Drought Vulnerability Framework

Hydrological update: Barmouth, Lleyn Harlech, Mid and South Ceredigion, North Eryri Ynys Môn

Dŵr Cymru Welsh Water

28 March 2019

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This document has 92 pages including the cover.

Document history

Revision	Purpose description	Originated	Checked	Reviewed	Authorised	Date
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Rev 2.0	Final	SA	NU	NU	BC	28/03/2019

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1. Introduction

This work was undertaken as part of applying the Drought Vulnerability Framework (DVF) to Dŵr Cymru Welsh Water's (DCWW) Water Resource Zones (WRZs). The overall project is reported separately (Atkins, 2019) and this report corresponds to additional rainfall-runoff modelling completed to support the assessment.

For WRZs where the perceived risk was higher the assessment was based on stochastically generated rainfall. A rainfall-runoff model was required to convert this rainfall into flow. Unfortunately, previous experiences of using the existing models have demonstrated that it is impractical to simulate very long (i.e. 12,000 year) rainfall sequences using the Hysim software. Therefore, new Catchmod models were developed. The Python coded version of the software, PyCatchmod, was then used to simulate stochastic flow for use in the drought vulnerability assessment.

As part of the same exercise Catchmod models were also developed for Mid and South Ceredigion. In this lower risk WRZ, however, the assessment was based on Extreme Value Analysis of historic hydrology so there was no requirement to process stochastically generated rainfall. The objectives were to use models to try to improve hydrological understanding of the Teifi catchment, and to provide tools for future assessments, for example simulating climate change impacts or stochastically generated flow.

It is important to note that the work described here was undertaken within the timescales of the DVF project. The overall objective was therefore to achieve the best possible calibrations in the time window available. Where further work could be undertaken to improve the calibrations, beyond the timescales of the DVF project, this is detailed below.

This report therefore outlines the Catchmod calibration of DCWW's reservoirs and river intakes catchments across the following WRZs (Table 1.1):

- Barmouth
- Lleyn Harlech
- Mid & South Ceredigion
- North Eryri Ynys Môn

following on from modelling last reported in AFW (2017).

Table 1.1 - Summary of streamflow being modelled with Catchmod rainfall runoff model

Water Resource Zone	Resource
Barmouth	Llyn Bodlyn
Lleyn Harlech	Llyn Cwm Dulyn
	Llyn Cwmstradllyn
	Afon Dwyfor at Garndolbenmaen
	Llyn Tecwyn Uchaf
	Llyn Eiddew Mawr
Mid & South Ceredigion	Teifi Pools (Pond y Gwaith, Llyn Teifi, Llyn Egnant)
	Afon Teifi at Llechryd
North Eryri Ynys Môn	Llyn Alaw
	Llyn Cefni
	Ffynnon Llugwy
	Marchlyn Bach
	Glaslyn

The locations of the Catchmod models being developed in this report are shown in Figure 1.1 and a summary of catchment characteristics extracted from the Low Flows Enterprise (LFE)[1] is presented in Table 1.2.

[1] https://www.hydrosolutions.co.uk/software/lowflowsenterprise/

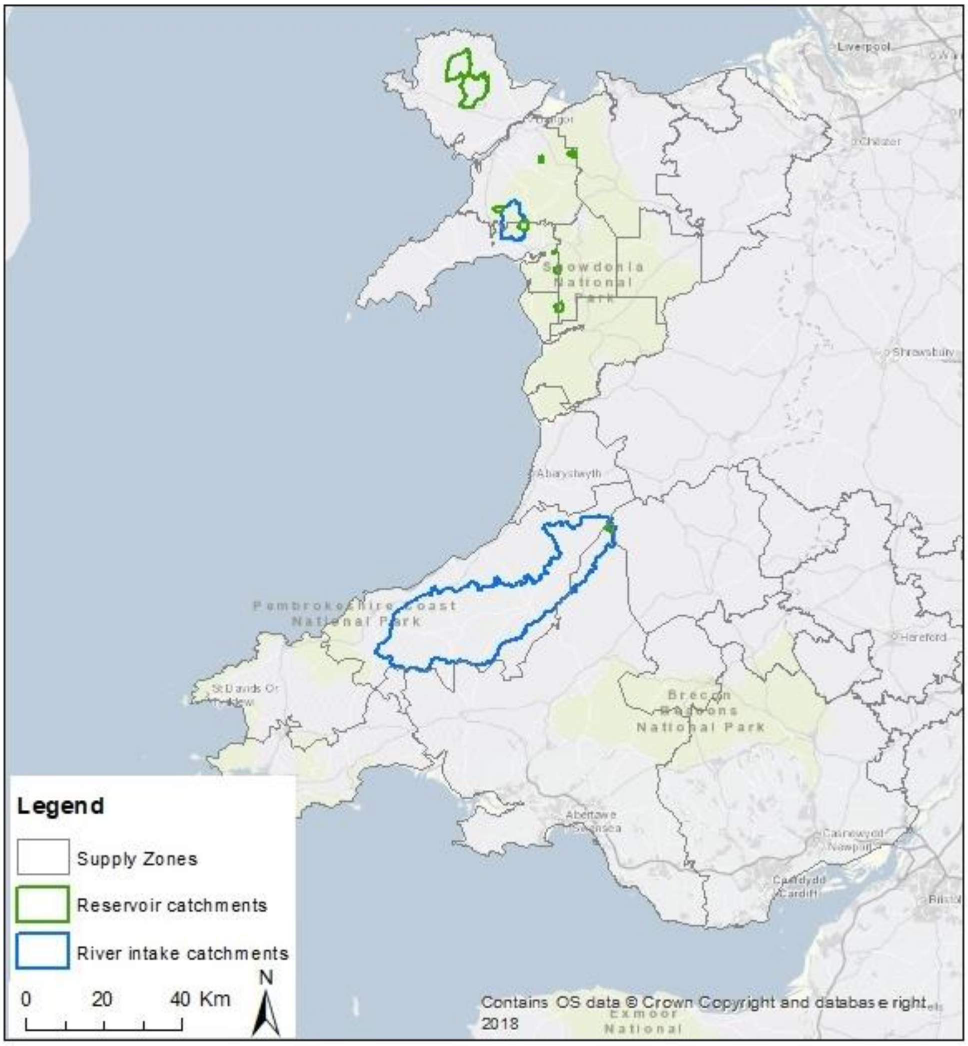

Figure 1.1 - Water Resource Zones for which hydrological inflows were calibrated by Atkins

Table 1.2 - LFE catchment characteristics for catchments calibrated by Atkins

Catchment	Catchment area (km^2)*	BFI HOST	Mean flow (m^3/s)	Q95 (m^3/s)
Llyn Bodlyn	3.66	0.31	0.210	0.026
Llyn Cwmystradllyn	5.02	0.36	0.272	0.029
Llyn Cwm Dulyn	2.51 (2.52)	0.37	0.174	0.021
Afon Dwfor at Garndolbenmaen	49.88 (49.61)	0.40	2.534	0.217
Llyn Tecwyn Uchaf	(0.40)	-	-	-
Llyn Eiddew Mawr	2.03 (1.94)	0.29	0.120	0.014
Llyn Teifi (part of Teifi Pools)	1.03 (1.72)	0.36	0.045	0.005
Afon Teifi at Llechryd	908.3 (908.0)	0.51	29.24	3.315
Llyn Alaw	33.39	0.42	0.51	0.061
Llyn Cefni	40.7	0.47	0.72	0.042
Ffynnon Llugwy	2.26	0.32	0.19	0.024
Marchlyn Bach	1.02	0.28	0.08	0.007
Glaslyn	20.82	0.37	1.55	0.14

* In brackets is the area of the shapefile sent by DCWW

For some of these zones, HYSIM rainfall runoff models have been previously developed to simulate streamflow (Table 1.3) and the results have been reported in AFW (2017).

Table 1.3 - Summary of existing HYSIM models

Water Resource Zone	HYSIM Model
Barmouth	Llyn Bodlyn
Lleyn Harlech	Cwm Dulyn
	Llyn Cwmstradllyn
	Afon Dwyfor
North Eryri Ynys Môn	Llyn Alaw
	Llyn Cefni
	Ffynnon Llugwy
	Marchlyn Bach
	Glaslyn

2. Model and data requirements

2.1. Rainfall runoff model

Catchmod is a rainfall runoff model frequently used by the Environment Agency that uses mathematical relationships to determine the runoff from precipitation upon a catchment (for detailed descriptions see e.g. Wilby, Greenfield and Glenny, 1994). It takes as input precipitation and potential evapotranspiration (PET). Water is routed through three stores, which conceptually represent upper soil zone, unsaturated zone and saturated zone (Figure 2.1). The model has an optional channel routing component, available for sub-daily mode only, to simulate translation and attenuation processes. For water supply planning in UK catchments, there is usually little benefit from understanding flow timing on anything other than a daily average (Watts, 2015). Catchmod does not have a snow module but given that snow only rarely occurs is Wales it is not usually important in water supply (Watts, 2015).

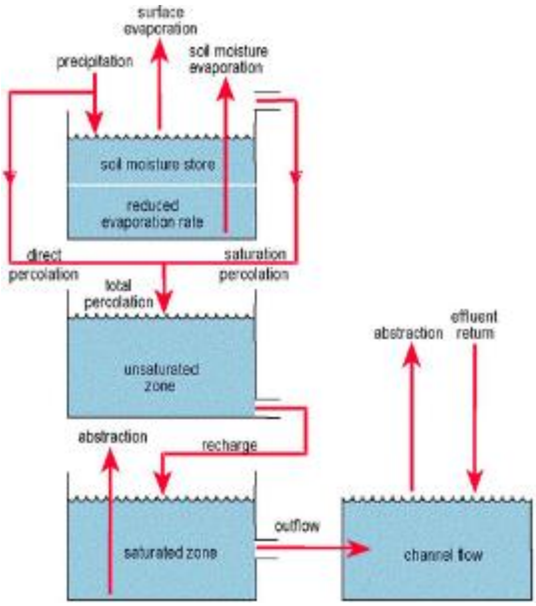

Figure 2.1 - Catchmod schematic. Image from Wilby et al., 2006.

The Catchmod model can be used in a lumped way or separated into discrete hydrologically similar zones. In this study, Catchmod will be used with up to three zones, depending on the complexity of the catchment being modelled. The individual calibration of each zone allows water to go through the stores at different rates, and empirically reflects the underlying processes in the catchment.

As mentioned previously, in this report the models are developed and calibrated in the Excel version of Catchmod, but the stochastic rainfall data were then processed with a much faster Python based version (PyCatchmod).

2.2. Input Data Requirements

Meteorological inputs:

Where HYSIM models exist, precipitation and PET were exported. Within HYSIM, the weather station distribution and an associated algorithm (together with a database of weather parameter time times) are used to calculate PET for any location in Wales.

For catchments without an HYSIM model, precipitation and PET time series are derived based on:

- The CEH Gridded Estimates of Areal Rainfall (CEH-GEAR) dataset, a 1 km gridded product derived from the interpolation of observed rainfall at all of the available daily and monthly rain-gauges in the UK (Keller *et al.* 2015, Tanguy *et al.*, 2016).
- The Climate, Hydrology and Ecology research Support System potential evapotranspiration (CHESS-PE) dataset, a 1 km gridded meteorological and land state dataset for Great Britain (Robinson *et al.*, 2016, 2017).

Observed reservoir and river flow data:

Observed data that have been used for the HYSIM calibration were supplied by DCWW. These data were used in the Catchmod calibration process and for comparison and validation of the modelled flows.

In addition to the data provided by DCWW, river flow data have been obtained from the National River Flow Archive (NRFA, 2018) for Llyfni at Pont Y Cim (station number 65015), Dwyfor at Garndolbenmaen (station number 65007), Teifi at Glanteifi (station number 62001), Teifi at Llanfair (station number 62002), Wye at Ddol Farm (station number 55026) and Wyre at Llanrhystud (station number 63003).

3. Barmouth

3.1. Overview of the zone

The Barmouth WRZ has a single inflow sequence, for Llyn Bodlyn, which is a small upland reservoir. A schematic representation of Barmouth WRZ is shown in Figure 3.1 and the catchment areas of the inflows are shown in Figure 3.2.

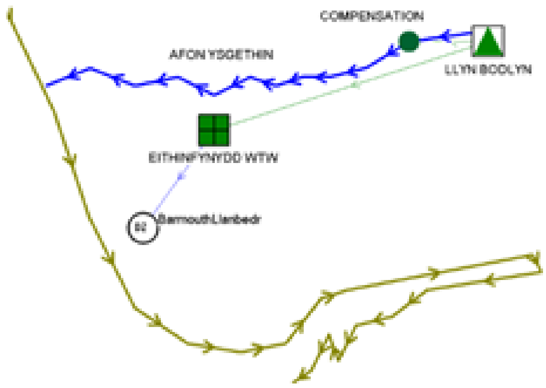

Figure 3.1 - WRAPsim Barmouth zone schematic

Figure 3.2 - Barmouth zone: catchment areas of inflows

3.2. Llyn Bodlyn

Llyn Bodlyn is in a small steep sided upland catchment (3.66 km^2) and the reservoir has a storage capacity of 439 Ml (Figure 3.3). The soils predominantly exhibit a peaty surface over rock and loam with bare rock and scree locally (Amec, 2012). The mean elevation of the catchment is 545m AOD.

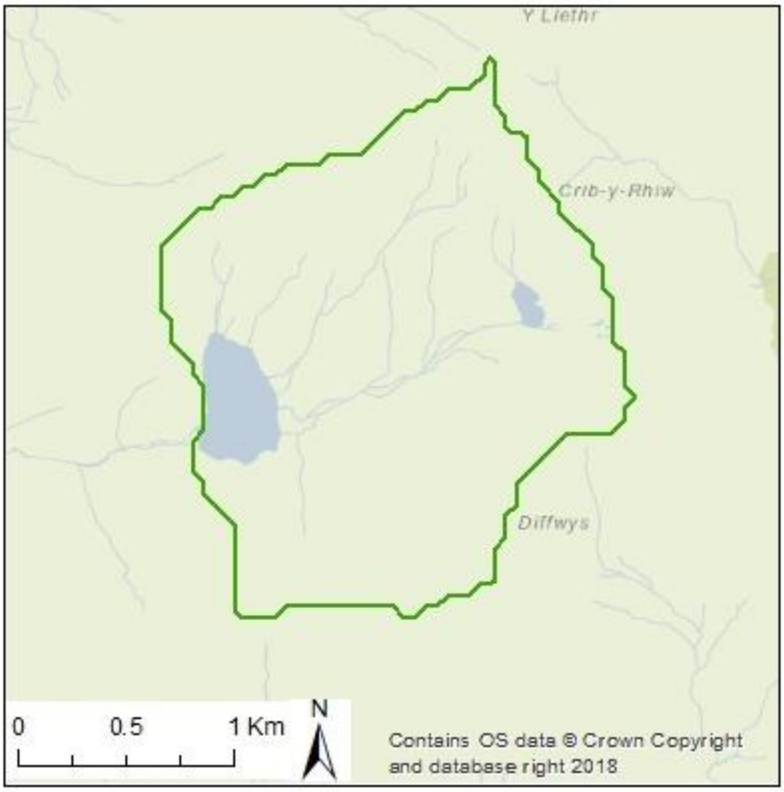

Figure 3.3 - Bodlyn reservoir and catchment location

Table 3.1 outlines key hydrological catchment characteristics extracted from LFE.

Table 3.1 - LFE catchment characteristics of Llyn Bodlyn catchment

Catchment	Catchment area (km^2)	BFI HOST	Mean flow (m^3/s)	Q95 (m^3/s)
Llyn Bodlyn	3.66	0.31	0.21	0.026

3.3. Model build

The latest calibration of the HYSIM model was performed by AFW (2017). AFW applied a scaling factor of 1.2 to precipitation, which is reassessed here. No observed inflow data were available for calibration, but a mass balance model based on observed storage and abstraction data have been used. As spill from the reservoir is not recorded the mass balance model can only be used during drawdown periods (i.e. it is not possible to back-calculate a full inflow sequence to use for calibration within the Catchmod software).

3.3.1. Precipitation and PET data

We started by assessing the scaling factor of 1.2 used by AFW (2017) in the precipitation timeseries. We extracted the precipitation timeseries from HYSIM (i.e. before any scaling factor has been applied), which was originally derived by HR Wallingford using Met Office gridded data, and compared it with (Figure 3.4):

- The mean annual precipitation from LFE;
- The CEH-GEAR dataset (Tanguy et al., 2016);
- A limited amount of observed precipitation data at the reservoir provided by DCWW; and
- Observed precipitation at station 525957 (Llyn Bodlyn) provided by National Resources Wales (NRW).

The mean annual precipitation calculated based on CEH-GEAR data (2048 mm) is closer to the value provided by LFE (2168 mm) and to the observed precipitation data provided by DCWW (2351 mm for the year of 2014), than the value calculated based on the timeseries used by AFW (2017) (1826 mm, before any scaling). However, the mean annual precipitation calculated based on years with complete data (1968, 1969, 1970, 1972, 1976 -1982, 1984 – 1991, 1993, 1994, 1997, 2002 – 2007, 2009 - 2014) as provided by NRW (1865 mm) is closer to the AFW (2017) data before scaling (1826 mm) than to the CEH-GEAR (2048 mm). After applying the scaling factor of 1.2 to the precipitation extracted from HYSIM, the mean annual precipitation (2191 mm) becomes much closer to the value provided by LFE (2168 mm).

