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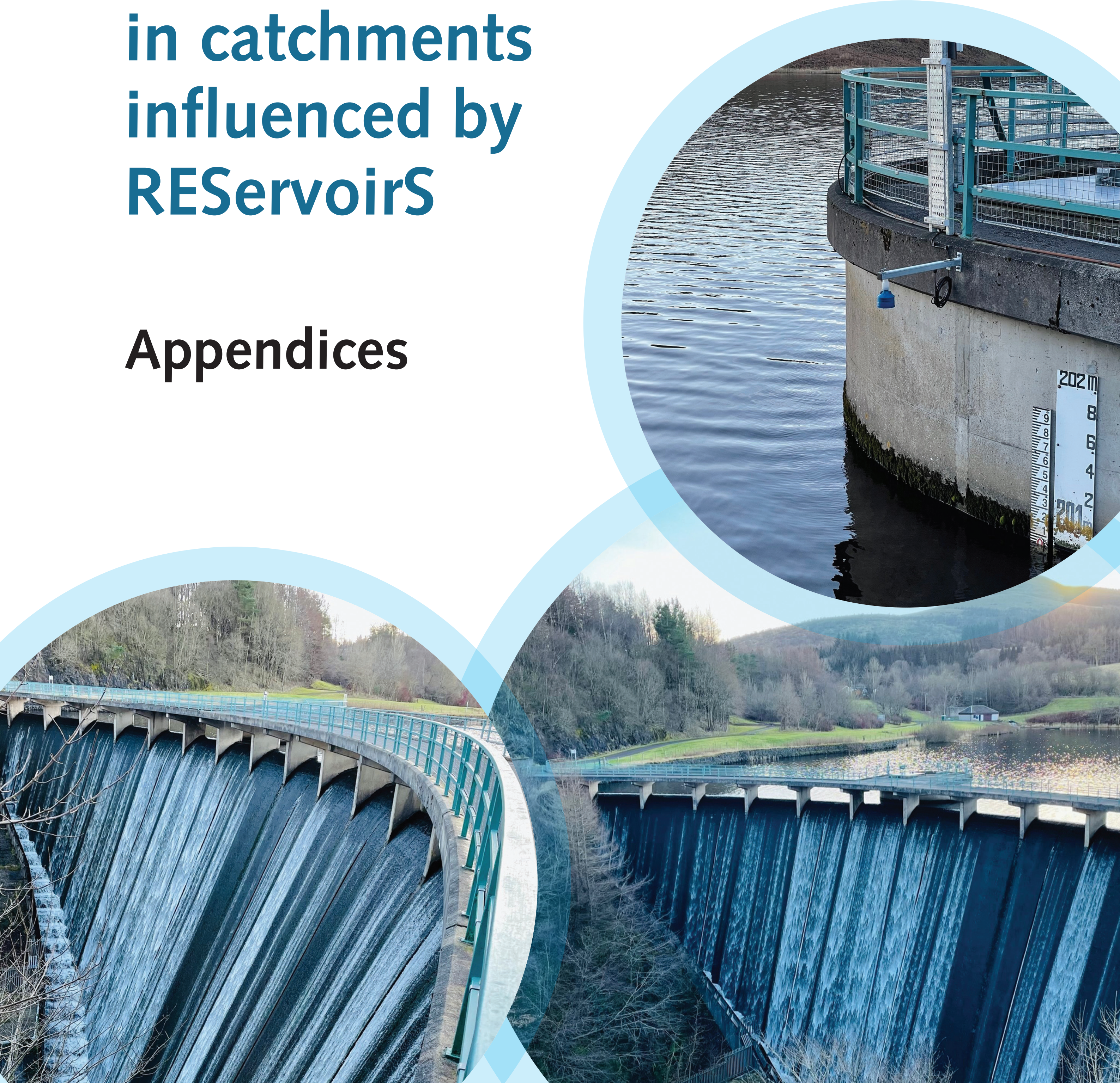
IMPRESS: Approaches to IMProve flood and drought forecasting and warning in catchments influenced by REServoirS

Appendices



IMPRESS: Approaches to IMProve flood and drought forecasting and warning in catchments influenced by RESservoirS

Robert J. Moore, Steven J. Cole

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Authors: Robert J. Moore[1], Steven J. Cole[1]
[1]UK Centre for Ecology & Hydrology, Maclean Building, Wallingford, Oxfordshire, OX10 8BB, UK

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All taken at the Castlehill Reservoir on the River Devon.

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Appendix 1.
IMPRESS Questionnaire

Question Theme	Question
Reservoir importance and role	Why are **reservoirs** important to your organisation and what is your role? *Direct:* water supply, hydropower, flood control, environmental flows, etc. *Indirect:* flood forecasting, drought forecasting, etc.
Forecasting reservoir inflows	Do you **forecast inflows to reservoirs** and, if so, what **methods** and **software** (including forecast platforms) are used? Consider both short-term and seasonal timescales, associated time-steps and frequency of forecasts. Are their uncertainty taken into account and, if so, how?
Meteorological forecasts	Do you use **meteorological forecasts** (precipitation, air temperature, etc.)? If so, for what purpose, and what are they (consider short-term and seasonal time-scales, lead-time and forecast frequency)?
Reservoir routing	Do you use **dynamic reservoir routing** and, if so, why and what method(s) (level-pool routing (Puls), hydrodynamic, etc.) and software are used? What time-step is used? Are reservoir losses (evaporation, etc.) accounted for and, if so, how? What **outlet controls** (weir, orifice, culvert) are used and how are these represented through **discharge equations**. How is **reservoir geometry** represented (bathymetry data, reservoir water level/surface area/volume/discharge relations)?
Control rules	What **control rules** govern the operation of reservoirs and how have these been derived (methods, software)? Consider both short-term (flood risk, dam safety, etc.) and long-term (water supply reliability, environmental flows, etc.) objectives. Providing case-study examples would be useful. We are seeking whether the rules are (i) informal and pragmatic, (ii) based on reservoir system optimisation methods or (iii) some combination of these. How are trade-offs managed in practice? Are reservoirs actively managed in creating flood storage (in contrast to making static provision)?
Water resource system models	What **water resource system** models and software do you use, and at what time-step? Are these used for forecasting (seasonal, medium, short term), or only for planning purposes? Do they involve reservoir system optimisation methods and/or decision-support systems (possibly accounting for uncertainty) and, if so, please provide details. What complexity of model formulation are used for reservoirs and for routing river flows for linked systems?
Data assimilation and uncertainty	For forecasting models (of inflows, reservoir, water resource system) what **data assimilation methods** are used for initialising to current conditions and improving forecast accuracy. Is **uncertainty** taken into account and, if so, how?
Monitoring	What **monitoring** is used in support of drought/flood forecasting affected by reservoir operation, indicating frequency of recording, spatial coverage and whether manual/automated/telemetry? Do you use other organisations monitoring data and, if so, what data? Which monitoring assets do you maintain and are these data shared with other stakeholders? What more would be helpful? Hydromet: raingauge, radar rainfall, snow, weather station, potential and actual evaporation (from land-covers and reservoir open-water), etc. Reservoir level, reservoir discharge, river level/flow, etc. Remote Sensing/Earth Observation data (water level, snow, etc.)
Partnership working	Considering stakeholders involved in flood/drought forecasting & warning influenced by reservoir operation, what **partnership arrangements** are in place to help coordinate and inform different parties (such as planned reservoir releases, dam safety and environmental flow concerns, sharing of river flow forecasts and flood/drought assessments). How might these be strengthened? What are the constraints on improvement and how are they best mitigated? Based on your experience, which are the key partnership interactions that have made the biggest difference?
Barriers, opportunities and plans	What do you see as the **main barriers** to successful flood and drought forecasting and warning in catchments influenced by reservoirs? Where do you see the greatest **opportunities for improvement** and why? What are your **future plans** in this regard?

