchment

Validation of the calibrated model and analysis of impact of inflows on water levels has been achieved (see Figure 10). The historic version of the model, using observed inflows, shows a good agreement with observations of water levels in Rescobie and Balgavies lochs. Considering the likely range of uncertainty of rainfall and Manning roughness coefficients, simulations are within the bounds to be expected. Where simulations deviate systematically from observations (e.g. during the Dec 2019-Jan2020 period), these can be explained by the presence of logjams in the river channel. This deviation between observed and simulated water levels could in future be used as a trigger to highlight the need for practical intervention in water management.

While the validation of the flow routing aspects of the model is not feasible due to shortage of observed data, the simulations generate plausible results which fit with qualitative observations.

The simulation of outflow from Balgavies Loch is very dependent on the effective Manning coefficient downstream of the loch, and further work might focus on direct measurement of this, along with the impacts of potential management interventions.

Objective 2. To explore impact of existing/potential hydraulic management options on water levels and water routing.

Exploration of scenarios of hydraulic management has been achieved (see Figure 17).

The historic model calibration provides the basis for some level of certainty about the modelled impact of existing and potential hydraulic management. The scenario analysis points to the rather low impact of installation of a tilting weir on upstream water levels, whether this were to be installed in either Reach 1 or Reach 2 of the Common Lade. However it also points to larger impact on water levels if dredging/vegetation management or other interventions that affect the Manning coeficient downstream ofBalgavies Loch are undertaken, in conjunction with tilting weir installation. It also shows that flow routing could be significantly impacted by a tilting weir, or by reinstatement of the blocked spillway downstream of the current spillway (see Figure 11), especially if combined with local dredging and/or vegetation management.

The modelling tool has potential for exploring impacts of other scenarios of hydraulic management, as well as of climate or land use change, in the context of multi-objective water management for flood risk, wetland conservation and low flow management. This could underpin a more science-based adaptive management at a catchment scale in future.

Objective 3. To provide a live service forecasting future water levels based on Met.Office 5d forecasts and showing past levels

The provision of a live forecasting service has been achieved (see Figure 27).

The modelling tool can now run in a semi-automated way to provide insight into past, present and future water levels, based on telemetered and forecast input data on stream flows and weather. Maintenance of this service will cost little more than the £500/year payment for Met.Office inputs, although interpretation and troubleshooting requires continued input from JHI hydrologists.

Objective 4. To develop an alerting system for stakeholders using 1 and 2.

This has been proposed as a year 6 objective for the current PESLES project, given the extension of funding in the current Scottish Government Strategic Research Programme (SRP) to 2021/2022 due to COVID. However, it might also form one of a potential suite of smart alerting measures to be explored in the new programme, post 2022.

Uncertainty in model outputs in the context of management

Uncertainties in model inputs and therefore in model outputs are hard to quantify for risk management. However, if model outputs could be organised into an empirical metamodel (as was done for steady state conditions in [1], then it would be much easier to quantify the impacts of input uncertainties. This might for a useful objective, along with development of a Bayesian statistical approach, in a next phase of development of the management tool.

Timing of development of the model in the context of project management.

Developing a working model of the hydrology/hydraulics has been a major undertaking, taking several years to complete. The conclusions would have been valuable earlier in the process of stakeholder engagement (ie with the Lunan catchment management group, and with local farming, wetland conservation and riparian interests). However, these delays have led to a compromise proposal that may have a stronger chance of adoption than would have been the case if the modelling work pointed to the value of a tilting weir for flood risk alleviation upstream, and not just to potential for ecological conservation. **Note that acceptance, in principle, of action to restore the blocked spillway shown in Figure 11, was given by riparian owners and Nature Scotland on the 31st March 2021.**

Next steps in stakeholder engagement

The project now enters a further phase of engagement with stakeholders. Previous stakeholder engagement has:

a. Explored through survey the willingness to pay/willingness to accept a Payment for Ecosystem Services scheme based around smart management of a tilting weir for 3 management objectives (flood risk, ecological conservation, low flow management), with local population, farmers and riparian owners;
b. Assessed qualitiatively through interviews and survey, preferences for different options for governance of hydraulic structures/flow management;
c. Discussed with statutory agencies, local council and farming and wildlife organisations the issues of catchment management in the Lunan Water, through a catchment group;
d. Facilitated implementation of consultant-led sediment mitigation plans and measures in the catchment.

In the context of the project, the proposals outlined in section 6 will now be taken forward:

a. Through the Lunan catchment management group
b. Through discussion with riparian owners, Scottish Wildlife Trust and Nature Scotland
c. Through liason with water envoronment consultants (e.g. Lockett Environental; Moir Environmental) who are already developing work on rural SUDS schemes in the upper Lunan Catchment.

Discussions will include consideration of a potential proposal to the Water Environment Fund or te Biodiversity Action Fund to re-instate the original engineered spillway downstream of Balgavies Loch.