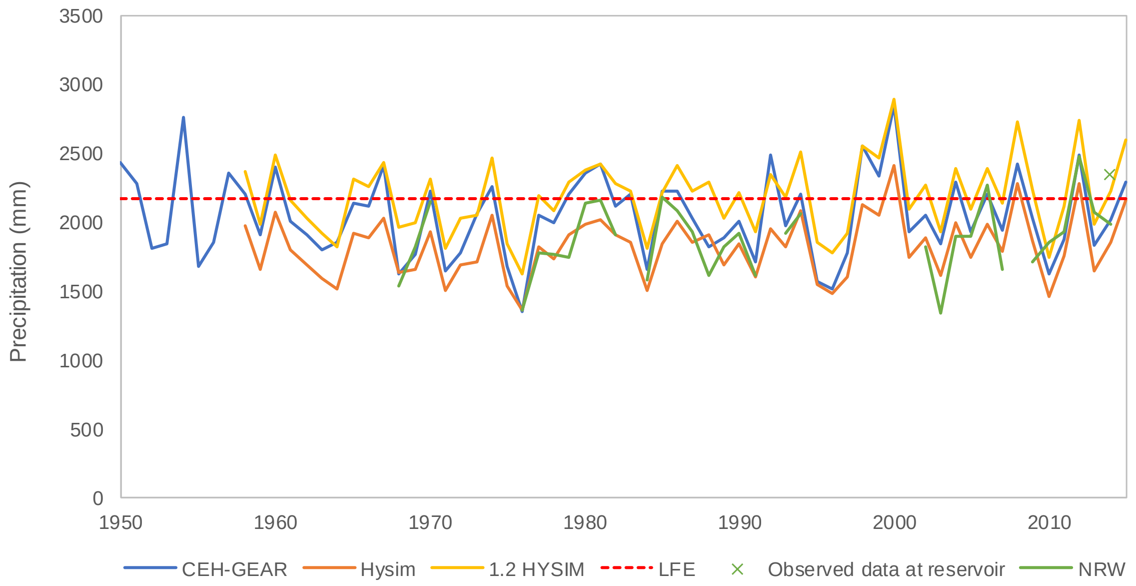

Figure 3.4 - Annual precipitation for the Bodlyn catchment

Without scaling, CEH-GEAR and HYSIM precipitation timeseries are significantly different, which would have a large impact on simulated flow given that the Llyn Bodlyn catchment responds very quickly and positively to a rainfall event (Jo Cullen, DCWW, pers comms).

Whilst it was necessary to scale the HYSIM dataset it did then allow Catchmod to recreate some features of the reservoir storage record more effectively than the CEH-GEAR dataset. Therefore, for this reason, and for consistency with previous modelling, the precipitation timeseries obtained from HYSIM with a scaling factor of 1.2 was used again in Catchmod.

For PET the same time series was used as per AFW (2017), as extracted from HYSIM.

3.3.2. Reservoir mass balance model

AFW (2017) used available observed reservoir data in a mass balance model to calibrate the HYSIM model; the main objective being to match as well as possible the observed reservoir drawdown rates and average monthly storage values. AFW used a fixed compensation flow of 2.18 Ml/d in the mass balance model. As noted in AFW (2017), the compensation flow is measured at a weir on the outflow channel, but the flow through the spillway is not measured, making the relationship between outflow and storage above the spill capacity unknown. Therefore, in the mass balance model the reservoir storage capacity was capped at the spill level capacity of 439 Ml. This means that reservoirs inflows can only be calibrated during periods of reservoir drawdown.

We compared the observed storage data sent by Gary Rowlands (Bodlyn Reservoir Levels with storage 1990_PRESENT DAY Amended.xlsx) and the storage data in the mass balance model from AFW (Figure 3.5). There are some differences between the two datasets, but apart from November 1997-February 1998 and March 2002-December 2003, those differences are always smaller than 1 Ml. The first time period with significant differences coincides with the forced drawdown of the reservoir to enable safety works to be undertaken and therefore was not used for calibration. Given the differences, calibration of the years 2002 and 2003 was approached with caution, especially given the previous AFW focus on 2003. It is also worth noting that daily reservoir level data is not available prior to 2004, which makes calibration a little more difficult given the level of interpolation required to produce a continuous record – see Figure 3.7).

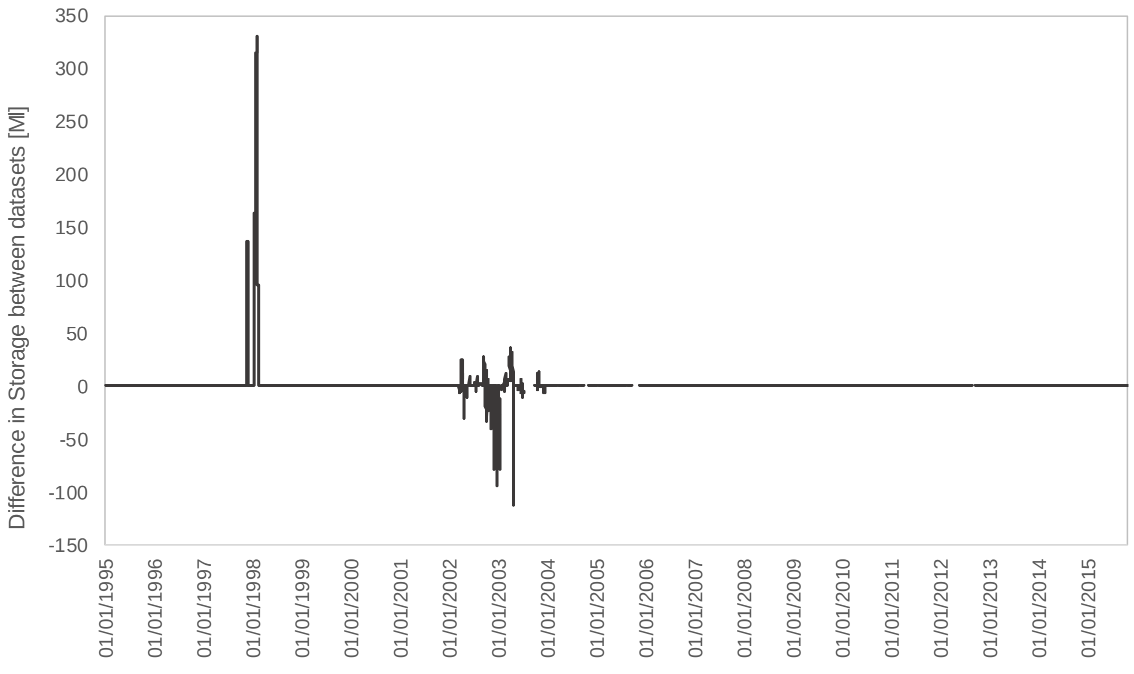

Figure 3.5 - Difference in storage between dataset sent by Gary Rowlands (Bodlyn Reservoir Levels with storage 1990-PRESENT DAY Amended.xlsx) and the AFW storage data.

Similar to AFW (2017), the main calibration objective was to match as well as possible the observed reservoir drawdown rates and the average monthly storage values. In addition, we analysed how the FDC of the simulated inflow compared with the FDC from LFE.

Figure 3.6 shows the change in flows (as a FDC) between HYSIM and Catchmod calibrations, and how they compare with the FDC from LFE. For Catchmod two distinct parameter sets are shown in Figure 3.6, with parameter set #12 (PS #12) representing the best calibration to the FDC of LFE, and parameter set #39 (PS #39) the best overall match to the mass balance model.

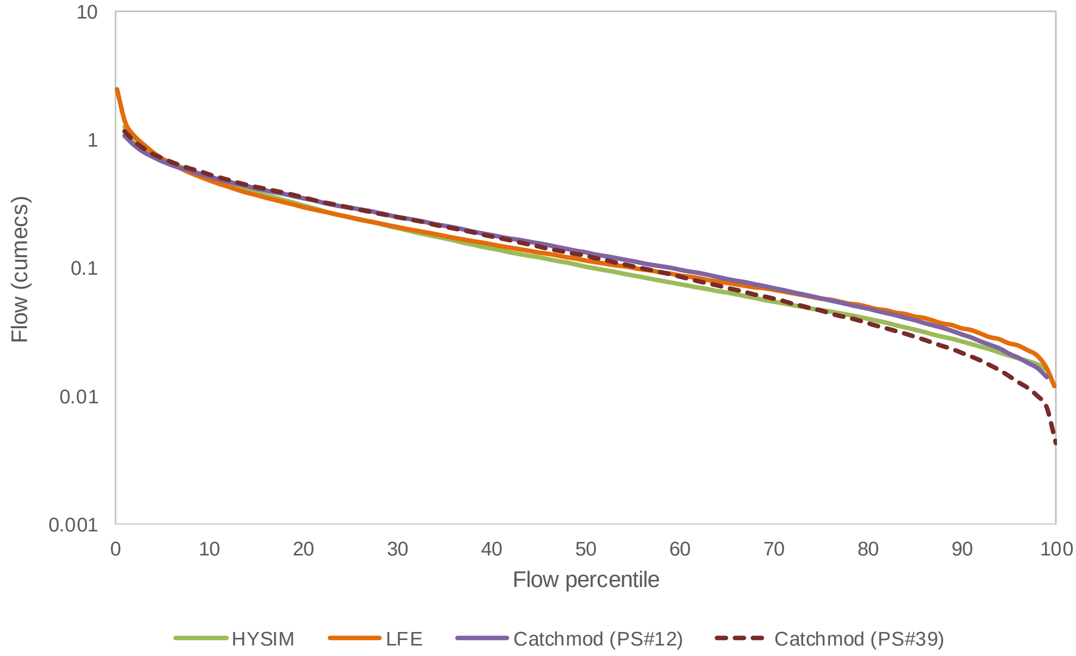

Figure 3.6 - Flow Duration Curves for the HYSIM calibration, for the Catchmod calibration (for two distinct parameter sets, #12 and #39) and from the LFE

The reservoir storage calculated from the Catchmod flow (parameter sets #12 and #39) is shown in Figure 3.7 and in Figure 3.8 for two distinct time periods, 2003 and 2006. The time periods in these two figures are the ones selected by AFW (2017) and were intended to represent a drier and a wetter year.

For the drier year (summer 2003, Figure 3.7), Catchmod for parameter set #39 is similar to the latest HYSIM calibration and much closer to the observed storage than when using Catchmod with parameter set #12 (which has the better LFE FDC fit). As noted above some caution is required in this event due to the discrepancies with the data.

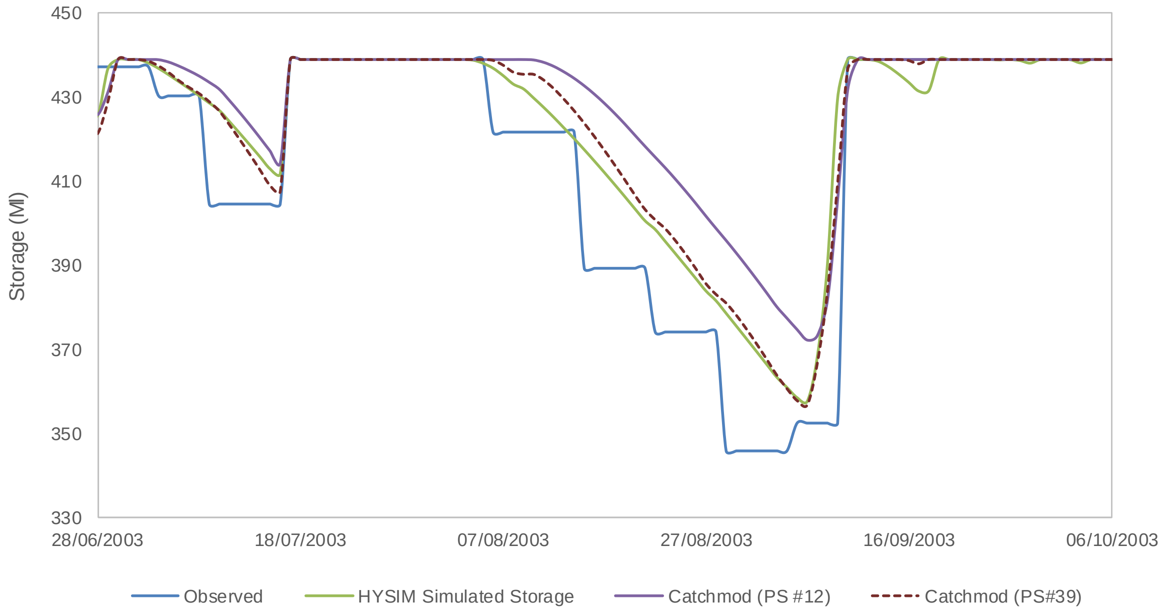

Figure 3.7 - Llyn Bodlyn observed and modelled storages for a drier year

For the AFW selected wetter year (spring / summer 2006, Figure 3.8), the Catchmod simulated storage with parameter set #39 tends to be closer to the observed storage than storage simulated with HYSIM. However, Catchmod with parameter set #39 does not always outperform Catchmod with parameter set #12.

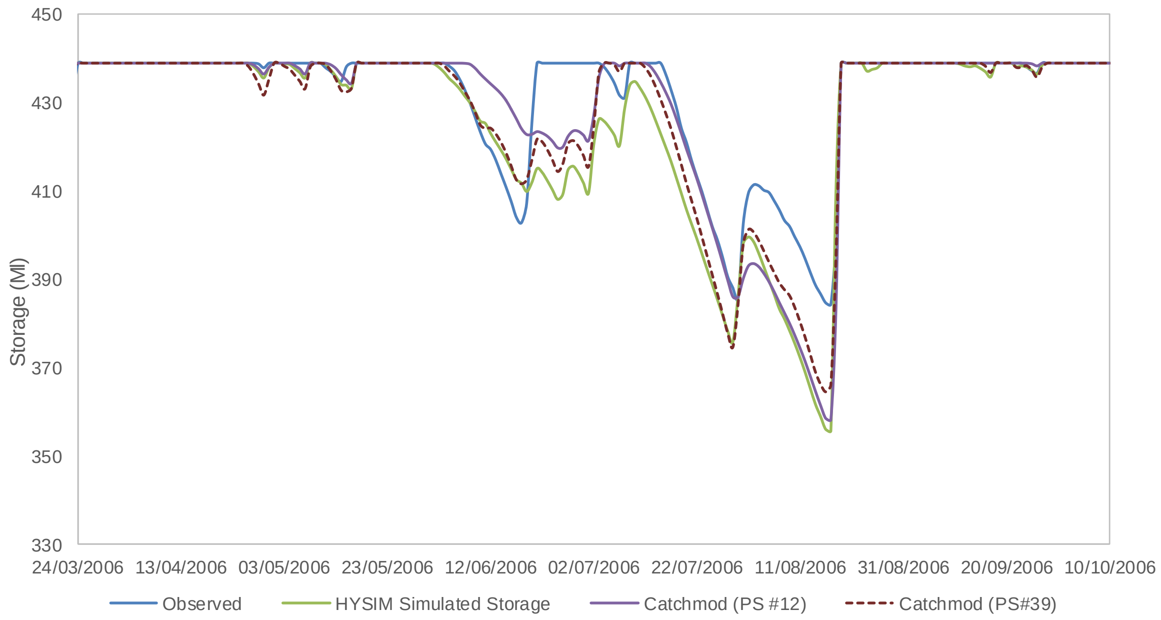

Figure 3.8 - Llyn Bodlyn observed and simulated storages for a wetter year

The relative performance of the models differs significantly depending on the drawdown period selected. For example, for May – December 2008 (Figure 3.9) simulated storage based on Catchmod parameter set #39 tends to be closer to observed storage than HYSIM. However, other time windows could be selected that would show the opposite.

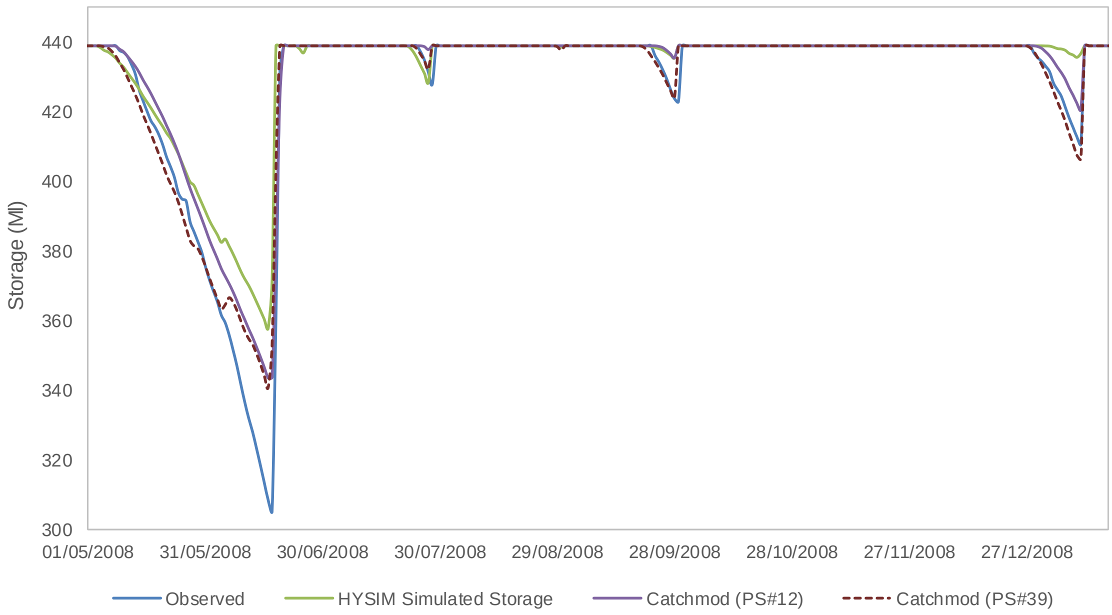

Figure 3.9 - Llyn Bodlyn observed and simulated storages for May – December 2008

In terms of monthly mean storage (Figure 3.10), Catchmod with parameter set #39 is closer to the observed storage than HYSIM. All models seem to show similar trends during the drawdown period but give poor results in winter (particularly between October and January). This may be related to the lack of spill data but has not been investigated in detail.