Appendix 2.
Level-pool reservoir routing: equations and accuracy analysis

A2.1 Introduction

This appendix provides the underpinning equations to the level-pool routing method (Section A2.2), the equations used by the method as implemented in Flood Modeller (Section A2.3), and an accuracy analysis of the method by Fread and Hsu (1993) (Section A2.4).

A2.2 Level-pool routing equations

In the level-pool method, unsteady flow routing in a reservoir is approximated by assuming the reservoir water level at time t, $h \equiv h(t)$, is horizontal over its surface area $A \equiv A(h)$. For a reservoir with water storage volume $S \equiv S(t)$, inflow $I \equiv I(t)$, and outflow $Q \equiv Q(t,S) \equiv Q(t,h)$, mass conservation gives

$$\frac{dS}{dt} = I - Q. \qquad \text{(A2.1)}$$

Note the outflow Q may be a time-varying controlled discharge and/or a function of the reservoir water level h above a control level (e.g. spillway crest, pipe outlet); typically the function is of power law form or represented in a tabular way. The inflow I is the sum of the water flow entering the reservoir from upstream and any lateral inflows, plus the flux of precipitation less open water evaporation over the reservoir area A (accounting for any variation with reservoir level).

Since

$$dS = A dh \quad \text{and} \quad \frac{dS}{dt} = \frac{dS}{dh}\frac{dh}{dt} = A\frac{dh}{dt} \qquad \text{(A2.2)}$$

an equivalent form of level-pool routing, in h rather than S, follows as

$$\frac{dh}{dt} = (I - Q) / A. \qquad \text{(A2.3)}$$

This h form has the advantage of not needing to calculate storage as part of the routing process. For the S form, Fenton (1992) discusses the need to develop different functions $S = f(Q)$ for controlled discharges under different gate or valve settings. The h form requires a function relating reservoir area to water level, $A = f(h)$, and is readily calculated from reservoir bathymetry data.

The traditional method of level-pool routing applies the trapezoidal rule to the S form to give the discrete-time equation

$$\frac{S_{t+\Delta t} - S_t}{\Delta t} = \frac{I_t + I_{t+\Delta t}}{2} - \frac{Q_t + Q_{t+\Delta t}}{2}, \qquad \text{(A2.4)}$$

introducing the subscript notation for the time interval $(t, t + \Delta t)$ of duration Δt. This is recast to the form

$$\frac{2S_{t+\Delta t}}{\Delta t} + Q_{t+\Delta t} = \left(I_t + I_{t+\Delta t}\right) + \left(\frac{2S_t}{\Delta t} - Q_t\right) \qquad \text{(A2.5)}$$

and the unknowns $h_{t+\Delta t}$, $S_{t+\Delta t}$ and $Q_{t+\Delta t}$ solved for by tabular data mapping of h and $(2S / \Delta t) + Q$. Whilst unconditionally stable, its accuracy can be improved upon.

Fread and Hsu (1993) use the h form and the trapezoidal rule to obtain the discrete-time equation

$$\left(\frac{A_{t+\Delta t}+A_t}{2}\right)\left(\frac{h_{t+\Delta t}-h_t}{\Delta t}\right)=\left(\frac{I_t+I_{t+\Delta t}}{2}-\frac{Q_t+Q_{t+\Delta t}}{2}\right) \qquad \text{(A2.6)}$$

which is solved for the unknowns $h_{t+\Delta t}$, $Q_{t+\Delta t}$ and $A_{t+\Delta t}$. Since the last two are known nonlinear functions of $h_{t+\Delta t}$, the equation can be solved for $h_{t+\Delta t}$ using an iterative method such as Newton-Raphson and then the outflow $Q_{t+\Delta t}$ obtained from a discharge equation for the reservoir outlet.

A2.3 Reservoir routing equations for Flood Modeller

Mass conservation for the reservoir gives

$$q_{net}-A(h)\frac{\partial h}{\partial t}=0 \qquad \text{(A2.7)}$$

where, at time t, $A(h)$ is the area of the reservoir (m^2) when the water surface elevation is h (m AD), and the net inflow (m^{3}s^{-1}) is

$$q_{net}=\sum_{i=1}^{N}q_i\,. \qquad \text{(A2.8)}$$

Here, q_i is the inflow at node i of N nodes associated with the reservoir. To ensure a level water surface for the reservoir across its N nodes, requires the level at node i to be

$$h_i = h,\quad i = 1,\ldots N. \qquad \text{(A2.9)}$$

In addition, up to four "Lateral Inflow" nodes can be attached, representing lateral inflows or direct rainfall/evaporation affecting the reservoir water balance. For a dry area of the reservoir, A_D, rainfall R can be modified using a rainfall factor, f_R, to give the adjusted volume increment

$$dV = R(A_W+f_R A_D) \qquad \text{(A2.10)}$$

where A_W is the wet area of the reservoir. It is noted that small reservoirs can be prone to instabilities that may require use of a smaller time-step.

A2.4 Accuracy analysis of level-pool reservoir routing method

An accuracy analysis by Fread and Hsu (1993) of the level-pool reservoir routing method, for different situations relative to a distributed dynamic routing model, is summarised here. The Root Mean Square Error (RMSE) – normalised by the peak outflow and expressed as a percentage – in the rising limb of the outflow hydrograph is shown to increase as reservoir mean depth (D) decreases, as reservoir length (L) increases and as the inflow hydrograph volume decreases.

Figure A2.1 shows these effects using the dimensionless parameters $\sigma_l = D / L$, $\sigma_t = L / \left[3600T (gD)^{1/2} \right]$ and σ_v the ratio of the hydrograph to reservoir volumes; here g is the acceleration due to gravity and T is the time in hours from the start of the hydrograph rise to its peak. It is seen that error increases as σ_t increases and as σ_l and σ_v decrease; also how the influence of σ_v increases as σ_l decreases. Analysis of these results shows that the error exceeds 10% for (i) most reservoirs experiencing rapidly rising unsteady flows where T is less than 1 hour (e.g. dam-break floods, intermittent turbine releases), and (ii) very long reservoirs (L exceeds 80km) subject to flash floods with T less than 18 hours.

