EARBA STORAGE

A GILKES ENERGY COMPANY

Earba Pumped Storage Hydro Scheme

CAR Licence Application Report

Appendix A: Hydrology Report

December 2024

Hydrology study: Loch Earba PSH

Gikes Energy

February 2024

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Hydrology study: Loch Earba PSH

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February 2024

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Executive Summary

Introduction

Gilkes Energy is pursuing an opportunity for a Pumped Storage Hydropower (PSH) scheme at Loch Earba. This would involve enlarging two existing lochs to provide a closed PSH system with Loch Earba (enlarged from Lochan Na H'Earba) as the lower reservoir and Loch Leamhain as the upper reservoir. The proposed scheme involves enlarging the two lochs via the construction of three dams. Gilkes are required to produce an environmental impact assessment as part of the project's planning application. This assessment investigates the potential implications of the scheme on river flows and existing hydropower operations in the wider catchment area, both during initial filling and future operation. The existing hydropower scheme of most immediate interest is Ardverikie, which generates energy from the outflow of the existing Lochan Na H'Earba.

Approach

A reservoir modelling exercise has been carried out to evaluate the impact of the proposed Loch Earba PSH on river flows and the neighbouring Ardverikie hydropower scheme. Reservoir models were developed by integrating local knowledge of the reservoir design and operations with daily scale hydrology simulated by the lumped hydrological GR6J + 2 zone snow model and HadUK gridded climate observations from the Met Office. In total three reservoir models were developed:

- Existing conditions model – simulates existing loch dynamics;
- Earba PSH scheme filling model – simulates reservoir dynamics during filling;
- Earba PSH scheme operational model – simulates reservoir dynamics whilst operational.

Existing conditions of Lochan Na H'Earba

Simulations of the existing conditions in Lochan Na H'Earba were visually evaluated against estimates derived from head level observations and compared reasonably well. Some periods when storage was under or over-estimated were identified and the magnitudes of spills could not be evaluated due to differences in estimation method. Findings from the existing conditions model highlight that between 1960 and 2021, 77% of inflows would be used to meet demand from the Ardveikie hydropower plant on average. A further 23% of inflows would be spilled downstream and there were negligible losses due to evaporation.

Filling of Earba PSH reservoir

The second assessment explored how long it would take to fill the reservoir. Simulations assumed flows throughout the entire year (January to December) contribute towards the filling of the reservoir and that no demand to Ardverikie is supplied, though a compensation release flow defined as the Q95 of net Earba PSH inflows was maintained. Under these conditions, reservoir storage levels are expected to reach 80% after two years on average, potentially allowing phased introduction of the PSH scheme.

The impacts on the Pattack hydropower scheme during scheme construction are likely to be minimal as it is assumed that the upper reservoir (Loch Leamhain) will be de-watered to form a construction area. It is then assumed that dewatering for the construction area will pass the water downstream into the Pattack catchment.

Future operation of Earba PSH reservoir

Finally, the dynamics of Earba reservoir under operation of the PSH scheme were explored and compared to the dynamics within the existing Lochan Na H'Earba. Ultimately, findings show that operations of the PSH scheme would enhance mean supply to Ardverikie hydropower plant. Furthermore, introduction of the PSH scheme will likely reduce mean spills and spill frequency substantially.

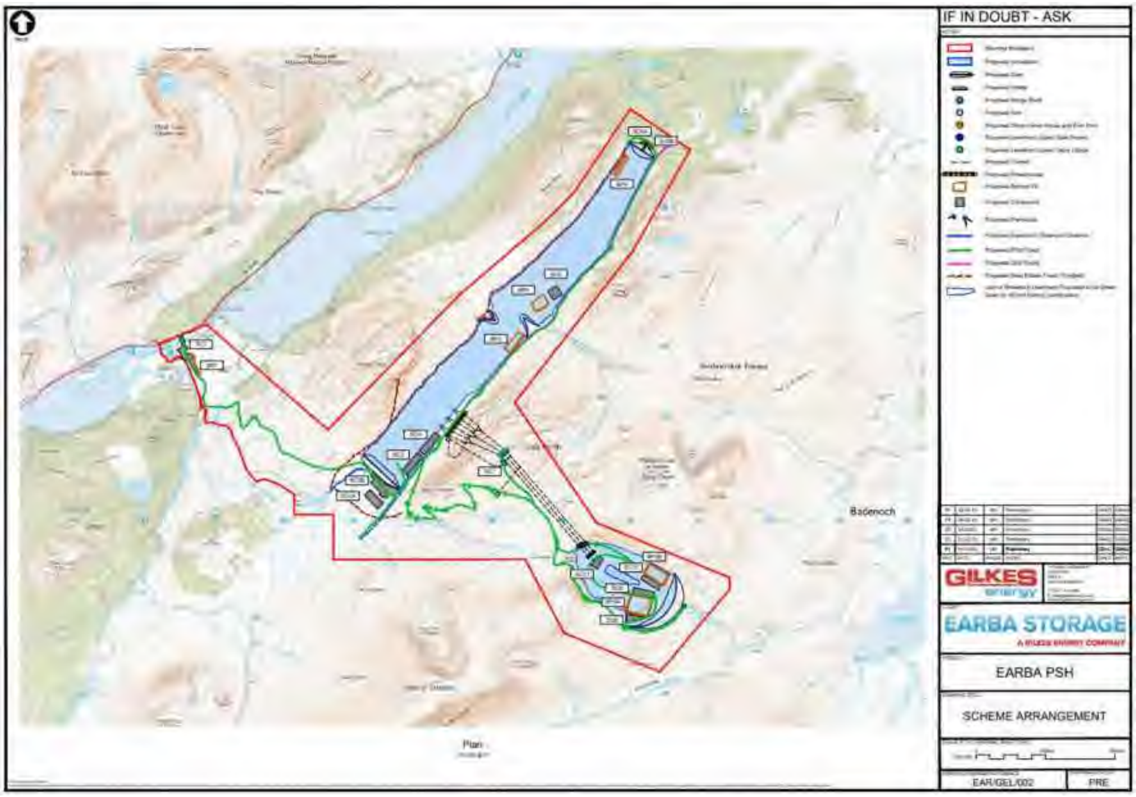
Modelling of the Earba PSH scheme assumes that Loch Leamhain catchment flows do not contribute to operations but are instead passed downstream to maintain natural flows in the River Pattack. Managing this would require monitoring of Earba PSH pumping operations and storage in the upper reservoir (Loch Leamhain) to determine the flow required to drain into the Pattack.

1 Introduction

1.1 Background

Gilkes Energy is pursuing an opportunity for a Pumped Storage Hydropower (PSH) scheme at Loch Earba (Figure 1.1). This would involve enlarging two existing lochs to provide a closed PSH system with Loch Earba (enlarged from Lochan Na H'Earba) as the lower reservoir and Loch Leamhain as the upper reservoir. Enlarging the two lochs would involve the construction of three dams. On Lochan Na H'Earba the SHIOS and SHUAS Dams would be constructed at the north-eastern and south-western ends of the Loch, respectively. A further dam would be constructed at the outfall of Loch Leamhain. Gilkes are required to produce an environmental impact assessment as part of the project's planning application. This assessment investigates the potential implications of the scheme on river flows and existing hydropower operations in the wider catchment area, both during initial filling and future operation. The existing hydropower scheme of most immediate interest is Ardverikie, which generates energy from the outflow of the existing Lochan Na H'Earba.

Figure 1.1: Gilkes Energy site plan for Earba PSH



Source: Gilkes Energy

Mott MacDonald has undertaken some previous work for Gilkes in the area, both in the Laggan catchment (in which Earba sits) and the Pattack catchment (which includes Leamhain). This study builds on this previous work by performing a hydrological modelling exercise for catchments associated to the Earba PSH scheme, which are each sub-catchments of either the larger Laggan or Pattack catchments.

1.2 Objectives

As mentioned above, the primary objective of this study is to understand the impact of Loch Earba PSH on river flows and neighbouring hydropower schemes in the wider catchment area.

1.3 Scope

The scope of the assessment covers the following specific items:

1. The natural hydrology of the Earba and Loch Leamhain catchments
2. Interpretation of gauging of both catchments by others and assessment of the Ardverikie Hydro operation
3. Producing FDCs for Earba and Loch Leamhain catchments as well as new gauging station and proposed abstraction locations (Appendix C.2).
4. Assessing existing residual flows in the Allt Labhrach between Lochan Na H'Earba and Loch Laggan, with no compensation flows currently released
5. Assessing / modelling the Average Annual Energy produced by the Ardverikie Hydro in its current state with no compensation releases and with compensation flows required by SEPA (typically Q95 HOF and Q80 residual flow at Q30)
6. Writing a summary of the hydrology assessed for the ES for planning and reviewing client proposals for compensation and freshet releases at Earba and Leamhain

A detailed energy modelling exercise has not been carried out but instead the availability of flow for the Ardverikie hydropower scheme has been determined. It is then assumed that the existing operational data will allow energy production to be estimated from the flows.

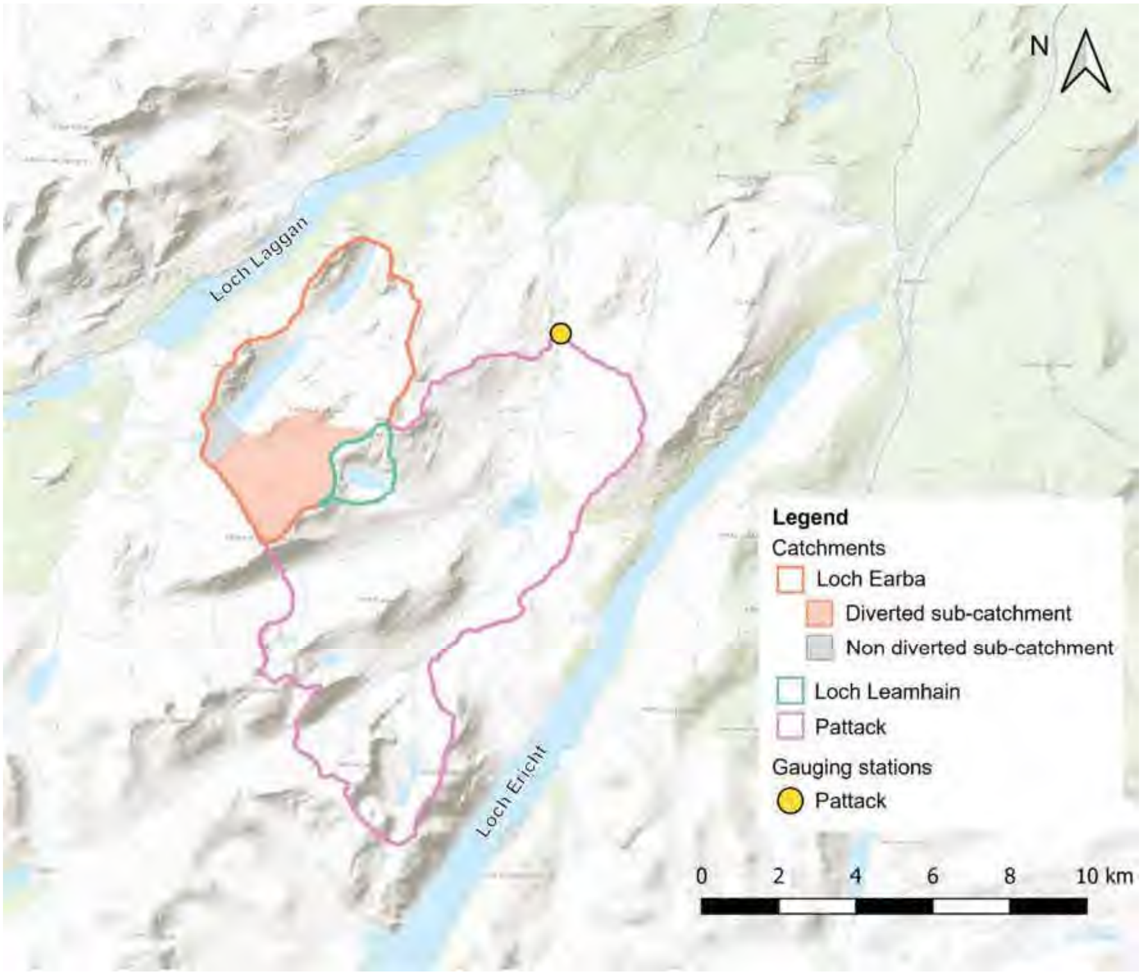
1.4 Approach

The approach of this study is to develop conceptual reservoir models of Loch Earba under both existing conditions and its proposed future configuration/design. These models integrate local knowledge regarding reservoir design and operations with daily-scale hydrological data simulated via a lumped hydrological model.

2 Catchments overview

The Earba and Pattack catchments which form the study area for the Loch Earba PSH scheme are located approximately 40km east of Fort William (Figure 2.1). Within the Earba catchment is the existing Lochan Na H'Earba which will be enlarged during reservoir filling to form the lower reservoir of the Earba PSH scheme. The construction of the proposed SHUAS Dam along the south-western edge of the Lochan Na H'Earba will prevent two sub-catchments from naturally draining into the lower reservoir of the PSH scheme. The majority of flows from one sub-catchment (the 'Diverted sub-catchment') will be diverted to Earba Reservoir via a constructed channel, albeit subject to a Hands-Off Flow condition. A second smaller sub-catchment (the 'Non diverted sub-catchment') will drain to the existing loch immediately to the south-west of Lochan Na H'Earba The upper reservoir in the Earba PSH scheme will be created by enlarging the existing Loch Leamhain. Loch Leamhain is an upland sub-catchment of the larger Pattack catchment which lies to the south-east of the Earba PSH scheme.

Figure 2.1: Overview of study area



There is considerable variation in the size of the catchments investigated in this study (Table 2.1). The largest catchment within this assessment is the Pattack at 64.50km^2 followed by the Earba catchment at 24.44km^2 and Loch Leamhain at 2.57km^2. Catchment boundaries are obtained from the Flood Estimation Handbook (FEH) Web Service provided by UK CEH (UK CEH 2023). The catchment areas are confirmed by GIS analysis and used for hydrological modelling. Shapefiles delineating the sub-catchments of Loch Earba not naturally draining into the proposed reservoir are provided by Gilkes Energy. GIS analysis determined that area which will have runoff diverted to Earba reservoir is 7.06km^2, whilst the area that will drain away from the reservoir is 1.09km^2.

Table 2.1: Earba PSH study catchments

Catchment name	Area (km^2)
Loch Earba	24.44
Earba sub-catchment (Diverted)	7.06
Earba sub-catchment (Non-diverted)	1.09
Loch Leamhain	2.57
River Pattack	64.50

3 Dataset review

3.1 Climate data

The Met Office HadUK-Grid Gridded Climate Observations product was selected to define climate variables used in hydrological modelling and to define the climate properties of the catchments. The data used are the latest update of the HadUK-Grid dataset, released in September 2022. Based on this dataset, time-series of precipitation, temperature, sunshine hours and wind speeds were produced for each of the study catchments, covering the period 1891 to 2021.

HadUK-Gridded datasets are available in NetCDF format and were extracted according to the following steps:

- 1km HadUK-Gridded data were downloaded from the Natural Environment Research Council's Data Repository for Atmospheric Science and Earth Observation online archive (Met Office 2021) for the time periods and temporal resolutions stated in Table 3.1
- The relevant grid cells were identified by overlaying the 1km HadUK-Grid and the catchment outlines with R-scripting
- Each grid cell was weighted based on the area included within the catchment outline
- Data was then extracted for the relevant grid cells (grid cells intersecting with catchment boundaries) using R-scripting
- The catchment rainfall was calculated as a fully weighted average of the 1km grid squares intersecting with the catchment boundaries

Table 3.1: HadUK climate data information

Data product	Units	Spatial resolution	Time period	Temporal resolution	Use
Precipitation	mm/d	1 km	1891 – 2021	Daily	• Hydrological model input
Temperature (Tmax, Tmin)	℃	1 km	1960 – 2021	Daily	• To determine PET
	℃	1 km	1891 – 1959	Monthly	• Hydrological model input (determines snowfall and melt)
Sunshine	hours	1 km	1929 – 2021	Monthly	• To determine PET
Wind	m/s	1 km	1969 – 2021	Monthly	• To determine PET

Maximum and minimum temperature, sunshine and windspeed climatological data were used to derive the PET time series for each of the catchments using the modified Penman-Monteith equation. Further details of the PET calculation can be found in Appendix A. To allow a consistent derivation of a daily PET series from 1891 to 2021, further processing of the temperature, sunshine and wind data was required.