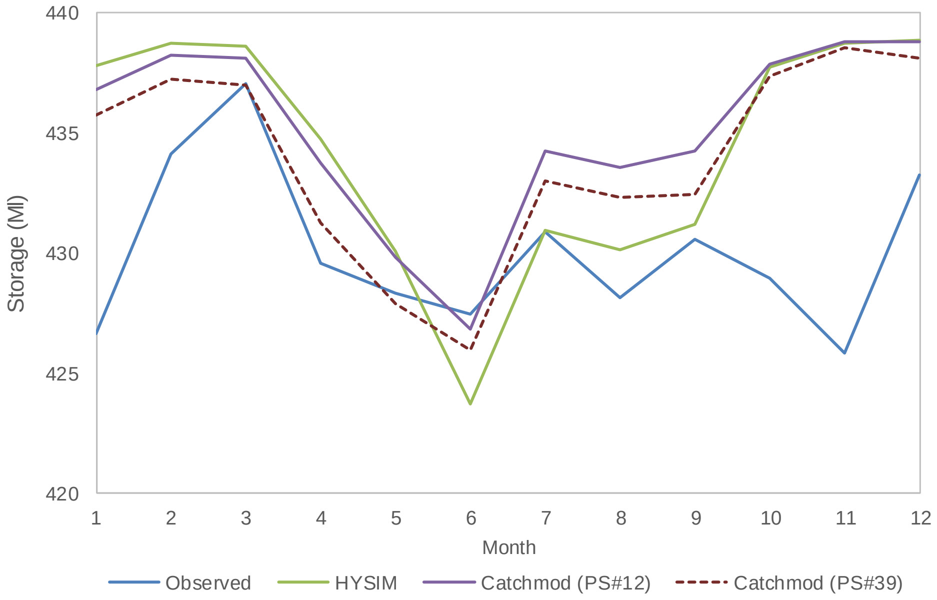

Figure 3.10 - Llyn Bodlyn monthly mean storage

3.4. Conclusions

A new Catchmod model has been developed for Llyn Bodlyn. The HYSIM scaled precipitation and PET data were retained, and the model was calibrated along similar lines to the HYSIM one. In addition to the two events that AFW presented in their report (2003 and 2006), we considered a wide range of other events and incorporated the LFE FDC into the calibration. Ultimately, we selected the calibration that performed best in comparison to the mass balance model (parameter set #39). The performance of this model is at least as good as the HYSIM model, and probably a little better (it is difficult to quantify performance in the mass balance calibration approach).

The relative performance of each of the Catchmod and HYSIM models and parameter sets varied considerably across different drawdown periods in relation to the mass balance model. This strongly suggests that the modelled inflows could be further improved with additional effort, either through further analysis of the existing data available for calibration, or possibly by taking new flow measurements. Unfortunately, this was not possible during the timescales available for this work.

4. Lleyn Harlech

4.1. Overview of zone

Lleyn Harlech WRZ has five inflow sequences:

- Llyn Cwmystradllyn - an impounding reservoir on the western edge of Snowdonia, lying on a tributary of the Afon Dwyfor;
- Llyn Cwm Dulyn - an impounding reservoir to the north of Cwmystradllyn;
- Afon Dwyfor – a river abstraction (pumped) at Dolbenmaen. The catchment of the Afon Dwyfor lies across the southeast part of the Lleyn Peninsula;
- Llyn Tecwyn Uchaf - an impounding upland reservoir on the edge of Snowdonia; and
- Llyn Eiddew Mawr - a lake on the edge of Snowdonia.

A schematic representation of Lleyn Harlech WRZ is shown in Figure 4.1 and the catchment areas of the inflows are shown in Figure 4.2.

The inflows to Llyn Cwmystradllyn, Llyn Cwm Dulyn and Afon Dwyfor have been modelled using Catchmod. The inflows to Llyn Tecwyn Uchaf and Llyn Eiddew Mawr have been derived by transposing from a nearby Catchmod model.

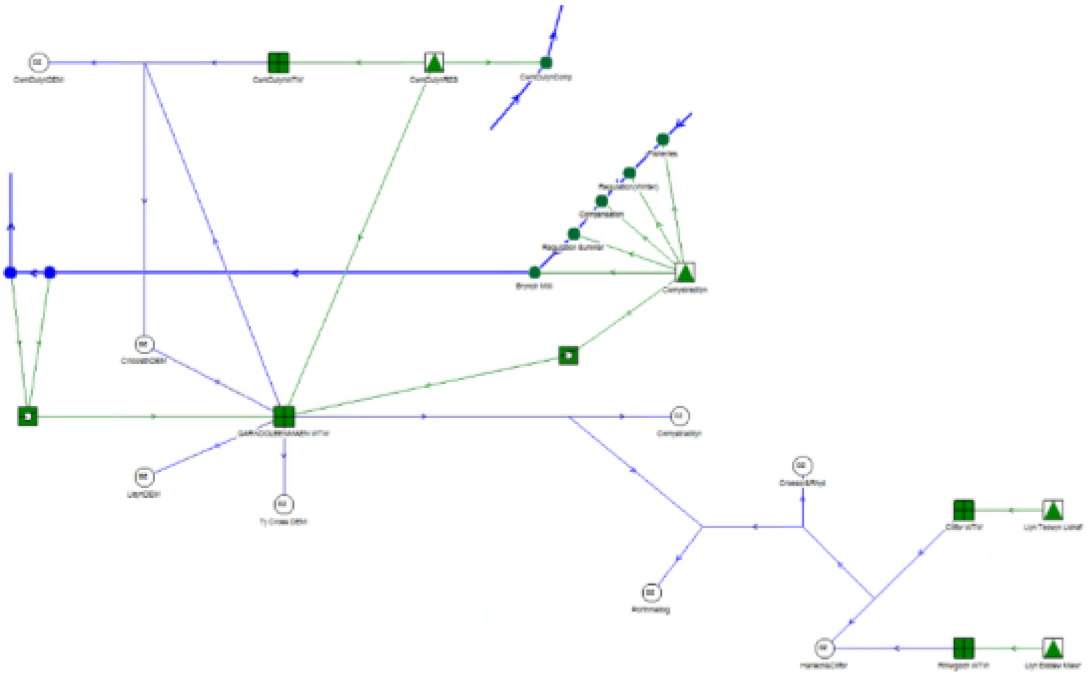

Figure 4.1 - WRAPsim Lleyn Harlech schematic

Figure 4.2 - Lleyn Harlech zone: catchment areas of inflows and donor catchment (Bodlyn)

4.2. Llyn Cwm Dulyn

4.2.1. Introduction

Llyn Cwm Dulyn has one main inflow from a steep, scree and bare rock covered catchment with gritty, loamy, very acid soils and a wet peaty surface horizon with frequent iron pan layers (Amec, 2012) (Figure 4.3). The mean elevation of the catchment is 423 m AOD. The reservoir has a storage capacity of 704 Ml (AFW, 2017) and has a compensation discharge requirement of 2.7 Ml/d (DCWW, 2015). Abstraction from the reservoir is limited to 2.9 Ml/d, limited by the associated WTW (DCWW, 2015).

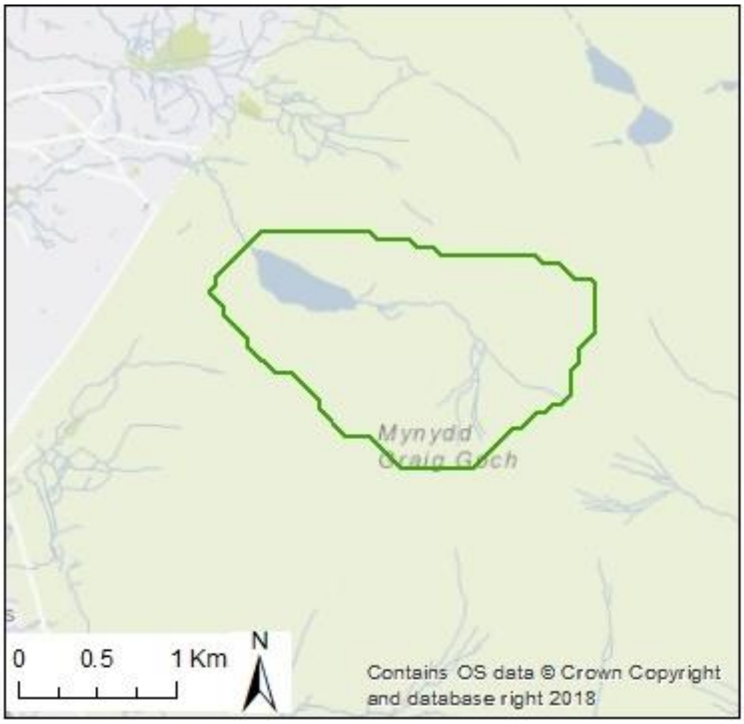

Figure 4.3 - Cwm Dulyn reservoir and catchment location

Table 4.1 outlines the key hydrological catchment characteristics extracted from LFE.

Table 4.1 - LFE catchment characteristics of Llyn Cwm Dulyn catchment

Catchment	Catchment area (km^2)	BFI HOST	Mean flow (m^3/s)	Q95 (m^3/s)
Llyn Cwm Dulyn	2.51	0.37	0.17	0.021

4.2.2. Model build

The latest calibration of the HYSIM model was performed by AFW (2017). AFW applied a scaling factor of 1.04 to precipitation, which is reassessed here. No observed inflow data were available for calibration, but a mass balance model based on observed storage and abstraction data have been used. As spill from the reservoir is not recorded accurately[2] the mass balance model can only be used during drawdown periods (i.e. it is not possible to back-calculate a full inflow sequence to use for calibration within the Catchmod software).

4.2.2.1. Precipitation and PET data

We started by assessing the scaling factor of 1.04 used by AFW (2017) in the precipitation timeseries. We extracted the original precipitation timeseries from HYSIM (i.e. before any scaling factor has been applied), which was originally derived by HR Wallingford using Met Office gridded data, and compared it with (Figure 4.4):

- The mean annual precipitation from LFE; and

[2] There is a gauging station just downstream but the stage-storage relationship would be very crude above the spillway.

- The CEH-GEAR dataset (Tanguy et al., 2016).

The mean annual precipitation calculated based on CEH-GEAR data (2366 mm, based on data between 1995 and 2015) is closer to the value provided by LFE (2564 mm), than the value calculated based on the timeseries used by AFW (2017) (2065 mm for 1995-2015 or 2023 for 1958-2012, both before any scaling). However, to allow comparison with the AFW (2017) results, we proceeded with the timeseries as extracted from HYSIM. AFW (2017) applies a scaling factor of 1.04 to this timeseries, which as per the HYSIM manual accounts for the fact that standard rain gauges collect less than a ground level gauge (Manley, 2006). Given that the precipitation timeseries is based on gridded data, and interpolated from a range of observations, the timeseries obtained from HYSIM is used here without the scaling factor.

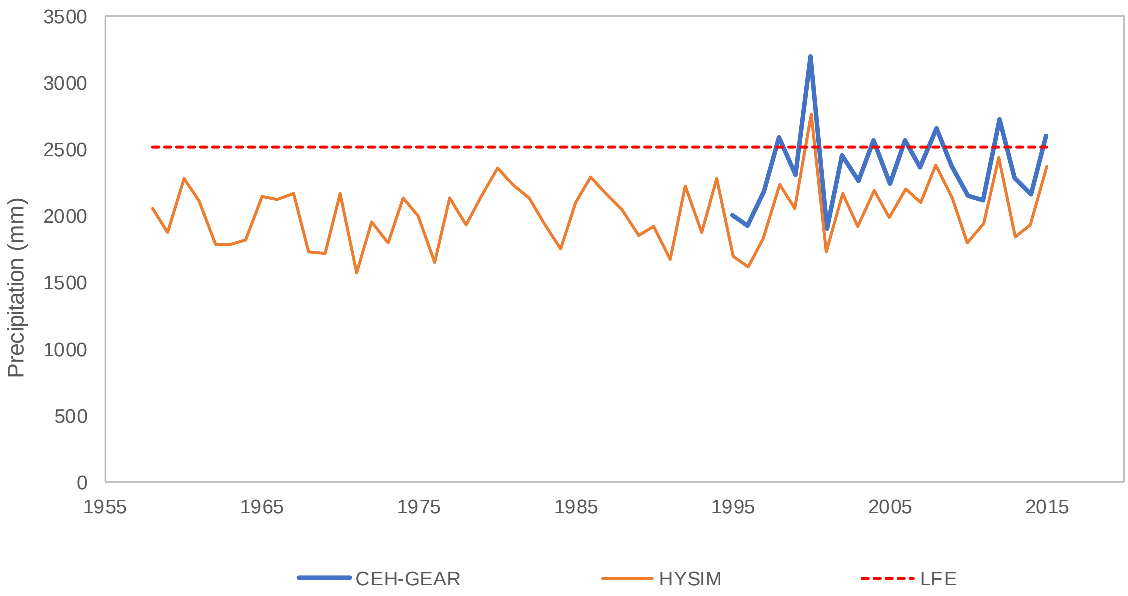

Figure 4.4 - Annual precipitation for the Cwm Dulyn catchment as extracted from HYSIM (precipitation has not been scaled by 1.04), derived from CEH-GEAR and mean annual precipitation from LFE

AFW (2017) derived PET using HYSIM (for latitude = 3492.08; longitude = 2499.60[3]; mean elevation = 427m AOD), which is used here.

4.2.2.2. Reservoir mass balance model

AFW (2017) used available observed reservoir data in a mass balance model to calibrate the HYSIM model, the main objective being to match as well as possible the observed reservoir storage during drawdown events. While there are observed data on abstraction, the spilled flows are not gauged accurately[2]. Therefore, in the mass balance model the reservoir storage capacity was capped at 439 Ml and a fixed compensation flow of 2.7 Ml/d was applied as per the AFW (2017) mass balance. This means that reservoirs inflows can only be calibrated during periods of reservoir drawdown.

We compared the observed storage data[4] and the storage data in the mass balance model from AFW (Figure 4.5). There are some differences between the two datasets up to November 2011, but these differences are never greater than 2.5 Ml/d. Here we used the storage data in the mass balance model from AFW (2017).

[3] The 'latitude' and 'longitude are not true latitude and longitude but correspond to National Grid References divided by 100m. However, in HYSIM they are labelled as 'latitude' and 'longitude'.
[4] 'Cwm Dulyn Reservoir Levels.xlsx' file sent by Gary Rowlands

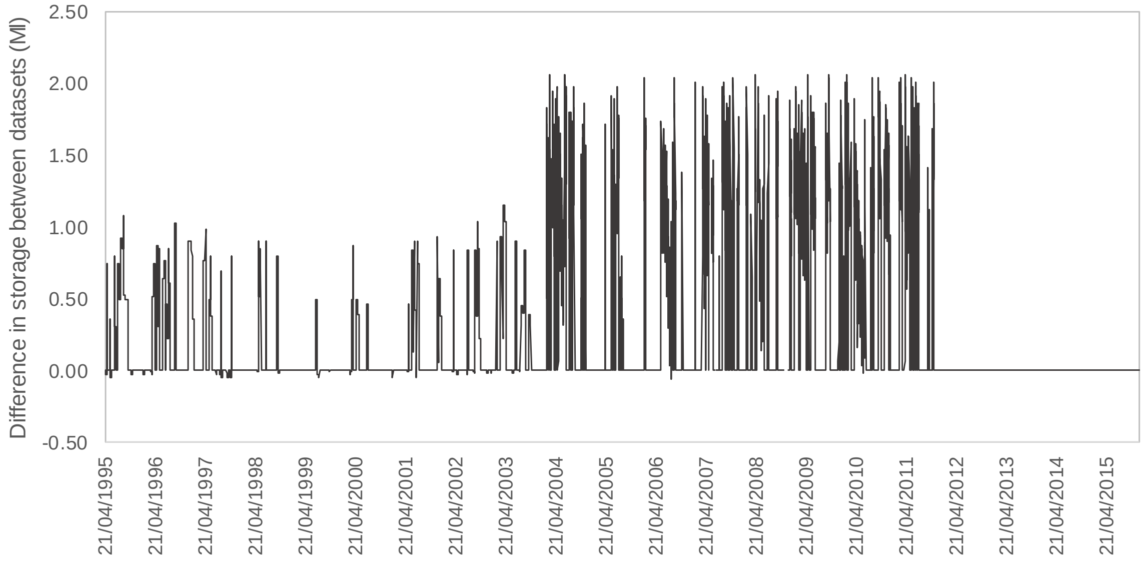

Figure 4.5 - Difference in storage between dataset sent by Gary Rowlands (file 'Cwm Dulyn Reservoir Levels.xlsx') and the AFW storage data

Similar to AFW (2017), the main calibration objective was to match as well as possible the observed reservoir drawdown rates.

Figure 4.6 shows the change in flows (as a FDC) between HYSIM and Catchmod calibrations, and how they compare with the FDC from LFE. For Catchmod two distinct parameter sets are shown in Figure 4.6, with parameter set #1 (PS #1) being closer to the FDC of LFE than parameter set #2 (PS #2).

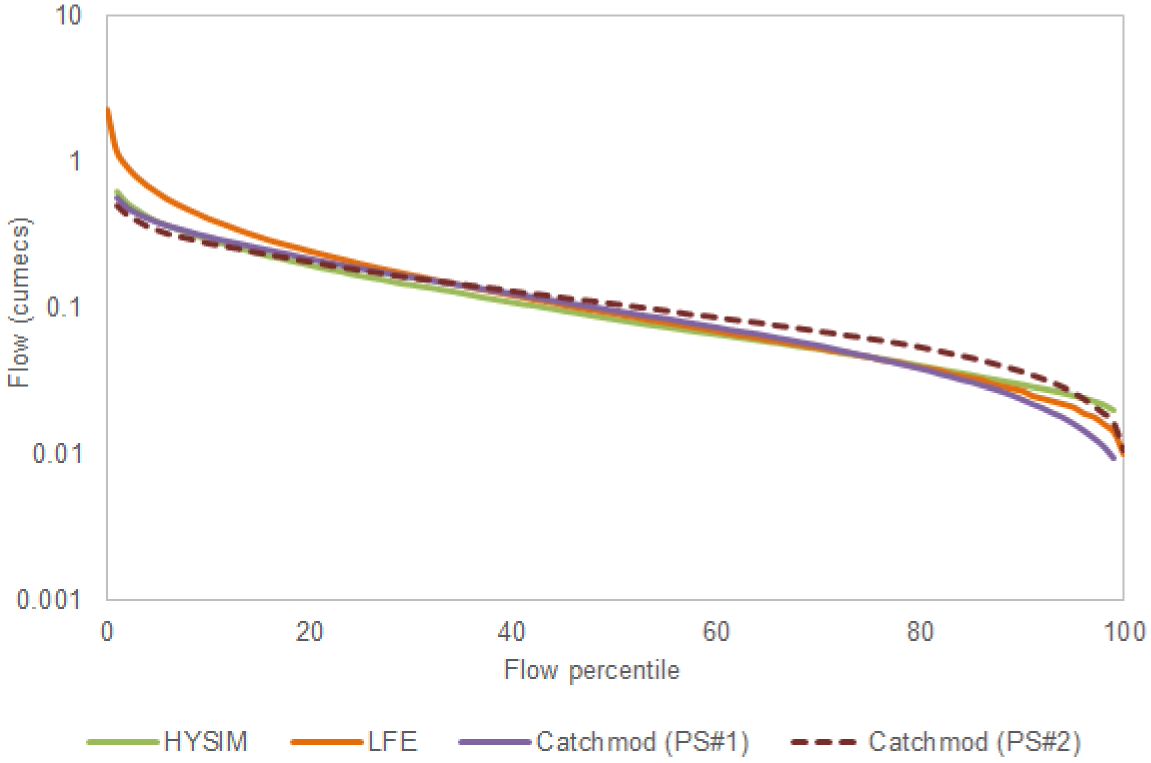

Figure 4.6 - Flow Duration Curves for the HYSIM calibration, for the Catchmod calibration (for two distinct parameter sets, #1 and #2) and from LFE

The reservoir storage calculated from the Catchmod flow (parameter sets #1 and #2) is shown in Figure 4.7, where the time period shown being the one selected by AFW (2017). Parameter set #1 gives the best match to the mass balance model in some events (Figure 4.8), but at other times parameter set # 2 is better (Figure 4.9).