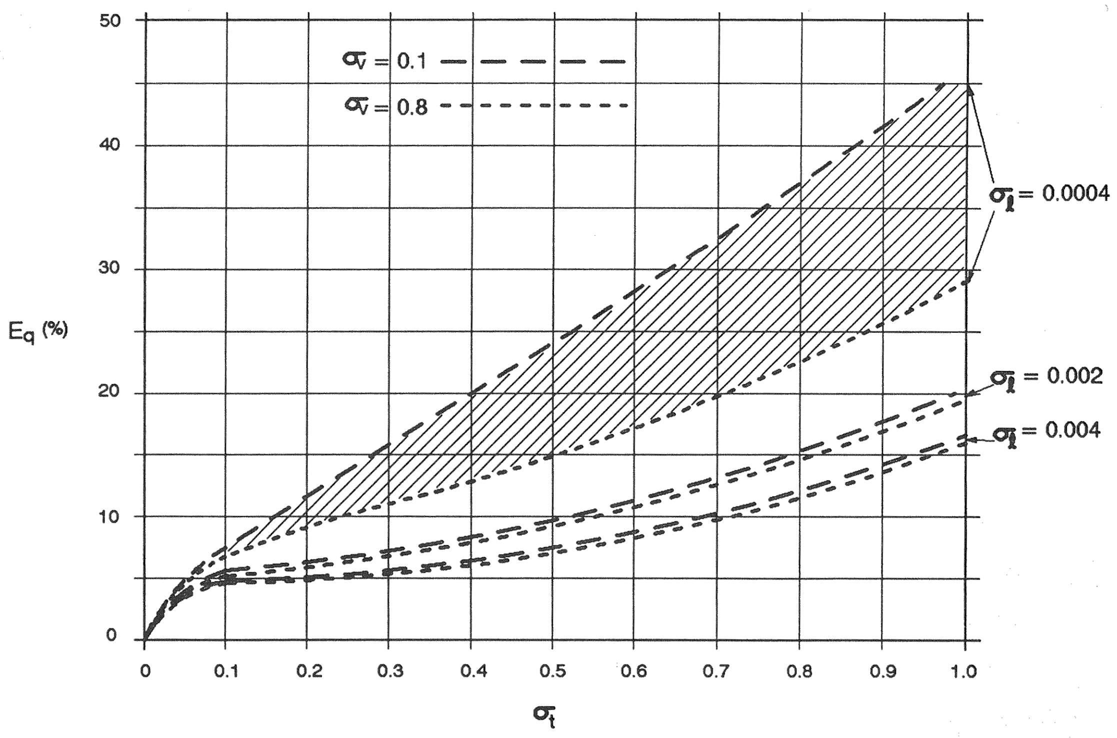

Figure A2.1 Error in level-pool routing (E_q) as a function of the dimensionless parameters σ_t , σ_l and σ_v representing relative time, length and volume effects.

Appendix 3

Reservoir routing using evaporation and precipitation over water body surface for water supply yield assessment: Loch Dee case study

A3.1 Background

Jacobs (2010a) investigated for Scottish Water the effect of loch storage in attenuating and delaying flows downstream and augmenting them during periods of dry weather, with flow duration curves used in water resource assessments reducing in steepness as a consequence. The Low Flows 2000 loch adjustment factor (CEH Wallingford, 2004), based on a few large gauged catchments, was thought to overestimate the adjustment needed for smaller catchments, which make up a very large proportion of Scottish water sources.

A3.2 Loch Dee case study

Loch Dee, in the Dumfries & Galloway district of south-west Scotland, was chosen for focussed investigation. It had good inflow and outflow (Blackwater at Loch Dee) records, and a surface and catchment area representative of water supply sources operated by Scottish Water. Also, Aquator models used in yield estimation (at the time in 2010) commonly ignored the rainfall and evaporation exchange at the water body surface as its area was judged small relative to the catchment area contributing to the inflow. This exchange was also ignored when calculating the loch adjustment factor (LAF), pointing to the need for a consistent methodology. The routing model is referred to as the SR06 routing model and was used to calculate the Q95 LAF; MBC (2009) provides further background. In the case of Loch Dee the loch area was 1km^2, 6.4% of its catchment area (15.72km^2).

The volume-area relation for the loch used the OS mapped area and an assumed 1:10 slope for the loch shore (although little sensitivity to this was noted). Mostly daily data were used, but there was one comparison with hourly data that demonstrated lack of sensitivity at low flows in terms of the derived flow duration curve. Potential evaporation was MORECS monthly PE for short grass spread uniformly to get daily values. To convert PE to open water evaporation, two methods were trialled : (i) Penman (1948) seasonal factors of 0.8 (May–Aug), 0.6 (Nov–Feb), 0.7 (Mar, Apr, Sep, Oct) used as divisors, (ii) Finch and Hall (2001) monthly adjustment factors used as multipliers: specifically the Jan to Dec profile values (1.43, 1.14, 0.92, 0.95, 0.91, 1.02, 1.24, 1.37, 1.47, 1.99, 2.29, 1.95). Flow duration curves for the inflows and outflows were calculated and the ratio of outflow to inflow at Q95 provided the LAF at this level. Comparisons were made with and without taking into account water exchanges over the loch surface area, with differences becoming apparent only below Q90.

A3.3 Case study findings

Figure A3.1 from Jacobs (2010a) shows zoomed-in hydrographs at the lowest flows that highlight the difference. This June 1992 period is likely to be the worst drought in the 27-year record available at the time, and results in a 30mm lower loch level if loch surface water exchange is included: equivalent to a water storage of 30ML (30,000 m^3).

The LAF at Q95 was estimated at 1.79 when taking account of evaporation and rainfall exchange over the loch surface area and 2.02 when not (Q95 of 0.123 and 0.139 m^{3}s^{-1} respectively), and 1.78 using gauged data alone: indicating the overestimate of adjustment needed for this small catchment when ignoring exchange. The control at the loch outlet was narrow compared to the downstream channel, and if of the same order would suggest an LAF even lower (1.3 to 1.5).