The background and outcome of these discussions will then be communicated to national stakeholders through a workshop organised to highlight the opportunities and challenges of developing Water Ecosystem Services schemes in (a) the Lunan Water (b) Loch Leven catchment (c) elsewhere.

Future research and knowledge gaps in modelling

Key areas where the modelling framework needs further development include:

a. Improved watercourse and floodplain cross section survey, for example between the two lochs;
b. Real time surveying of water levels and flows in longitudinal transects of the main channel of the Lunan Water;

both these actions will help to improve estimation of Manning coefficients;

c. Improved representation of groundwater inputs, possibly focusing on piezometric measurements in the zone peripheral to the wetlands; Appendix 1 describes work to date on trying to establish functions to describe groundwater input to the lochs; One calibration of the hydraulic model in our archive makes use of these functions; (eg..\Backup\upperlunan2.g21,..\Backup\upperlunan2.u17)
d. Improving hydraulic model stability through better interpolation of measured cross sections and better representation of hydraulic structures;
e. Time series of observations of impact of existing weir gate management on upstream water levels and flows;
f. Better keeping and communication of records of weir,vegetation and stream bed management.

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11. Acknowledgements and further information

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2. **Lunan Riparian stakeholder associations, including the Rescobie Loch Development Association chaired by Andrew Wilson and Balgavies Loch committee;**
3. **Individual riparian interests including Mr Tom Sampson of Mains of Balgavies, Mr James Osborne of Mains of Balmedie, Mr Ian Guthrie of Ward of Turin for permissions to install water level recording equipment and carry out vegetation surveys and water management investigations on their property;**
4. **The Meteorological Office for provision of forecast rainfall data;**
5. **The National River Flow Archive, administered by NERC, for access to river and rainfall flow records;**
6. **David Riach, Helen Watson, Carol Taylor, Claire Abel and other support staff at James Hutton Institute;**
7. **Remi Trenkmann of ENGEES, Strasbourg, France, for contributing during his internship at JHI.**

Project modelling files

The HECRAS versions of catchment geometry and hydrology for plan 85 (see Table 5) are in files:

C:\hecras\Backup\upperlunan2.g34

C:\hecras\Backup\upperlunan2.u45

They draw data from:

wemyss_westerton_observed_flows.dss newhydroWW 1d forecast.dss

(for observed flow inputs) (for flow inputs based on forecasts)

The output data is in

upperlunan2.dss

Links

For more information on stakeholder engagement and development of mitigation measures for sediment and nutrient runoff control, please consult the following weblinks:

https://www.hutton.ac.uk/sites/default/files/files/SUDS%20update%20report.pdf

https://www.hutton.ac.uk/research/projects/lunan-water-diffuse-pollution-monitoring-project-first-10-years

12. Glossary of terms

Mesotrophic	*Having a moderate amount of dissolved nutrients*
Culvert	*a tunnel carrying a stream or open drain under a road or railway*
Dredging	
Manning coefficient (n)	*a coefficient which represents the roughness or friction applied to the flow by the channel.*
Stage-discharge relationship	*The relationship between the amount of water flowing in a river or stream and stage at any particular point*
baro-diver	*a datalogger for long-term uninterrupted, real-time atmospheric pressure monitoring. Can monitor shallow water levels by comparing submerged diver with air mounted diver*
Telemetry	*in situ collection of measurements or other data at remote points and their automatic transmission to receiving equipment (telecommunication) for monitoring*
Anticline	*a ridge or fold of stratified rock in which the strata slope downwards from the crest*
Equifinality problem	*principle that in open systems a given end state can be reached by many potential means*
Aquifer Transmissivity	*the rate at which water passes through a unit width of the aquifer under a unit hydraulic gradient*
Hydraulic control structures	*a device designed to retain, regulate, or control the flow of water*
Nash-Sutcliffe coefficient	*one minus the ratio of the error variance of the modeled time-series divided by the variance of the observed time-series*
Logjam	*a crowded mass of logs blocking a river*
Tilting Weir	*type of weir used for raising and lowering a head of water by controlling the flow of water to a lower catchment area or drainage basin*
Invert	*base interior level of a channel*

13. Picture and map gallery

From Source to sea[1]

Topographic map of Lunan catchment showing main watercourses
View from Turin Hill, source of Baldardo Burn
Outlet of Restenneth Moss to Lunan Water
Rescobie Loch
Disused eel trap on Lunan Water between Rescobie and Balgavies Lochs
Balgavies Loch (SWT reserve)
Bankside protection at Friockhem
Outlet to the sea at Lunan Bay

Water Management Issues

Map showing estimated positions of septic tanks in Lunan Water catchment
Flooding on B9ii3 Forfar to Montrose road, 4 February 2021
Flooding of Rescobie Loch boathouse, January 2017, following storm Frank
Cyanobacterial bloom at outlet to Balgavies Loch
Flooding of private road at Clocksbriggs
Chapel Mires filled with floodwater, January 2017
Permitted maximum abstraction on water licences in Lunan Water catchment
Flooding in fields downstream of A92 on Montrose to Inverkeilor Road

Details of Balgavies Loch outflow

Balgavies Loch outflow at low flow
Balgavies Loch outflow after storm Frank
Flooding of field south of Milldens Lade
Spillway from Lunan Water (sluggish section) into Chaoel Mires. Right hand channel is start of common Lade.
Common Lade (on right) and Lunan Water (on left) from downstream of Milldens weir during storm Frank
Swamped gates from Common Lade to Milldens Lade (foreground) and Return to Lunan water (background).