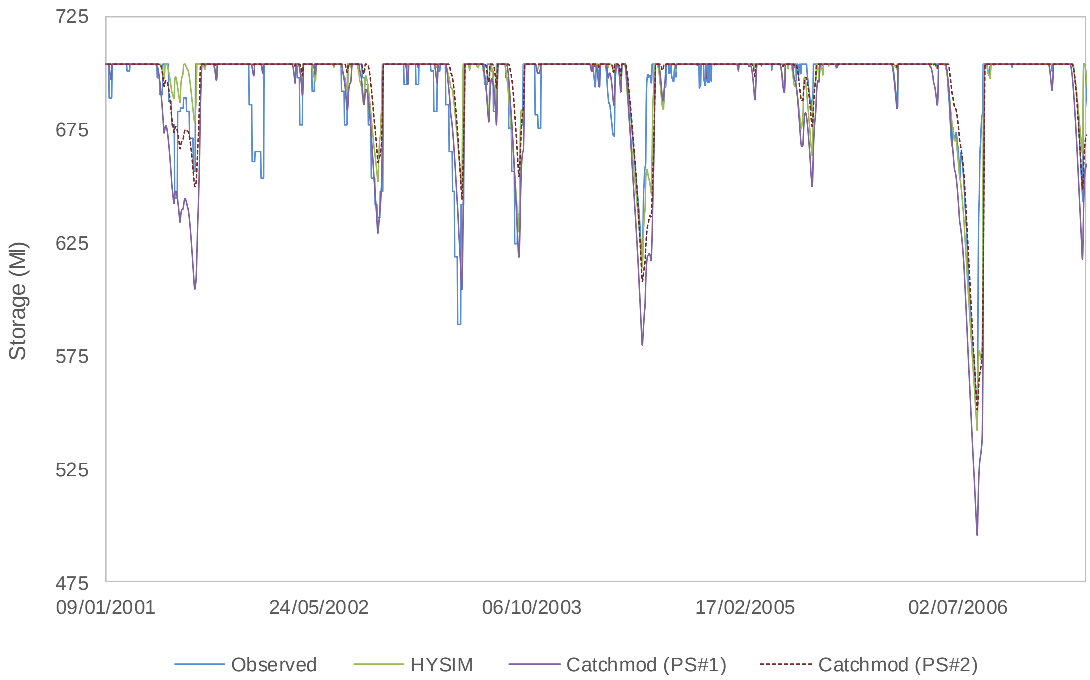

Figure 4.7 - Llyn Cwm Dulyn observed and modelled reservoir storages

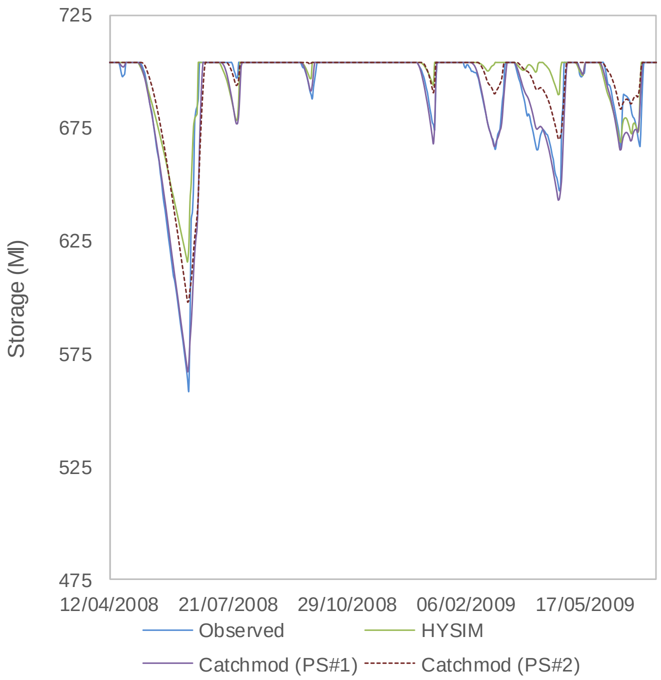

Figure 4.8 - Llyn Cwm Dulyn observed and modelled reservoir storages between April 2008 and June 2009

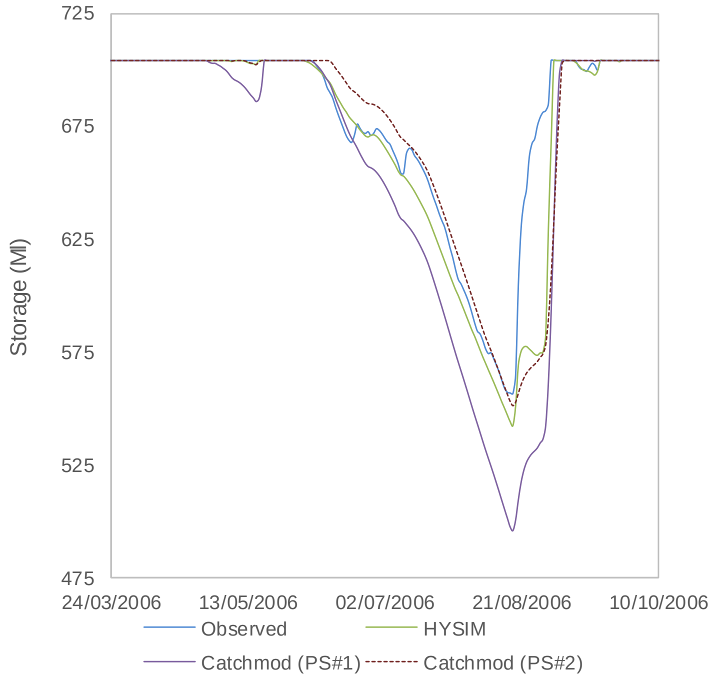

Figure 4.9 - Llyn Cwm Dulyn observed and modelled reservoir storages between March and October 2006

Another way of assessing model performance is by plotting observed against modelled storage (Figure 4.10). The closer the points are to the 1:1 line, the better the model is performing. Any points closer to the reservoir storage capacity (704 Ml) should be ignored, as the mass balance caps the reservoir storage at the capacity of the reservoir. From visual inspection of Figure 4.10, Catchmod with parameter set #2 seems to perform better than other models. However, given the high density of points this assessment can be challenging.

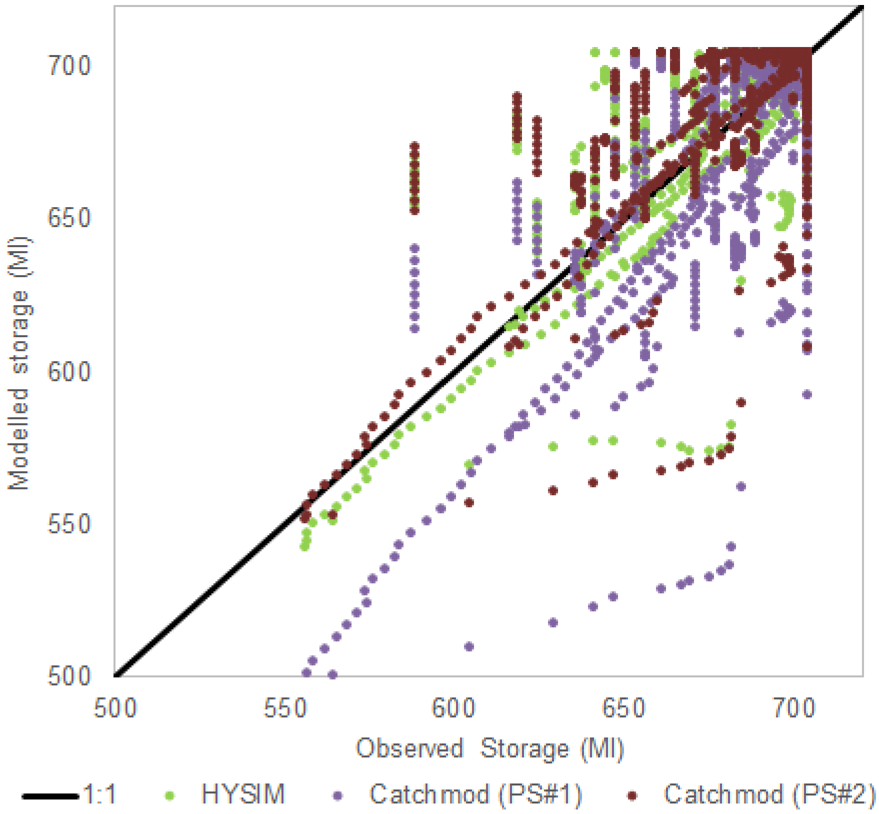

Figure 4.10 - Llyn Cwm Dulyn observed against modelled reservoir drawdown for HYSIM and Catchmod calibration. Data shown here covers the time period between 13/01/2001 and 20/04/2007 to be consistent with the time period selected by AFW (2017).

4.2.3. Transposition from a nearby catchment

As alternative the nearby catchment Llyfni at Pont Y Cim (Figure 4.11, Table 4.2) was assessed to see if it possible to use is as a source for transposition (Jo Cullen, DCWW, pers comms).

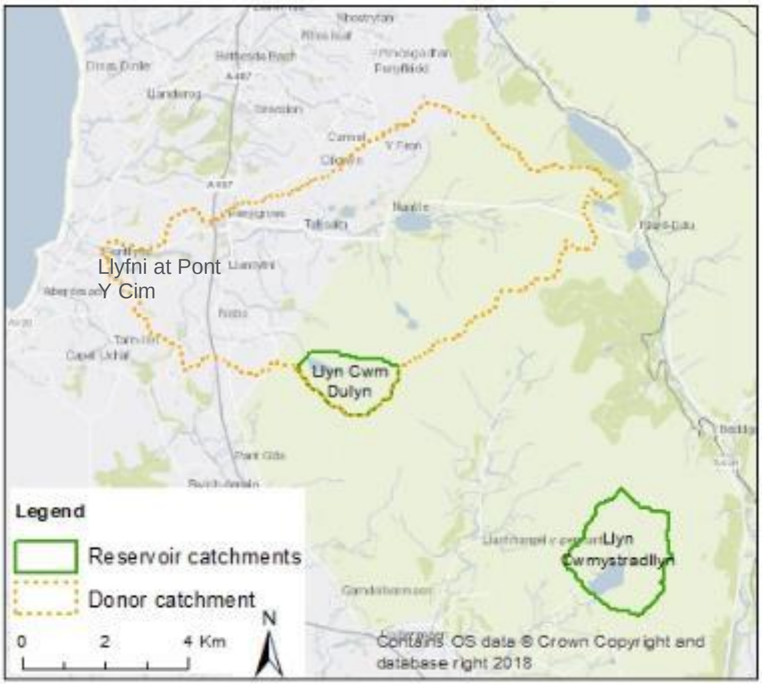

Figure 4.11 - Location of Llyn Cwm Dulyn catchment and the nearby catchment Llyfni at Pont Y Cim (yellow dashed line, station 65015)

Table 4.2 - Llyfni at Pont Y Cim catchment characteristics from NRFA[5]

Catchment	Catchment area (km^2)	BFI HOST	Mean flow (m^3/s)	Q95 (m^3/s)
Llyfni at Pont Y Cim	48.1	0.45	2.383	0.594

We transposed flow observed at Llyfni at Pont Y Cim to Cwm Dulyn based on average daily flow (ADF), according to Eq. (1).

$$\text{Cwm Dulyn inflow} = 0.073 \times \text{Llyfni at Pont Y Cim} \quad (1)$$

The transposition factor 0.073 is the ratio between the ADF for Llyfni at Pont Y Cim (2.396 cumecs estimated based on data for 1996-2015) and the ADF for Cwm Dulyn (0.1746 cumecs from LFE after being adjusted for the difference in areas between LFE and the shapefile provided by DCWW).

The reservoir storage calculated from flow transposition based on Llyfni at Pont Y Cim catchment is shown in Figure 4.12. The results obtained are not as good as when Catchmod was calibrated using the mass balance model.

[5] National River Flow Archive, 2018, https://nrfa.ceh.ac.uk, NERC CEH, Wallingford.

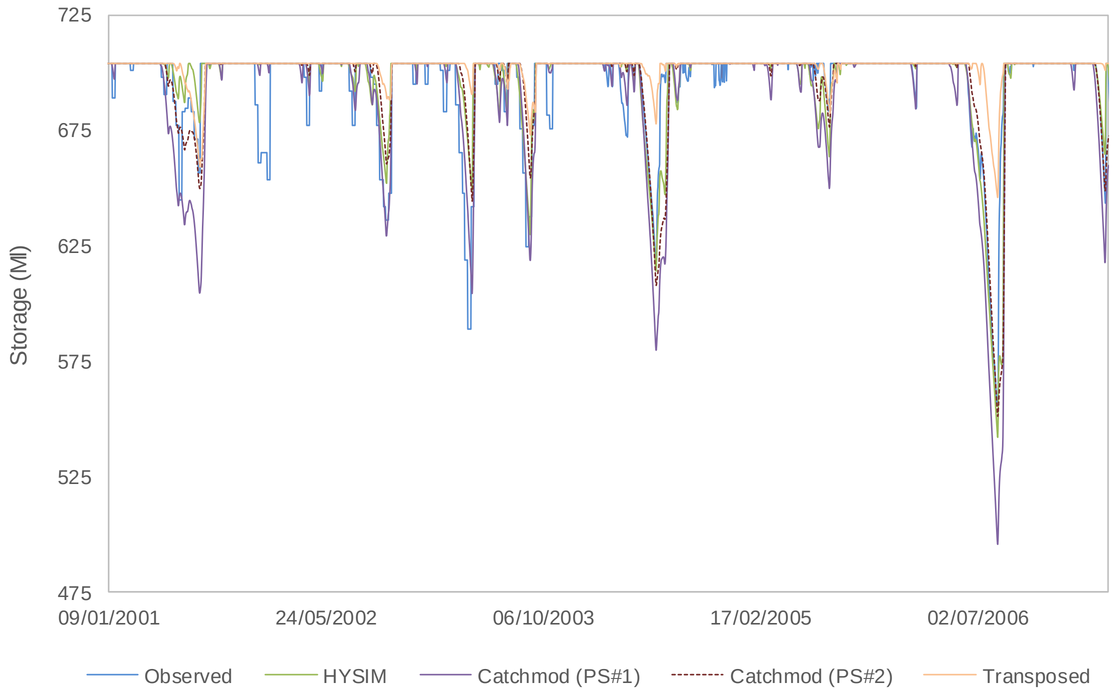

Figure 4.12 - Llyn Cwm Dulyn observed and modelled storages, including flow transposed from Llyfni at Pont Y Cim catchment

4.2.4. Conclusions

A new Catchmod model has been developed for Llyn Cwm Dulyn. The HYSIM precipitation (without scaling factor) and PET data were retained, and the model was calibrated along similar lines to the HYSIM one. In addition to the events that AFW presented in their report (2001-2006), we considered other events (2008) and incorporated the LFE FDC into the calibration. Ultimately, we selected the calibration that performed best in comparison to the mass balance model (parameter set #2, Appendix A.2). The performance of this model is at least as good as the HYSIM model (it is difficult to quantify performance in the mass balance calibration approach).

The relative performance of each of the Catchmod and HYSIM models and parameter sets varied considerably across different drawdown periods in relation to the mass balance model. This strongly suggests that the modelled inflows could be further improved with additional effort, either through further analysis of the existing data available for calibration, or possibly by taking new flow measurements. Unfortunately, this was not possible during the timescales available for this work.

4.3. Llyn Cwmystradllyn

4.3.1. Introduction

Llyn Cwmystradllyn drains an area of 5.02 km^2 (Figure 4.13); the reservoir has a total storage capacity of 2910 Ml and has a compensation discharge requirement of 3.01 Ml/d (DCWW, 2015). Abstraction from the reservoir is limited to 12.3 Ml/d (DCWW, 2015). The catchment is a mixture of peaty soils over loam and rock with bare rock and scree locally (Amec, 2012). The geology is predominantly sandstone with some mudstone and siltstone to the south-east (AFW, 2017). The mean elevation of the catchment is 340 m AOD.

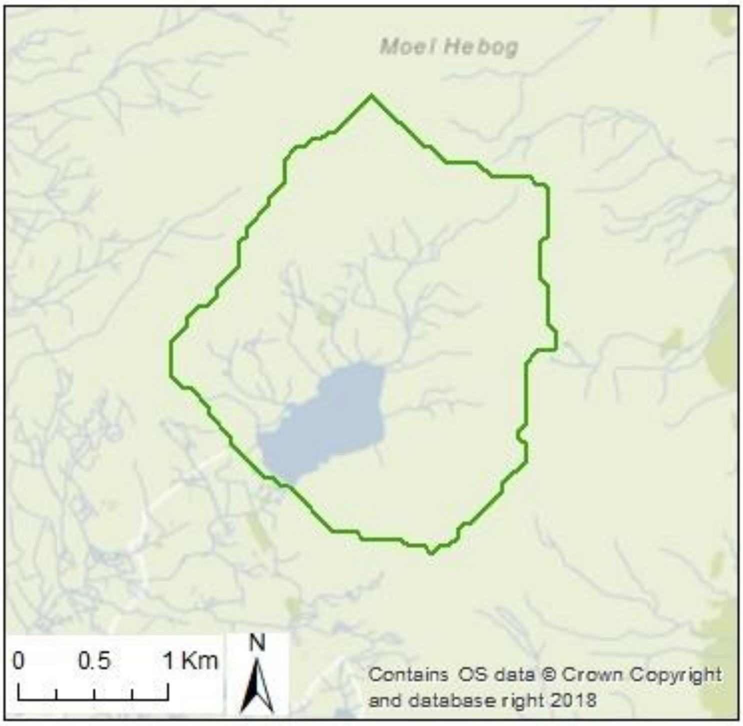

Figure 4.13 - Cwmystradllyn reservoir and catchment location

Table 4.3 outlines the key hydrological catchment characteristics extracted from LFE.