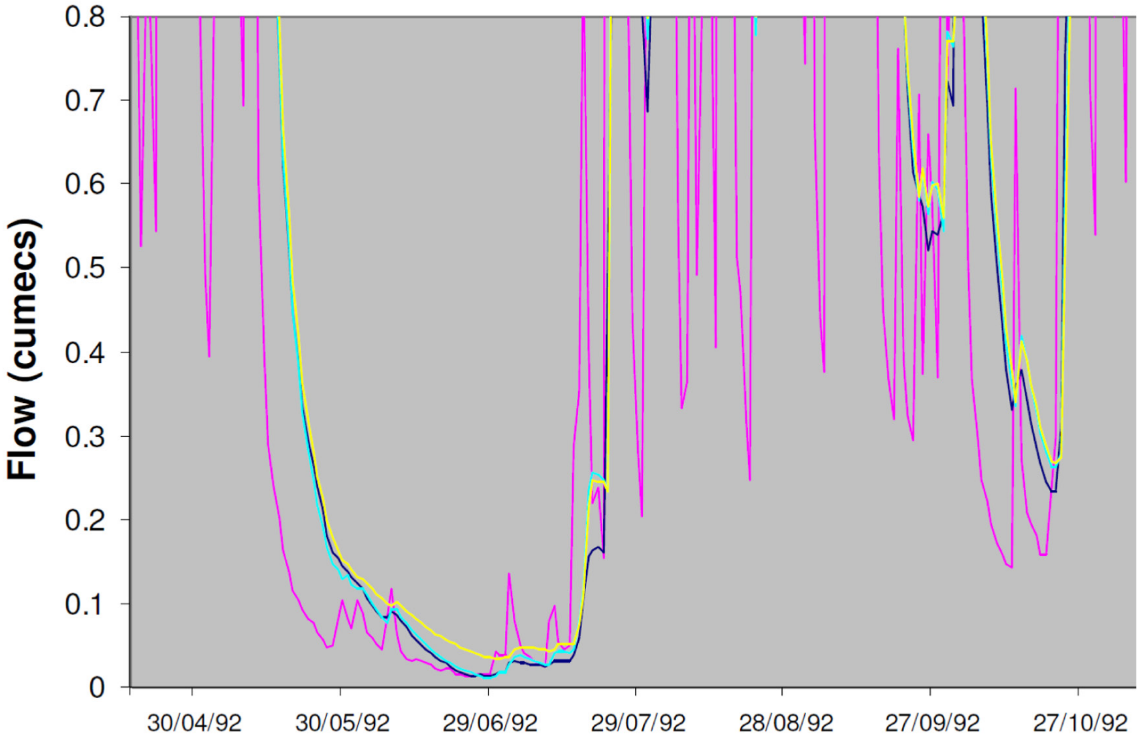

Figure A3.1 Routing of flow through Loch Dee with (blue) and without (yellow) taking account of evaporation and rainfall exchange at the loch surface. Black: gauged outflow, Pink: inflow. Zoomed in view below 0.8 m^3s^{-1}. (Source: Jacobs for Scottish Water)

A3.4 Follow-on work

A subsequent study (Jacobs, 2010b) for SEPA included a further four lochs (Avich, Maree, Shiel, Hope) and additional detail on the sensitivity of the routing model, focussed on deriving the flow duration curve at low flows for water yield assessments. The sensitivity analysis considered weir representation at the loch outlet (weir width and coefficient of discharge) of especial relevance where loch outflows are ungauged, and inflow estimation (flashiness and ungauged areas) in addition to routing time-step and loch surface water exchange via evaporation and precipitation.

The routing model developed for SEPA now forms the basis of the Aquator VBA customisation employed by Scottish Water, including representation of the hydraulic control of the outlet to Loch Chaorunn in its natural condition. Their experience, especially for smaller lochs, is that a sub-daily time-step (usually hourly), and including evaporation and precipitation over the loch, provides a better representation. This is invoked as a sub-daily loop calculation, with the aggregated daily spill passed forward within Aquator.

A3.5 Future opportunities

There is clearly an opportunity to revisit investigations of this type with the benefit of improved representation of loch surface water exchanges (open water evaporation and precipitation), loch inflows (especially for ungauged areas), loch routing (including outlet weir representation and their calibration for ungauged outlets) and inflow modelling for ungauged areas. Also to extend their purpose to include the flood regime and improvements to flood forecasting downstream.

Appendix 4.
Reservoir routing using Flood Modeller: case studies

A4.1 Introduction

This Appendix provides two case studies of the application of Flood Modeller for reservoir routing that include use of the FM Reservoir Gauge Updating unit. The first concerns Loch Lomond in Scotland for SEPA and the second for the Upper Mersey, in the Pennines east of Manchester, for the Environment Agency.

A4.2 Loch Lomond Case Study

In September 2016 SEPA commissioned Halcrow (then a CH2M company and now Jacobs) to develop a set of models for real-time flood forecasting within FEWS-Scotland, one of which concerned Loch Lomond (CH2M, 2017). PDM rainfall-runoff models were used for inflow forecasting to Loch Lomond and Flood Modeller (a rebranding of ISIS in November 2014) for hydraulic reservoir routing. This "Upper Lomond" model is referred to here as the Loch Lomond model. Catchment maps and model schematics are shown in Figure A4.2.1 and A4.2.2, whilst Figure A4.2.3 shows observed and modelled hydrographs over the winters of 2014 and 2015, assuming gauged inflows are known. Also note there is no operation of the barrage (not represented in the model), controlling discharge from the loch into the River Leven, above 40 m^3s^{-1}. In real-time, the reservoir routing model allows observed loch levels (at Ross Priory) to be used to reset the modelled level (and associated water storage) using FM Gauged Updating units. Observations of loch level at Ross Priory are only used in the validity range of 7.5 to 12m AOD. Except for the Figure A4.2.2 model schematic, there are no configuration details given of the reservoir routing model in relation to loch bathymetry and losses from the loch through evaporation and abstraction.

The discharge of Loch Lomond into the River Leven is controlled by the River Leven Barrage at Balloch, a system of seven electrically operated tilting gates. The barrage is managed by Scottish Water to maintain an optimum water level in Loch Lomond for amenity purposes whilst making provision for water supply and compensation flows into the River Leven downstream. Water level is controlled between 26 feet AOD (~7.93m), the statutory control level (fully lowered with unrestricted flow above this), and 20 feet (~6.10m), the barrage sill level. The first level of operational flood warning is set at 9m AOD, so ignoring barrage operation is not of critical importance, and given the reservoir level can be reset in real-time to that observed through the FM Gauge Updating unit. A pumping station near Ross Priory has a licence to abstract up to 454.6 Ml day^{-1}, with the barrage operated to offset its effect on water levels when required in summer months.

The complexities of the Loch Lomond water balance, mapped in Figure A4.2.4, are discussed in Jolley (2000) and a daily water balance model developed to assess the impact of barrage operation. The paper notes that the bathymetric survey of the lake dates back to 1910 (Murray and Pullar, 1910) and that a major source of uncertainty relates to ungauged inflows to the loch. However, the net inflow to the loch on a daily basis can be inferred from changes in level and the outflow time-series, without explicitly considering gauged and ungauged inflows or losses from abstractions and evaporation. Change in storage is calculated as change in level multiplied by loch area. A linear loch storage-level relation with a slope of 70,850 Ml m^{-1} is used in the water balance model when considering a change to the barrier operation, whilst using the net inflow series inferred from historical observations. Loch Lomond has an available storage of 86,000 Ml below the control level, providing a source of water supply of 455 Ml/day (Cormie, 1970). The loch covers a surface area of 71km^2 over a length of 39km with its catchment draining an area of 784.3km^2 to the River Leven at Linnbrane gauging station.