Temperature

- Between 1891 and 1959 when HadUK data is not available, the Braemar station of the MIDAS dataset is used to give a daily pattern in minimum and maximum temperature
- Occasional gaps in the Braemar record were infilled using the Edinburgh Blackford Hill station

- The Braemar series was subsequently adjusted to maintain the monthly average values of the HadUK dataset

Sunshine

- Sunshine data is available from 1929 so the dataset has been infilled with a monthly average profile prior to this date.
- The monthly average time series is then converted to a daily scale by assuming the sunshine hours for each day within that month is equal to the monthly average

Wind

- Wind data is available from 1969 so the dataset has been infilled with a monthly average profile prior to this date
- The monthly average time series is then converted to a daily scale by assuming the wind speed for each day within that month is equal to the monthly average

3.2 Digital Terrain Model

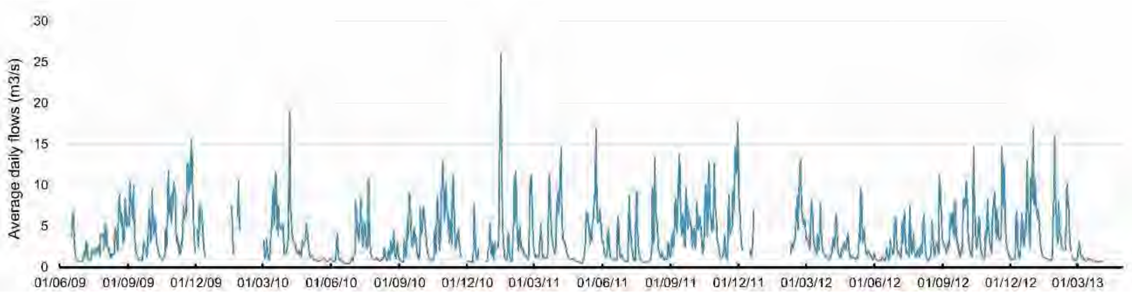
The Ordnance Survey 50m Digital Elevation Model was used to understand the topography of the study area. Furthermore, mean catchment elevations were used to determine time series of atmospheric pressure, which are subsequently used when calculating catchment PET time series.

3.3 Hydrological data

3.3.1 Observed Pattack streamflows

Approximately three years and nine months of streamflow observations are available for the river Pattack starting from June 2009 and continuing until April 2013 (Figure 3.1). Observations are available at a 15-minute time step with 88% of the record having measurements. As hydrological modelling is performed at a daily time step, the observed Pattack hydrograph is aggregated to this coarser temporal resolution by averaging the available values for a given day (Figure 3.1). Days are defined using the water-day which begins at 9am of every calendar day. Measurements are available for 89% of the record when aggregated to a daily temporal resolution.

Figure 3.1: River Pattack daily scale hydrograph



Availability of daily streamflow observations is particularly poor in December and January. As highlighted by Figure 3.2, the daily streamflow record is typically complete between February and November, with only a few missing days of data in November 2010 and February 2012. However, no observed streamflow data is available in January 2012 and only nine and twelve days of data is available in January 2010 and December 2009 and 2011, respectively.

This seasonal disparity in data availability means that a simple average of the available flow values is unlikely to be representative of the overall average flow at the site.

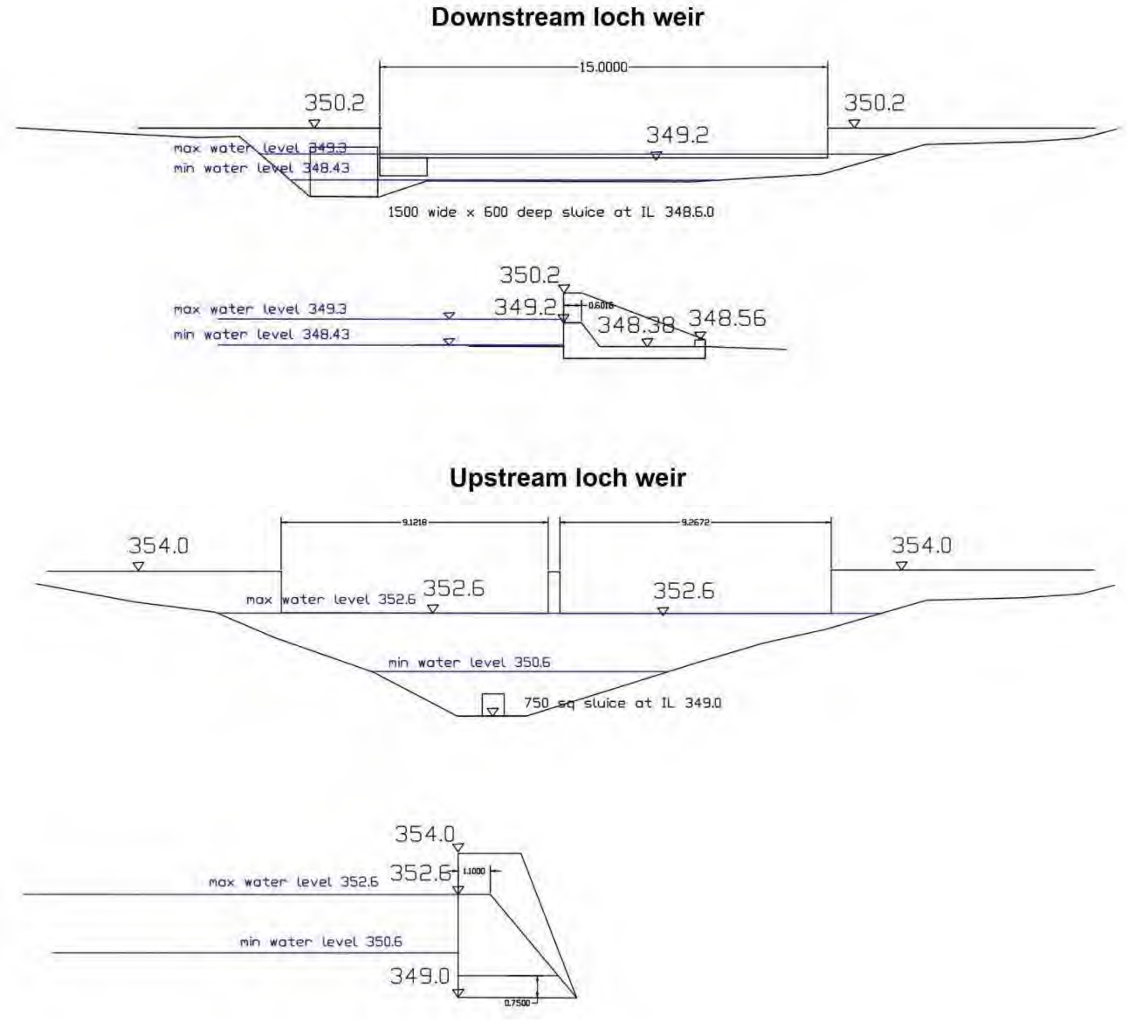
Figure 3.2: River Pattack daily streamflow record data availability

Year	Days in month with streamflow data available											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2009	0	0	0	0	0	14	31	31	30	31	30	12
2010	9	0	30	30	31	30	31	31	30	31	23	20
2011	31	28	31	30	31	30	31	31	30	31	30	12
2012	0	21	31	30	31	30	31	31	30	31	30	31
2013	30	25	29	5	0	0	0	0	0	0	0	0

3.3.2 Loch Earba and Ardverikie data

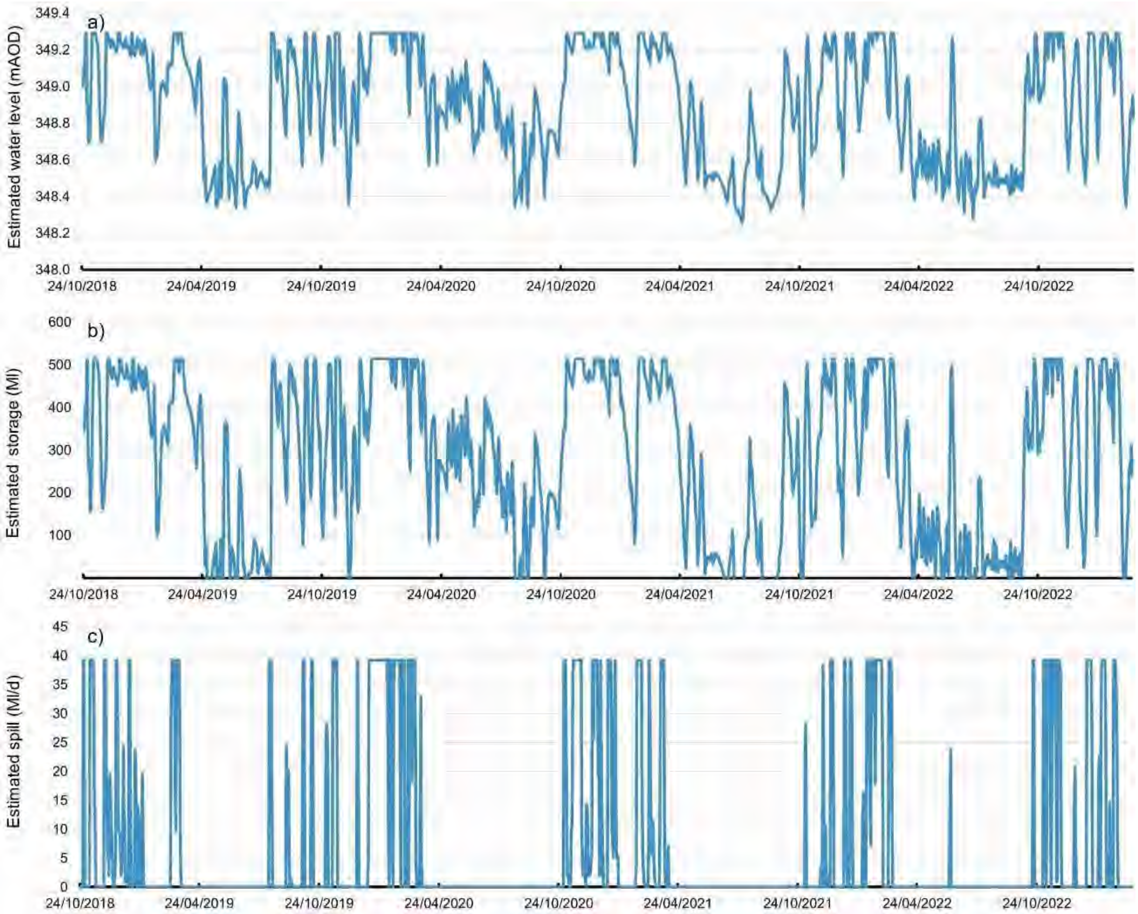
Useful information regarding minimum and maximum water levels, spill levels and weir parameters is provided by configuration drawings for the weirs of Lochan Na H'Earba (Figure 3.3). Water levels in the downstream loch are believed to be constrained between a minimum water level of 348.43mAOD and a maximum water level of 349.29mAOD. However, water levels above 349.20mAOD will be spilled downstream across a weir with a width of 15m. Similarly, water levels in the upstream loch are constrained between minimum and maximum water levels of 350.57mAOD and 352.60mAOD, respectively. At water levels above 352.6mAOD, water is spilled over the 18.3m width weir towards the downstream loch.

Figure 3.3: Weir configuration drawings for the downstream and upstream Earba Lochs



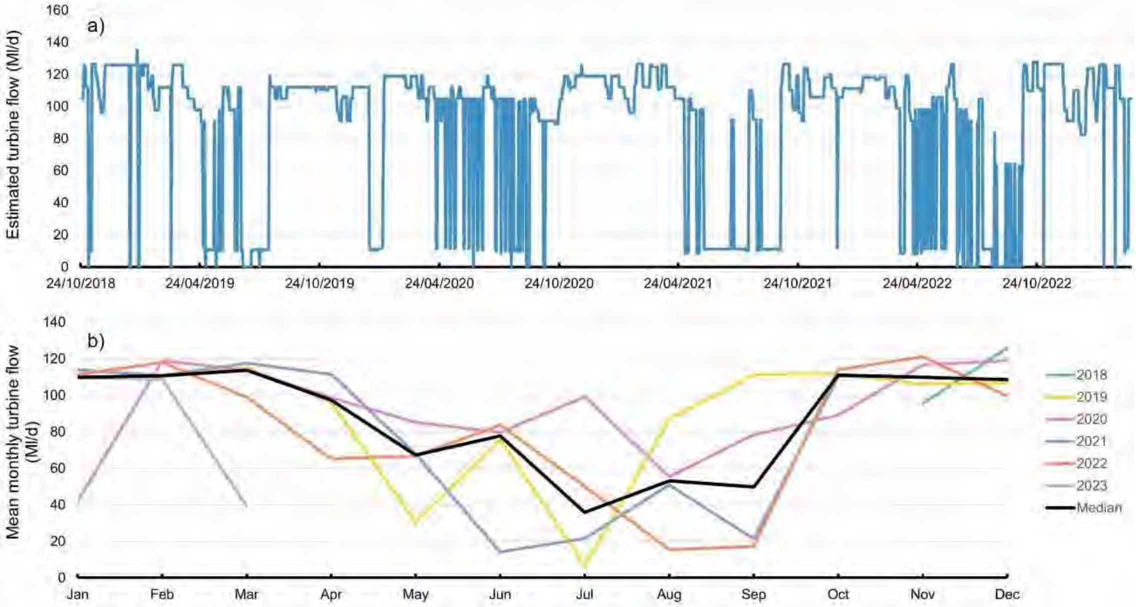
Head level observations are available for the downstream loch of Lochan Na H'Earba at a daily resolution between October 2018 and March 2023. Head levels are recorded as a percentage of maximum head (achieved at a water level of 349.29mAOD) and have been used by Gilkes Energy to model loch water levels, storage and spills (Figure 3.4). On average, water levels in the loch are 348.9mAOD and mean loch storage is 282Ml. As previously stated, the loch's maximum water level is 349.29mAOD and this corresponds to a storage of 514Ml. The Gilkes model estimates mean spills of 7Ml/d with spills occurring on 26% days in the record. The Gilkes model estimates spill when water levels exceed the spill level (349.2mAOD) of the downstream loch (Figure 3.3). Maximum estimated spill is 39Ml/d which is associated to the maximum water level (349.29mAOD) that can be recorded at the weir. In practice the actual spill would be higher if the level exceeds this nominal maximum, which is likely to occur at times of high rainfall and runoff.

Figure 3.4: Estimated timeseries of a) water level; b) storage; and c) spill at Loch Earba



Abstractions from Loch Earba to Ardverikie hydropower plant can be determined from the total turbine flows at the plant. Gilkes Energy have estimated total turbine flows at a daily resolution between October 2018 and March 2023 using the power generated by the plant's turbines. Figure 3.5a shows the timeseries of Ardverikie's water demand which is on average 87Ml/d and has a maximum of 135Ml/d. Figure 3.5b shows the estimated mean monthly turbine flows for each year in the record as well as a median profile across the different years. Typically mean monthly turbine flows are higher in winter months and lower between July and September. In addition to the main turbines generating power at Ardverikie hydropower plant, there is a small turbine which can be used to generate power in lower flow conditions. According to correspondence with Gilkes Energy, the flow required to operate this small turbine is 10.4Ml/d.

Figure 3.5: a) time series; b) seasonal profiles of estimated turbine flows



3.3.3 The Laggan catchment

Laggan Dam provides some control in the lower catchment, and specifically facilitates transfers to Loch Treig for the Lochaber scheme. The study scope (section 1.3) included quantifying winter spill at Laggan Dam as part of assessing how the proposed PSH scheme reservoir could be filled without adversely impacting other schemes such as Lochaber. Information regarding the spill at Laggan and the associated operation of the siphons at this structure is not in the public domain. Therefore, it was not possible to obtain data that could be used for such an assessment, so a qualitative review has been undertaken on the basis of our experience of the hydrology of this part of Scotland.

Whilst the final scheme will operate as a closed system, the start-up of the scheme will involve impounding a substantial volume of water. This will reduce downstream flows during this period, potentially impacting on the Lochaber hydropower scheme. However, if the impoundment can take place at times of high flow when there would be spill at Laggan Dam there would be no adverse impact on Lochaber because it would just lead to a reduced rate of spill. Nonetheless, if filling of Earba reservoir occurs more generally throughout the year minor reductions in downstream flows would be expected.

Flows are generally above the long-term average through the winter (October to April, with flows towards the end of the period supported by snowmelt). As a minimum it is suggested that impoundment be limited to this period, with a minimum release (compensation) maintained. However, autumn flows typically contribute towards refilling storage, including Loch Treig, and limiting filling of the new PSH reservoir to the period from December is considered more realistic.

It should be noted that the Earba catchment provides only a small part of the flow reaching Laggan Dam, so reducing the Earba outflow during impoundment will only have a small impact on total flow and spills at Laggan Dam. The Earba catchment area of about 24km^2 represents about 6% of the overall direct catchment to Laggan Dam (375km^2). Furthermore, if transfers into the Laggan catchment (particularly from the Spey) are considered, its share of the Laggan Dam catchment drops to about 4%, while its share of the overall catchment contributing to the

Lochaber scheme is about 3%. Hence impacts to stakeholders downstream of Laggan Dam are not expected to be substantial.

4 Methodology

4.1 Hydrological modelling

Hydrological simulations are performed using the GR6J + 2 zone snow model. This is a lumped catchment hydrological model which simulates streamflow at a daily resolution. One of the benefits of this model is its constrained data requirements, as daily series of precipitation, minimum and maximum temperatures, sunshine hours and wind speeds are the only required model inputs (Table 3.1). Due to the likely importance of snowmelt processes on streamflow in the study catchments, a snow accumulation and snowmelt routine has been developed by Mott MacDonald and added to the original model. A more detailed description of the GR6J + 2 zone snow model can be found in section B.1.