Chapel Mires

Centre: map of National Vegetation Classification for Chapel Mires. Pink and red areas show extent of sediment tolerant Phalaris, Sparganium and Phragmites rich associations.
Left from top. Spillage of sediment rich water over sluggisg section bank into Chapel Mires - February 2021 event
Phalaris and Sparganium stands justSouth of Lunan Water sluggish section
Phalaris and Iris mixed stand in centre of wetlands
Pond margin
Right from top: Overview of chapel mires from Southwest
Carex stand adjacent to pond
Carex paniculata/Bogbean stand in small, high value wetland on southern fringe of Chapel Mires
Bottom: diagram of effect of sediment on vegetation in Carex-rich wetlands ([2]

Catchment monitoring

Water sampling and hydrometric stations on Lunan Water 2006-present (not all are currently active). Note that Wemyss is the station for the Baldardo Burn, Westerton 1 is the station for Balgavies Burn. These two stations are still operated by James Hutton Institute. Murton is the station for Burnside Burn, Newmills is the station for Newmils Burn. These two stations were operated by SEPA . Kirkton Mill is the NRFA station for the Lunan Water.

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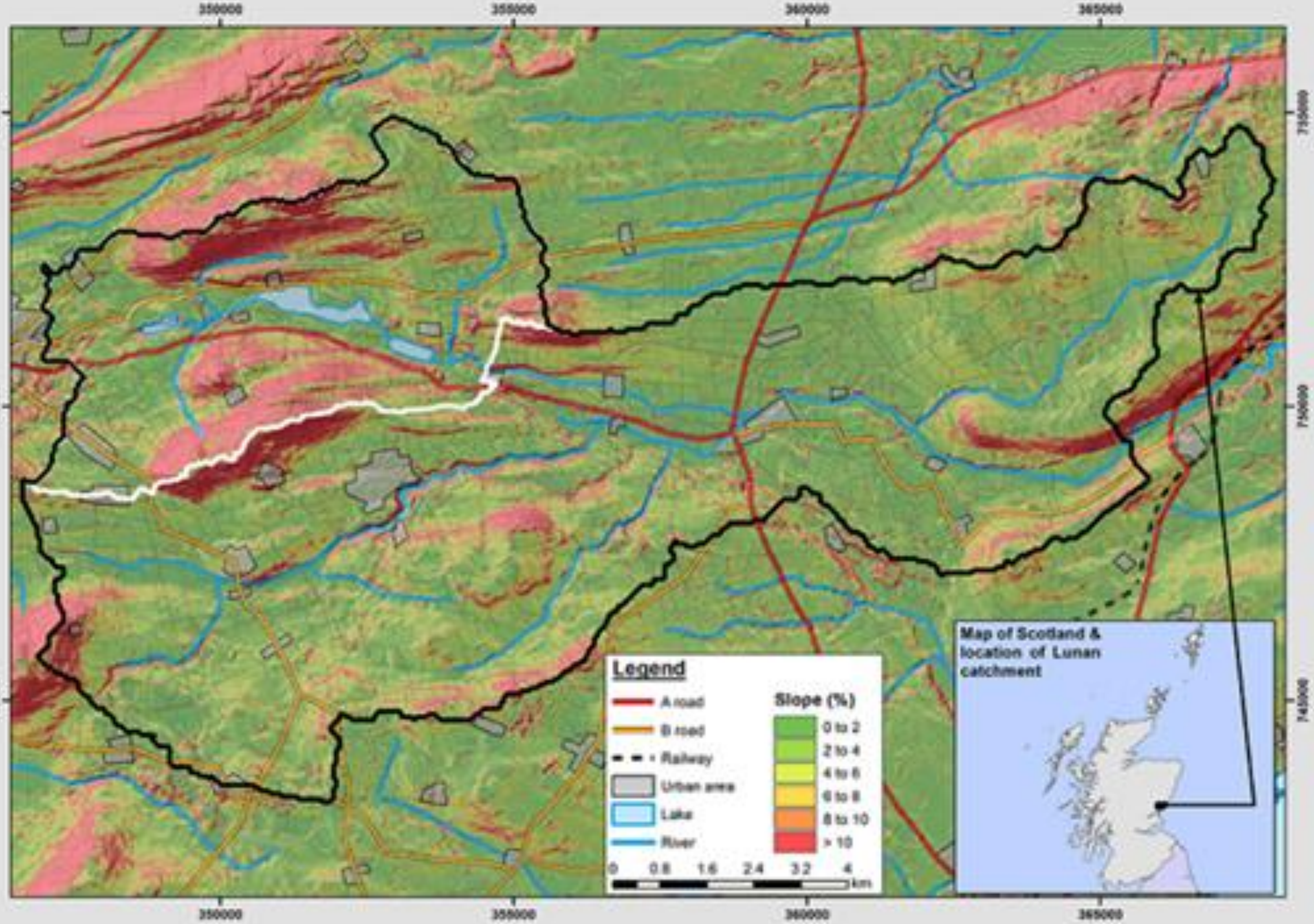
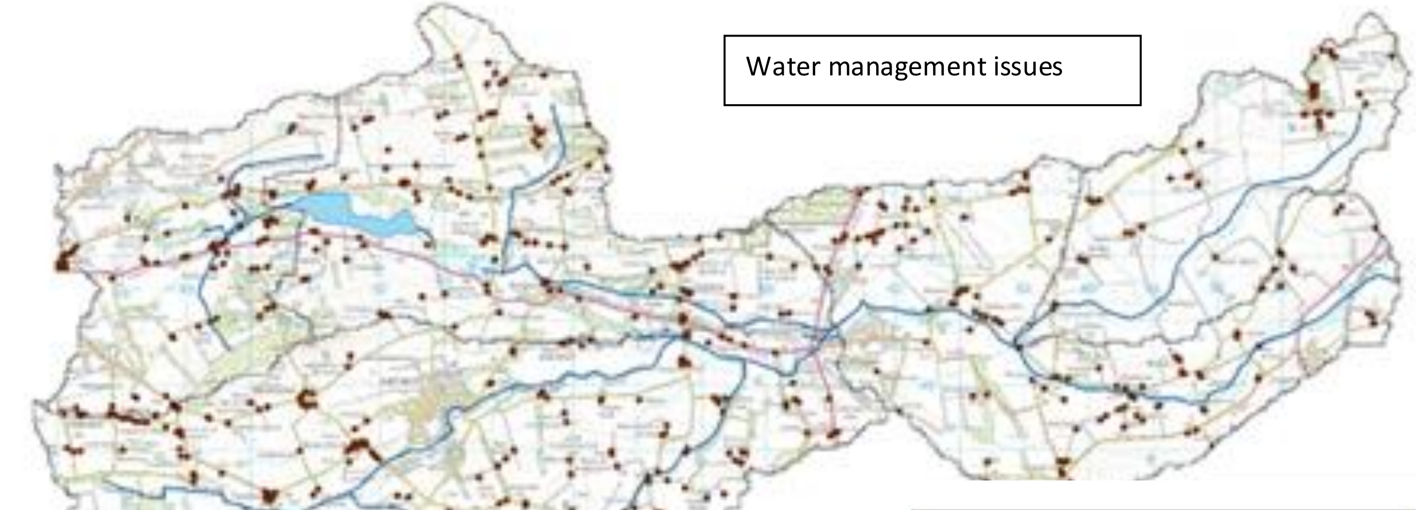
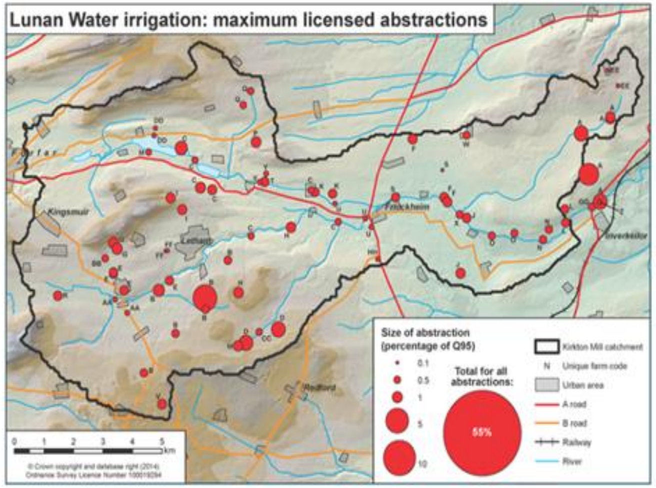
[1] Picture titles are from top left, clockwise unless otherwise stated