Table 4.3 - LFE catchment characteristics of Llyn Cwmystradllyn catchment.

Catchment	Catchment area (km^2)	BFI HOST	Mean flow (m^3/s)	Q95 (m^3/s)
Llyn Cwmystradllyn	5.02	0.36	0.27	0.029

4.3.2. Model build

The latest calibration of the HYSIM model for the Cwmystradllyn catchment was performed by AFW (2017). AFW applied a scaling factor of 1.04 to precipitation, which is reassessed here. No observed inflow data were available for calibration, but a mass balance model has been used. As compensation, spill and abstracted flows were available, AFW (2017) generated an inflow timeseries (through back-calculation), which is reassessed here.

4.3.2.1. Precipitation, PET and naturalised flow data

We started by assessing the scaling factor of 1.04 used by AFW (2017) in the precipitation timeseries. We extracted the original precipitation timeseries from HYSIM (i.e. before any scaling factor has been applied), which was originally derived by HR Wallingford using Met Office 5 km x 5 km gridded data, and compared it with (Figure 4.14):

- The mean annual precipitation from LFE; and
- The CEH-GEAR dataset (Tanguy et al., 2016).

The mean annual precipitation calculated based on CEH-GEAR data (2030 mm, based on data between 1960 and 2015) is closer to the value provided by LFE (2017 mm), than the value calculated based on the timeseries used by AFW (2017) (2294 mm for 1960-2015, before any scaling). The difference between the value provided by LFE and the timeseries used by AFW (2017) is further increased once the scaling factor of 1.04 is applied. As per Llyn Cwm Dulyn, the HYSIM timeseries is used here without any scaling factor.

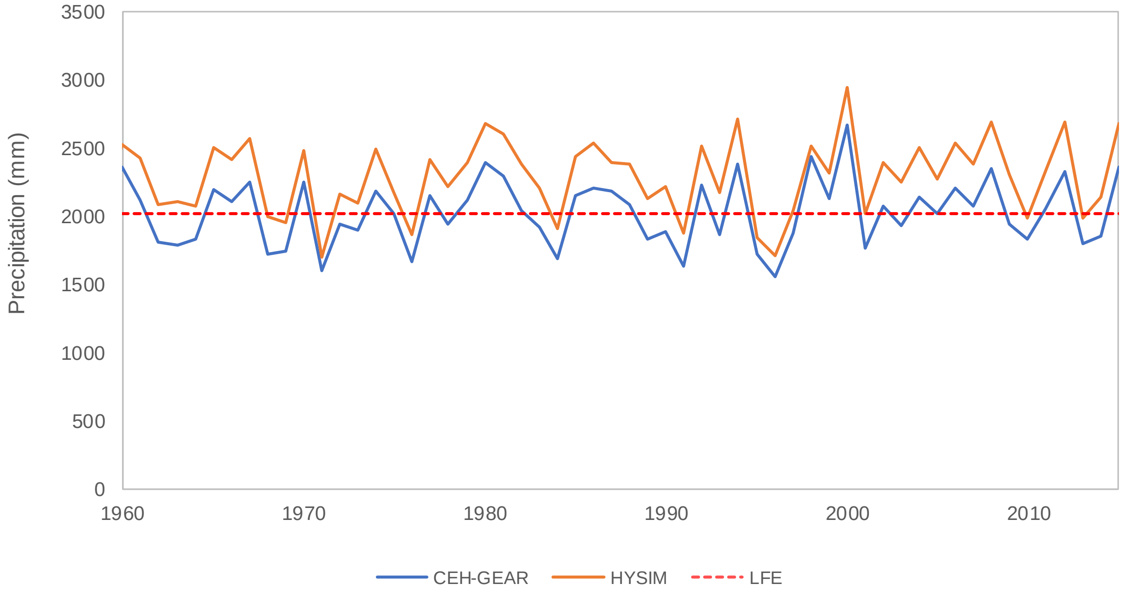

Figure 4.14 - Annual precipitation for the Cwmystradllyn catchment calculated based on: precipitation extracted from HYSIM, CEH-GEAR dataset and LFE

AFW (2017) derived PET using HYSIM (for latitude = 3450.44; longitude = 2565.02[6]; mean elevation = 340m AOD), which is used here.

We also extracted the daily streamflow timeseries used to calibrate HYSIM (back-calculated from the mass balance model).

The annual values of precipitation, PET and streamflow, as extracted from HYSIM are shown in Figure 4.15. For years such as 1988 and 2005 the annual streamflow shown in Figure 4.15 is too low, but that is to be expected as for those years there are 315 and 109 days with missing data, respectively (the annual streamflow was calculated by accumulating daily flows, and assuming that flow was equal to 0 when data were missing). However, for the years 1997, 1998, 1999 and 2000 (red boxes in Figure 4.15), with nearly no missing data, the annual streamflow is unrealistically high (note that for those years the annual streamflow is almost always greater than the annual precipitation). There must be a problem with the data used, as the water mass balance does not close for those years. For the remaining years, it is difficult to assess the quality of the data due to the large number of days with missing data.

[6] The ‘latitude’ and ‘longitude are not true latitude and longitude but correspond to National Grid References divided by 100m. However, in HYSIM they are labelled as ‘latitude’ and ‘longitude’.

Figure 4.15 - Annual values calculated based on data extracted from HYSIM files. The numbers in the plot represent the number of days with missing flow data in each year when calculating the flow annual value. For days with missing data, the flow was assumed to be equal to zero, when calculating the annual value.

To further assess the quality of the naturalised flow extracted from HYSIM, we used it together with precipitation and PET, to calibrate Catchmod using data between November 1988 and November 2001 (with November 1988 - November 1989 used as warm up period). The resulting volumetric fit is shown in Figure 4.16. Up to the end of 1996 the calibration of Catchmod seems to give good results in terms of volumetric fit, as the accumulated simulated flow and the accumulated observed flow are very close (it is expected for the observed flow to be slightly lower than simulated, because there are 224 days with missing data between 11/11/1989 and 31/12/1996). However, from 1997 onwards, there is a change in trend of the observed data. This point in time is consistent with when we noticed problems with the water mass balance (Figure 4.15).

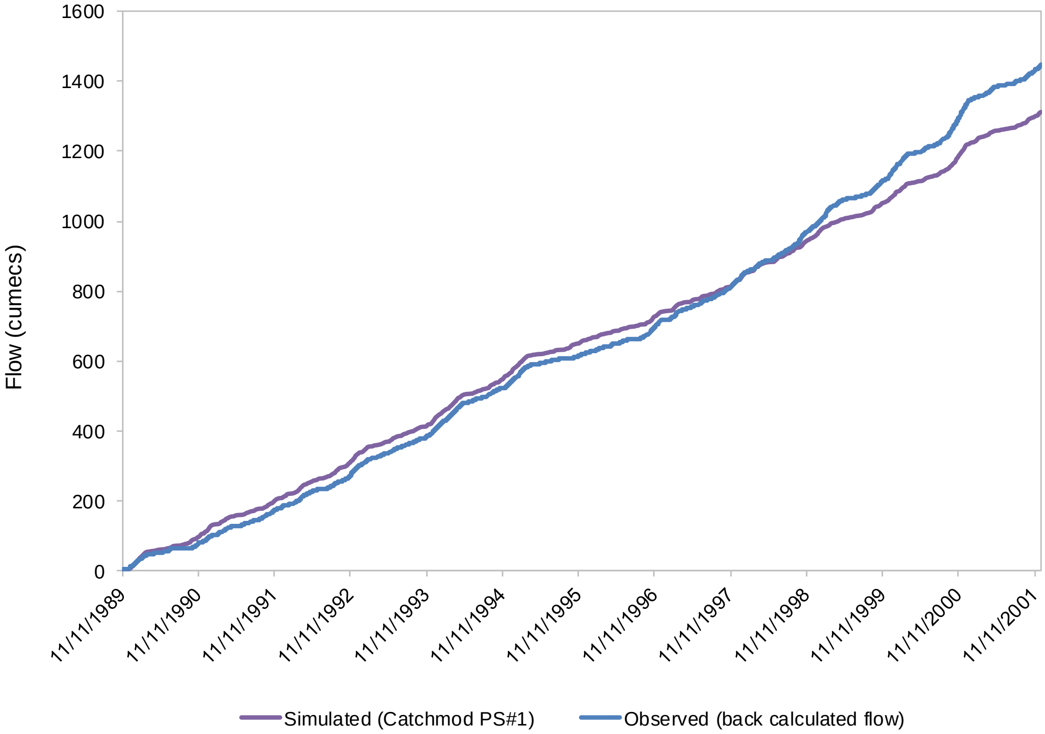

Figure 4.16 - Volumetric fit for Cwmystradllyn reservoir catchment

We calculated a FDC based on data for 11/11/1989 – 31/12/2001 and another FDC based on data for 11/11/1989 – 11/12/1996. Figure 4.17 shows the two resulting FDC, which do not overlap. Given that we are trying to simulate naturalised flow, this should not happen unless something would have changed in the system we are modelling. From Figure 4.17 it is also noticeable how different the curves are from the flow duration curve from LFE.

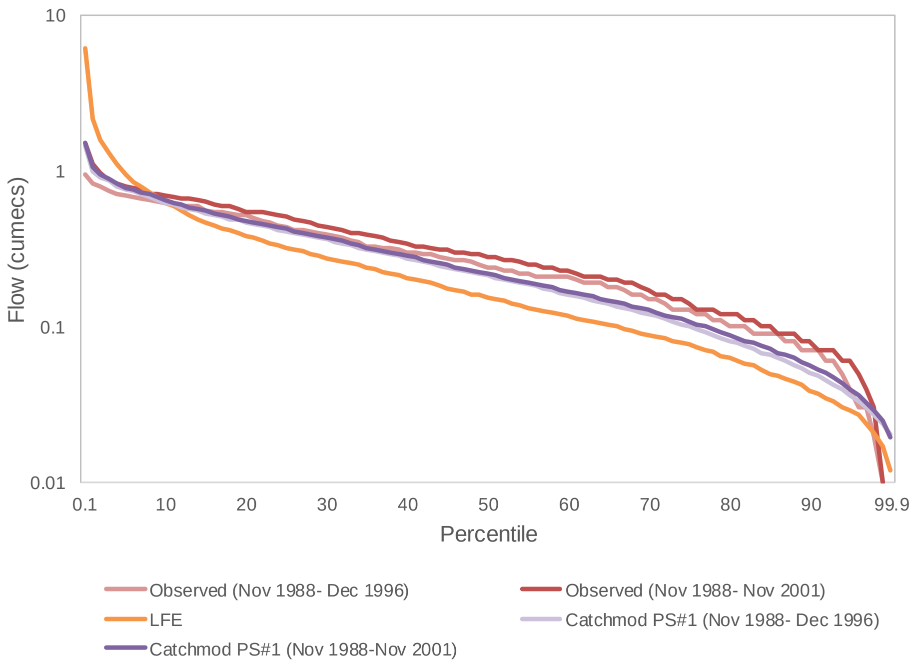

Figure 4.17 - Flow duration curves for Cwmystradllyn reservoir catchment based on observed and simulated streamflow

4.3.2.2. Reservoir mass balance model

Assuming that the data between 1998 and 1996 is of better quality, we have re-calibrated Catchmod, with the main objective being to match as well as possible the observed FDC estimated based on data for this time period. Figure 4.18 shows how well the new parameterisation of Catchmod (PS#2) matches the observed FDC.

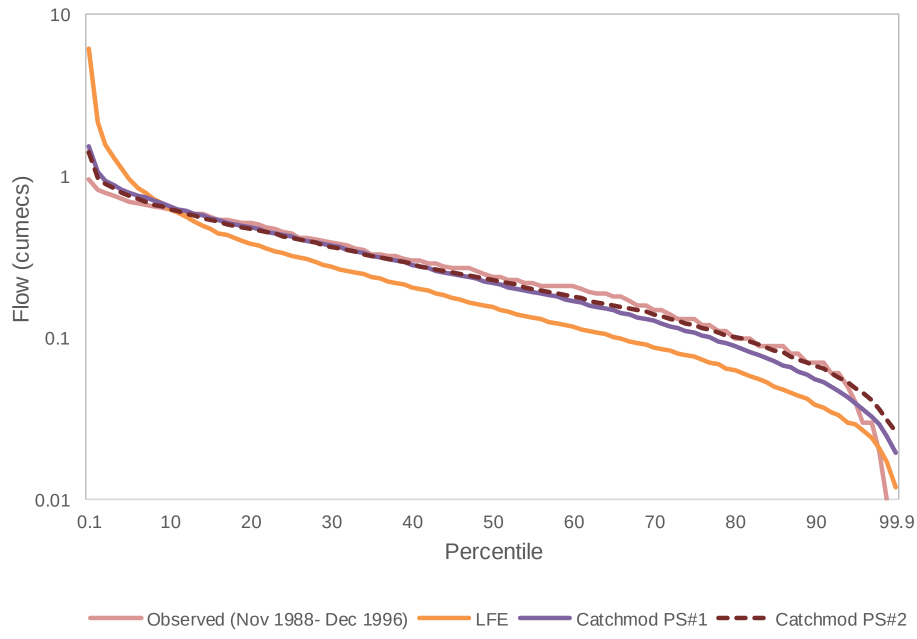

Figure 4.18 - Flow duration curves for Cwmystradllyn reservoir catchment based on observed and simulated streamflow

The Catchmod flow for both parameter sets (parameter sets #1 and #2) is shown in Figure 4.19 (time period consistent with that shown by AFW). Figure 4.20 shows the results of inputting the modelled flows into the AFW mass balance model. Note that the back calculated flows in Figure 4.19 were estimated based on observed abstractions, compensation and spill, while in Figure 4.20 abstraction and compensation flow rates in the mass balance model to 13 and 4 Ml/d respectively (AFW approach mirrored to allow comparison against the HYSIM calibration). The performance of the Catchmod model is of a similar standard to HYSIM. Whilst parameter set #2 provided a better fit to the LFE FDC, parameter set #1 was selected on the basis of slightly better fit to the mass balance calculated inflows and observed storage.

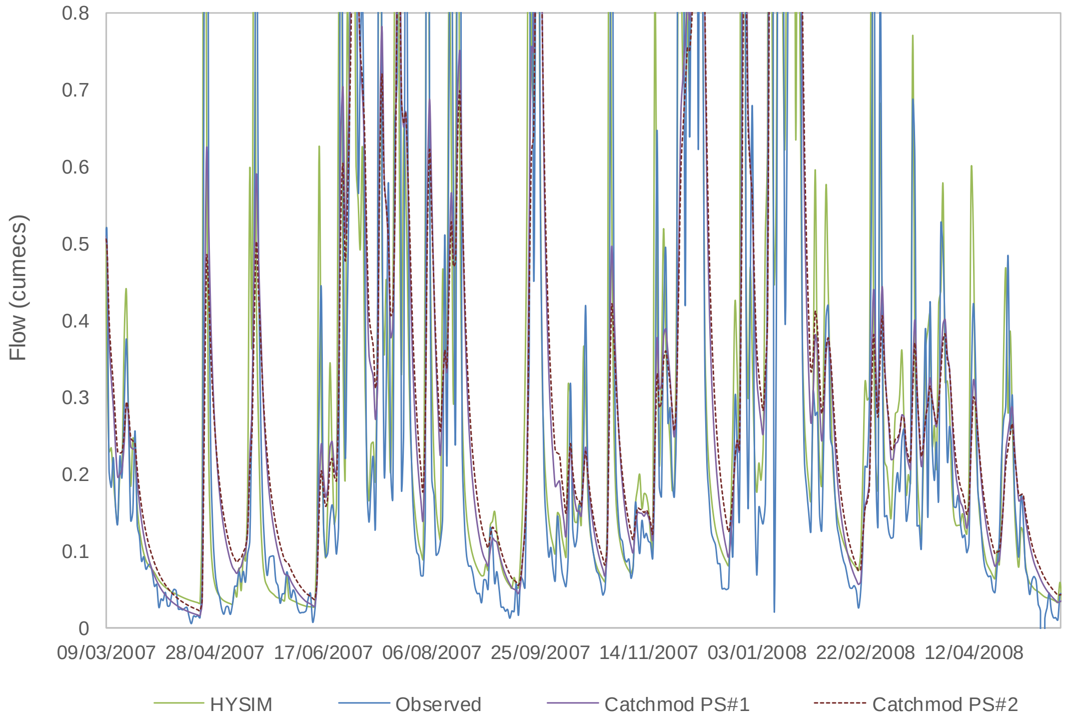

Figure 4.19 - Cwmystradllyn simulated and observed naturalised flows with focus on low flows

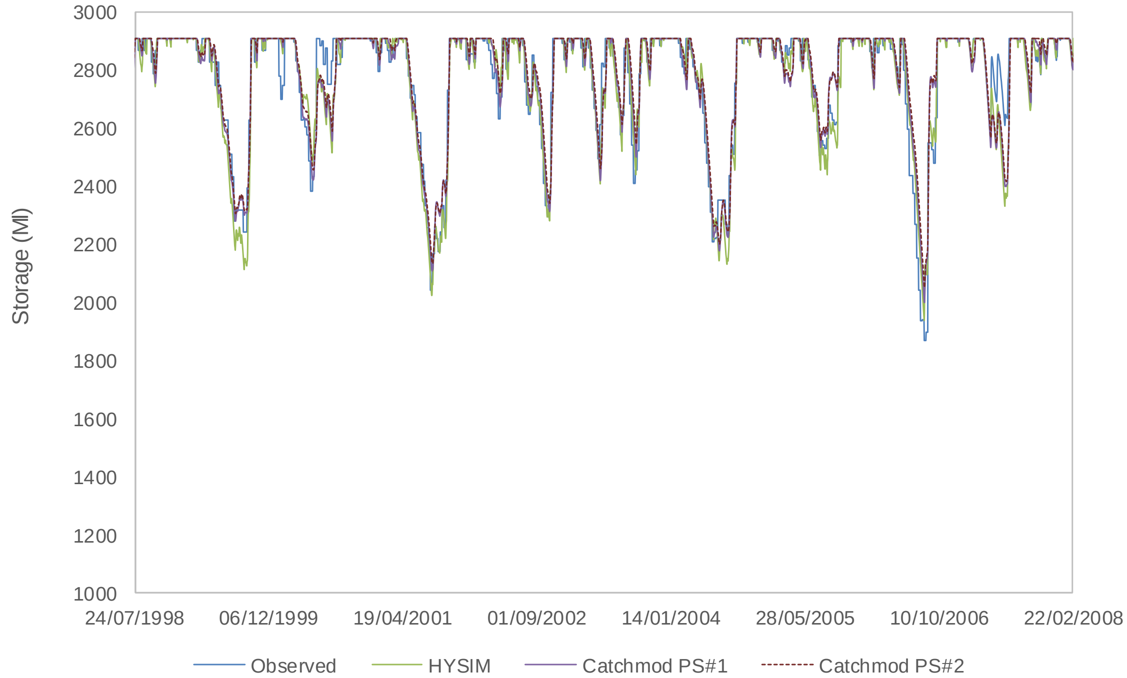

Figure 4.20 - Llyn Cwmystradllyn observed and modelled storages. As per AFW (2017), the modelled storages in this figure were calculated using fixed compensation and regulation amounts (abstraction rate =13 Ml/d and compensation release =4 Ml/d).