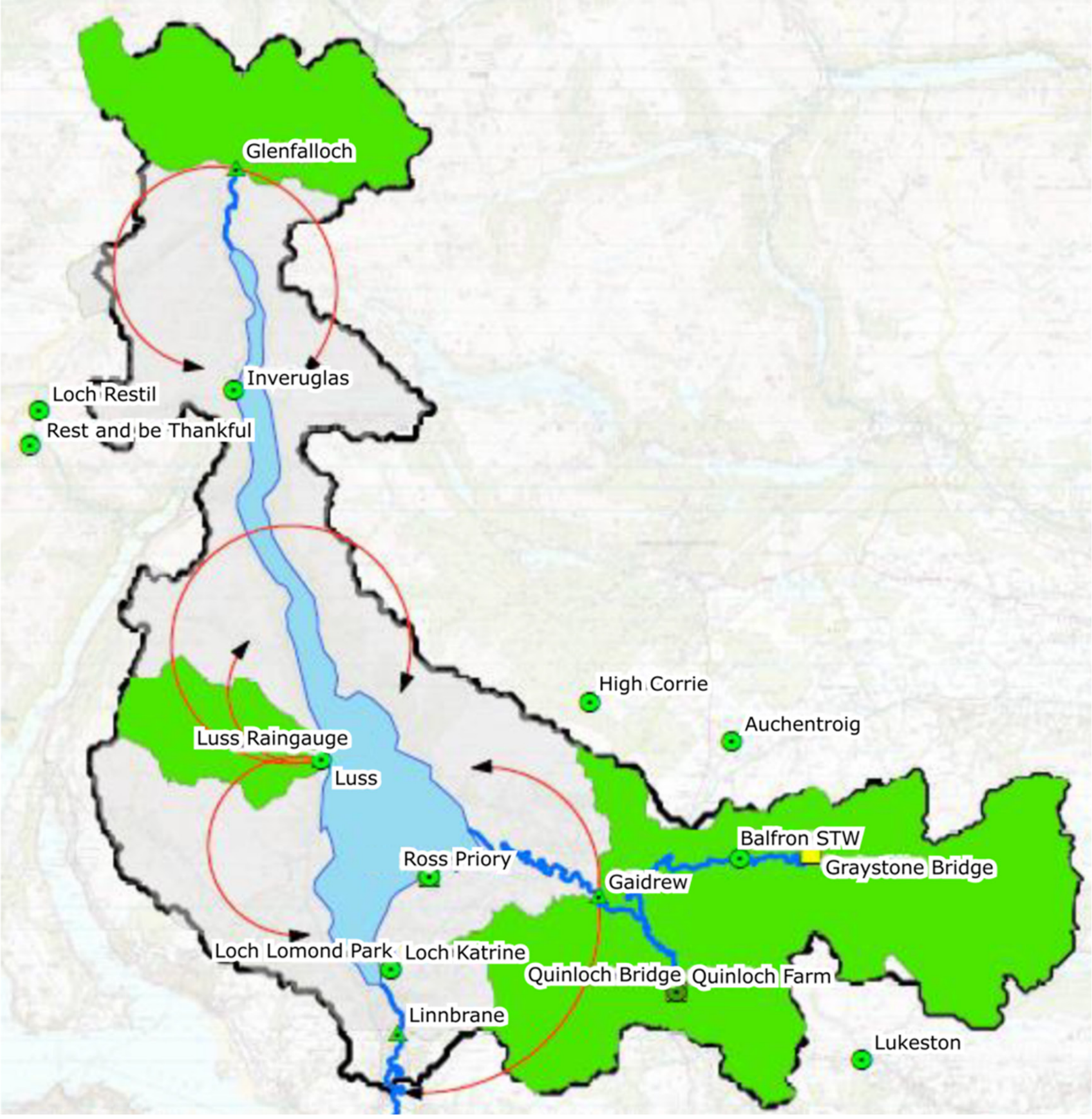

Figure A4.2.1 Catchment map of the Loch Lomond model. The three catchments modelled using PDM in green with their flows scaled for six ungauged areas (indicated by arrows). The Flood Modeller hydraulic routing model for the Loch extends from Glenfalloch to Linnbrane gauging station (catchment boundary indicated by the bold black line) and also includes routing of flows from the Gaidrew gauging station to the Loch. (Source: CH2M (2017))

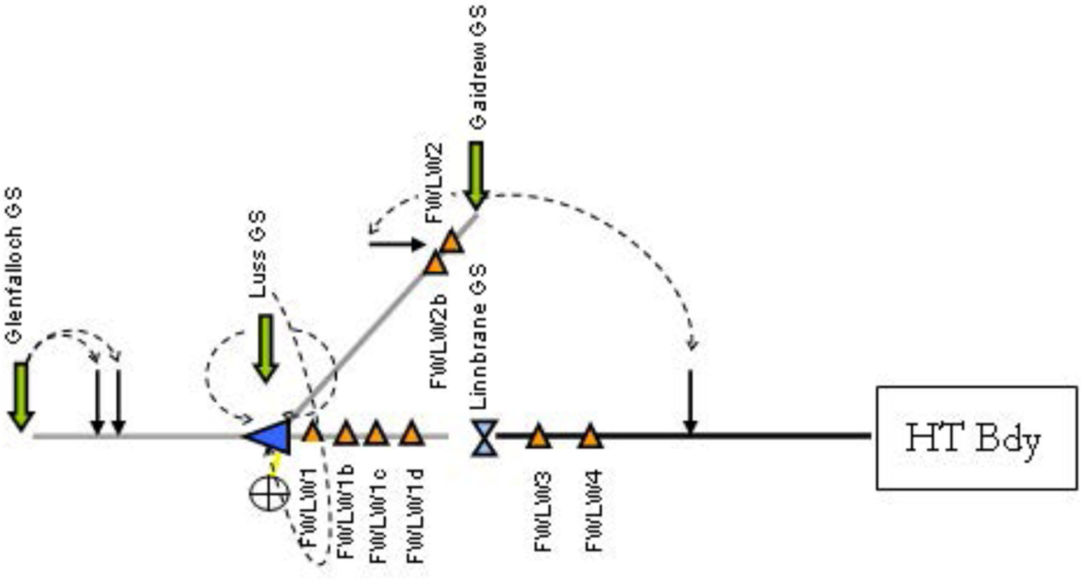

Figure A4.2.2 Loch Lomond model schematic using Flood Modeller (Source: CH2M (2017))