As streamflow records are only available for the river Pattack, the hydrological model is calibrated for this catchment only. To maximise use of the relatively short record of streamflow observations on the river Pattack, the model calibration period (July 2009 to March 2013) used all the available data. Model calibration implemented an automatic calibration approach to increase efficiency and ensure the most optimum solution is found (Appendix B.2). The automatic calibration procedure is aiming to minimise a bespoke objective function developed by Mott MacDonald referred to as 'BiasMM', which combines the following performance measures, NSE, Log-NSE, Log-NSE FDC and Log-NSE FDC ≤Q95. Further details of the objective function and each individual performance measure are provided in Appendix B.2.1.

The identified best performing model parameter set is then transferred to Loch Earba and Loch Leamhain catchments which are then modelled using their own respective climate time series (Section 3.1). Daily streamflow series are then simulated for the entire period from January 1891 to December 2021 for each catchment using the entire record of available climate data. This includes a 1-year model warm-up period after the start of the rainfall and PET series, so useable flow series cover 1892 to 2021. However, a shorter period may be considered more appropriate for assessing likely future operation. Hydrological simulations for the Loch Earba sub-catchments ('diverted' and 'non diverted') were performed using the climate series extracted for Loch Earba but applying the relevant catchment areas (Table 2.1).

4.2 Reservoir modelling

Water balance models for the existing Loch Earba and proposed Earba reservoir under both reservoir filling and operational regimes have been developed. Each of these three models simulate the evolution of stored volumes and spillages during the 1960-2021 period at a daily timestep, albeit with different configurations and operations of the loch/reservoir. Details for each of the model configurations are discussed further in Sections 4.2.1, 4.2.2 and 4.2.3, though there are some commonalities which are discussed below:

- Lochs and reservoirs are assumed to have a fixed area that does not vary with water level
- Loch or reservoir excess evaporation = open water evaporation – evapotranspiration
  - This represents the additional loss from a water surface compared to a "normal" catchment surface
  - It is applied to the proportion of the catchment that comprises a water surface in excess of that in the calibration catchment.
- Spill depth (m) is the depth of water above the reservoir spill level
- Spill (m^3/s) = $b \times C_d \times h^a$ whereby
  - b is the weir width (m)

– C_d is the weir discharge coefficient (-)
– h is the spill depth (m)
– a is the weir exponent (-)

4.2.1 Existing conditions

In its existing condition, Loch Earba consists of two lochs connected via a small stream. The existing conditions water balance model therefore consists of two storage buckets, each representing one of the lochs. This model simulates the storages and spills of the lochs, with outflows (releases + spill) from the upstream loch becoming an inflow to the downstream loch. As such, the upstream loch attenuates flows to the downstream loch. Visual inspections of simulated storage in the downstream loch found that considering this attenuation was important for reasonably capturing storage dynamics of the downstream loch when comparing simulated outputs to the Ardverikie data.

Simulated Loch Earba catchment flows are the input to the two lochs. 78% of these flows drain directly to the upstream loch with the remaining flows draining directly to the downstream loch. The directly draining flow is the only inflow into the upstream loch, whereas inflows into the downstream loch include the directly draining flows and upstream loch outflows. The scaling of flows was determined by comparing the area of the total Loch Earba catchment to the catchment area for the upstream loch outfall.

Model outputs include the following:

- Releases from the upstream to the downstream loch
- Abstractions to Ardverikie hydropower plant
- Additional loch evaporation
- Spill

Release flows are only modelled for the upstream loch and no compensation release flows are modelled for the downstream loch. Release flows from the upstream loch are discharged via the 750mm square sluice at the bottom of the weir (Figure 3.3). This information alone is insufficient to accurately simulate outflows, but assumptions have been made following discussions with Gilkes Energy. The assumptions and rules were developed to give a reasonable comparison between simulated downstream loch water levels and those estimated though head level measurements. Assumptions made to model release flows from the upstream loch are detailed in Table 4.1 and are as follows:

- Release flows are assumed to be zero at water levels below 350.57mAOD
- Release flows are assumed to be 1m^3/s or 86.4Ml/d at water levels of 351.57mAOD or above.
- At water levels between 350.57 and 351.57mAOD, release flows are linearly interpolated between 0 and 1m^3/s according to the water level.

Water supply to meet demand from the Ardverikie hydropower plant is modelled using the median seasonal profile realised in Figure 3.5b. This profile takes the average turbine flow estimated at the Ardverikie hydropower plant for each month in the data record and then uses the median seasonal profile for the different years in the record.

In the upstream and downstream loch spills occur at water levels of 352.6mAOD and 349.2mAOD respectively (Table 4.1). Spills are simulated using the spill/weir equation in section 4.2 and an estimate of the spill depth which is the estimated water level above the spill level. The weir properties (i.e., weir width, coefficient of discharge and the weir exponent) used in the spill equations are provided in Table 4.1 and followed recommendations from Gilkes Energy. Simulations are initiated with maximum storage levels in both lochs, as this is typically the case in winter.

Table 4.1: Loch Earba existing conditions model parameters

Parameter	Value - upstream loch	Value - downstream loch
Max storage (Ml)	2,145	520
Min water elevation (mAOD)	350.57	348.43
Weir width (m)	18.3	15
Cd (-)	1.3	1.5
Weir exponent (-)	1.5	1.5
Spill level (mAOD)	352.60	349.20
Sluice max flow water level (mAOD)	351.57	N.A.
Sluice zero flow level (mAOD)	350.57	N.A.
Max flow through sluice (m^3/s)	1	N.A.

4.2.2 Reservoir filling

Modelling of the proposed Earba reservoir during filling used a water balance model consisting of one storage bucket. With the construction of the proposed scheme, the two existing lochs within the Earba catchment would be enlarged to form a single larger reservoir (Figure 1.1). Furthermore, it is assumed that during filling of Earba Reservoir, Loch Leamhain which forms the upper reservoir within the PSH scheme will be drained to form a construction area, with de-watering activities moving the water downstream into the Pattack catchment. Therefore, it is reasonable to conceptualise the system as inflows and outflows from a single bucket representing the reservoir. The reservoir filling time is then estimated by setting the initial reservoir storage to zero and by assessing the time taken for simulated storage to reach the reservoir's maximum storage of 70,821Ml (Table 4.2).

Again, model inputs include simulated Loch Earba catchment flows, although these flows are not partitioned between two buckets in this scenario. Construction of the proposed SHUAS Dam to the southwestern edge of Lochan Na H'Earba would prohibit a sub-catchment of the Earba catchment from draining naturally into the reservoir. To determine inflows into Earba Reservoir, flows from the sub-catchment draining away from Earba reservoir as well as flows under the Hands-Off Flow condition for the diverted sub-catchment are subtracted from the total Earba catchment flows. The Hands-Off Flow condition for the diverted sub-catchment is set to the Q95 of sub-catchment flows (5.79Ml/d), such that only excess flows are diverted to the reservoir. Additionally, it is assumed that when draining the Loch Leamhain catchment to form a construction area, these flows will be directed downstream into the Pattack catchment. Therefore, Loch Leamhain catchment flows are not included as an inflow to the Earba PSH during reservoir filling simulations.

Model outflows include the following:

- Compensation releases
- Additional loch evaporation
- Spill

Compensation release flows are defined as Q95 of the net inflows into the Earba reservoir model (Table 4.2). Filling of the reservoir is assumed to occur throughout the whole year (January to December) and demand by Ardverikie is not supplied.

Table 4.2: Earba reservoir PSH filling model parameters

Parameter	Value
Max storage (Ml)	70,821
Min water elevation (mAOD)	350
Max water elevation (MAOD)	376
Min allowable storage (Ml)	0
Weir width (m)	15
Cd (-)	1.5
Weir exponent (-)	1.5
Spill level (mAOD)	376
Compensation	Q95

4.2.3 Operational reservoir

Like reservoir filling, modelling the proposed operational use of Earba reservoir used a single bucket water balance model. Therefore, the model conceptualises the PSH scheme as one enclosed system and does not try to simulate water transfers between the upper (Loch Leamhain) and lower (Lochan Na H'Earba) reservoir. The reason for this is that the PSH scheme will essentially involve recirculating the same water.

Minimum allowable storage for reservoir operations is defined as 63,754Ml to preserve this water for operating the PSH scheme. This provides 7,067Ml buffer storage (i.e., reservoir storage between water levels of 355mAOD and 358mAOD) to the scheme with a maximum storage of 70,821Ml. At the beginning of the reservoir operations simulation, initial storage is assumed to be halfway between maximum reservoir storage and the storage reserved to run the PSH scheme (minimum storage), based on initial model runs that showed the average start-year storage to be around 50%.

Earba reservoir inflows during operations are modelled identically to those during the filling of the reservoir. Hence flows from the sub-catchment draining away from Earba reservoir and flows under the Hands-Off Flow condition for the diverted sub-catchment are subtracted from the total Earba catchment flows to determine Earba reservoir inflows. It is assumed that simulated catchment flows of Loch Leamhain do not contribute to the operation of the PSH scheme as the upper reservoir would be managed to maintain natural flows in the Pattack.

Model outflows include the following:

- Compensation releases
- Abstractions to Ardverikie hydropower plant
- Additional loch evaporation
- Spill

Again, compensation release flows are defined as Q95 of the net inflows into the Earba reservoir model (Table 4.3). During reservoir operations, it is assumed that supply to Ardverikie hydropower plant will return to pre-construction levels and therefore the seasonal abstraction profile defined in Figure 3.5b is used for modelling.

Table 4.3: Earba reservoir PSH operational model parameters

Parameter	Value
Max storage (Ml)	70,821
Max water elevation (MAOD)	376
Min allowable storage (Ml)	55,340
Weir width (m)	15
Cd (-)	1.5
Weir exponent (-)	1.5
Spill level (mAOD)	376
Compensation	Q95

5 Results

5.1 Catchment climate characterisation

The HadUK climate data is analysed to characterise the historic climatology of each of the catchments. Further understanding of catchment climatology can help understand the dominant hydrological drivers and how they interact over time. Consequently, this can also assist with the interpretation of the simulated hydrological series used in the Earba reservoir models.

The catchment climatology characterisation is organised according to three timescales. Firstly, the annual average properties are described to provide an overview of the general catchment climate. Secondly, we investigate the inter-annual variability in climate variables to identify any trends or patterns which could have important implications for water resource availability. Finally, we assess the seasonality of climate properties and how these have varied annually, which could affect the reservoir operations during both filling and future operations.

Although climate data is available from 1891-2021, this study focuses primarily on the period from 1960 to 2021 as this is believed to be the most reasonably representative of likely future climate conditions. The selection of this shortened time period is discussed further in section 5.4.

5.1.1 Long-term average climate characteristics

Generally, the four catchments have similar average climatological properties with mean annual precipitation far exceeding mean annual Potential Evapotranspiration (PET) and low mean temperatures (Table 5.1). For the period of 1960 to 2021, mean annual precipitation across the four catchments varies from 1921mm/year in the Loch Earba catchment to 2159mm/year in the more upland Loch Leamhain catchment. Differences in precipitation are likely due to differences in elevation (Table 5.1). There are less substantial differences in the mean annual PET across the four catchments as they only vary from 452 mm/year to 489 mm/year. Leamhain has the lowest mean annual PET, again likely due to its higher average elevation and consequently lower temperatures. Mean temperatures for the catchments are typically around 5.0℃ though Leamhain has a lower mean temperature of 3.9℃. For each catchment precipitation is dominant, exceeding atmospheric water demand by a factor of five in Loch Leamhain and a factor of four in the remaining catchments.

Table 5.1: Catchment mean annual climate characteristics (1960 - 2021) and elevation

Catchment	Mean annual precipitation (mm/year)	Mean annual PET (mm/year)	Mean temperature (℃)	Mean elevation (mAOD)
Loch Earba	1921	489	5.2	585
Loch Leamhain	2159	452	3.9	791
River Pattack	2057	479	4.7	655

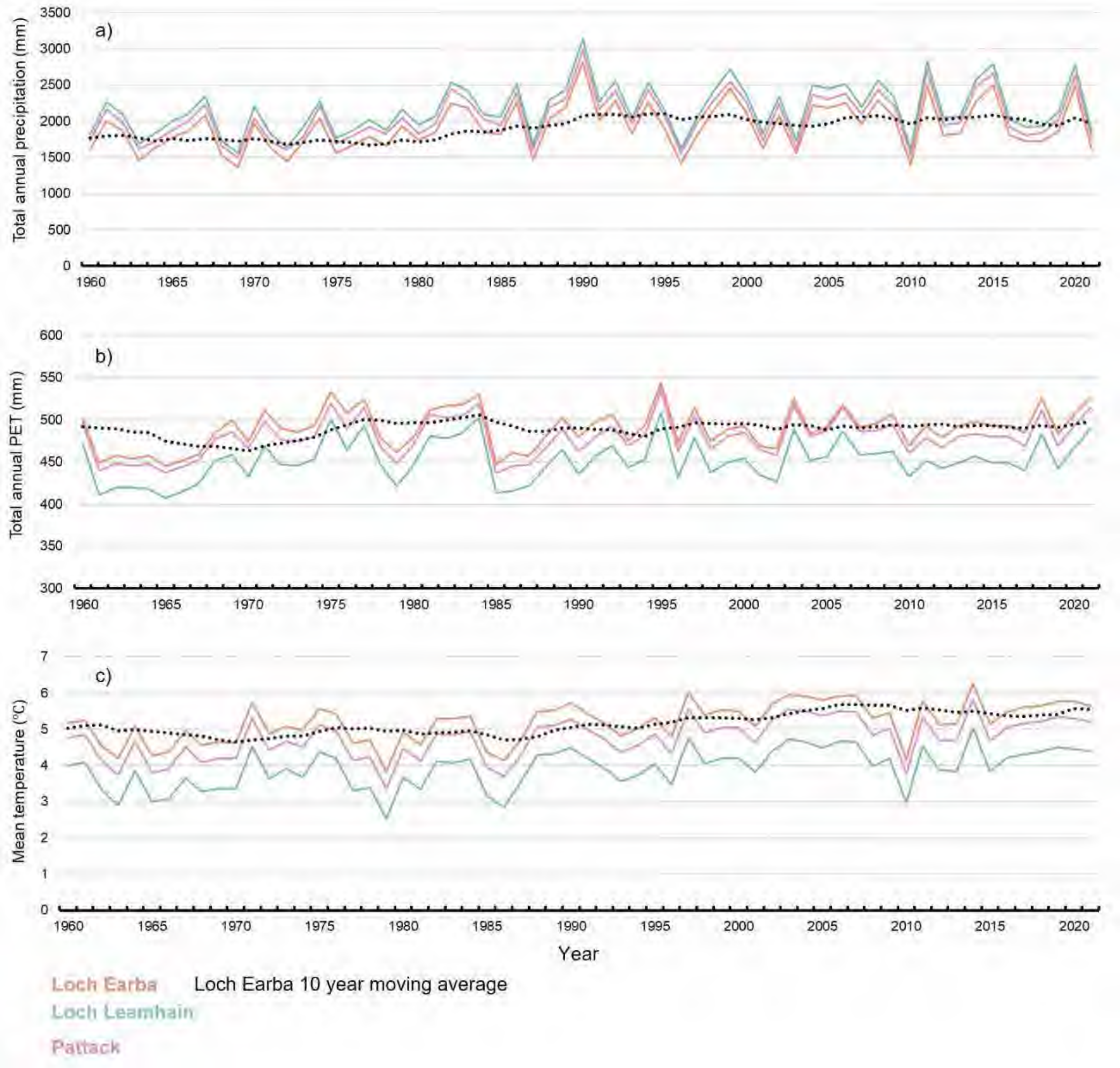
5.1.2 Inter-annual variability

Annual variability in catchment average precipitation, PET and temperatures are highly correlated between all study catchments (Figure 5.1), which is likely due to the spatial proximity of the catchments to one another. Pearson correlation coefficients between the annual time series of precipitation, PET and mean temperatures are 0.99 for all pairs of catchments investigated in this study.

For all the study catchments, annual precipitation totals are greater and more variable in the period after 1990 than between 1960 and 1980 (Figure 5.1a). Mean annual precipitation totals are approximately 17% greater after 1990 than they were between 1960 and 1980. For example, in the Earba catchment mean precipitation increased from 1731mm/year to 2026mm/year. This general trend in annual precipitation is further highlighted by the moving average series of annual precipitation for the Loch Earba catchment (Figure 5.1a), which is calculated using a ten-year backward-looking window. Furthermore, standard deviations in annual precipitation have increased by approximately 70% from between 1960-80 and the period after 1990, so there is more variability in annual rainfall. Using Loch Earba as an example catchment, standard deviations in annual precipitation totals increase from 200mm/year between 1960 and 1980 to 337mm/year between 1990 and 2021.

There is no obvious trend in annual PET rates (Figure 5.1b). Since 1990 mean annual PET has only increased by between 3mm/year and 8mm/year when using a ten-year backward-looking moving average window. Similarly, Figure 5.1c only shows increases in mean annual temperatures after 1980. Again, using the ten-year backward looking moving average window, mean temperatures have increased by approximately 0.6℃ between 1980 and 2021 for each of the catchments, which is slightly below the UK average of approximately 1.0℃ of warming over the same period (Kendon 2023). The lack of a positive trend in annual PET is likely explained by only modest increases in mean temperatures as well as only a moderate positive correlation between PET and mean temperature. Pearson correlation coefficients between annual PET and annual mean temperatures are only between 0.51 and 0.54. This demonstrates the importance of additional climate variables in determining PET, most probably wind speeds.