From Source to sea



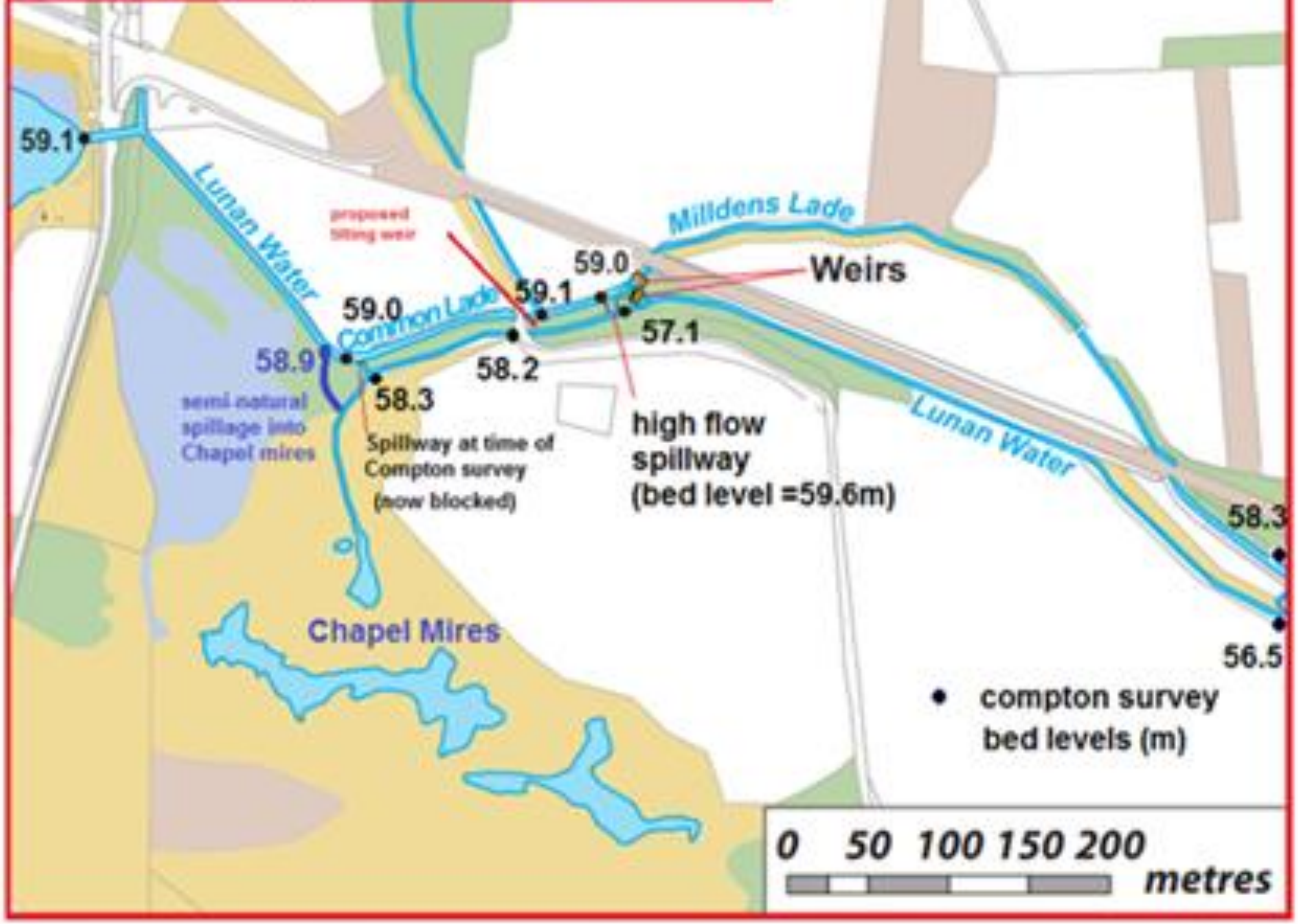
Water management issues

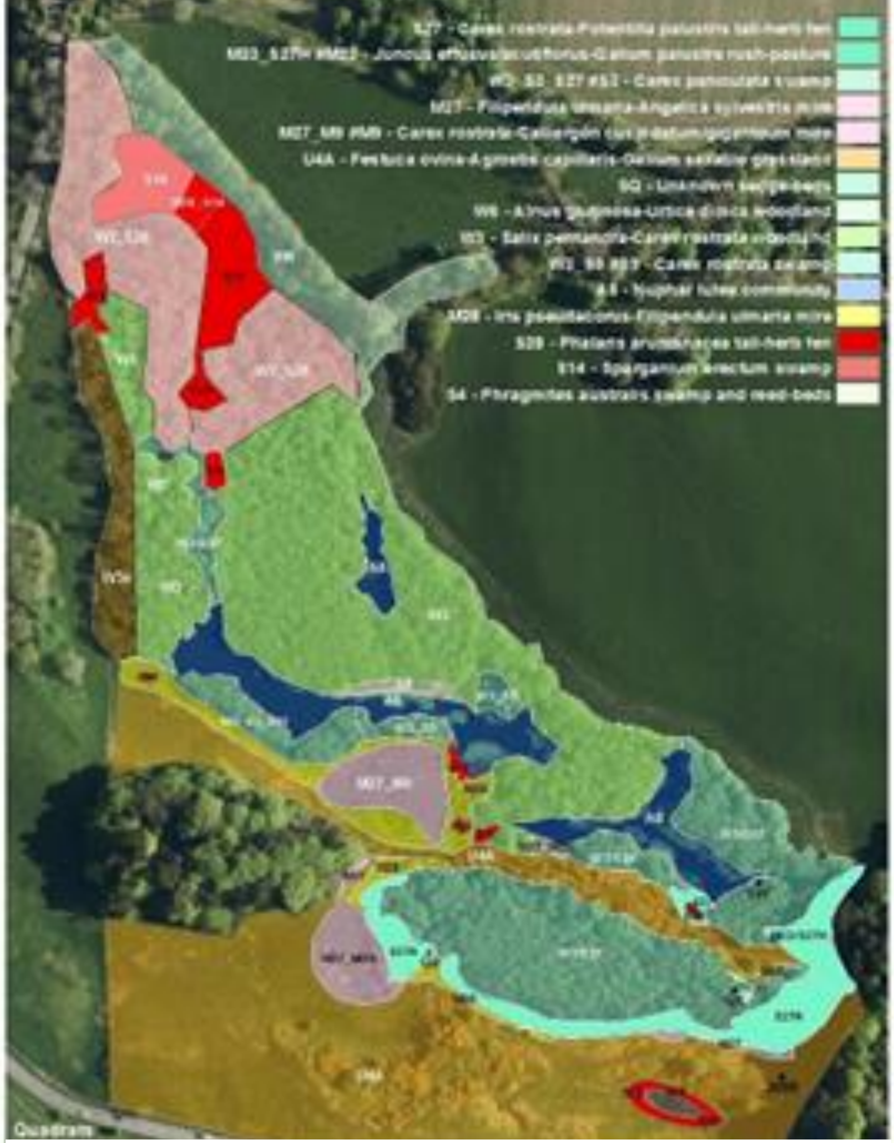




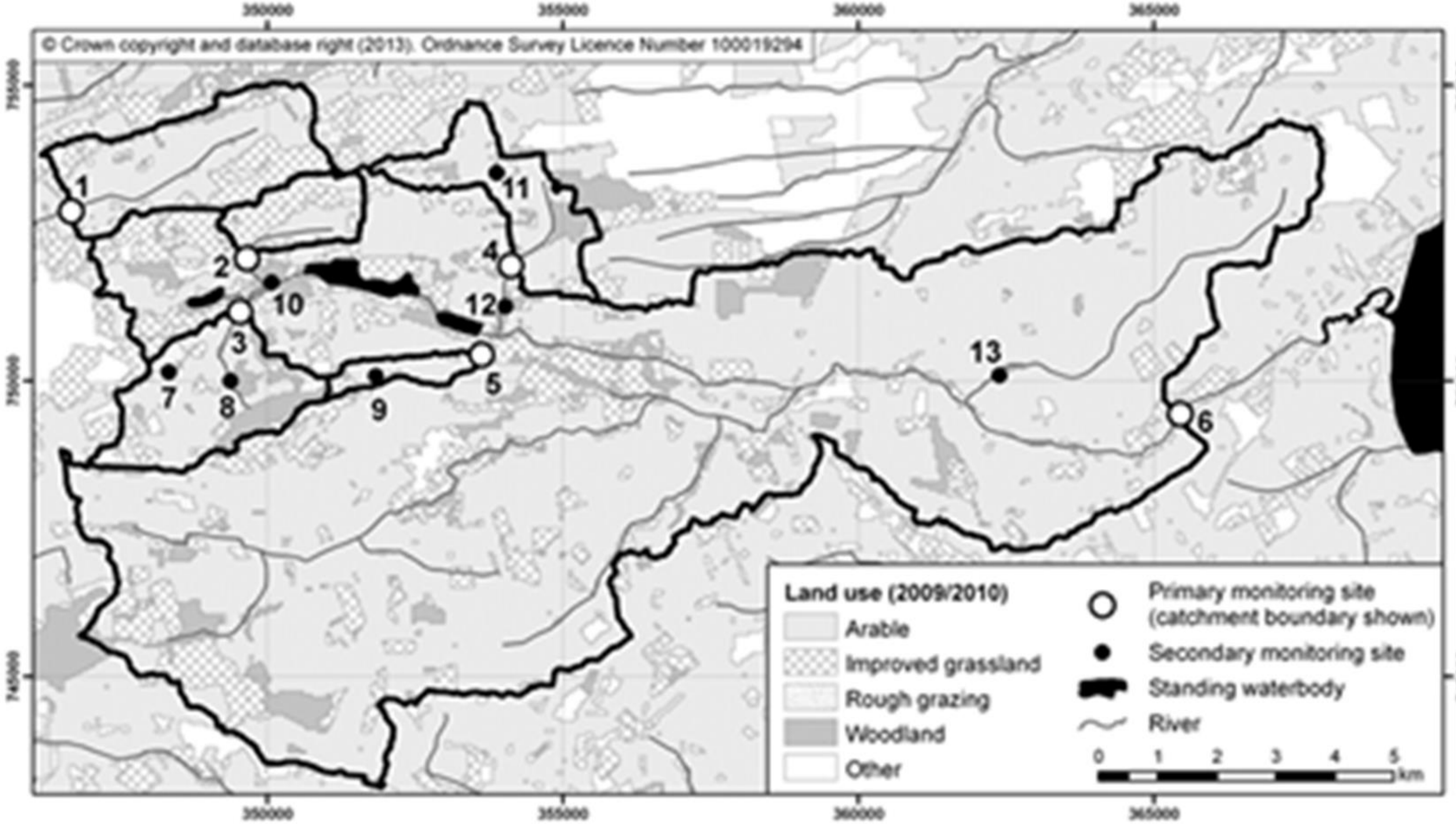



Detail of Balgavies Loch outflow



Sedimentation reduces micro-topography of Carex tussocks making them vulnerable to invasion by Phalaris