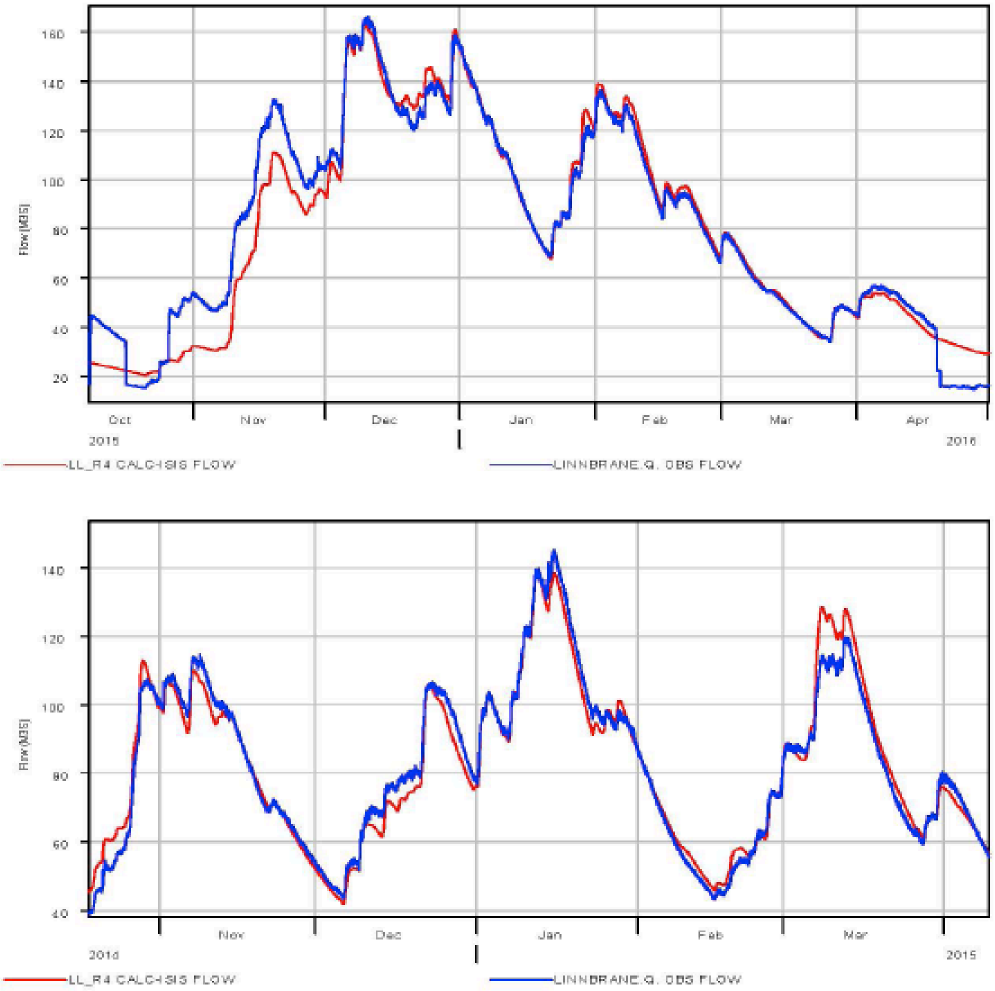

Figure A4.2.3 Loch Lomond modelled (red line) and observed (blue line) hydrographs over winter 2014 and 2015 for the River Leven at Linnbrane using Flood Modeller (ISIS hydraulic routing model). (Source: CH2M (2017))

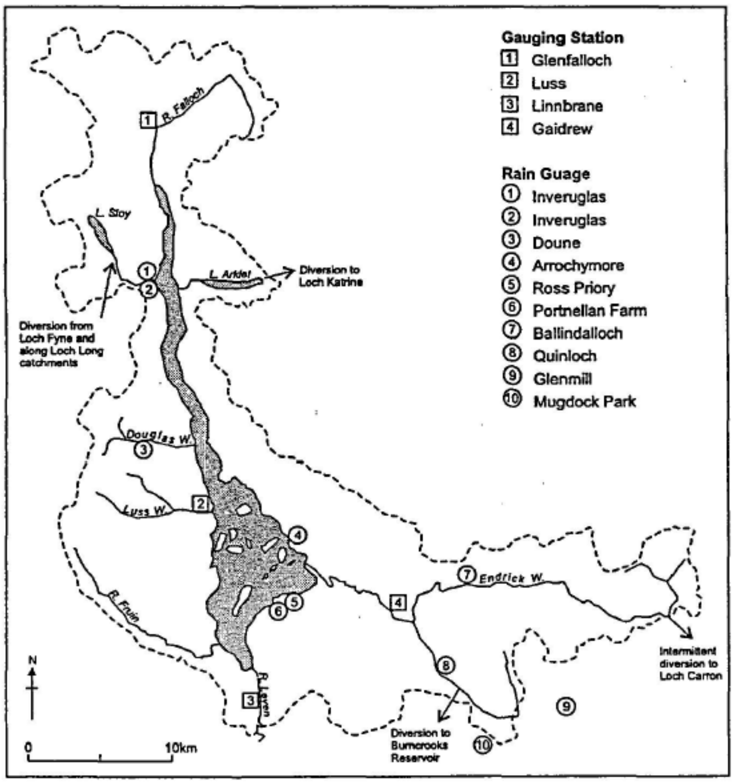

Figure A4.2.4 Loch Lomond catchment showing hydrometric network and anthropogenic influences (Source: Jolley (2000)).

A4.3 Upper Mersey Case Study

As part of the Mersey Flood Forecasting System, the Upper Mersey catchment to Didsbury drains an area of 550km^2 of the Pennines east of Manchester, receiving contributions from the Etherow (156km^2), Goyt (183km^2) and Tame (150km^2). The Etherow catchment containing the Longdendale Reservoir group, is managed by United Utilities for water supply so as to balance storage between the reservoir sequence Woodhead, Torside and Rhodeswood; Valehouse and Bottoms reservoirs, lacking sufficient head to support gravity-supply, provide compensation water. Arnfield reservoir, located outside of the five-reservoir cascade, also supplies water. Semi-rigid rules govern reservoir operation to maximise yield. A model schematic of the configuration is shown in Figure A4.3.1.

Woodhead Reservoir at the top of the reservoir chain, with the greatest direct catchment, provides water to the Rhodeswood Reservoir used as the principal extraction reservoir. Woodside discharges to Torside via a draw off tunnel, valve shaft and associated pipework; overflows via a spillway at Top Water Level (TWL) are directed via Etherow Pool to Torside. If required, water can be delivered directly from Woodhead to Rhodeswood Conduit for treatment.

Flood Warnings are issued for flood risk areas (FWAs) on the Upper Etherow (one FWA) and Lower Etherow (four FWAs), with flood forecasts required on the Etherow to provide timely closure of the flood gates protecting the industrial site at Woolley Bridge and accurate inflows to the wider Upper Mersey forecast model. A gauge at Woolley Bridge Gates (WBG) is 2km downstream of Bottoms Reservoir. Once the reservoirs are full, or operation changes made, the reservoirs can lead to a rapid transfer of flows to WBG. Forecasts of levels at WBG were often over-predicted, resulting in false alarms, and required improved modelling.

As part of updating the flood forecasting for the Upper Mersey, CH2M (2016) reviewed the supporting bathymetry data for the five reservoirs in the Upper Etherow against data held by United Utilities. This led to minor revision of the stage-area curves used in FM Reservoir Units: the example for Woodside is shown in Figure A4.3.1.