Figure 5.1: Inter-annual variability of a) annual precipitation; b) annual PET; and c) mean temperatures for the period 1960-2021



5.1.3 Seasonality

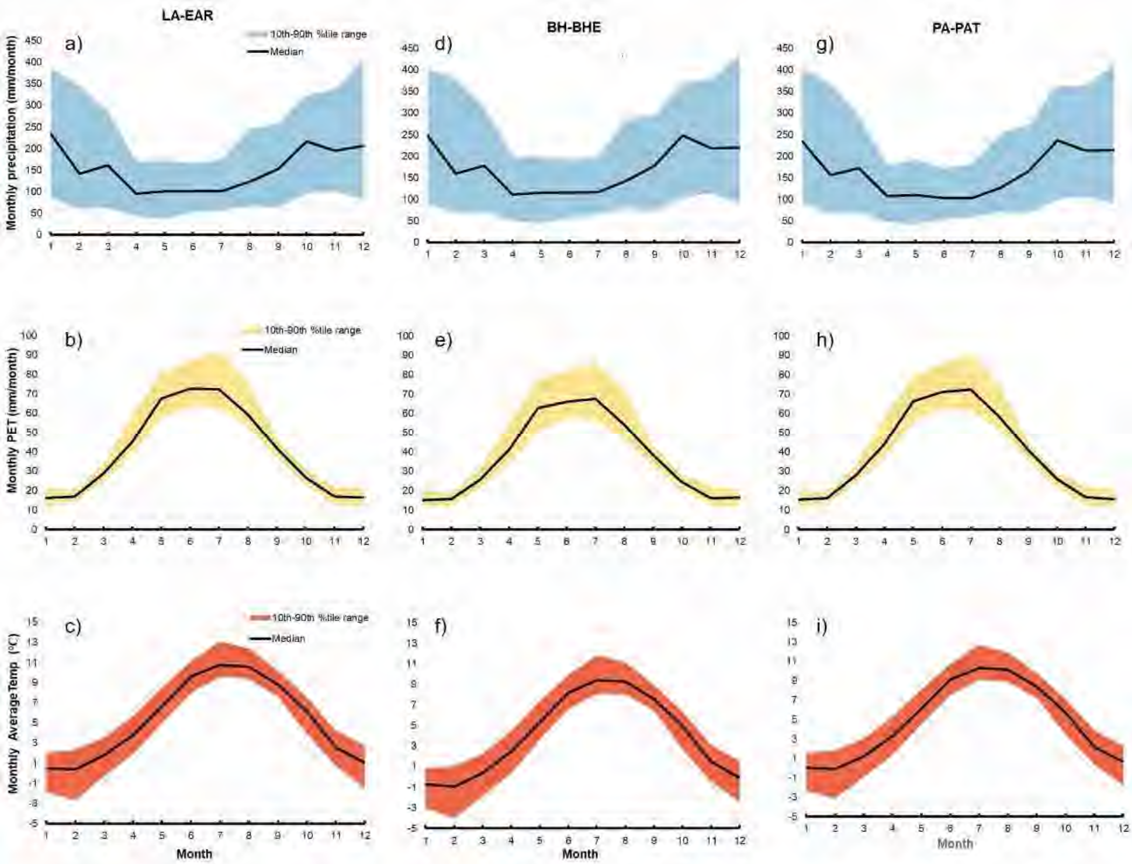
In the study catchments PET and mean monthly temperatures have very distinct seasonal profiles, whereas the seasonal profile for precipitation is much less pronounced (Figure 5.2). Figure 5.2 shows the long-term (1960-2021) seasonality of precipitation, PET and mean monthly temperatures. Shaded areas represent the 10th to 90th percentile range of monthly values, whilst the median value is shown via the black line. Due to spatial proximity of the study catchments to one another, they have very similar seasonal distributions of precipitation, PET and temperature.

Both PET and mean temperatures have distinct seasonal profiles with highs between June and August and lows typically from November to February. PET typically peaks at approximately 70mm/month in June and July with mean monthly temperatures peaking a month later between July and August at approximately 10^{o}C. This again demonstrates the importance of wind speeds in PET estimation which was previously highlighted at inter-annual time scales. Between November and February, PET and monthly mean temperatures fall to approximately

15mm/month and between -1 °C to 2 °C, respectively. Furthermore, the relatively constrained shaded area (10th to 90th percentile range) indicates that there is only moderate inter-annual variability in the seasonal profiles for PET and mean monthly temperatures.

In contrast, the seasonal profile of precipitation is much less pronounced but varies more from year to year, as highlighted by the greater range between the 10th and 90th percentiles. Using these percentile ranges, monthly precipitation in winter months (October - March) is typically 165-430mm/month whilst in summer months (April -July) it can vary from approximately 100 to 200mm/month. Nonetheless, precipitation is typically higher in winter months than summer months, with median precipitation rates of 200-220mm/month and 100-115mm/month, respectively.

Figure 5.2: Seasonal distribution of a,d,g) total monthly precipitation; b,e,h) total monthly PET; and c,f,i) monthly mean temperatures for the period 1960-2021



5.2 Rainfall runoff modelling

5.2.1 Pattack model calibration

To maximise use of the relatively short record of streamflow observations on the river Pattack, the model calibration period (July 2009 to March 2013) used all the available data. Therefore, no subsequent validation of the Pattack hydrological model was possible.

The best performing parameter set identified via the automatic calibration procedure (Appendix B.2) can be found in Table C.1. As part of the calibration, adjustment factors of 4% and 6% were identified for the catchment precipitation and PET series. These factors uplift the precipitation and PET by a calibrated percentage to ensure that the water balance is being adequately represented. This adjustment compensates for uncertainty in the gridded meteorological dataset used for this study, particularly in upland environments. Overall, the model delivers a strong calibration performance in metrics associated to flow duration curves and reasonably well in NSE and Log-NSE (Table 5.2) but underestimates volumes by approximately 5%.

Table 5.2: Calibration performance metric scores

Performance metric	Value
Volume error	-5.4%
NSE	0.699
Log-NSE	0.738
Log-NSE FDC	0.974
Log-NSE FDC ≤Q95	0.999

Note: Metrics highlighted in bold were used within the calibration objective function

Visual inspection of the observed and simulated flow duration curves highlights that the model performs better at the extreme ends of the distribution than it does between Q10 and Q90 (Figure 5.3). The distribution of low flows (< Q95) appears to be particularly well captured by the model. In contrast, substantial over-estimates are observed between Q7 and Q65 and some less significant under-estimates can be seen between Q67 and Q95. Comparing the simulated to observed hydrological time series for the Pattack (Figure 5.4) also highlights the under-estimation of some peak flows and some relatively minor over-estimation of low flows.

Figure 5.3: Observed and simulated Pattack flow duration curves for the calibration period

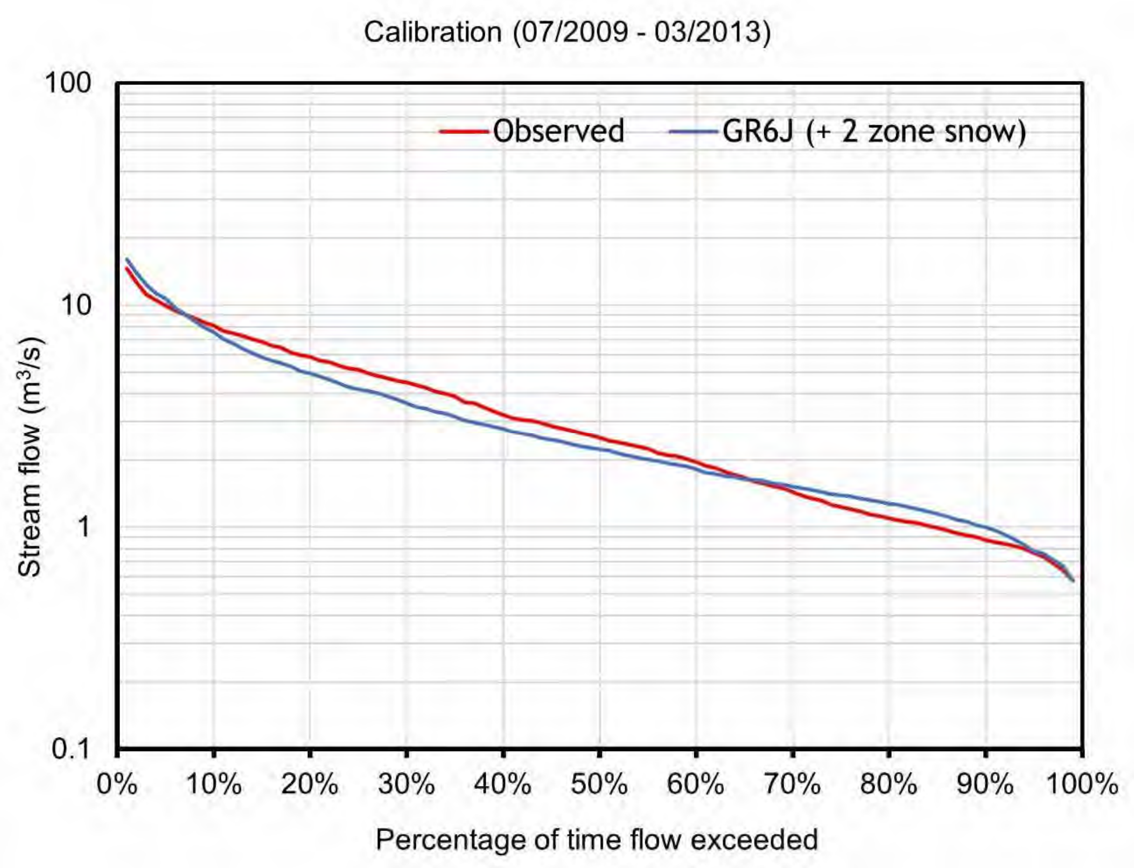
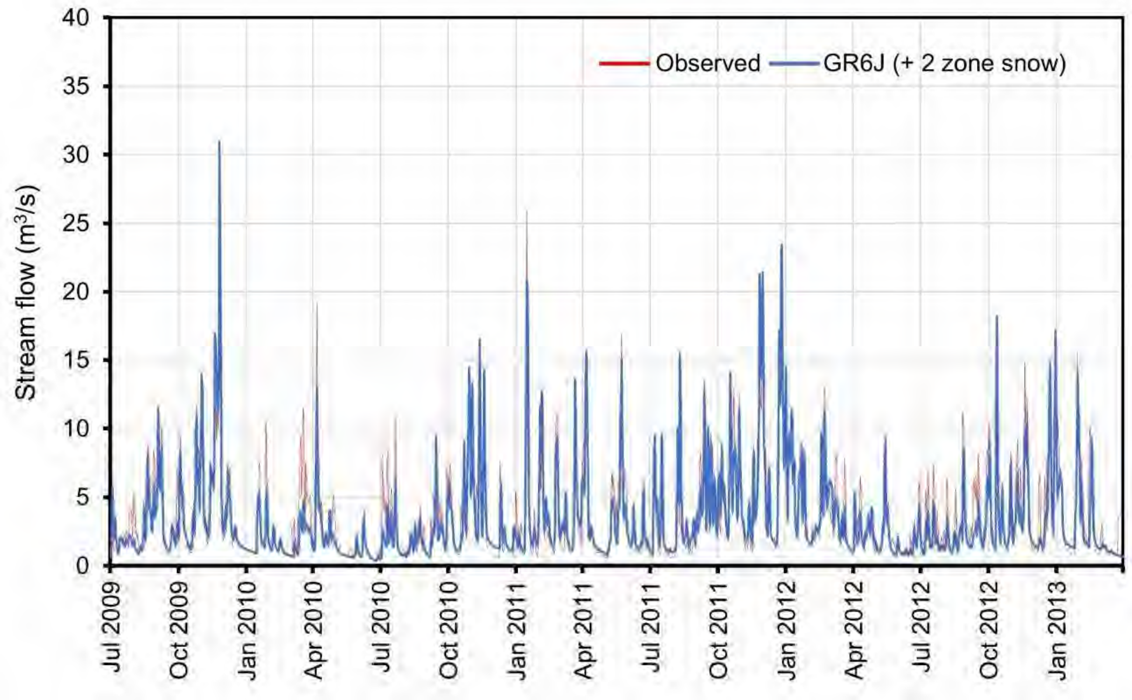


Figure 5.4: Observed and simulated Pattack hydrographs for the calibration period



5.3 Catchment streamflow characterisation

Simulated streamflow timeseries from the hydrological modelling exercise are used to characterise the historic catchment hydrological behaviour. Like the catchment climate characterisation, this assessment is organised according to the following time scales, long-term mean conditions, inter-annual variability and seasonality. Subsequently, flow duration curves for each catchment are assessed to understand how estimated streamflows are generally distributed.

5.3.1 Long-term average hydrological properties

Although all study catchments convert approximately 80% of their precipitation to runoff, long-term (1960-2021) mean annual catchment flows vary considerably due to differences in catchment size (Table 5.3). On average, simulated flows in the Loch Earba catchment are an order of magnitude greater those within the Loch Leamhain catchment. Moreover, simulated flows within the Pattack catchment are approximately three times larger than those of Loch Earba. Differences in streamflow are attributed to different catchment sizes. Slightly greater estimated runoff rates of 1788mm/year in the Loch Leamhain catchment are due to the generally wetter climate in this catchment due to its higher elevation (Table 5.1).

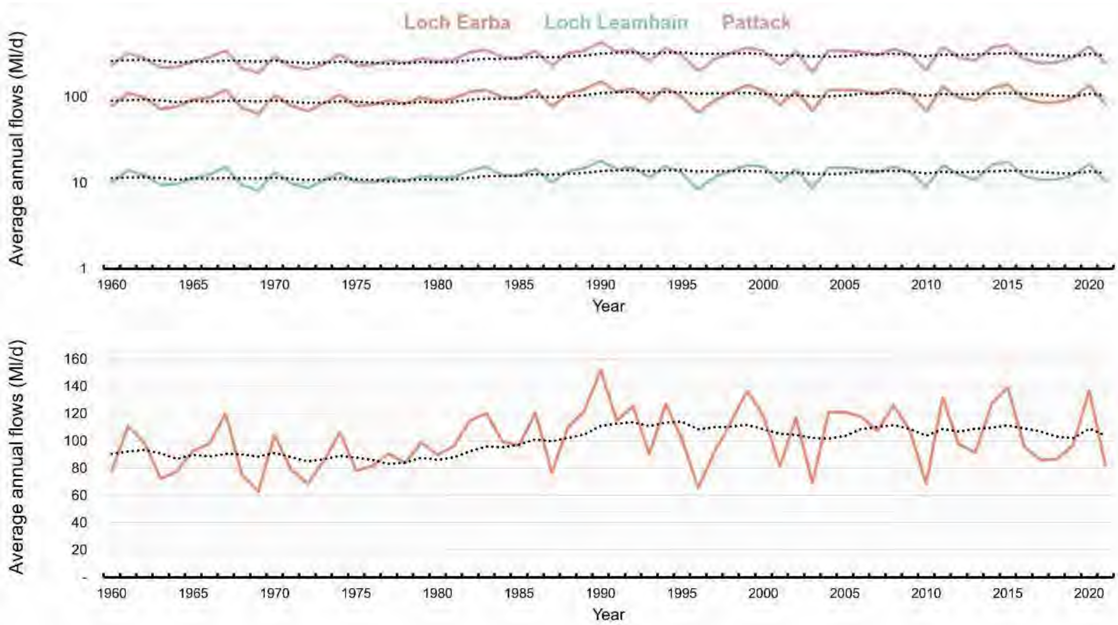
Table 5.3: Catchment mean annual hydrological properties (1960-2021)

Catchment	Mean annual flows (Ml/d; m^3/s)	Median flows (m^3/s)	Mean annual runoff (mm/year)	Mean annual precipitation (mm/year)	Average Runoff percent (%)
Loch Earba	101; 1.2	0.7	1507	1921	78
Loch Leamhain	13; 0.14	0.09	1788	2159	83
River Pattack	293; 3.4	2.0	1657	2057	81

5.3.2 Inter-annual variability

For all the study catchments, mean annual streamflows are greater and more variable in the period after 1990 than prior to 1990 (Figure 5.5). Figure 5.5 shows a comparison of mean annual flows in Loch Earba, Loch Leamhain and Pattack catchments (top) with a focus on the Earba catchment below. Mean annual streamflows increase by approximately 15% for all study catchments. For example, mean annual streamflows in the Loch Earba catchment increase from 94Ml/d prior to 1990 to 108Ml/d after 1990. This general trend in annual streamflow is further highlighted by the moving average series of annual streamflow for each of the catchments (Figure 5.5), which is calculated using a ten-year backward-looking window. The top part of the chart uses a log scale to show all three series, with the lower part showing just Earba on a standard scale to better illustrate changes during the period. Furthermore, standard deviations in mean annual streamflows have typically increased by approximately 33% from before 1990 to the period after 1990. Again, using the Loch Earba catchment as an example, standard deviations in mean annual streamflows increase from 17Ml/d up to 22Ml/d for the periods before and after 1990. In comparison to increases in inter-annual precipitation variability, increases in inter-annual streamflow variability are less substantial, which could be linked to reduced variability in PET at these timescales.