4.3.3. Conclusions

A new Catchmod model has been developed for Llyn Cwmystradllyn. The HYSIM precipitation and PET data were retained, and the model was calibrated along similar lines to the HYSIM one. In addition to the events that AFW presented in their report (2007-2008 for naturalised flow and 1998-2008 for storage) and FDC, we also incorporated volumetric fit into the calibration. Ultimately, we selected parameter set #1 (Appendix A.2) on the basis of slightly better fit to the mass balance calculated inflows and observed storage.

While the performance of each of the Catchmod and HYSIM models and parameter sets was relatively consistent across different drawdown periods, there were apparent issues with the data used in the calibration process, with the annual streamflow exceeding the annual precipitation for some of the years with observed data (1998-2001). This suggests that the modelled inflows could be further improved through further analysis of the existing data available for calibration. Unfortunately, this was not possible during the timescales available for this work.

4.4. Afon Dwyfor at Dolbenmaen

4.4.1. Introduction

The Garndolbenmaen gauge on the Afon Dwyfor drains a catchment area of 51.6[7] km^2. The Dolbenmaen abstraction on the Dwyfor is located at SH505431 at 90m AOD (Amec, 2012) and drains a catchment area of 49.6 km^2 (as per shapefile provided by DCWW). Llyn Cwmystradllyn is within the catchment draining to the Afon Dwyfor abstraction point (Figure 4.21). Soil ranges from loamy permeable with wet peaty surface (predominant) to slowly permeable seasonally waterlogged fine silty and clayey soils (Amec, 2012).

Figure 4.21 - Afon Dwyfor at Garndolbenmaen catchment (gauging station catchment 65007), Afon Dwyfor at Dolbenmaen catchment (DCWW river intake catchment) and Llyn Cwmystradllyn catchment

Table 4.4 outlines the key hydrological catchment characteristics extracted from LFE. Based on the catchment area of the LFE file provided by DCWW, we assumed that this refers to Afon Dwyfor at Dolbenmaen.

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[7] Note that while in the National River Flow Archive (https://nrfa.ceh.ac.uk) it says the catchment area is 52.4 km^2 under station info, the shapefile provided there has an area of 51.6 km^2.

Table 4.4- LFE catchment characteristics of Afon Dwyfor at Dolbenmaen catchment

Catchment	Catchment area (km^2)	BFI HOST	Mean flow (m^3/s)	Q95 (m^3/s)
Afon Dwyfor at Dolbenmaen	49.88	0.40	2.534	0.217

4.4.2. Model build

The latest calibration of the HYSIM model for the Afon Dwyfor at Dolbenmaen catchment was performed by AFW (2017). AFW applied a scaling factor of 1.047 to precipitation, which is reassessed here. Naturalised flows were produced from flow observations at the gauging station at Garndolbenmaen (gauging station 65007) and recorded abstractions at Dolbenmaen. The resulting timeseries was used for calibration of HYSIM.

4.4.2.1. Precipitation, PET and naturalised flow data

We started by assessing the scaling factor of 1.047 used by AFW (2017) in the precipitation timeseries. We extracted the original precipitation timeseries from HYSIM (i.e. before any scaling factor has been applied), which was originally derived by HR Wallingford using Met Office 5 km x 5 km gridded data, and compared it with (Figure 4.22):

- The mean annual precipitation from LFE; and
- The CEH-GEAR dataset (Tanguy et al., 2016).

The mean annual precipitation calculated based on CEH-GEAR data (2026 mm, based on data between 1958 and 2015) is closer to the value provided by LFE (2037 mm), than the value calculated based on the timeseries used by AFW (2017) (2117 mm for 1958-2015, before any scaling). The difference between the value provided by LFE and the timeseries used by AFW (2017) is further increased once the scaling factor of 1.047 is applied. Therefore, the HYSIM precipitation timeseries without any scaling factor is again used here.

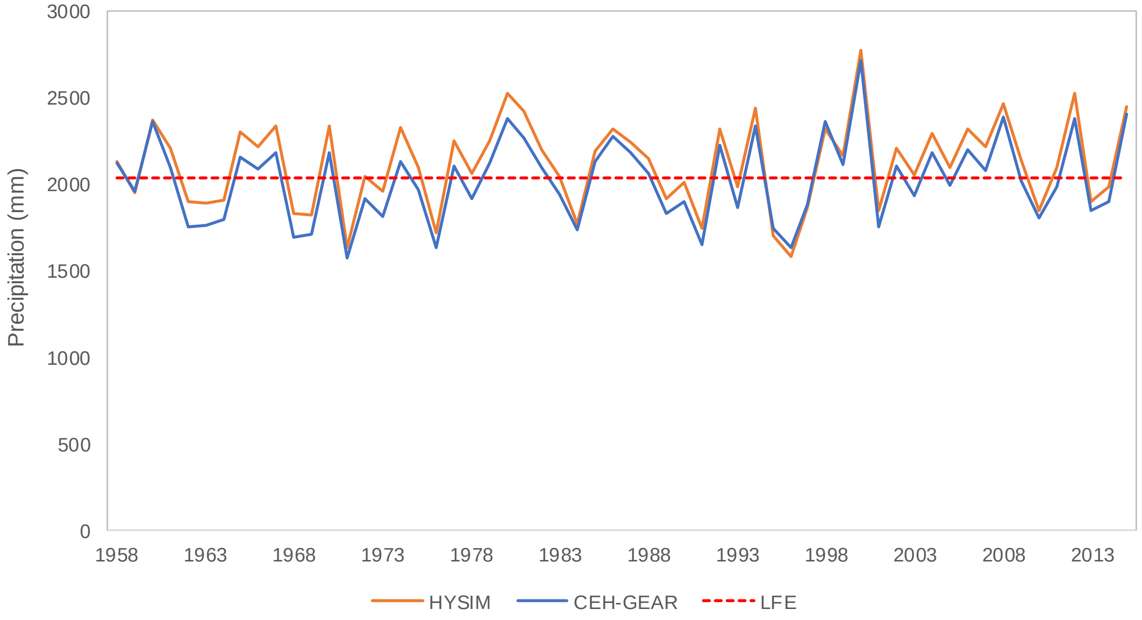

Figure 4.22 - Annual precipitation for the Afon Dwyfor at Dolbenmaen catchment calculated based on: precipitation extracted from HYSIM, CEH-GEAR dataset and LFE

AFW (2017) derived PET using HYSIM (for latitude = 3458.00; longitude = 2538.00[8]; mean elevation = 272m AOD), which is used here.

The naturalised flows derived by AFW (2017) were produced from flow observations at the gauging station at Garndolbenmaen (gauging station 65007) and recorded abstractions at Dolbenmaen. This timeseries refers to the downstream Garndolbenmaen gauging station, instead of Dolbenmaen. Therefore, we scaled down the flow timeseries based on the area difference between the two catchments, that is we multiplied the naturalised flow

[8] The ‘latitude’ and ‘longitude are not true latitude and longitude but correspond to National Grid References divided by 100m. However, in HYSIM they are labelled as ‘latitude’ and ‘longitude’.

timeseries by a scaling factor of 49.6/51.6 and used it to calibrate Catchmod (it is recommended that the hands off flow condition in the Aquator model is correspondingly scaled if it is applied at the intake location).

4.4.2.2. Model calibration

Catchmod was calibrated using the HYSIM precipitation and PET timeseries and the flow timeseries scaled by 49.6/51.6. A catchment area equal to 49.6 km^2 was used in the model, as per shapefile provided by DCWW.

Figure 4.23 shows the change in flows (as a FDC) between HYSIM and Catchmod calibrations, and how they compare with the observed FDC. HYSIM provides a better fit to high flows, but Catchmod provides a better fit to low flows (Figure 4.23, Figure 4.24). A good fit for low flows is particularly important here, as there is a hand off flow condition that restrains abstraction when water levels are low.

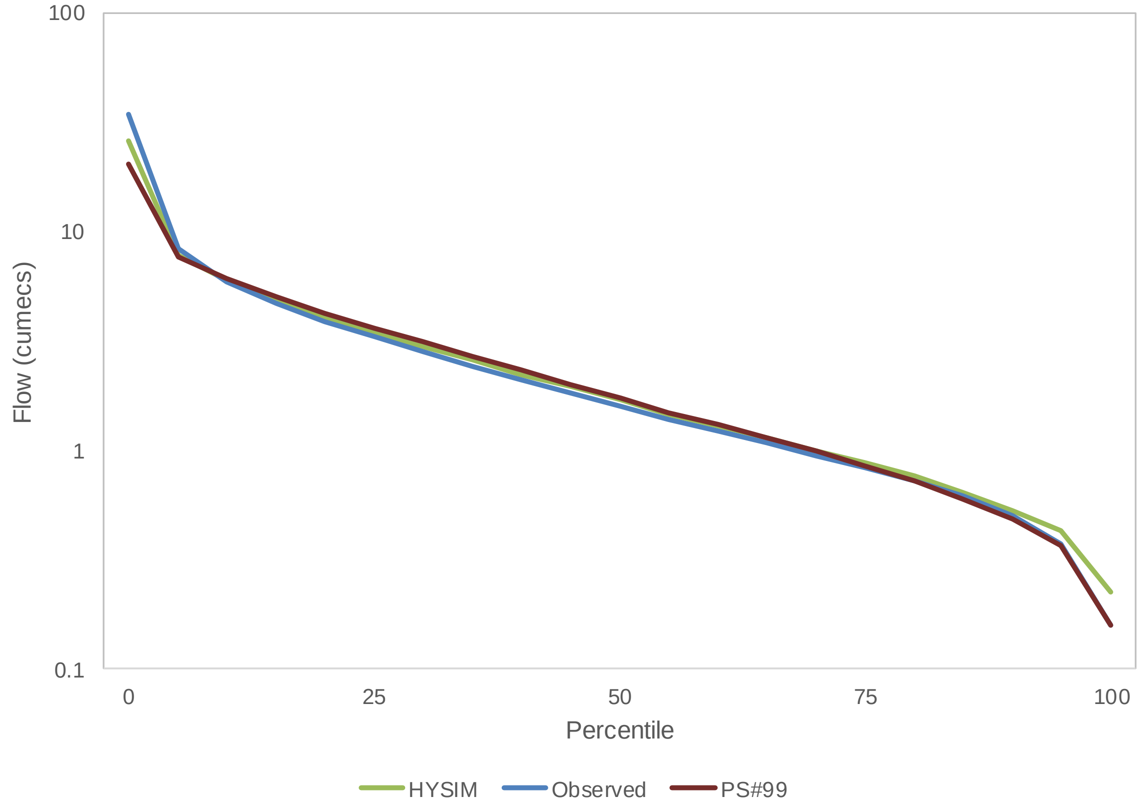

Figure 4.23 - Flow Duration Curves for Afon Dwyfor at Dolbenmaen

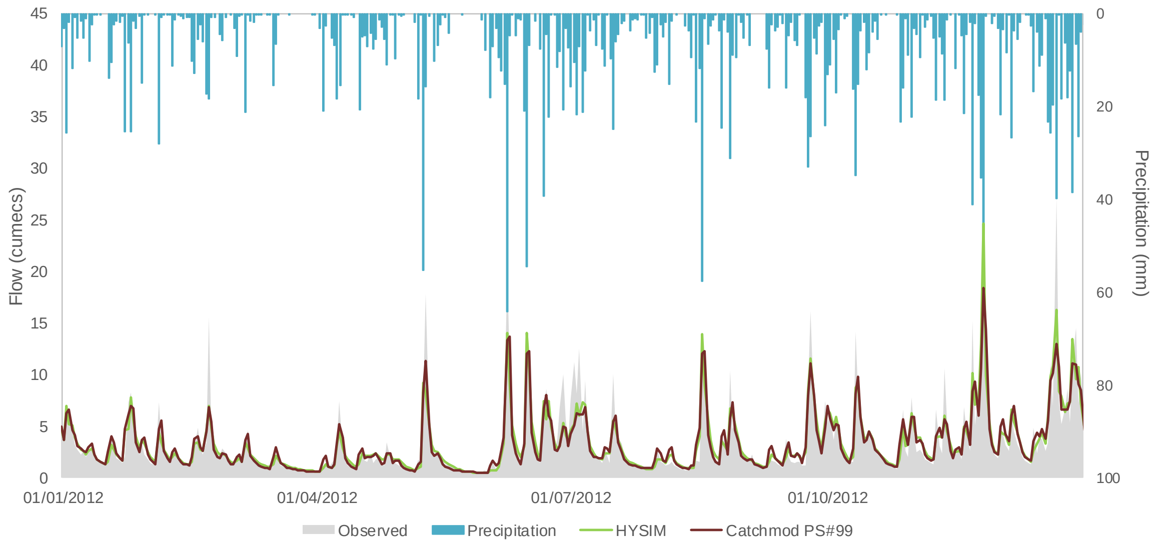

Figure 4.24 - Simulated and observed naturalised flows for Afon Dwyfor at Dolbenmaen

In terms of volumetric fit both models perform equally well (Figure 4.25).

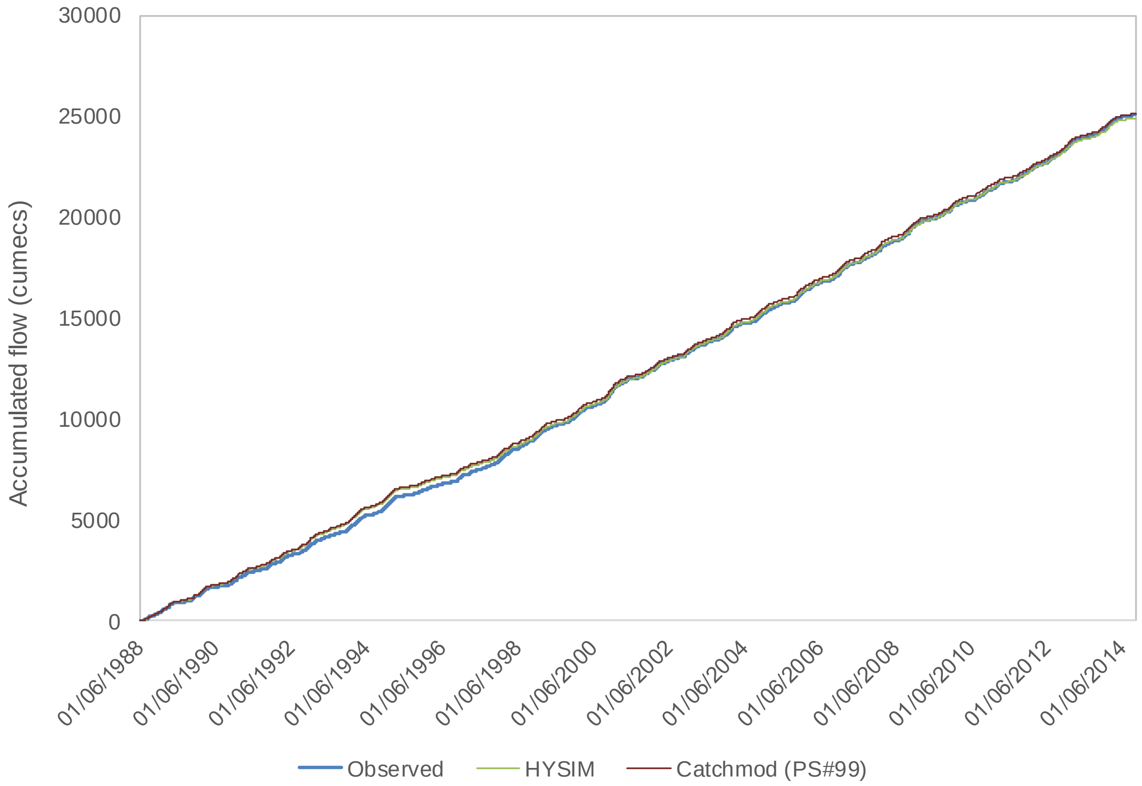

Figure 4.25 - Volumetric fit for Afon Dwyfor at Dolbenmaen

4.4.3. Conclusions

A new Catchmod model has been developed for Afon Dwyfor at Dolbenmaen (Appendix A.2). The HYSIM precipitation and PET data were retained, while the HYSIM flow timeseries was scaled down to reflect the difference in area of the catchment at Garndolbenmaen (where flow is measured at the gauging station) and at Dolbenmaen (where the abstraction is and where the calibration was performed). The performance of Catchmod is slightly better than HYSIM for low flows, but slightly worse for high flows. However, given the hands off flow condition, it is particularly important that the model performs well during times of low flows.

The Dolbenmaen abstraction is controlled by flow at Garndolbenmaen. To scale down the hands of flow condition in the Aquator model, it is necessary to multiply it by the scaling factor 49.6/51.6.

4.5. Llyn Tecwyn Uchaf

4.5.1. Introduction

Llyn Tecwyn Uchaf drains an area of 0.405 km^2 and the reservoir has a total storage capacity of 619 Ml and the abstraction licence authorises a take of 3.4 Ml/d (DCWW, 2015). The mean elevation of the catchment is 176 m AOD.