The Upper Mersey Model comprises a network of gauged or scaled PDM rainfall-runoff models in conjunction with FM for river and reservoir routing, along with ARMA error-prediction at gauged locations (Figure A4.3.2). Reservoir Gauge Updating units are used for Woodhead, Torside and Bottoms reservoirs, using weekly or 15-minute reservoir level data as available.

The effect of gauge updating on forecasts at WBG, using POD, FAR and CSI criteria, was investigated through a sensitivity analysis. This analysed the effect of each reservoir updating unit and on possible failure of one or more reservoir-level gauges, in forecast-mode for lead-times of 0, 1, 2, 3, 4 and 6 hours. Compared to other gauged sites, forecast errors were found to be least for WBG, mostly due to use of the reservoir updating units. With the units removed, this reduced POD and increased POD for all lead-times and thresholds. The model was found to overestimate more with no reservoir updating (increasing false alarms), but underestimate more with reservoir updating only for Woodhead Reservoir (increasing the number of misses). Gauge updating at Woodhead Reservoir was found to have a net negative effect, and led to omission of the Gauge unit and a recommendation to review the reservoir-level record once sufficient 15 minute data had been obtained.

Thus overall, the modelling study for the Upper Mersey showed that inclusion of the FM Reservoir Gauge unit was usually of benefit, provided the reservoir-level gauge data could be relied upon. Further commentary on the quality of the Woodhead reservoir-level gauge is not given.

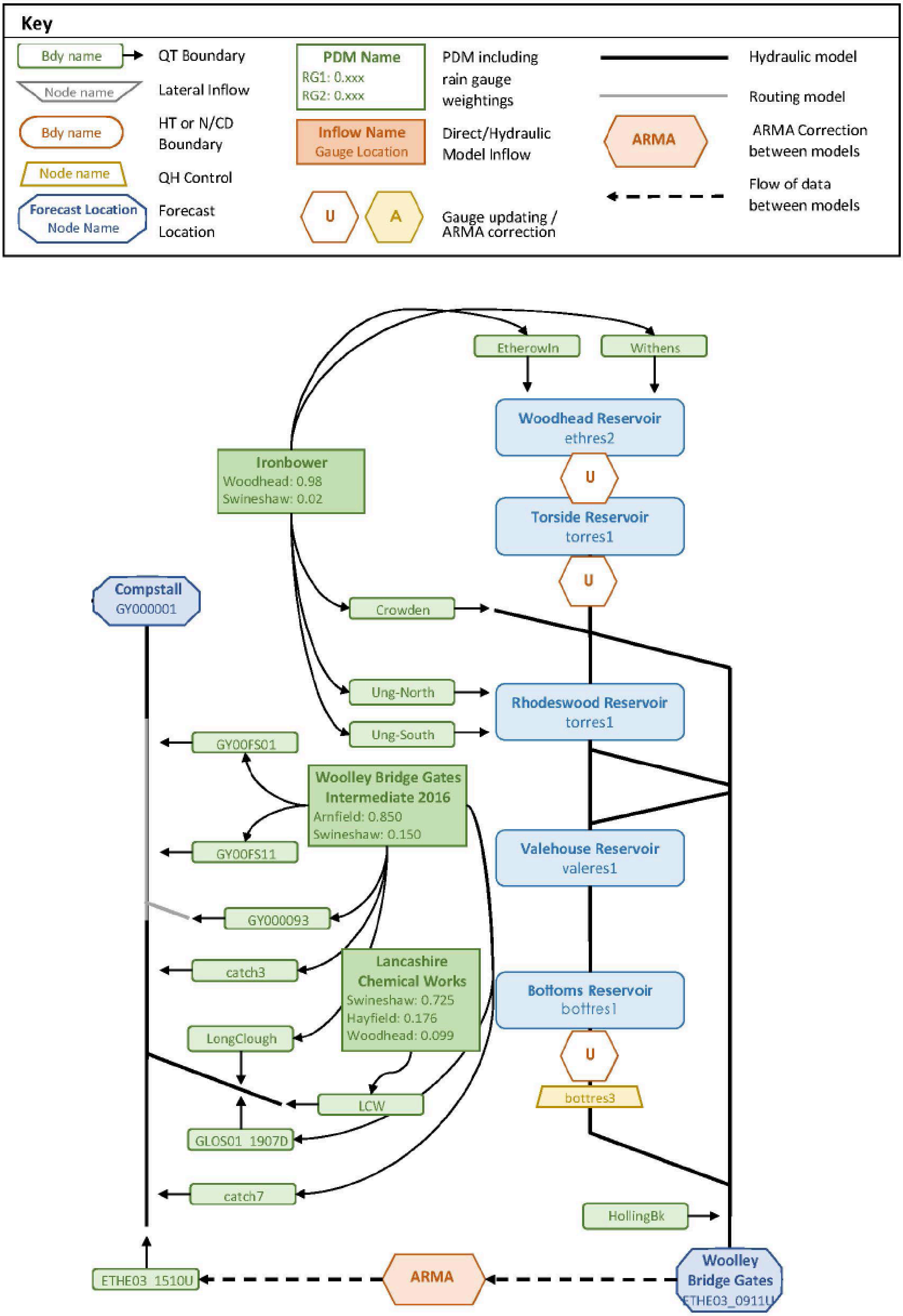

Figure A4.3.1 Schematic of the Upper Mersey Model incorporating FM Reservoir units on the Upper Etherow with Updating units on Woodhead, Torside and Bottoms reservoirs (Source: CH2M (2016))

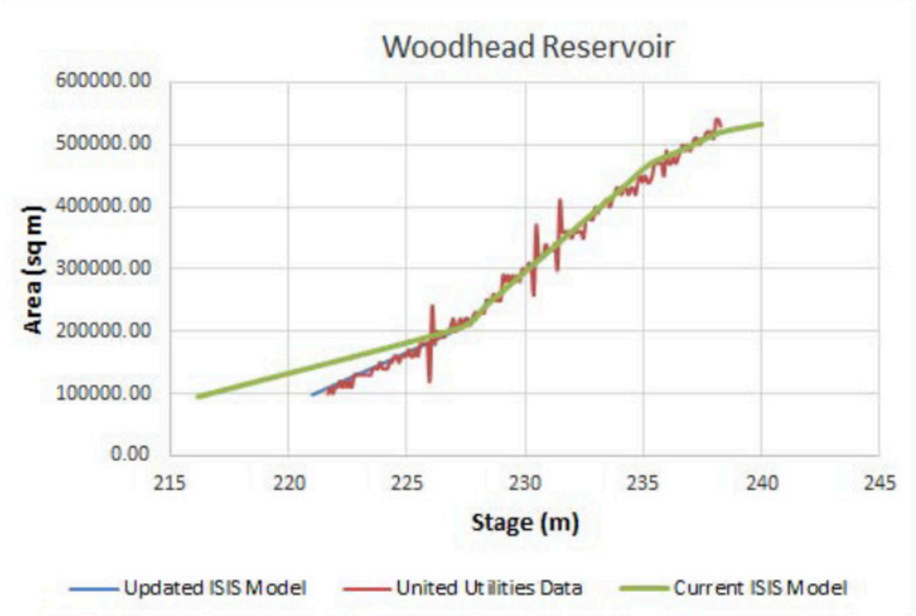

Figure A4.3.2 Comparison between current (green) and updated (blue) stage-area curves for FM (ISIS) models and United Utilities data (red) for Woodhead Reservoir. (Source: CH2M (2016))

Appendix 5.