Figure 5.5: Inter-annual variability in simulated flows for the period 1960-2021

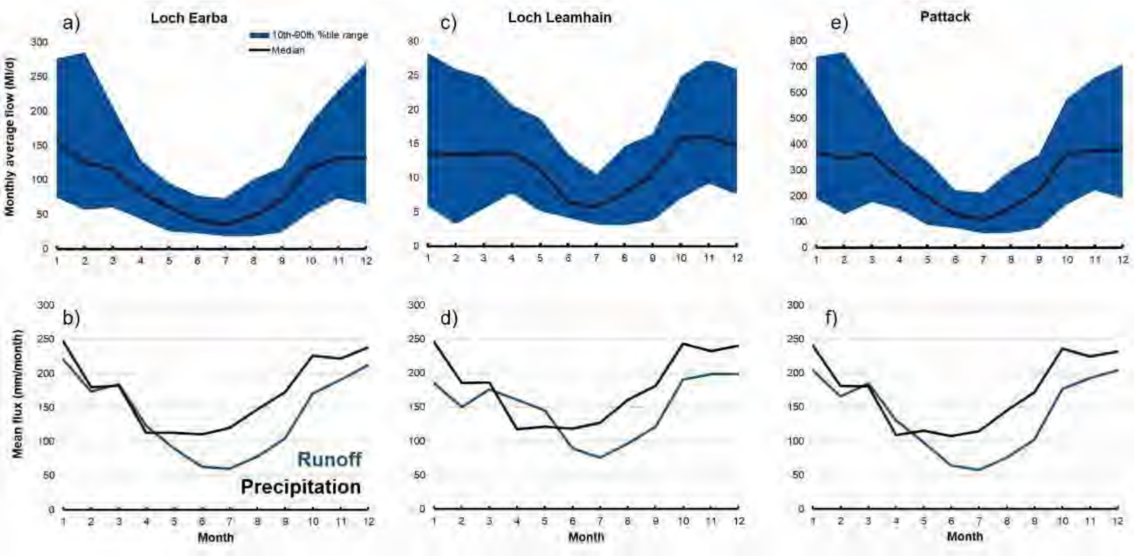


5.3.3 Seasonality

Simulated catchment flows are on average between 50% and 106% greater in winter (October to February) than during summer months. Figure 5.6 (a,c,e) shows the long-term (1960-2021) seasonality of simulated streamflows in the study catchments. Shaded areas represent the 10th to 90th percentile range of monthly values for the period from 1960-2021, whilst the median value for this period is shown via the black line. For example, mean flows in the Loch Earba catchment between October and February are 144Ml/d and 70Ml/d between March and September. In Loch Leamhain, flows typically remain high throughout spring which is likely due to the contribution of snowmelt to runoff in this time of year. The influence of snowmelt processes on spring river flows is less evident in the Loch Earba and Pattack catchments as they are at lower elevations (Table 5.1). Mean monthly flows are then at their lowest between June and August for each study catchment.

Nonetheless, high inter-annual variability in winter flows suggests that flows can be similar to levels estimated for summer periods. For Loch Earba, standard deviations in monthly stream flow between October and February vary from 50Ml/d to 82Ml/d. In comparison, between June and August standard deviations in monthly flow are much lower and vary from 19Ml/d to 30Ml/d. Comparing the 10th percentile winter (October-February) flows to the 90th percentile summer flows (June to August) reveals that winter flows can drop to levels that are similar to summer flows. For example, in Loch Earba, the 10th percentile of monthly winter (October-February) flows varies from 53Ml/d to 75Ml/d which is similar to flow levels estimated for some of the wetter summers (June to August). Similarly, monthly winter flows can be more than three times greater than typical for these months.

Figure 5.6: Seasonal distribution of a,c,e) total monthly flows and b,d,f) runoff and precipitation for the period 1960-2021

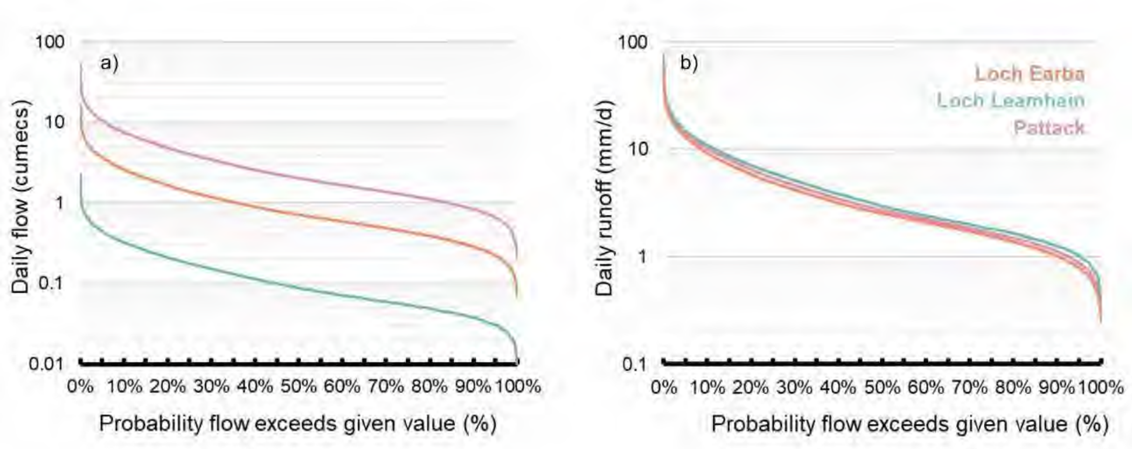


The fraction of precipitation converted to runoff varies seasonally and is greatest throughout spring when snowmelt contributes to runoff and is lowest in the summer months Figure 5.6 (b,d,f). Figure 5.6 (b,d,f) compares the long-term (1960-2021) mean monthly runoff and precipitation series for each of the study catchments. This highlights how the efficiency of converting precipitation to runoff varies seasonally for each study catchment. In spring (March-May), runoff rates are typically similar to or exceed precipitation rates. This is caused by the springtime melting of snow precipitated during winter months. This process is particularly evident in Loch Leamhain, where mean runoff rates are typically between 19% and 37% greater than mean precipitation rates during April and May. Conversely, mean monthly runoff rates between June and August are approximately on average between 46% and 60% of precipitation rates. Whilst still converting a considerable proportion of their precipitation to runoff, the efficiency of the study catchments in generating runoff is reduced during this period due to elevated summer PET (Figure 5.2).

5.3.4 Flow duration curves

Flow duration curves reveal large differences in the magnitudes of flow in each of the study catchments during wet, dry and average conditions (Figure 5.7a). Median simulated flows in Loch Earba are approximately an order of magnitude greater than those in Loch Leamhain at $0.7m^3/s$ and $0.1m^3/s$, respectively. Median flows in the Pattack catchment are greater still at $2.0m^3/s$. Differences in simulated catchment flows are large again when using the 10th percentile and 90th percentile to compare wet and dry flow conditions in each of the study catchments. Under dry flow conditions, the Loch Earba, Loch Leamhain and Pattack catchments generate an estimated 0.3m^3/s, 0.04m^3/s and 0.8m^3/s, respectively. Whilst wet condition flows for each catchment are 2.6m^3/s, 0.3m^3/s, 7.6m^3/s, respectively. For all of the study catchments, the slopes of their flow duration curves are relatively shallow, which highlights that flows are not highly variable and that there is a somewhat damped response of runoff to rainfall. This can arise for several reasons, such as wide-spread and year-round rainfall and groundwater contributions to streamflow.

Figure 5.7: Simulated a) flow-duration curves; b) runoff-duration curves for the period 1960-2021



Despite large differences in the magnitudes of flow generated by each catchment, the shapes of their flow duration curves are very similar (Figure 5.7). This results from using the same model parameterisations during hydrological simulations and the spatial proximity of the catchments to each other. Identical model parameterisations and similar meteorological forcing results in almost identical runoff duration curves (Figure 5.7b), albeit with Loch Leamhain generating slightly higher runoff rates

5.4 Model period selection

The period 1960 to 2021 was selected for modelling Loch Earba in its existing condition and its proposed configuration for the Earba Reservoir PSH scheme during both reservoir filling and operations. This period was selected as recent periods are likely to be more representative of near future conditions than periods towards the beginning of the 20th century. Furthermore, climate/meteorological data uncertainty is greater towards the beginning of the 20th century than for more recent periods. Nonetheless, the period selected still shows that annual scale climatology and simulated hydrology display substantial variability. Therefore, model simulations still consider climate and hydrological variability without modelling the entire period from 1891 to 2021. The key changes in annual scale climate and hydrological properties between 1960 and 2021 are discussed in Section 5.1 and Section 5.3 but also summarised below:

- Precipitation – increasing mean annual precipitation and inter-annual variability
- PET – reducing inter-annual variability
- Temperature – increasing mean annual temperatures
- Simulated flows – increasing mean annual flows and inter-annual variability

If a more recent (and shorter) period was selected (eg 1991-2021) overall average flows would be higher, leading to increased energy generation as well as faster initial filling of the reservoir.

However, it is considered unwise to exclude historical drought years such as 1976 and 1984 that are within living memory.

5.5 Reservoir modelling

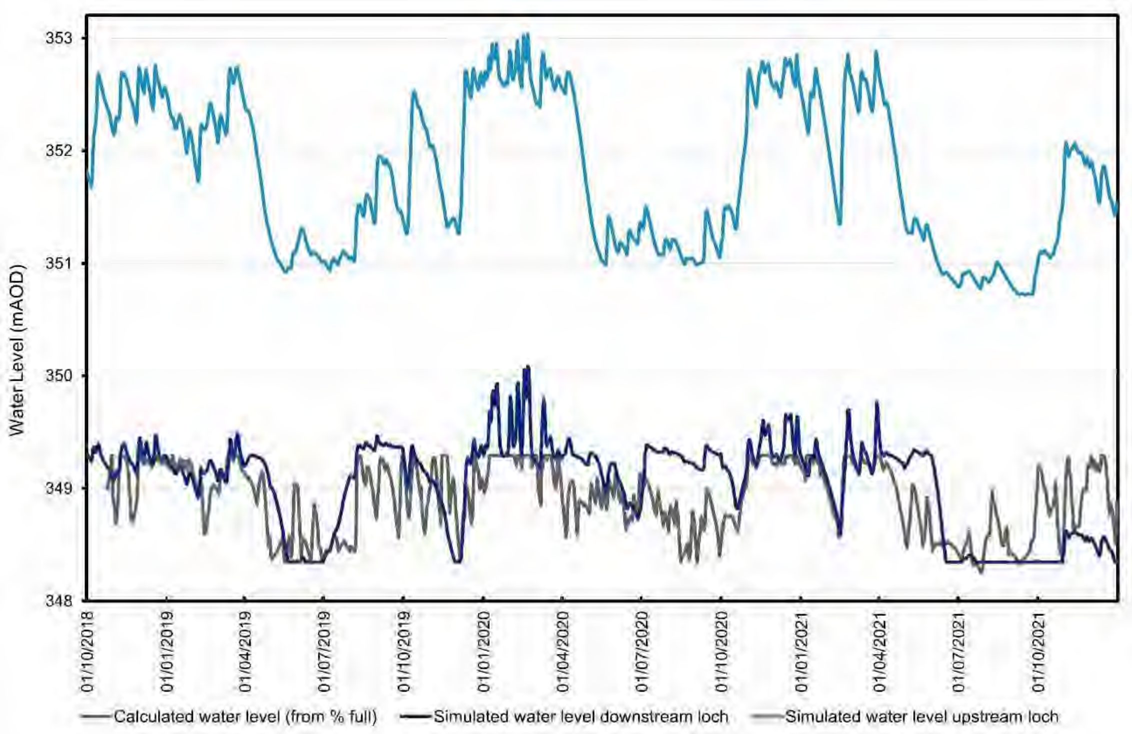
Water balance models for the existing Loch Earba and proposed Earba reservoir under both reservoir filling and operational regimes have been developed. The following three sections discuss findings from each of these models.

5.5.1 Existing conditions

Water level, storage and spill estimates for the downstream loch of Lochan Na H'Earba were evaluated by comparing them to estimates derived from head level observations (Section 3.3.2). Model evaluation involved visually comparing the corresponding time series to determine whether the model reasonably captured the dynamic behaviour of the loch. This comparison could only be completed when both loch Earba simulated data and the head level-based estimates were available (i.e., between October 2018 and December 2021). No head level-based data was available for the upstream loch, so its storage and spill dynamics were not independently evaluated. Instead, evaluation of the upstream loch is more implicit, as reasonable representation of the downstream loch's behaviour depends on also adequately capturing upstream loch behaviour.

Simulated water level (Figure 5.8) and storage (Figure 5.9) dynamics of the downstream loch compare reasonably well to those estimated from head level observations. Nonetheless, there are periods when simulations either underestimate or overestimate water levels and storages. For example, simulations overestimate storage and water levels throughout the summer of 2020. This might occur because the releases (i.e., turbine flows) at Ardverikie hydropower plant for this period are greater than the seasonal profile used to represent Ardverikie's demand. Between May and September 2020, turbine flows at Ardverikie were on average 79Ml/d in contrast to 57Ml/d according to the seasonal profile. Moreover, Figure 5.10 shows that operation of Ardverikie hydropower plant during the summer of 2020 is far more complex than is represented by the seasonal profile, with intermittent periods of high and low turbine flows.

Figure 5.8: Time series of upstream and downstream loch water levels



Likewise, throughout the autumn/winter of 2021 simulated water levels and storages are below those estimated from head level observation and increases in loch storage are not captured. Water level and storage estimates derived from head level observations are constrained to a head level of 100%, which is realised at a water level of 349.29 m AOD. However, Mott MacDonald water level and storage simulations are not constrained by this 100% head level. Therefore, during periods of high flow, water level and storage estimates at the downstream loch can exceed this upper bound, with the peak being almost 1m above the spill level.

Figure 5.9: Time series of upstream and downstream loch storage volumes

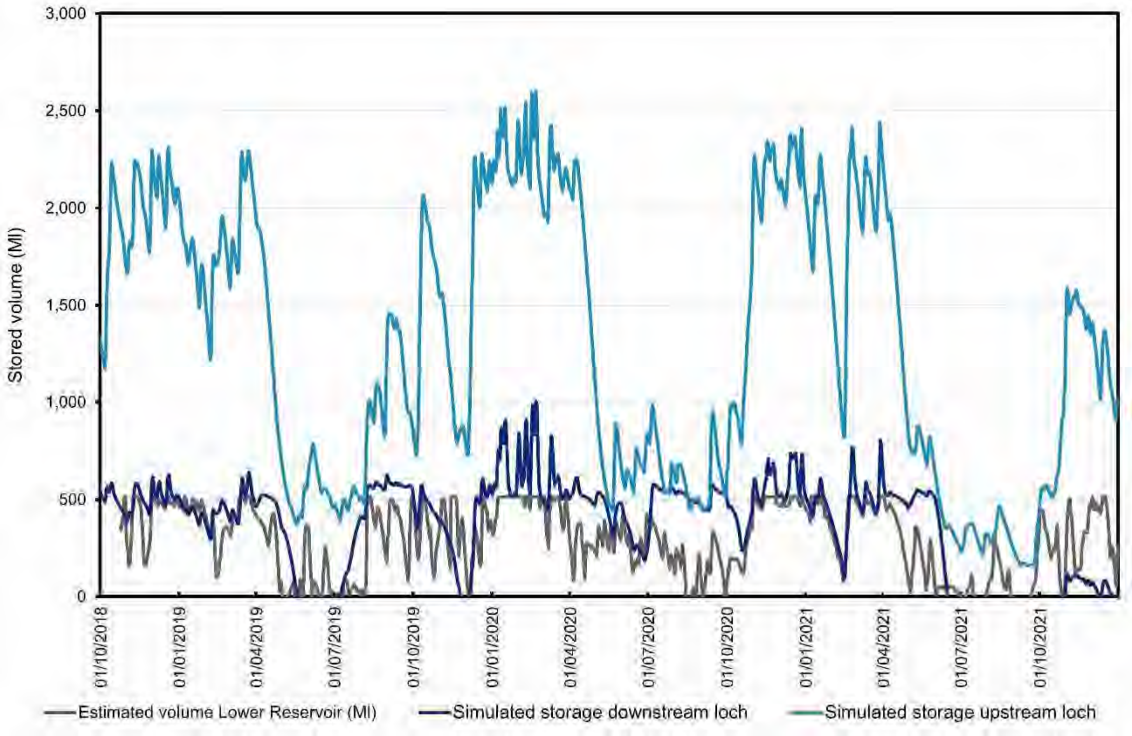
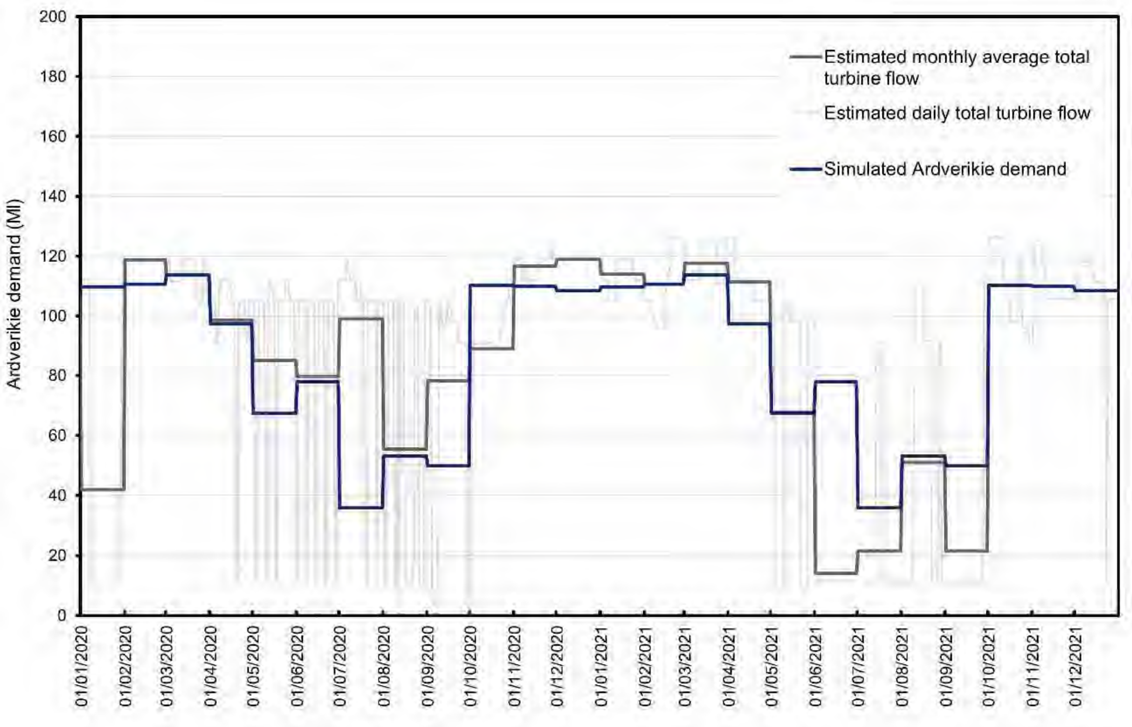