Primary sub-catchments: 1, Hatton; 2, Wemyss; 3, Murton; 4, Westerton One; 5, Newmills; 6, Kirkton Mill.

Secondary sampling locations: 4, Westerton Two; 7, Auchterforfar; 8, Mid Dod; 9, Finneston; 10, Rescobie inlet; 11, Pitkennedy; 12, Balgavies House; 13, Gighty Burn.

Appendix 1 . Estimation of groundwater contribution to surface flows for whole Lunan catchment and upper Lunan catchment.

Note that some of the work in this Appendix has been superceded by the work described in the main report, which does not include an explicit representation of groundwater. The HECRAS versions of catchment geometry and hydrology that include the approach below are in files shown below and have been used for winter 2020/21 live simulations. These will be replaced by files described in the main report from March 2021.

C:\hecras\Backup\upperlunan2.g25

C:\hecras\Backup\upperlunan2.u03

They draw data from:

ForecastDataForNew
Model.dss

rescobie
Balgavies.dss

We note that one can expect an unknown portion of the leakage to groundwater to be recovered further down the catchment, shown by the well closed water balance for the whole Lunan Water catchment defined by the SEPA flow monitoring station at Kirkton (A=124 km^2). This suggests a conceptual model of the whole Lunan catchment as depicted in Figure 5.

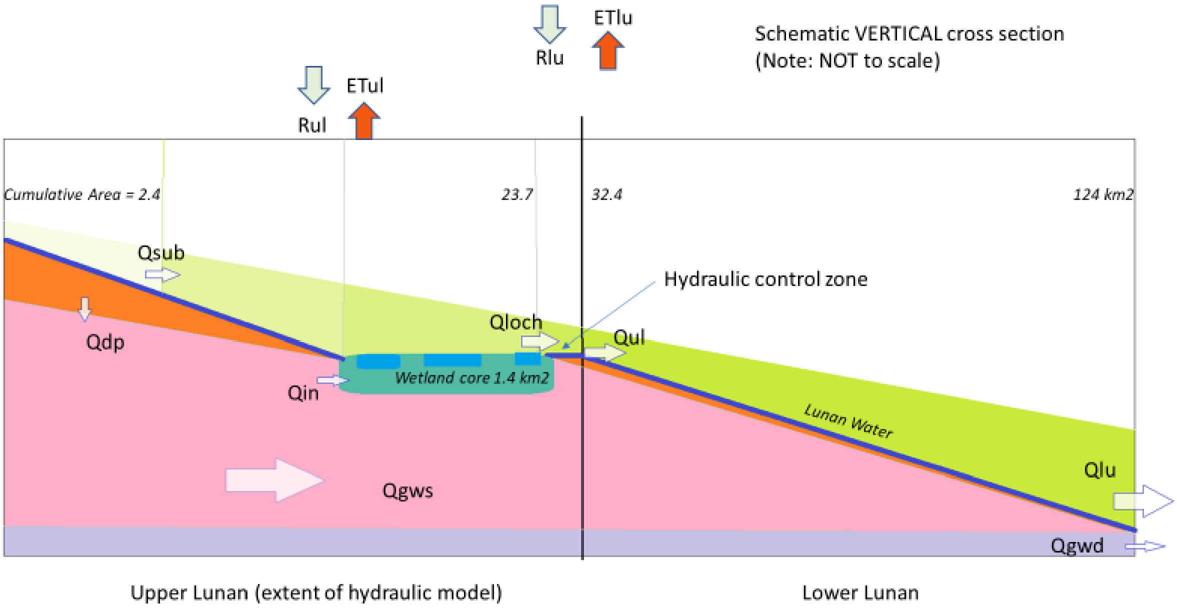


Figure A1. Schematic of Lunan Water catchment and upper catchment hydrology. The subcatchment shown is the Wemyss subcatchment, with a topographic catchment area of 2.4 km^2. The outlet of Balgavies Loch is also shown, with a catchment area of 23.4km^2 and the Lunan Water at Milldens bridge, just downstream of Milldens Mill, and the whole catchment at Kirkton Mill, are also shown. The part of the river system controlled by the hydraulic structures downstream of Balgavies Loch is represented by the “hydraulic control zone). Q_{gws} represents shallow aquifer flow uncaptured by the wetlands in the upper catchment and Q_{gwd} represents regional groundwater flow that does not interact with surface water dynamics. We do not attempt to estimate either of these flows in our model of the upper Lunan Water.