Scottish Canals case-study: the Smart Canal scheme for north Glasgow

The questionnaire response from Scottish Canals is supplemented here by a case-study, further informed from web sources, which utilises the Forth and Clyde Canal for flood mitigation under the "Smart Canal" scheme for north Glasgow. This flood risk mitigation scheme has allowed Glasgow City Council to release 110 hectares of land for redevelopment (shops, businesses, homes).

The area had a previous history of surface water flooding and the combined sewer system had insufficient capacity to handle increased runoff from a new development. The Forth & Clyde Canal which runs through the area had closed for navigation in 1963, but reopened for amenity use in 2001 following a major restoration project. The "Smart Canal" scheme recognised its flood mitigation value as a storage for excess surface water runoff. A 100mm adjustment in canal level allows for an additional 55,000m^3 of additional water storage, whilst preserving the navigation function of the canal.

AECOM developed a control system (a part of the North Glasgow Integrated Water Management System, NGIWMS) utilising information from remote sensors and rainfall forecasts to feed into Innovyze's ICMLive system. This optimises control of the canal to maintain a level of 46.9m AD in real-time through lock regulation and automatic control of sluice valves at three discharge points (contributing to flows in the River Kelvin, but constrained to avoid flooding). Figure A5.1 provides a map of the scheme with its feeder and discharge sluices and the redevelopment site at Sighthill.

Operation is such as to lower canal levels in advance, based on the rainfall forecasts, to accommodate the inflows from the natural catchment and development area, with levels returning to normal after. There was also a need to avoid unnecessary refill of the canal from its feeding reservoirs, with the possibility of incurring abstraction licence penalties. Thus the control strategy needed to balance constraints on inflow, storage and outflow, whilst recognising uncertainty in the Met Office rainfall forecast which worsens with lead-time and the penalty of acting too early.

The predicted inflow volume is used to set a target canal level to accommodate a proportion of the predicted runoff. A hydraulic model of the system, initialised to monitored flow and level conditions, along with the logic control is used to optimise the feeder (Woodhall and Papermill) and discharge sluice (Ruchill, Shirva, Craigmarloch) positions, which are communicated to the SCADA system that invokes operation. New rainfall forecasts trigger the model and control system to run again. Runoff to the canal and discharges to the River Kelvin are available to view.

The real-time control of the "Smart Canal" complements the SuDS-based design of the redevelopment. As a project, it was undertaken within "The Metropolitan Glasgow Strategic Drainage Partnership" (Duffy et al., 2022) including Scottish Canals and Scottish Water as stakeholders.

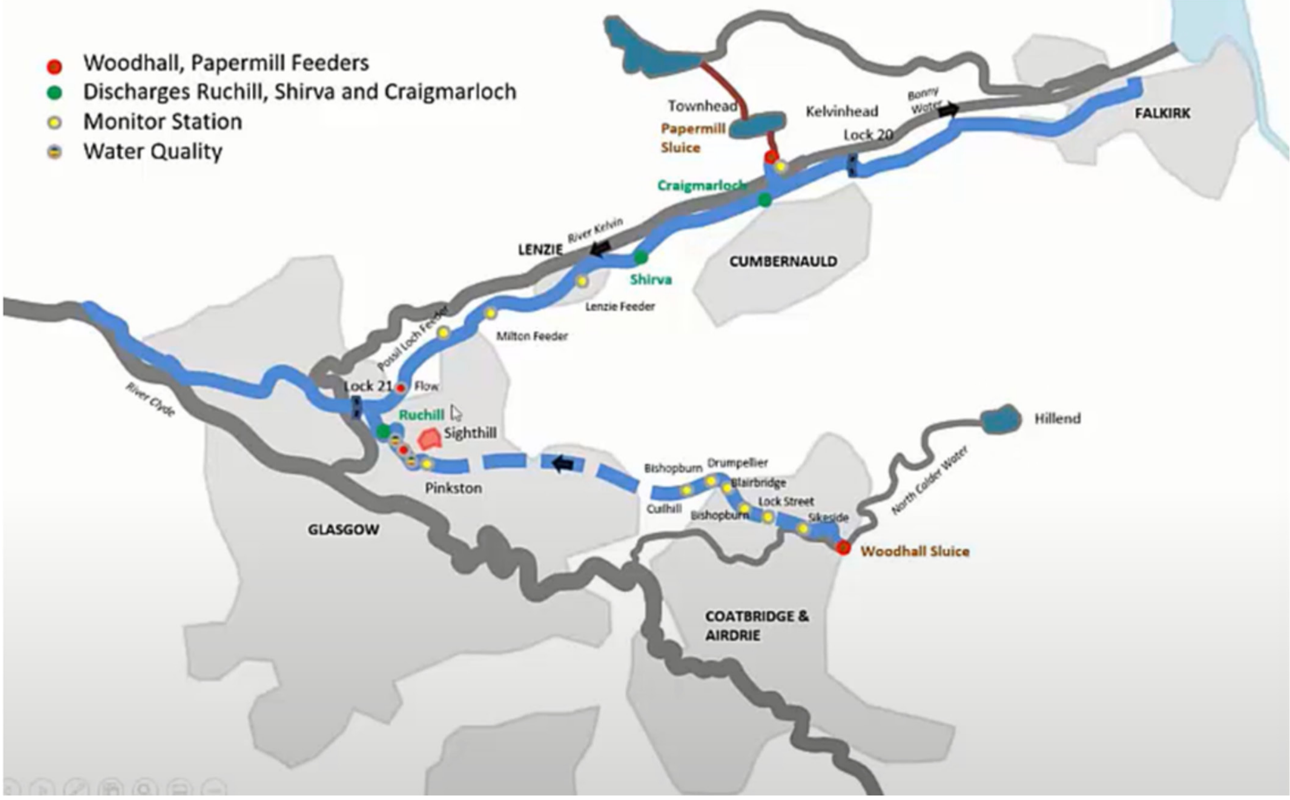

Figure A5.1 The "Smart Canal" scheme in north Glasgow showing part of the Forth & Clyde Canal and its discharge points to the River Kelvin (draining to the River Clyde) and the two feeders from Hillend and Townhead (Bantoch Loch) reservoirs. Sighthill is the development site. (Source: Scottish Canals)

CREW Facilitation Team

Hydro Nation International Centre
James Hutton Institute
Craigiebuckler
Aberdeen AB15 8QH
Scotland UK

Tel: +44 (0)344 928 5428

Email: enquiries@crew.ac.uk

www.crew.ac.uk

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