Figure 5.10: Time series of Ardverikie demand



The timing of simulated spills compares reasonably well to those estimated from head level observations (Figure 5.11). Due to differences in the modelling approaches, it is not expected that spill volumes estimated by Mott MacDonald simulations will match those estimated by the head level observation model. However, as spill timings appear reasonably well captured, the water balance model for Loch Earba in its existing condition can be regarded as plausible. From these simulations, it is evident that substantial spills in the downstream loch are predominantly driven by spills in the upstream loch during periods of high flow. These periods of more substantial simulated spill, largely align with periods of spill according to head level observation estimates. Nonetheless, Mott MacDonald simulations realise small amounts of spill during the summer and autumn of 2020, when head level observations do not show any spill. This aligns with when simulated water levels are above those suggest from head levels observations as previously discussed. Likewise, in the winter of 2021, head level observations indicate spill when none is simulated by the Mott MacDonald model. During this time period, storage levels in the upstream loch fail to recover which contrasts previous years and potentially indicates that simulated Loch Earba flows are low. Discrepancies are likely to be explained by two main factors, inaccuracies in the simulated flows and actual abstractions for Ardverikie being different from the average profile assumed in the model.

Figure 5.11: Time series of upstream and downstream loch spill estimates

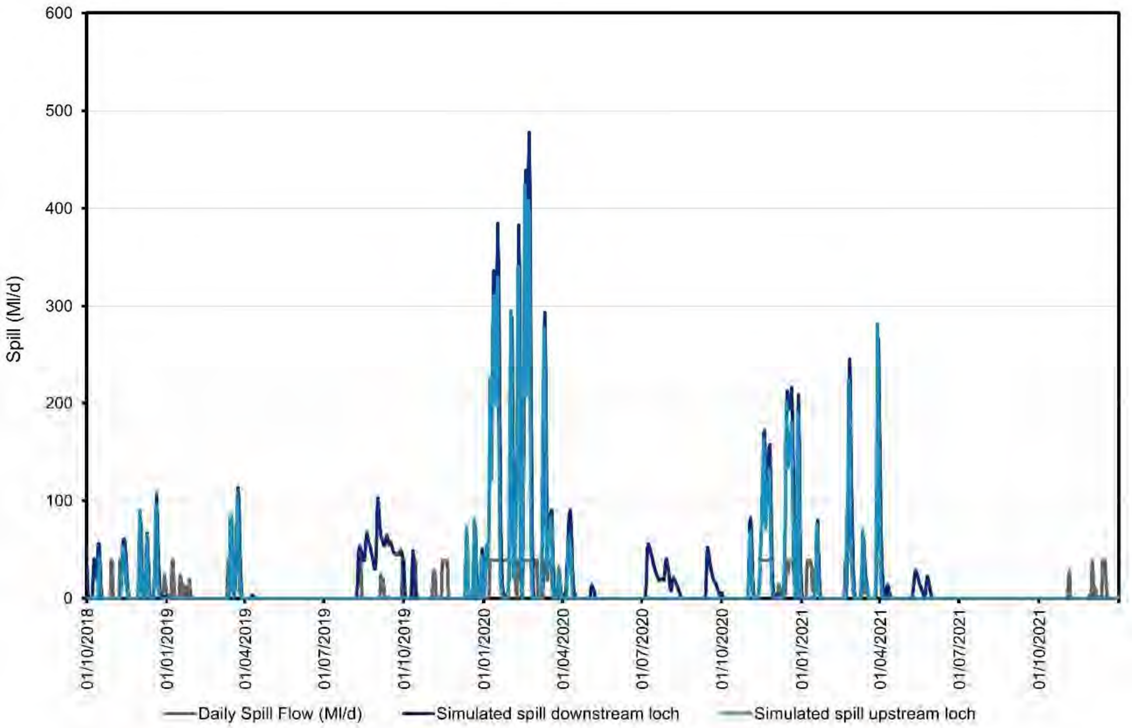


Table 5.4 summarises the mean simulated inflows and outflows for Loch Earba. Simulations show that on average 78% of Loch Earba's inflows between 1960 and 2021 are used to meet demand at Ardverikie hydropower plant. A further 22% of inflows are spilled downstream with only a negligible amount of water being lost to evaporation.

Moreover, mean supply to Ardverikie (78Ml/d) only accounts for 90% of the hydropower plant's demand. This likely arises as Ardverikie's demand is simulated using a seasonal demand profile derived from estimates between 2018 and 2023. This profile will therefore not reflect the operation/management of the hydropower plant in drier periods such as those seen between 1960 and 1980 (Figure 5.1 & Figure 5.5)

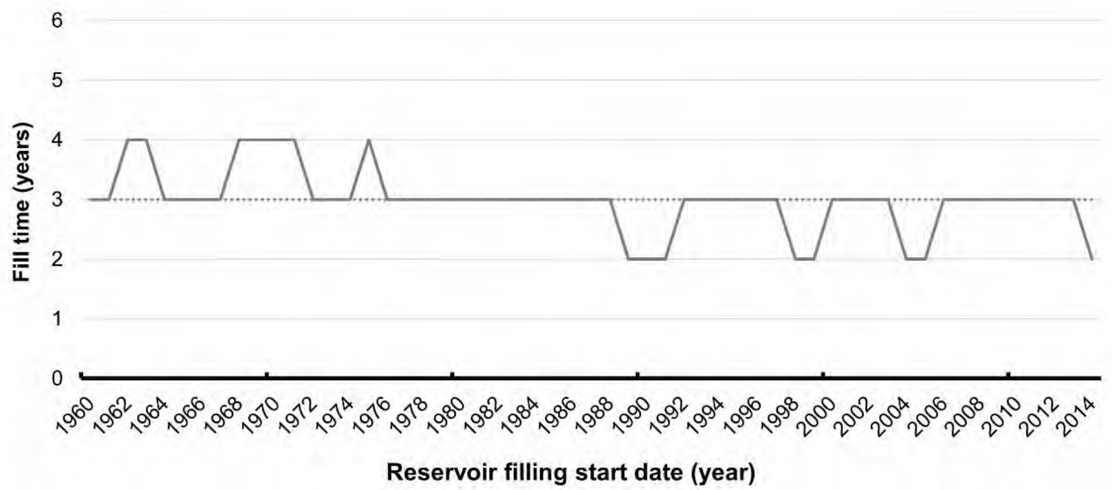
Table 5.4: Simulated Loch Earba inflows and outflows

	Mean inflow	Mean evaporation	Mean compensation	Mean spill	Mean supply to Ardverikie	
	(Ml/d)	(Ml/d)	(Ml/d)	(Ml/d)	(Ml/d)	(% of profile)
1960-2021	100.8	0.6	0.0	22.8	77.5	89%
2019-2021	105.1	0.6	0.0	23.0	83.1	96%

5.5.2 Reservoir filling

Figure 5.12 shows the number of years required to fill Earba Reservoir when using different years to initiate simulations. All years from 1960 to 2014 are tested as a simulation initiation year. Years after 2014 are not used to test reservoir fill times to avoid any risk of results being impacted by the hydrological time series ending before the reservoir fills. All simulations are initiated on the 1st of January. These reservoir fill time estimates assume that flows throughout the whole year (January to December) contribute towards the filling of the reservoir and no demand by Ardverikie is supplied. Furthermore, a compensation release flow defined as the Q95 of net Earba PSH inflows is applied. Under these conditions, the expected time required to fill Earba PSH reservoir is estimated to be two and four years.

Figure 5.12: Reservoir fill time variability



Source: The solid line shows the number of years required to fill Earba Reservoir for different simulation start dates. The dashed line shows the median time required to fill the reservoir across all tested simulation start dates. Simulations consider compensation release flows which are defined as Q95 of the net inflows into the Earba reservoir.

50% of simulations fill the reservoir PSH scheme within 3 years (Figure 5.13). 90% of simulations realise a filled reservoir within 4 years. Figure 5.13 shows the reservoir storage levels for a given number of years of filling The shaded area represents the 10th to 90th percentile range of fill times across all simulations (i.e., when testing different simulation start dates) and the median is represented by the solid black line. After only one year of filling, 50% of simulations realise reservoir storage levels of at least 40%, rising to 80% and 100% after two and three years respectively.

Figure 5.13: Probable reservoir storage levels after N filling seasons

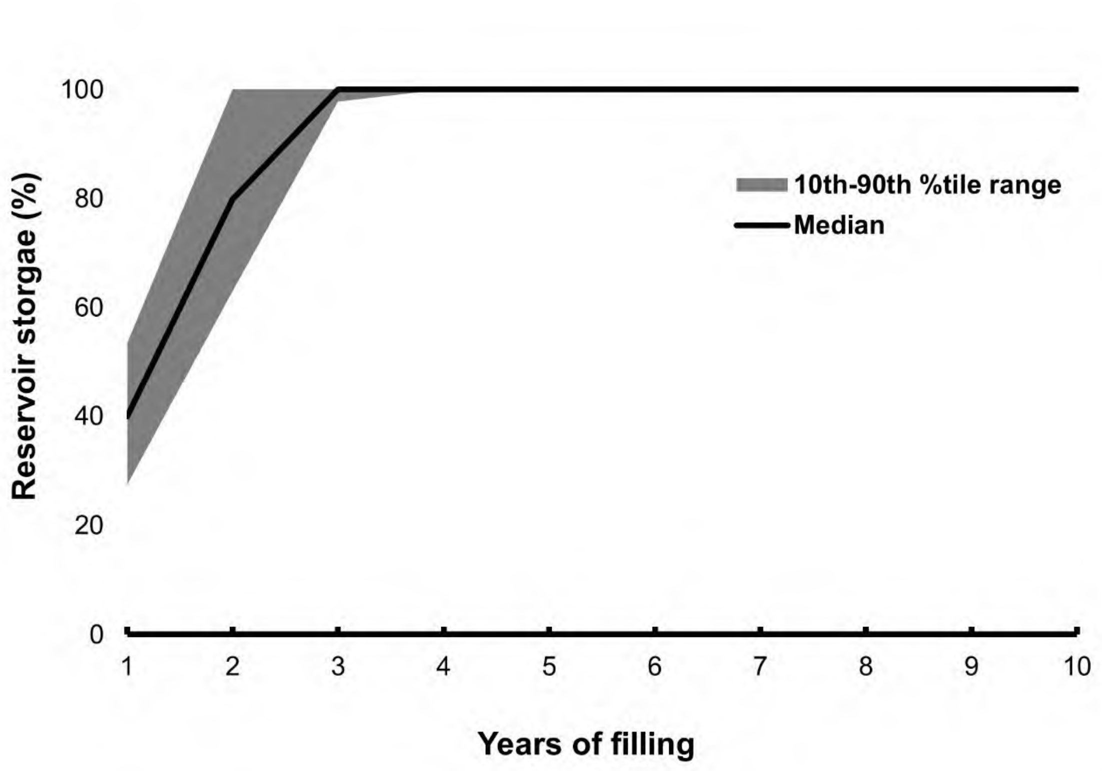


Table 5.5 shows the distribution of reservoir storage after a given number of filling seasons across all simulations Reservoir storage after one year of filling is expected to be 28.3MCM (as a median across all simulations). Storage is then estimated to increase up to 56.5MCM after two seasons of filling and 70.8MCM after three years of filling, on average.

Table 5.5: Reservoir storage levels after N filing seasons (MCM)

N filling seasons	Worst case	10th percentile	50th percentile	90th percentile	Best case
1	15.8	19.4	28.3	37.9	46.9
2	35.7	44.6	56.5	70.8	70.8
3	62.8	69.2	70.8	70.8	70.8
4	70.8	70.8	70.8	70.8	70.8
5	70.8	70.8	70.8	70.8	70.8
6	70.8	70.8	70.8	70.8	70.8
7	70.8	70.8	70.8	70.8	70.8
8	70.8	70.8	70.8	70.8	70.8
9	70.8	70.8	70.8	70.8	70.8
10	70.8	70.8	70.8	70.8	70.8

Note: Reservoir storage levels assume that flows throughout the year can be used to fill Earba PSH scheme and that the small turbine demand at Ardverikie is not supplied.

5.5.3 Reservoir operations

Historical simulations between 1960 and 2021 of Earba PSH reservoir show that the scheme would have emptied its buffer storage for approximately 16% of the period (Figure 5.14). The buffer storage is assumed to be reservoir storage between water levels of 355mAOD and 358mAOD and is estimated at 7,067Ml. The proposed buffer storage (with reservoir capacity at 70,821Ml and spills occurring at 376mAOD) is required for meeting demand at Ardverikie hydropower plant as the remaining reservoir storage is used for operating the Earba PSH scheme. When buffer storage is reduced to zero, water is not available to meet Ardverikie demand. Most of the occurrences when the reservoir's buffer storage is reduced to zero occur between 1960 and 1980 and become less frequent thereafter. This aligns with the period in which simulated annual flows in the Earba catchment are substantially lower (Figure 5.5). Therefore, if the near future climate conditions and hydrology reflect conditions over the last 20 years instead of the last 60 years, the frequency at which buffer storage empties could be more favourable.

In practice, when the buffer storage is at full capacity, Earba PSH scheme will operate with a Stop Pumping Level (SPL) at 358mAOD. The SPL will then reduce towards 355mAOD as the buffer storage is used to supply Ardverikie. This will require monitoring to manage changes in control levels.

Figure 5.14: Simulated reservoir storage with proposed buffer capacity

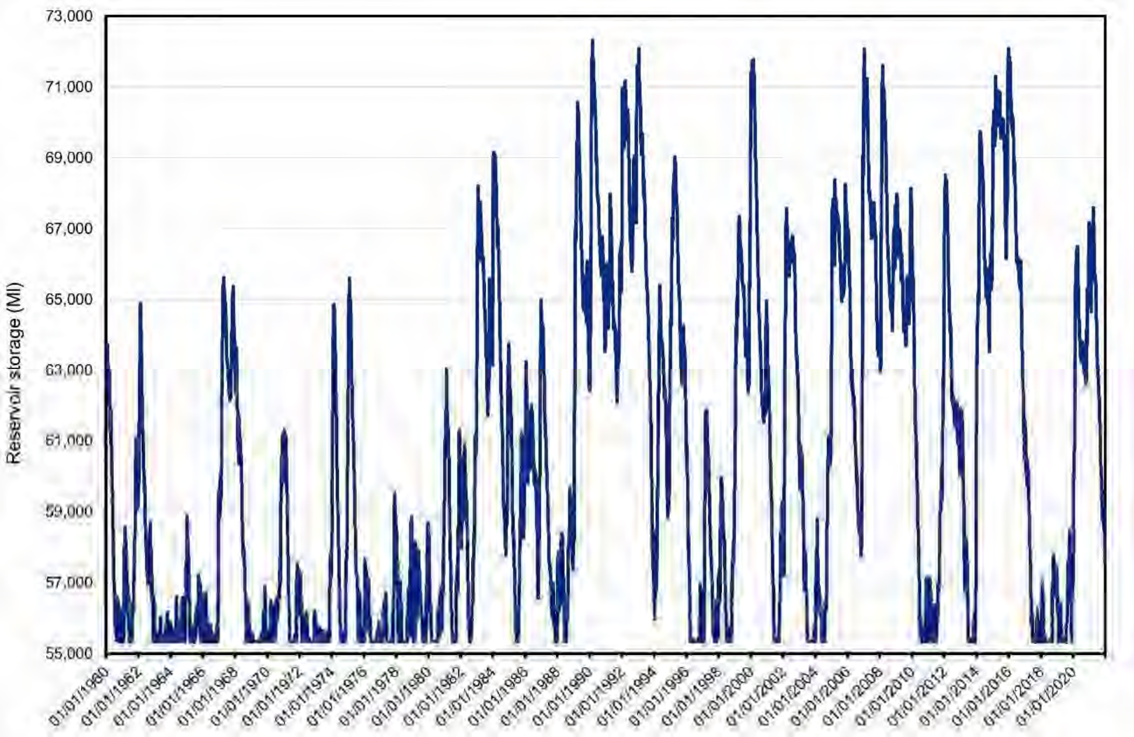


Table 5.6 shows the mean reservoir inflows and outflows under operation of the Earba PSH scheme between 1960 and 2021. Mean inflows and outflows are provided for a scheme using the proposed buffer storage capacity of 7,067Ml. Similar findings are also presented for the 2019 to 2021 simulation period and for the existing conditions of Lochan Na H'Earba. It is important to note that mean inflows are not perfectly equal to the summation of the mean outflows as the final reservoir storage may differ from initial storage.