Groundwater flows into Lochs (Q_{in} in Figure A1)

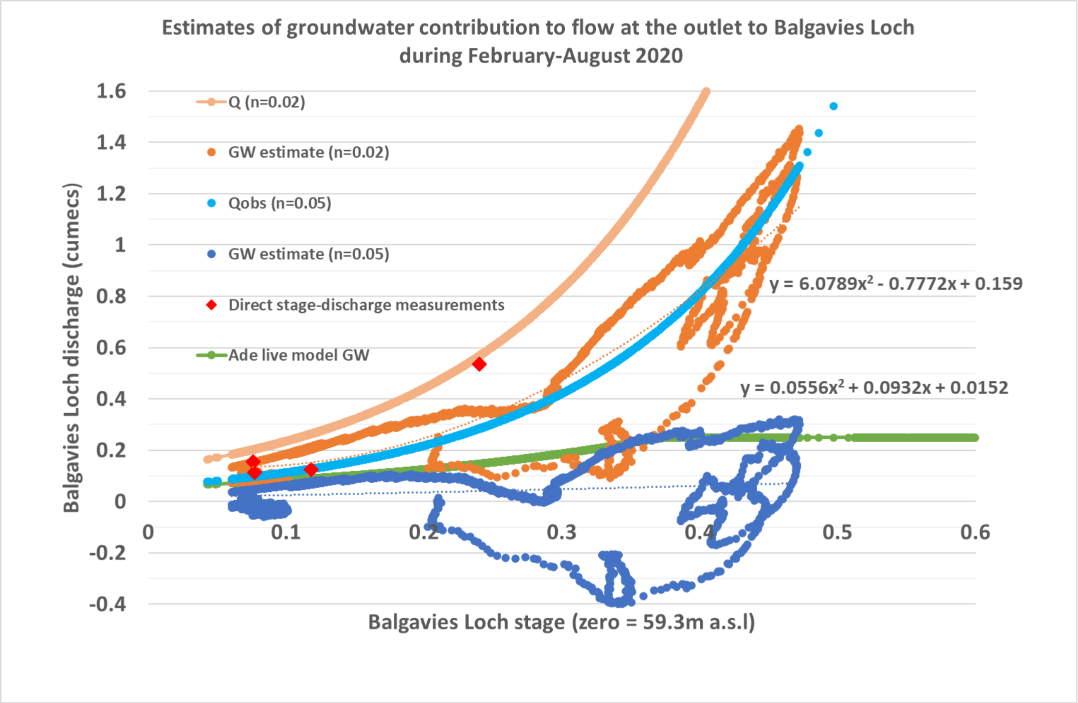
The observed recession of Balgavies loch stage is slower than can be explained by the modelled inflows and modelled hydraulic resistance during flow in the upper Lunan reaches. The likely explanation for this is that the core wetlands of the upper catchment act as sinks for at least some of the groundwater leakage that occurs from the more elevated parts of the upper catchment (as shown in FigureA1). The water balance equation to describe this at the upper catchment outlet is as follows:

$$\Sigma Q_{ul} = (\Sigma Q_{Sub1}+\Sigma Q_{Sub2}+\Sigma Q_{Sub3}+\Sigma Q_{Subn})+\Sigma Q_{in}$$

We can also simulate the discharge using HECRAS, based on the modelled inflows, assuming zero (or fixed) groundwater inputs. Assuming zero inputs of groundwater makes the hydraulic modelling unstable at low flows, so we carried out simulations with the following fixed inflows associated with groundwater.

1. Minimum flows on each of the input streams, amounting in total to 0.062 cumecs.
2. Two fixed groundwater inflows into the two loch water bodies amounting to 0.2 cumecs.

We then ran HECRAS and obtained the simulated flows over the period from 1 Feb 2020 to 31 August 2020. We calculated the difference between the estimated observed discharge based on the observed stage in Balgavies Loch, and the HECRAS simulated flows. After compensating for the assumed groundwater inputs in the simulations, the difference between HECRAS simulations of discharge and the discharge estimated from the observed loch stage provides estimates of the groundwater flow input. The estimate of outflow from Balgavies Loch, and the estimate of the groundwater contribution to this outflow, depends on the assumed value of the Manning roughness coefficient n, in the reach below the Loch. See figure below.



Also shown on this figure is the equation we are currently using for the live/forecast model, which is based on a fit to a shorter section of the n=0.05 GW timeseries, and includes a maximum GW contribution of 0.25 cumecs. This equation is an attempt to represent the situation at low flows, when GW makes a significant contribution to water levels, while not over-representing the highly uncertain nature of the groundwater contribution at high flows. The equation for this line is:

$$Qin = 0.0805*\exp((H_{bal,obs}-59.39)*4.0018)$$

Where $H_{bal,obs}$ is the observed water level in the Loch, a continuously measured data source, suitable for driving a dynamic realtime and forecasting model, along with the stream inflow data described above.