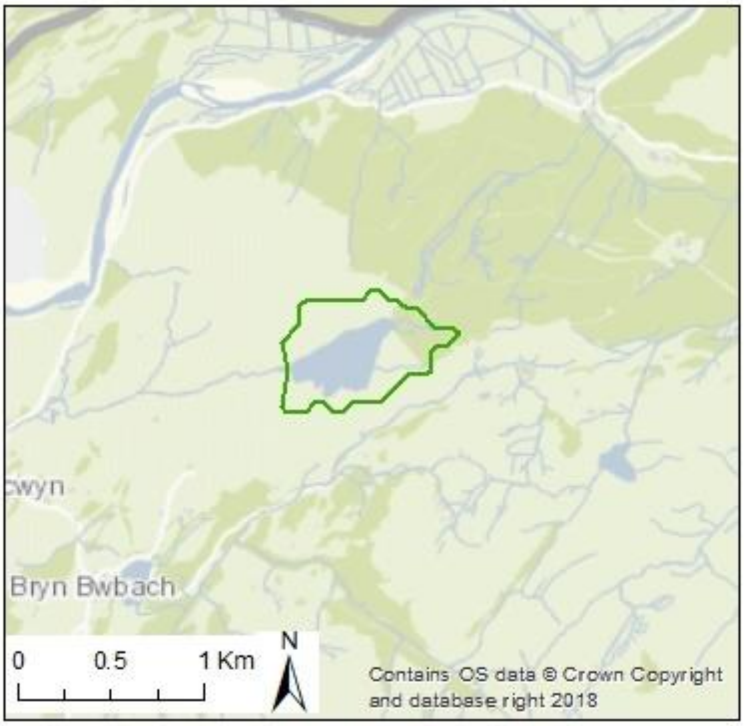

Figure 4.26 - Tecwyn Uchaf reservoir and catchment location

Table 4.5 outlines the key hydrological catchment characteristics (AFW, 2017).

Table 4.5 - Llyn Tecwyn Uchaf catchment characteristics as in AFW (2017)

Catchment	Catchment area (km^2)	BFI HOST	Mean flow (m^3/s)
Llyn Tecwyn Uchaf	0.405	0.574	0.014[1]

[1] Catchment too small to be calculated in LFE. Calculated using 'catchment losses method' provided by DCWW

4.5.2. Streamflow simulation

The latest calibration of inflows to Llyn Tecwyn Uchaf was performed by AFW (2017), by transposing from Bodlyn HYSIM model. No observed flow data were available for calibration, but a mass balance model based on observed storage, abstraction data and transfers from Tallin stream has been used. As spill from the reservoir is not recorded the mass balance model can only be used during drawdown periods. Reflecting the WRAPsim model configuration, the mass balance model storage capacity has been capped at 540 Ml to reflect leakage trough the dam in the top 0.5 m.

4.5.2.1. Mass balance model

Similar to AFW (2017), we transposed from Bodlyn, but using the results from Catchmod. The transposition factors were adjusted accordingly, and the total flows were calculated as:

$$Tecwyn\ Uchaf\ inflow\ =\ direct\ inflows + Tallin\ transfer \quad (2)$$

where

$$direct\ inflows\ =\ 0.062 \times Bodlyn\ flow$$

$$Tallin\ transfer\ =\ 0.077 \times Bodlyn\ flow\ up\ to\ a\ maximum\ of\ 4.5\ Ml/d$$

The AFW mass balance model includes transfers from the Tallin stream, as well as direct inflows. The reservoir storage calculated from the Catchmod flow and observed transfers is shown in Figure 4.27, where the time period shown being the one selected by AFW (2017). The performance of the Catchmod model is of a similar standard to HYSIM.

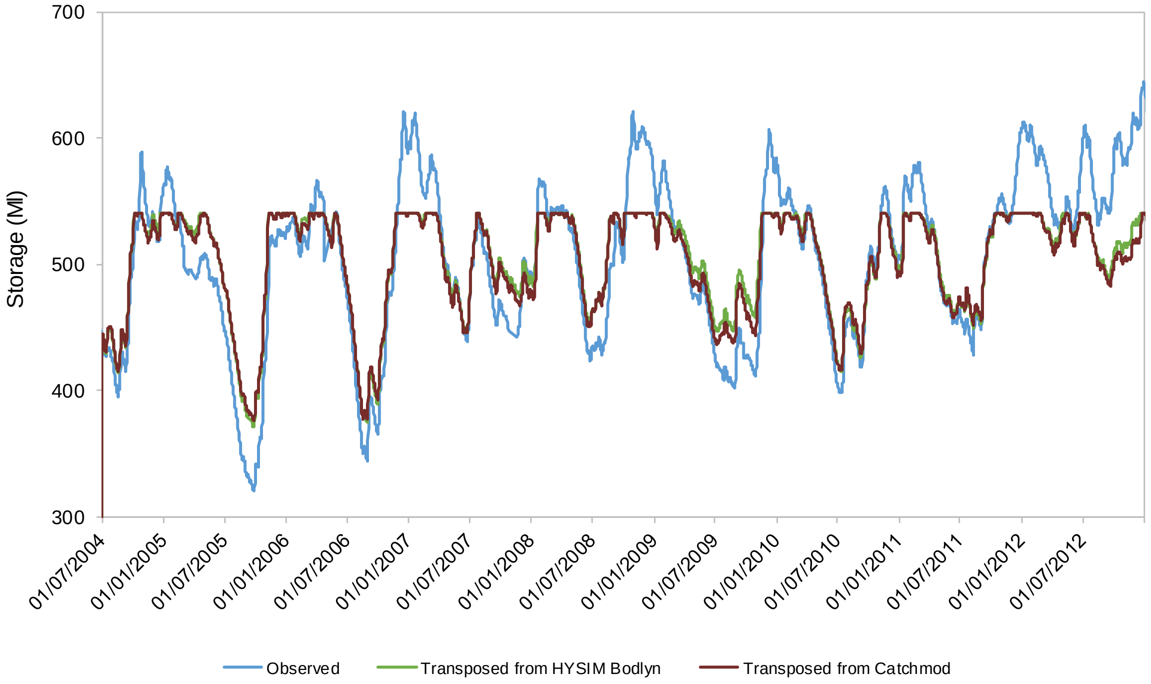

Figure 4.27 - Llyn Tecwyn Uchaf observed and simulated storages

4.5.3. Conclusions

The inflows for Llyn Tecwyn Uchaf were derived by transposing from Bodlyn. The performance of using Bodlyn Catchmod model to transpose is similar to using Bodlyn HYSIM model. With more time than was afforded by the Drought Vulnerability Framework programme it would have been possible to calibrate a Catchmod model directly to the observed storage rather than transposing flow from Bodlyn. Further review is recommended in the future.

4.6. Llyn Eiddew Mawr

4.6.1. Introduction

Llyn Eiddew Mawr drains an area of 1.939 km^2 and the lake has a total storage capacity of 213 Ml and the abstraction licence authorises a maximum of 2.27 Ml/d (DCWW, 2015). The mean elevation of the catchment is 455 m AOD.

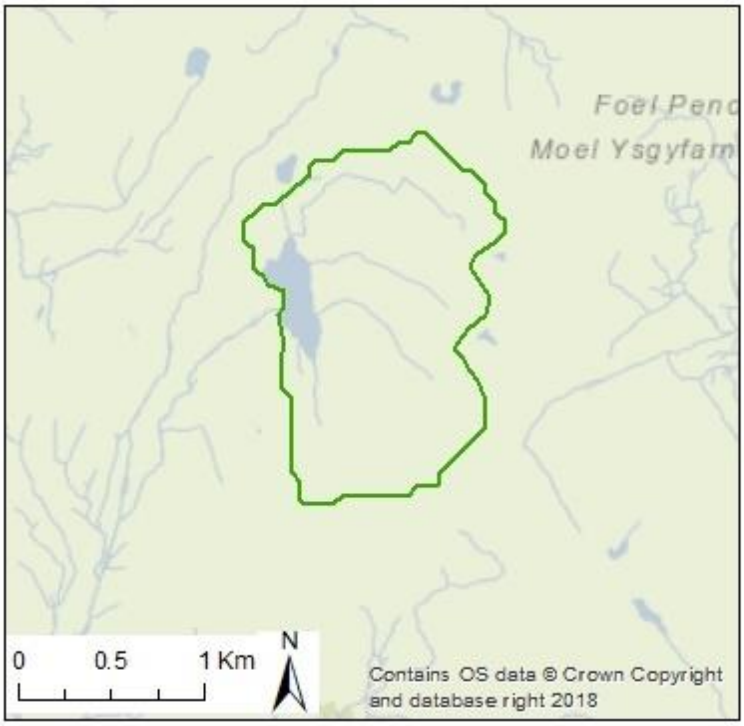

Figure 4.28 - Eiddew Mawr reservoir and catchment location

Table 4.6 - LFE catchment characteristics of Llyn Eiddew Mawr catchment

Catchment	Catchment area (km^2)	BFI HOST	Mean flow (m^3/s)	Q95 (m^3/s)
Llyn Eiddew Mawr	2.033 (Shapefile 1.939)	0.290	0.12	0.014

4.6.2. Streamflow simulation

The latest calibration of inflows to Llyn Eiddew Mawr was performed by AFW (2017), by transposing from Bodlyn HYSIM model. No observed flow data were available for calibration, but a mass balance model based on observed storage and abstraction data have been used. Spill and compensation flow were not measured. Compensation flow was assumed to be equal to 2.6 l/s, while noting that it is likely to be higher than that at times (AFW, 2017).

We started by updating the transposition factor. The ADF calculated based on the Catchmod simulated flow (parameter set #39) for Bodlyn for the period 2000-2015 was 0.227m^3/s, and the ADF provided by the LFE (after being adjusted to account for catchment area discrepancy between LFE and the shapefile provided by DCWW) was 0.114 m^3/s, leading to a transposition factor equal to 0.504.

Figure 4.29 shows the results of inputting the modelled flows into the AFW mass balance model. Even though Catchmod provides better results than HYSIM (Figure 4.30), the match to observed storage is clearly poor. As pointed out in AFW (2017) and also as highlighted by DCWW during the course of the project, the mass balance model is unable to replicate the observed patterns of drawdown. Possible reasons given include a broken crest (no proper spillway as it is a natural lake), inaccurate level measurements and different compensation flow from what was assumed (2.6 l/s).

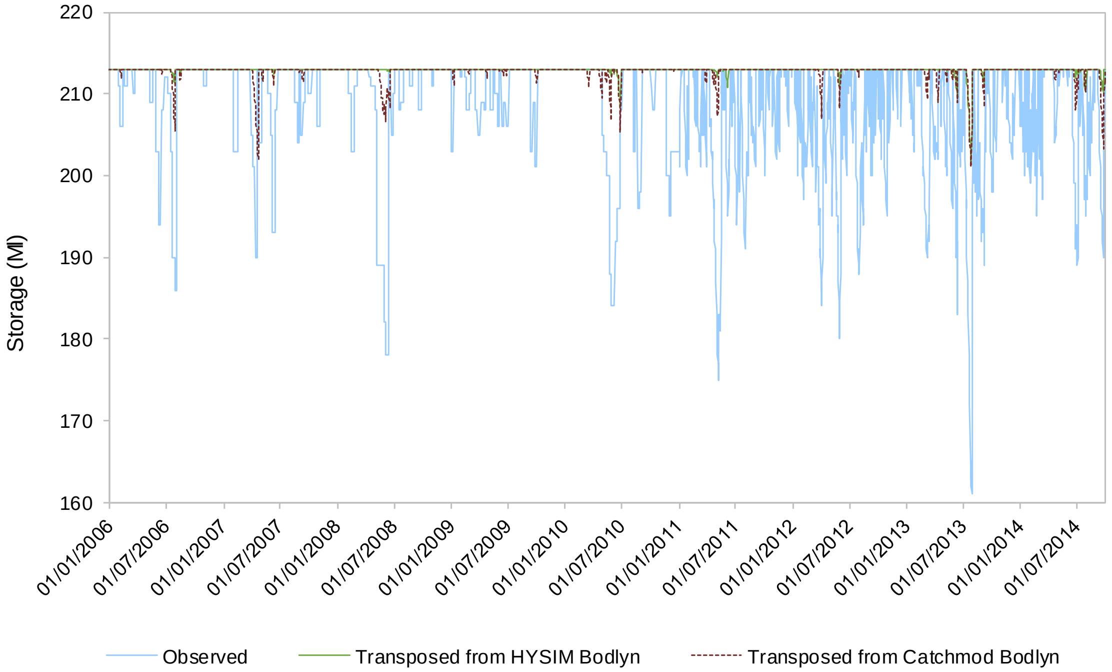

Figure 4.29 - Llyn Eiddew Mawr observed and simulated storages for 2006-2014

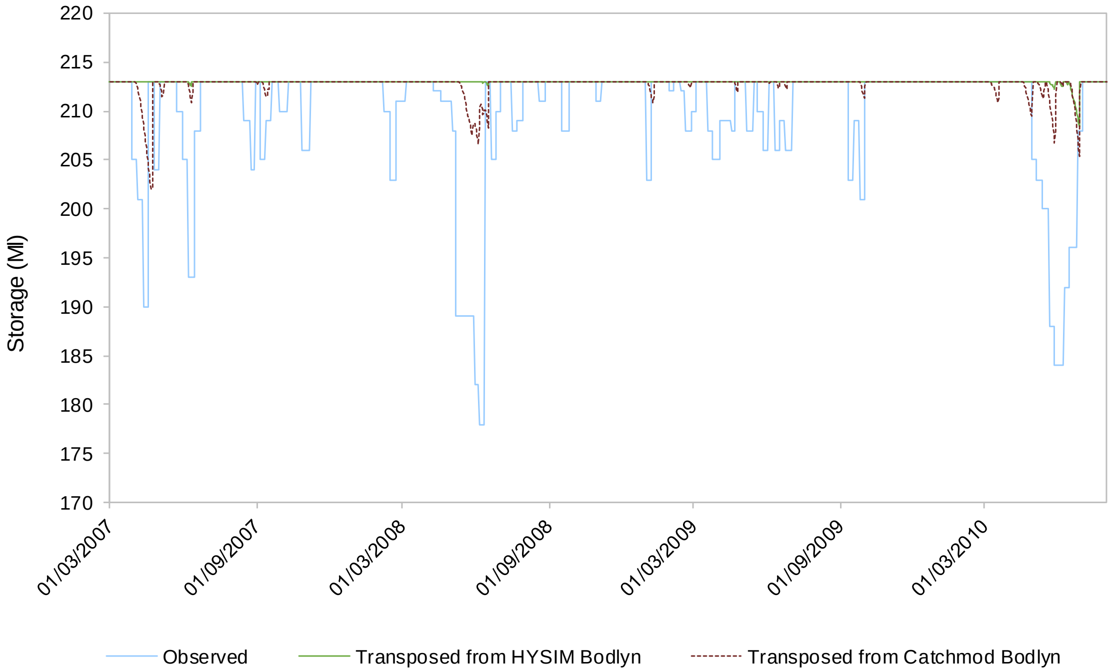

Figure 4.30 - Llyn Eiddew Mawr observed and simulated storages for 200-2010

4.6.3. Conclusions

The inflows for Llyn Eiddew Mawr were derived by transposing from Bodlyn. Whilst the match to observed storage records has been improved, the level of confidence in the mass balance model is low. Therefore, further review is recommended; unfortunately, this was not possible during the timescales available for this work.

5. Mid and South Ceredigion

5.1. Overview of the zone

The Mid and South Ceredigion WRZ includes two inflows:

- The Teifi Pools reservoir group, which includes Llyn Teifi, Llyn Egnant and Pond y Gwaith;
- A river abstraction on the River Teifi at Llechryd.

The catchment areas for these inflows are shown in blue and green in Figure 5.1. Two gauging stations exist along Afon Teifi, one at Glanteifi (station number 62001) close to Llechryd and another at Llanfair (station number 62002) further upstream. Other two gauging stations potentially relevant for modelling Teifi Pools, include Wyre at Llanrhystud (station number 63003) and Wye at Ddol Farm (station number 55026). The corresponding donor catchment areas are also shown in yellow in Figure 5.1.

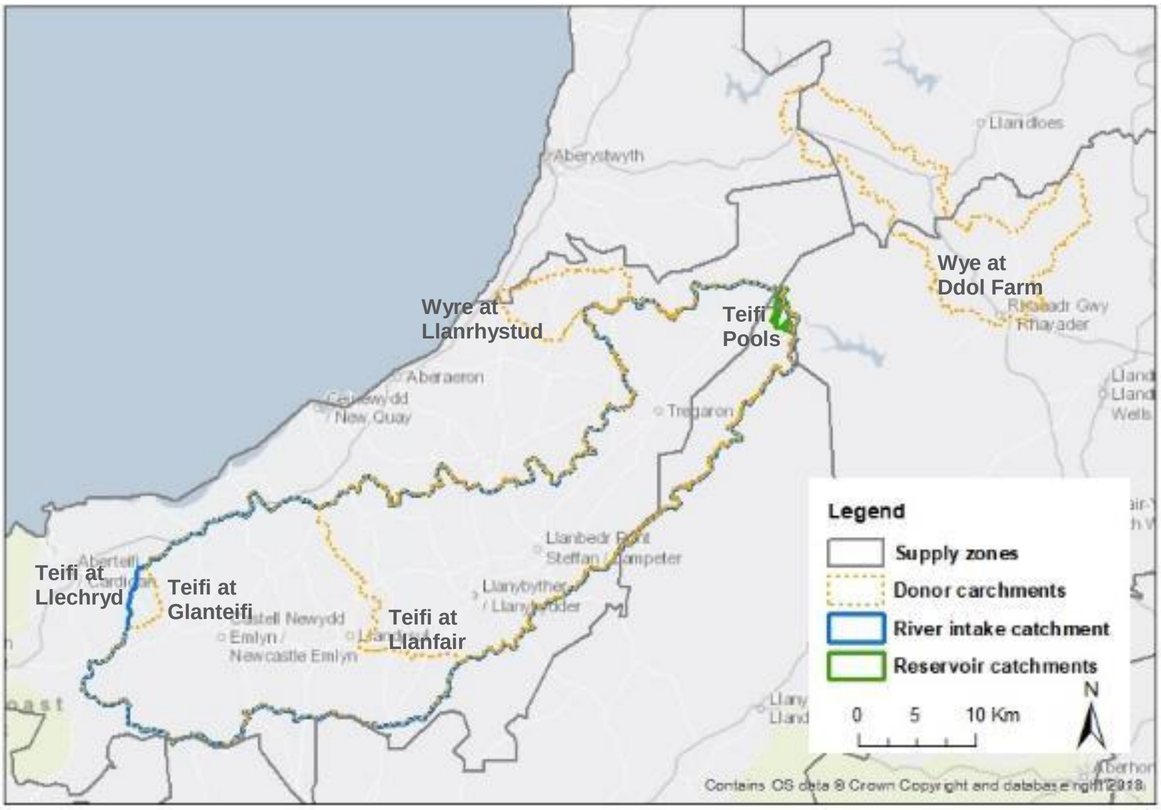

Figure 5.1 - Mid and South Ceredigion zone: catchment areas of inflows and donor catchments

Table 5.1 outlines the key hydrological characteristics of the catchments being modelled and catchments used as donors.