Long-term (1960-2021) mean spills simulated by the operations model for Earba Reservoir are 2.3Ml/d which is substantially lower than the 22.8Ml/d estimated for existing conditions (Table 5.6). Furthermore, introducing the Earba PSH scheme is expected to increase supply to Ardverikie from 77.5Ml/d under existing conditions to 81.4Ml/d. Even with frequent emptying of the buffer storage between 1960 and 1980, the Earba PSH scheme is still estimated to supply 94% of Ardverikie's demand in comparison to 89% under existing conditions. Slight shortfalls in meeting Ardverikie's demand under both existing conditions and the proposed operations of Earba PSH are likely due to the use of an average demand profile, whereas historic operation would have taken more water in wet periods and less in dry periods. It is also interesting to note Ardverikie's mean demand from the reservoir (86.9Ml/d) accounts for a large proportion of the mean reservoir inflow, which further explains why buffer storage falls to zero in low flow periods between 1960 and 1980. In comparison, mean compensation flows (assumed as Q95 of catchment inflows) account for 12% of catchment inflows and mean Earba Reservoir evaporation only 1% of catchment inflows. There will also be additional evaporation from the upper loch of the PSH scheme (Loch Leamhain) but this will likely be less than that estimated for the operational Loch Earba due to a smaller surface area and lower PET.

In the future operation of Earba PSH, evaporation losses (1.3Ml/d on average; 10th percentile of 0.2Ml/d; 90th percentile of 2.6Ml/d) from the scheme will be approximately two times greater than what is currently realized under existing conditions (0.6Ml/d on average; 10th percentile of 0.1Ml/d; 90th percentile of 1.2Ml/d) (Table 5.6). Nonetheless, evaporative losses are still expected to account for a small proportion of the total water balance.

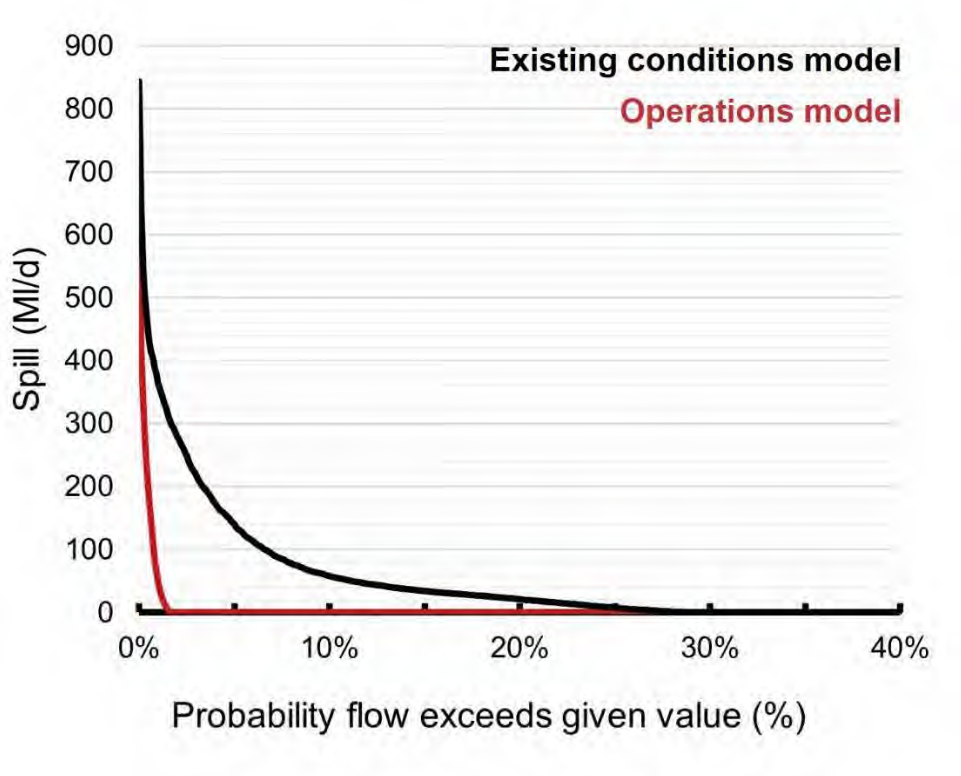
Table 5.6: Comparison of simulated reservoir inflows and outflows

	Mean inflow (Ml/d)	Mean evaporation (Ml/d)	Mean compensation (Ml/d)	Mean spill (Ml/d)	Mean supply to Ardverikie (Ml/d)
Operations model					
1960-2021	91.7	1.3	10.9	2.3	81.4 (94% of profile)
2019-2021	95.8	1.3	10.9	0.0	86.9 (100% of profile)
Existing conditions model					
1960-2021	100.8	0.6	0.0	22.8	77.5 (89% of profile)
2019-2021	105.1	0.6	0.0	23.0	83.1 (96% of profile)

The shortened simulation period from 2019 to 2021 roughly aligns with the period when data was available for defining Ardverikie's seasonal demand profile (Figure 3.5) and therefore the operational reservoir model should meet Ardveikie demand during this period. Findings largely confirm this as 96% of Ardveikie's demand is supplied when using the existing conditions model. This increases to 100% of Ardverikie's demand being met under operational conditions and the proposed buffer storage not being emptied at any period during the simulation (Table 5.6).

Furthermore, findings show that mean estimated spills during operation of the Earba PSH scheme are expected to be substantially less than is currently experienced under the existing condition of Lochan Na H'Earba (Table 5.6). For the 1960 to 2021 simulation period, mean spills under operation of Earba PSH are estimated at 2.3Ml/d, whereas under existing conditions mean spills are estimated to be 22.8Ml/d. Furthermore, Figure 5.15 shows that spills occur far more frequently under existing conditions than they are expected to under the operation of Earba PSH. Under existing conditions spills occur 29% of the time, whilst spills only occur 2% of the time during operation of Earba PSH. The main reason for the reduced spill is that the proposed buffer storage capacity is much larger than the available storage in the existing lochs. It should be noted that the reduction in flow immediately downstream of Earba is much smaller than indicated by comparing the spill figures because with the PSH operating there are also compensation releases.

Figure 5.15: Comparison of spill duration curves (1960-2021)



6 Conclusions

6.1 Models developed

A reservoir modelling exercise has been carried out to evaluate the impact of the proposed Loch Earba PSH on river flows and the neighbouring Ardverikie hydropower scheme. Reservoir models were developed by integrating local knowledge of the reservoir design and operations with daily scale hydrology simulated by the lumped hydrological GR6J + 2 zone snow model and HadUK gridded climate observations from the Met Office. In total three reservoir models were developed:

- Existing conditions model – simulates existing loch dynamics;
- Earba PSH scheme filling model – simulates reservoir dynamics during filling;
- Earba PSH scheme operational model – simulates reservoir dynamics whilst operational.

6.2 Existing conditions

Simulations of the existing conditions in Lochan Na H'Earba were visually evaluated against estimates derived from head level observations and compared reasonably well. Although periods when storage was under and over-estimated were identified and the magnitudes of spills could not be evaluated due to differences in estimation method. Findings from the existing conditions model highlight that between 1960 and 2021, 77% of inflows would be used to meet demand from the Ardveikie hydropower plant on average. A further 23% of inflows would be spilled downstream and there were negligible losses due to evaporation.

6.3 Initial filling of the new reservoir

The second assessment explored how long it would take to fill the reservoir. Estimated filling times of Earba PSH reservoir are between two and four years when assuming inflows for the whole calendar year (January to December) contribute towards reservoir filling and no water is supplied to Ardverikie Hydropower. Furthermore, if these conditions are implemented during filling, reservoir storage levels are expected to reach 80% after two years on average, potentially allowing phased introduction of the PSH scheme.

The impacts on the Pattack hydropower scheme when filling the upper reservoir are likely to be minimal as it is assumed that the upper reservoir (Loch Leamhain) will be de-watered to form a construction area. It is then assumed that dewatering for the construction area will pass the water downstream into the Pattack catchment.

6.4 Future operation

Finally, the dynamics of Earba reservoir under operation of the PSH scheme were explored and compared to the dynamics within the existing Lochan Na H'Earba. Ultimately, findings show that operation of the PSH scheme would enhance mean supply to Ardverikie hydropower plant. Furthermore, introduction of the PSH scheme will likely reduce mean spills and spill frequency substantially.

Modelling of the Earba PSH scheme assumes that Loch Leamhain catchment flows do not contribute to operations but are instead passed downstream to maintain natural flows in the River Pattack. Managing this would require monitoring of Earba PSH pumping operations and storage in the upper reservoir (Loch Leamhain) to determine the flow required to drain into the Pattack.

When looking to the near future, if climate and hydrology conditions reflect conditions over the last 20 years, operation of Earba PSH would be more favourable than represented by the last 60 years. This results from drier conditions and consequently lower flows between 1960 and 1980. However, it is considered that these drier conditions could occur in the future, so it is recommended that analysis of potential energy generation should consider the period from 1960 to 2021. Nonetheless future studies should investigate the impact of climate change on the operation of Earba PSH scheme.

7 Bibliography

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A. PET calculation

PET was estimated using the modified Penman-Monteith equation for the reference crop as suggested by the Food and Agricultural Organisation (FAO) (Allen 1998) as follows:

$$ET_0 = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T + 273} \cdot u \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u)}$$

where:

- ET_0 reference evapotranspiration (mm day^{-1}),
- R_n net radiation at the crop surface (MJ m^{-2} day^{-1}),
- G soil heat flux density (MJ m^{-2} day^{-1}),
- T mean daily air temperature (°C),
- u wind speed (m s^{-1}),
- e_s saturation vapour pressure (kPa),
- e_a actual vapour pressure (kPa),
- e_s-e_a saturation vapour pressure deficit (kPa),
- Δ slope vapour pressure curve (kPa °C^{-1}),
- γ psychrometric constant (kPa °C^{-1}).

The FAO report provides formulae to obtain the different variables based on available weather information. This includes the saturation vapour pressure as a function of maximum and minimum temperature, the actual vapour pressure as a function of dew point temperature (assumed equal to minimum temperature), and the net radiation at the crop surface as a function of the latitude, day length (based on day of the year) and sunshine hours.

B. Hydrological modelling

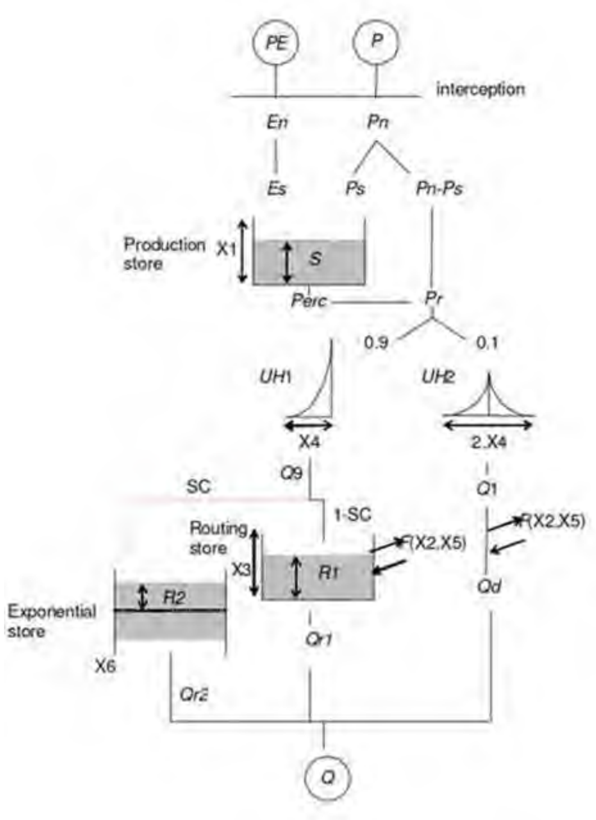
B.1 GR6J

B.1.1 Description of GR6J model

The GR6J model (in French, modèle du Génie Rural à 6 paramètres Journalier) was developed by (Pushpalatha 2011) as an improved version of GR4j developed by Cemagre, Water Quality and Hydrology Research Unit. It is a daily lumped six-parameter rainfall-runoff model, belonging to the family of soil moisture accounting algorithms, and intended to provide a more parsimonious answer without losing accuracy with respect to more sophisticated models.

The model has three stores (see Figure B.1), a production one, representing the soil package; a routing one, representing the delay in runoff reaching the outlet (interflow and baseflow); and an exponential store parallel to the routing store to differentiate between interflow and baseflow. Runoff can be generated either by exceeding the infiltration capacity of the soil, obtained as a function of its saturation, or by percolation from it, also derived from the soil moisture content. Total runoff is split into direct (10% of total) and routed (90% of total), the former simulating the quick response. Each runoff component is distributed through time-based unit hydrographs. A non-linear store routes the slow runoff component before joining the quick one.

Figure B.1: GR6J model schematic



Source: (Pushpalatha 2011)

A groundwater exchange term F that acts on both flow components can simulate imports or exports of water with the underground (i.e., connections with deep aquifers or surrounding catchments). It is a function of the volume in the routing store with greater interchange when it is drained.

B.1.2 Two zone snowmelt routine for GR6J

A snow accumulation and snowmelt routine has been added to the model whereby snow is accumulated below and melts above two discrimination temperatures (zone 1 and zone 2 "snow thresholds"). These zones were specified by a zone 1 proportion parameter, splitting the catchment into upper and lower stages. A distinct melt rate of snowmelt was incorporated for each zone. Temperature data used in the snow accumulation and snowmelt routine for each catchment are available from the HadUK climatological datasets.

B.2 Model calibration

The approach for this assessment was to adopt a three year and nine-month calibration period based on the available streamflow record on the river Pattack (July 2009 to March 2013). No validation of the Pattack hydrological was performed due to limited data availability.

- Model calibration: 01/07/2009 to 31/03/2013

B.2.1 Calibration objective functions

The goodness of fit and adequacy of each simulation has been measured using the following criteria:

- Examination of the daily flow chart to confirm if the model matches the low flow periods, has a similar rate of recession, and matches summer and winter storm peaks. Not every feature can be replicated with a model, but this assessment provides an adequate representation of the hydrograph shape and how this might vary in key years or stages in the calibration period.
- Examination of the Flow Duration Curve (FDC) to help identify how good the fit is for lower flows and higher flows. Although the aim is to achieve a good fit over the whole record, the fit at lower flows is almost always most important for water resource assessments. The use of a log curve to display FDCs accentuates the lower part of the FDC allowing, at a glance, the goodness of the fit at low flows to be assessed.
- Comparison of the mean observed ($\overline{Q_o}$) and modelled ($\overline{Q_m}$) flows and calculation of a volume error:

$$Volume\ error = \frac{\sum Q_m - \sum Q_o}{\sum Q_o} \times 100\%$$

- The Nash-Sutcliffe Efficiency (NSE) coefficient, which is a normalised statistic that determines the relative magnitude of the model's residual variance compared with the reference data variance, has also been calculated and reported for the calibration and validation periods. The NSE is sometimes referred to as the Nash Sutcliffe correlation coefficient. The NSE is calculated by reference to the mean of observed flows ($\overline{Q_o}$) and the daily time series of observed (*o*) and modelled flows (*m*) as follows:

$$NSE = 1 - \frac{\sum(Q_m - Q_o)^2}{\sum(Q_o - \overline{Q_o})^2}$$

  An NSE value of 1 corresponds to a perfect match between observed flows and modelled flows.
- As a statistical measure, the NSE tends to be biased towards higher flows. An additional statistic has therefore been calculated which places more weight on the performance of the model at lower flows which are more critical from a water resources perspective. As such the

log of the flows ($\ln(Q_o)$ and $\ln(Q_m)$) are substituted in the above NSE equation. This statistic is referred to as the Log-NSE.

- Furthermore, in order to statistically assess the relative fit of the FDC the above NSE equation has been calculated based on the log flow percentiles from Q1 to Q99 inclusive. This statistic is referred to as the Log-NSE FDC. Although comparisons of specific flow percentiles have been made (eg Q90) this statistic gives a broader measure of how good the fit is across the whole FDC.
- An additional statistic has been incorporated into the automatic calibration that focus on FDC fit below Q95. The statistics is referred to as Log-NSE FDC ≤Q95 and is derived on a similar basis for the Log-NSE FDC but only considering Q95 to Q99. This statistic provides a measure of how well the model is predicting the lowest flows.

Calibration performance is a compromise based on these various measures and it is not possible to make a definitive classification of performance based on one statistic or measure alone. While the FDC provides a good overall estimate of the calibration performance it cannot be used in isolation without reference to the daily flow series. A common rule suggests the following broad aims for calibration:

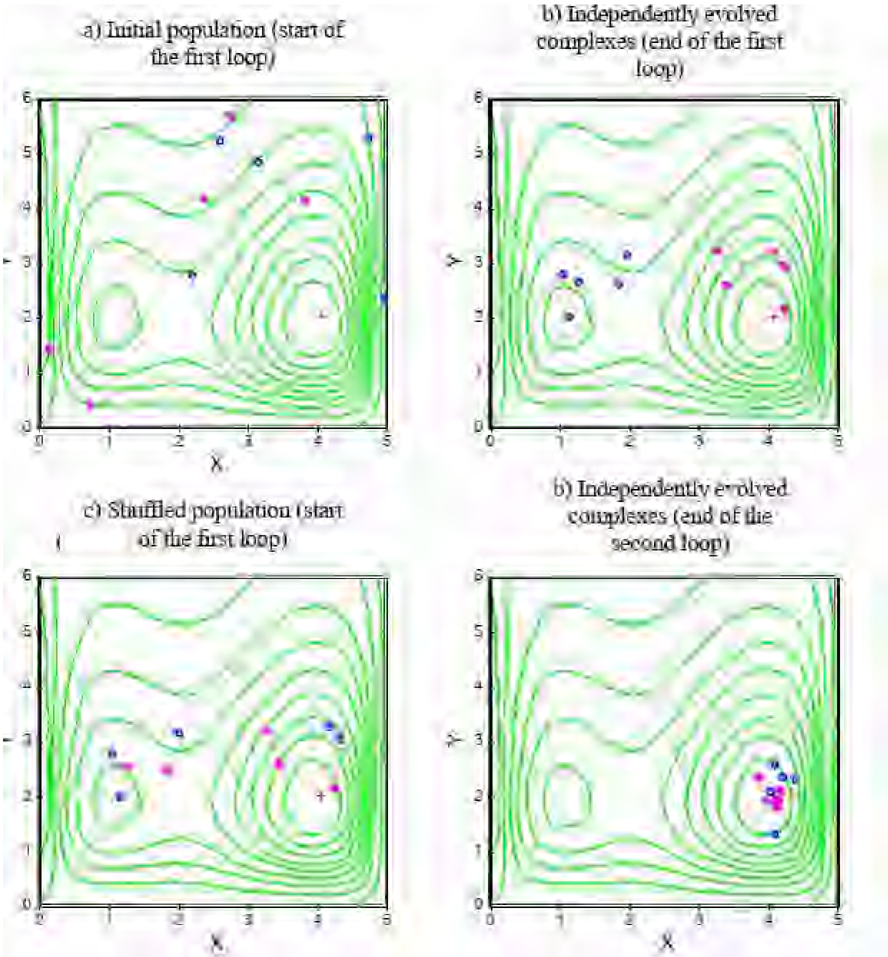
- a mean flow percentage error of less than 5% (and ideally less than 1%); and,
- a NSE greater than 0.7 (and ideally greater than 0.8).

In order to take account of multiple performance measures, Mott MacDonald have developed a bespoke objective function, referred to as 'BiasMM' which combines the volume error, NSE, Log-NSE and Log-NSE FDC. This has been developed as an aid to automatic calibration of the GR6J models in order to help derive a calibration which is balanced across a variety of different performance measures. A variation of the objective function has also been developed which only considers NSE, Log-NSE and Log-NSE FDC for situations where issues with flow records prevents a volume balance being obtained.

B.2.2 Automatic calibration methodology

The GR6J modelling has adopted automatic calibration for GR6J in order to increase efficiency and ensure the most optimum solution is found. The automatic calibration used a global search algorithm called Shuffle Complex Evolution (SCE) which is a mixture of direct search and random methods (Figure B.2) (Q. Y. Duan 1993). Genetic algorithms are designed to explore complex response surfaces in a more efficient manner than uniform random sampling methods. An advantage of using SCE is that it can reliably find the global optimum.

Figure B.2: Shuffled Complex Evolution (SCE) algorithm



Source: (Q. S. Duan 1992)

The GR6J simulation model integrated with the automatic calibration process, was coded into python and typically took around 0.2 seconds to run per simulation. Thus, allowing for a maximum of 100,000 runs for the model to find the global optimum, models take around 5.5 hours to calibrate, but often finish sooner. This automatic calibration had set parameter ranges in which the python script was able to search with the aim of minimising the combined objective function developed by Mott MacDonald (referred to as ‘MMBias’).

After an initial calibration run, manual checks were undertaken. Once the model was calibrated, it was then reviewed and approved by two separate modellers to ensure satisfactory results. Further information regarding hydrological model parameters, parameter set ranges and the final parameter values used can be found in Table C.1.

C. Model results

C.1 River Pattack model calibration

Table C.1: GR6J model parameters and constraints

Parameter	Description	Unit	Parameter constraint range	Best performing parameters set
x1	Maximum capacity of the production store. This parameter can be adjusted to correct the water balance. An increase in x1 will lead to a reduction in flows as more water infiltrates the soil and less water percolates from it.	mm	10 – 2000	604
x2	Maximum interchange capacity during a day. A positive value will increase total flow and vice versa. It affects low flows greatly.	mm	-1 – 1	0.34
x3	Maximum capacity of the routing store. This parameter affects the slope of the recessions. Higher values will result in milder recession slopes	mm	0.1 – 100	16.64
x4	Base time of unit hydrograph for slow runoff component (or half duration of direct runoff) Lower values will lead to a flashier response.	days	1 – 14.99	1.26
x5	It includes a modified expression for the water interchange that allows reversing its direction below a certain stored volume in the routing tank.	mm	0 – 1	0.70
x6	Exponential store parallel to the routing store to differentiate between interflow and baseflow.	mm	0.1 – 100	1.83
Zone 1 proportion	The proportion of the catchment divided within zone 1 (lower catchment)	(-)	0 – 1	0.59
Zone 1 snow threshold	Snow in zone 1 (lower catchment) is accumulated below and melts above this discrimination temperature.	°C	0 – 5	0.02
Zone 2 snow threshold	Snow in zone 2 (upper catchment) is accumulated below and melts above this discrimination temperature.	°C	0 – 5	0.89
Zone 1 melt rate	Zone 1 corresponding single degree day melt rate.	mm/day /°C	0.1 – 10	8.43
Zone 2 melt rate	Zone 2 corresponding single degree day melt rate.	mm/day /°C	0.1 – 10	3.87
PET factor	Factor applied to PET input data	(-)	1 – 1.1	1.06
P factor	Factor applied to rainfall input data	(-)	1 – 1.1	1.04

C.2 Simulated flow duration curves

C.2.1 Gauging stations

Following discussions with Gilkes Energy, flow duration curves have also been determined at four additional locations where gauging stations have recently been installed (Figure C.3). Flows for each of these catchments were estimated by scaling the flows of previously modelled catchments. Scale factors were determined by dividing the catchment area of each of these four locations by the catchment area of the nearest previously modelled catchment. Details of the gauging station locations and catchment areas as well as the donor catchments used in modelling and the scale factors applied are in Table C.2. Percentile flows for each of these four catchments are provided in Table C.3.

Table C.2: Gauging station locations, catchment areas and donor catchments

Gauging station name	GPS reference	Easting	Northing	Catchment area (km^2)	Donor catchment	Scale factor
Loch a Bhealaich outflow	NN 50981 79146	250981	779146	3.64	Loch Leamhain	1.42
Allt Coire a Chlachair	NN 45999 80976	245999	780976	2.61	Loch Earba	0.11
Lochan na h-Earba	NN 50109 85730	250109	785730	24.35	Loch Earba	1.00
Allt Coire Pidridh US	NN 46366 80904	246366	780904	4.66	Loch Earba	0.19

Figure C.3: Simulated flow duration curves for gauging station catchments

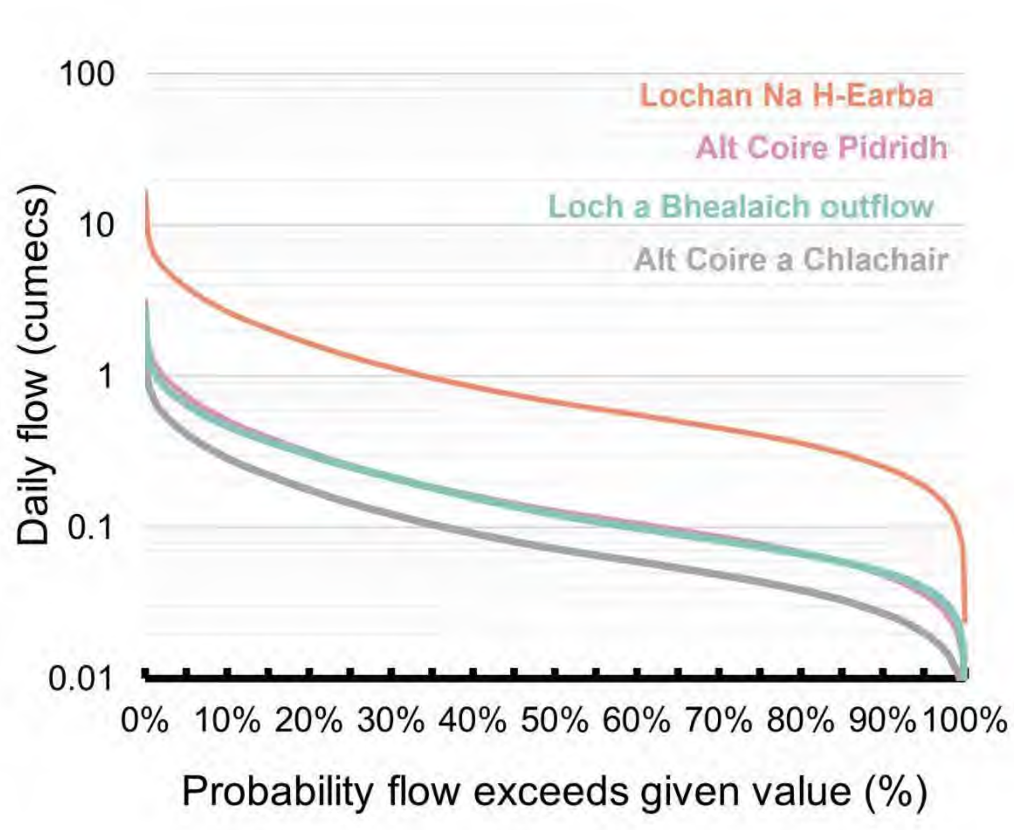


Table C.3: Flow percentiles at specified gauging station locations (m^3/s)

Flow percentile	Loch a Bhealaich	Allt Coire a Chlachair	Lochan na h'Earba	Allt Coire Pidridh
Q99	0.02	0.01	0.11	0.02
Q95	0.04	0.02	0.19	0.04
Q90	0.05	0.03	0.25	0.05
Q80	0.07	0.04	0.36	0.07
Q70	0.08	0.05	0.45	0.09
Q60	0.10	0.06	0.56	0.11
Q50	0.12	0.07	0.68	0.13
Q40	0.16	0.09	0.85	0.16
Q30	0.22	0.12	1.14	0.22
Q20	0.30	0.18	1.65	0.32
Q10	0.47	0.29	2.68	0.51
Q5	0.65	0.42	3.88	0.74
Q1	1.07	0.70	6.56	1.26

C.2.2 Abstraction locations

Gilkes Energy also requested that flow duration curves be approximated for six abstraction locations (Figure C.4). Flows for the catchments associated to these abstraction points were scaled from a previously modelled catchment. Like the additional gauging station locations, scale factors were determined by dividing the catchment area of each of the six locations by the catchment area of the nearest previously modelled catchment. Details of the abstraction locations and catchment areas, donor catchments and scale factors are provided in Table C.4. Percentile flows for each of these catchments are provided in Table C.5.

Table C.4: Abstraction locations, catchment areas and donor catchments

Gauging station name	GPS reference	Easting	Northing	Catchment area (km^2)	Donor catchment	Scale factor
Allt an Labhrach	NN 50232 85917	250232	785917	24.48	Loch Earba	1.002
Allt Coire Pitridh	NN 46510 80683	246509	780682	4.64	Loch Earba	0.190
Allt Coire a' Chlachair	NN 46192 80333	246191	780333	0.95	Loch Earba	0.039
Allt Coire a' Chlachair tributary 1	NN 46408 80545	246408	780544	0.20	Loch Earba	0.008
Allt Coire a' Chlachair tributary 2	NN 46101 80233	246100	780232	0.20	Loch Earba	0.008
Allt Loch a Bhealaich Lemhain	NN 50789 79249	250788	779249	2.56	Loch Leamhain	0.996

Figure C.4: Simulated flow duration curves for abstraction location catchments

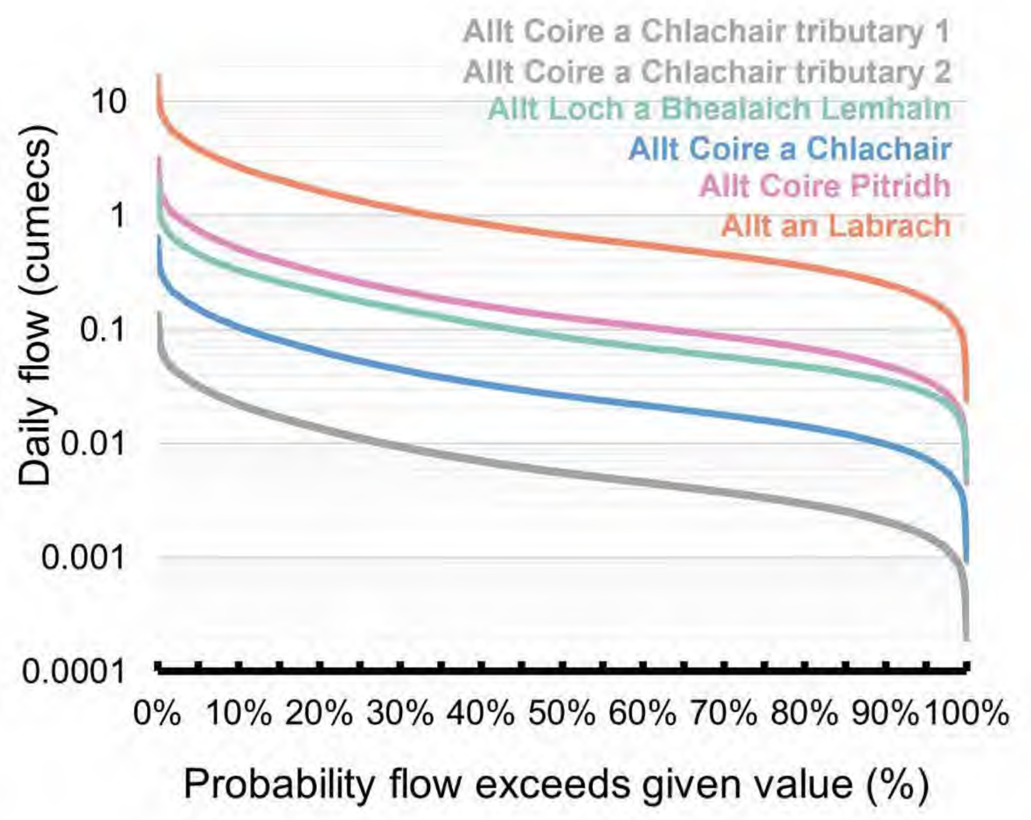


Table C.5: Flow percentiles at specified abstraction locations (m^3/s)

Flow percentile	Allt an Labhrach	Allt Coire Pitridh	Allt Coire a' Chlachair	Allt Coire a' Chlachair tributary 1	Allt Coire a' Chlachair tributary 2	Allt Loch a Bhealaich Lemhain
Q99	0.11	0.020	0.004	0.001	0.001	0.017
Q95	0.19	0.036	0.007	0.002	0.002	0.028
Q90	0.25	0.048	0.010	0.002	0.002	0.036
Q80	0.36	0.068	0.014	0.003	0.003	0.047
Q70	0.46	0.087	0.018	0.004	0.004	0.058
Q60	0.56	0.106	0.022	0.005	0.005	0.070
Q50	0.68	0.129	0.026	0.006	0.006	0.086
Q40	0.86	0.163	0.033	0.007	0.007	0.111
Q30	1.15	0.218	0.045	0.009	0.009	0.151
Q20	1.66	0.315	0.064	0.014	0.014	0.213
Q10	2.69	0.510	0.104	0.022	0.022	0.329
Q5	3.90	0.739	0.151	0.032	0.032	0.458
Q1	6.60	1.251	0.256	0.054	0.054	0.754

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