Table 5.1 - Flows investigated for transposition to Mid and South Ceredigion inflows

Gauge Name	Period of record	Percent complete	Catchment area (km^2)[1]	BFI HOST	ADF (m^3/s)[4]	Factors affecting runoff
Teifi Pools	-	-	1.27+1.72+1.09[2]	0.36[3]	0.045[3]	
Teifi at Llechryd	-	-	908.0[2]	0.51	29.24[5]	
Teifi at Glanteifi (62001)	1959 - present	99%	897.6	0.51	29.54	S: Reservoir(s) in catchment affect runoff. P: Runoff reduced by public water supply abstraction.

Teifi at Llanfair (62002)	1971 - present	58%	517.6	0.54	16.271	S: Reservoir(s) in catchment affect runoff. P: Runoff reduced by public water supply abstraction.
Wyre at Llanrhystud (63003)	1968 - present	58%	40.6	0.47	1.012	N: Natural to within 10% at the 95 percentile flow.
Wye at Ddol Farm (55026)	1937 - 2017	>99%	172.1	0.42	6.676	P: Runoff reduced by public water supply abstraction.

[1] Catchment areas for Teifi Pools and Afon Teifi at Llechryd are derived from the shapefiles provided by DCWW. For the remaining catchments, areas are derived from the shapefiles on the NRFA website.

[2] The LFE file provided by DCWW has an area of 1.03 km^2 for Teifi Pools and 908.3 km^2 for Afon Teifi at Llechryd.

[3] BFI HOST and ADF for Teifi Pools were extracted from the LFE file provided by DCWW. However, those values do not cover Teifi Pools as the catchment area in the LFE file is only 1.03 km^2.

[4] For the catchments with a gauge, ADF is calculated from the full gauged record, as per NRFA website. For Teifi Pools and for Teifi at Llechryd ADF comes from LFE.

[5] The LFE based ADF at Llechryd is slightly lower than the ADF based on gauged flow at upstream Glanteifi.

5.2. Afon Teifi at Llechryd

5.2.1. Introduction

The Glanteifi gauge on the Afon Teifi drains a catchment area of 897.6[9] km^2. The Llechryd abstraction on the Afon Teifi is located a short distance downstream of the gauge. Afon Teifi at Llechryd drains an area of 908.0 km^2, as per shapefile provided by DCWW. Teifi Pools are within the catchment draining to the Afon Teifi abstraction point (Figure 5.2).

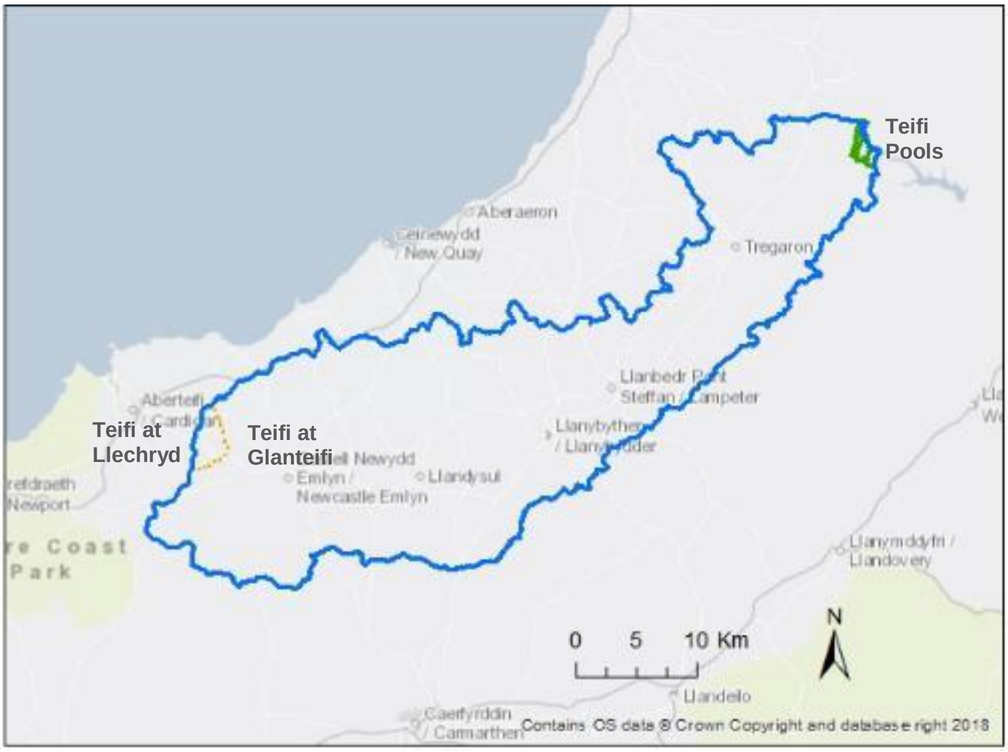

Figure 5.2 - Afon Teifi at Llechryd (DCWW river intake catchment), Afon Teifi at Glanteifi (gauging station catchment 62001) and Teifi Pools

Table 5.2 outlines the key hydrological catchment characteristics extracted from LFE.

[9] Note that while in the National River Flow Archive (https://nrfa.ceh.ac.uk) it says the catchment area is 893.6 km^2 under station info, the shapefile provided there has an area of 897.6 km^2

Table 5.2 - LFE catchment characteristics of Afon Teifi at Llechryd catchment

Catchment	Catchment area (km^2)	BFI HOST	Mean flow (m^3/s)	Q95 (m^3/s)
Afon Teifi at Llechryd	908.3	0.51	29.24	3.315

5.2.2. Model build

AFW (2017) scaled the flows by the area at Glanteifi (where a gauging station exists) to estimate flow at Llechryd. Flows at Glanteifi were previously infilled with Wye at Ddol Farm data (scaled by ADF) for periods with missing data (prior to 01/07/1959 and between 01/04/1970 and 30/09/1970). We evaluated whether better results could be achieved by transposing Catchmod calibrated parameters at Glanteifi to Llechryd.

Developing rainfall-runoff models will not only provide a better hydrological understanding of the Teifi catchment, but also will allow climate change precipitation and PET factors to be directly applied in the WRZ, thereby improving future climate change assessments. It also allows stochastic flows to be easily generated should the requirement arise (but note that drought vulnerability is presently assessed using Extreme Value Analysis of historic flows and storage levels).

5.2.2.1. Precipitation, PET and flow

The daily precipitation timeseries for Teifi at Glanteifi and for Teifi at Llechryd were derived from CEH-GEAR (Tanguy et al., 2016) for 1950-2015 (Figure 5.3). The timeseries result from the averaging of 1km x 1km grid cells. For PET, we used the CHESS-PE dataset (Robinson *et al.*, 2016), which is available from 1961 onwards.

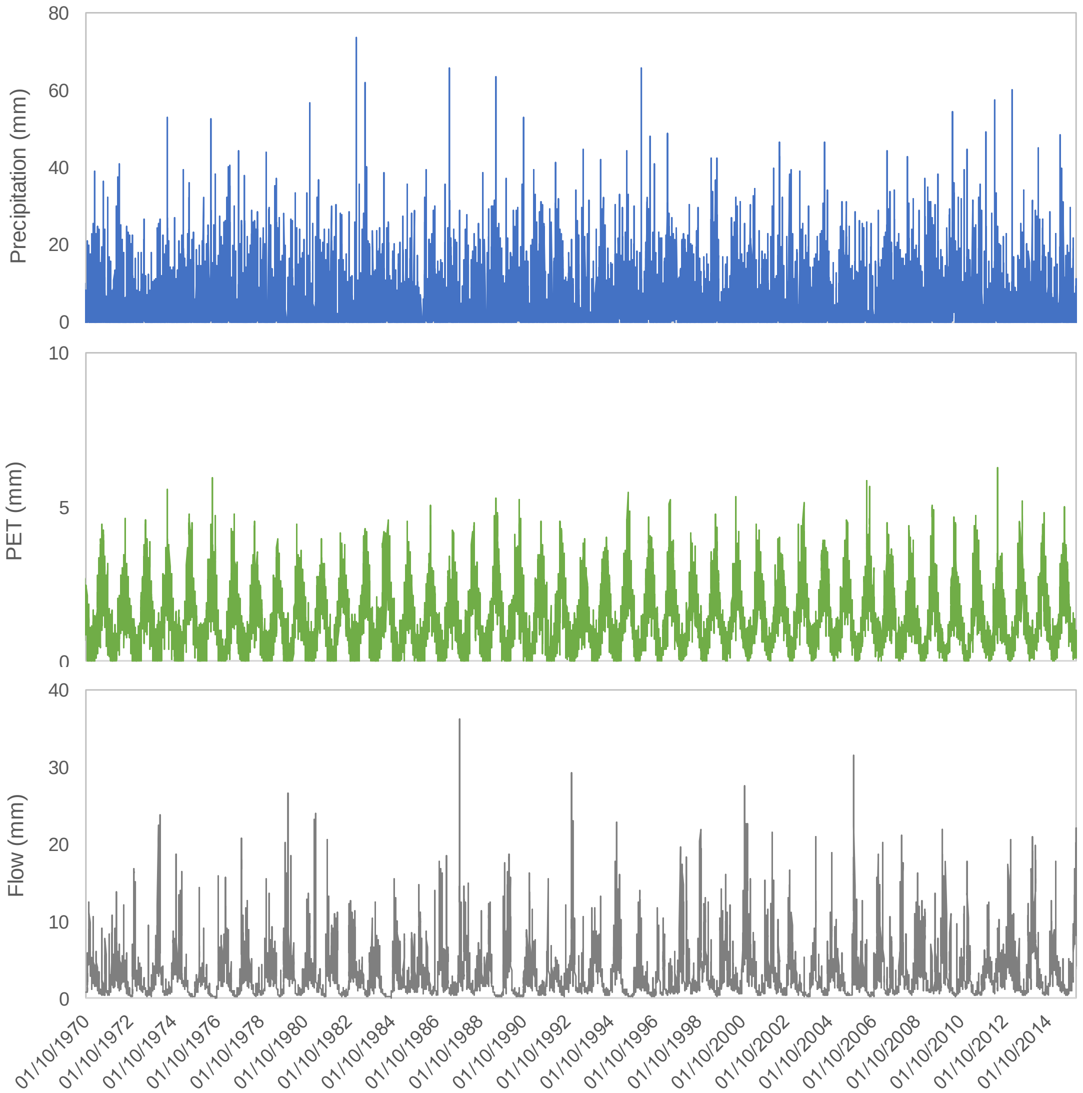

Figure 5.3 - Precipitation, PET and flow timeseries for Afon Teifi at Glanteifi for 01/10/1970 – 31/12/2015

The gauge at Glanteifi (station number 62001) started operating in 01/07/1959. The only period of missing data is between 01/04/1970 and 01/10/1970. AFW (2017) infilled this period and prior to 01/07/1959 with data from Wye at Ddol Farm (station 55026). In here, we chose not to infill the timeseries and instead calibrate Catchmod using data from 01/10/1970 onwards (Figure 5.3). 45 years of data is a long enough period to obtain a robust model calibration. This avoids transposing stream flow from a catchment that may not be that similar to Teifi at Glanteifi (for example, Teifi at Glanteifi BFI HOST is 0.51, while for Wye at Ddol Farm BFI HOST is 0.42, Table 5.1). Figure 5.4 shows for two distinct time periods how different flows transposed from Ddol Farm to Glanteifi (transposition factor based on ADF = 29.54/6.676 = 4.43) can be from observed flows at Glanteifi.

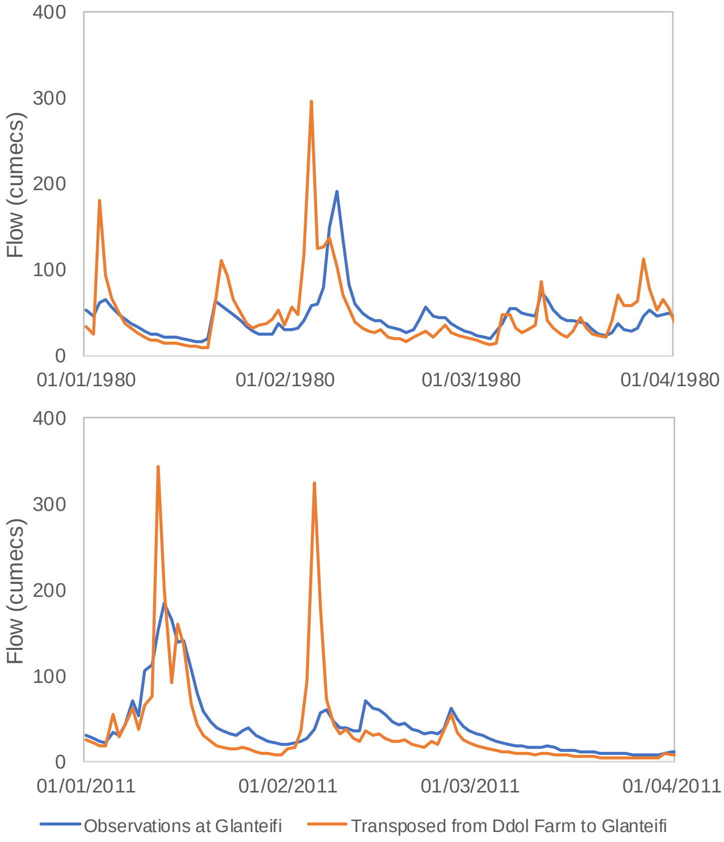

Figure 5.4 - Two distinct time periods showing how different transposed flows from Ddol Farm to Glanteifi (transposition factor based on ADF) are from observed flows at Glanteifi

5.2.2.2. Transposition from Teifi to Glanteifi

We have calibrated Catchmod for the period 01/10/1970 to 31/12/2015, using the first 365 days as a warm up period (Figure 5.5 and Figure 5.6). Teifi Pools, minor agricultural abstractions and Tregaron bog (10 km^2) have a partial effect on flows, but nonetheless this is a sensibly natural flow regime catchment.

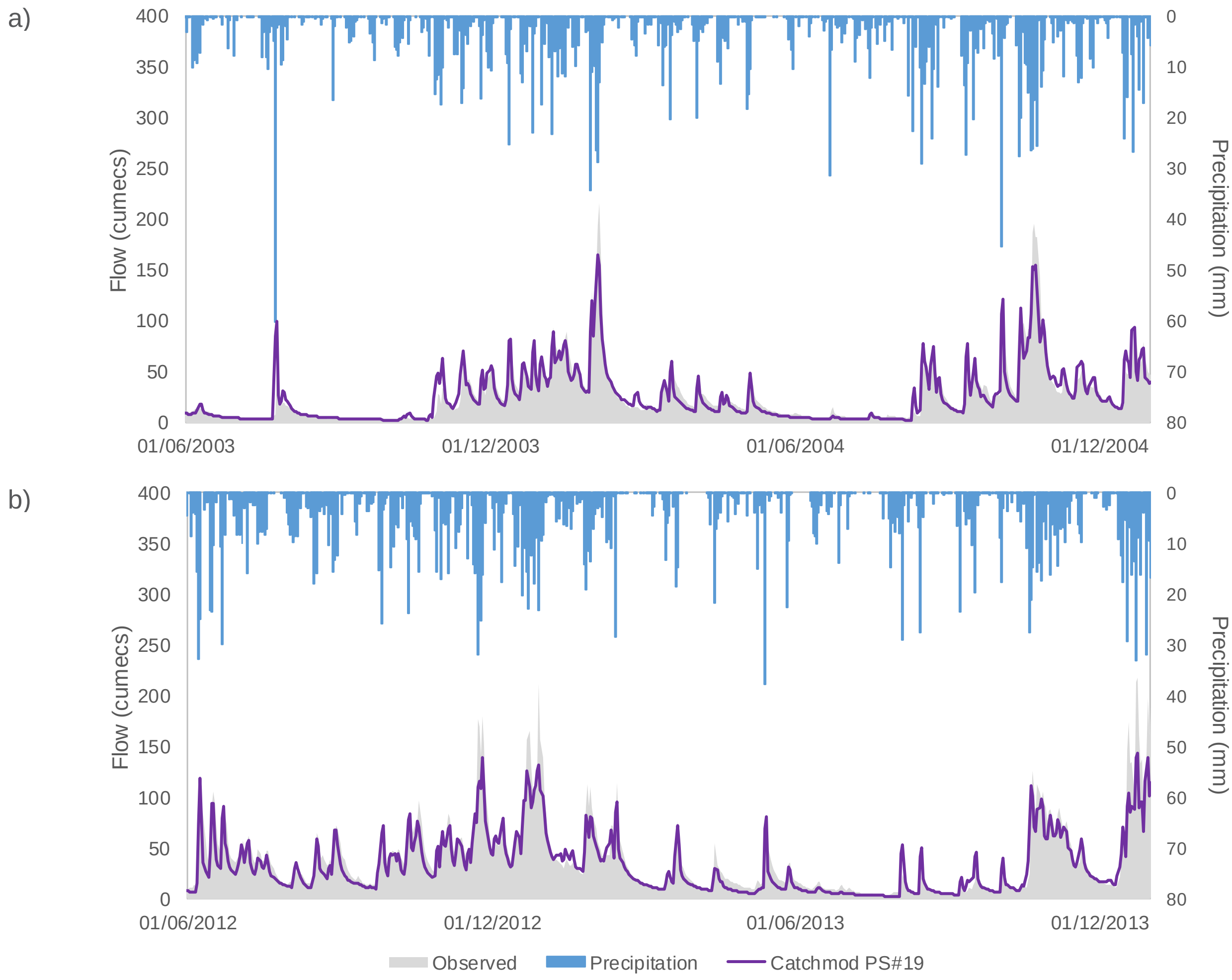

Figure 5.5 - Observed and simulated streamflow for Afon Teifi at Glanteifi for two time periods: a) June - December 2004; b) June - December 2013

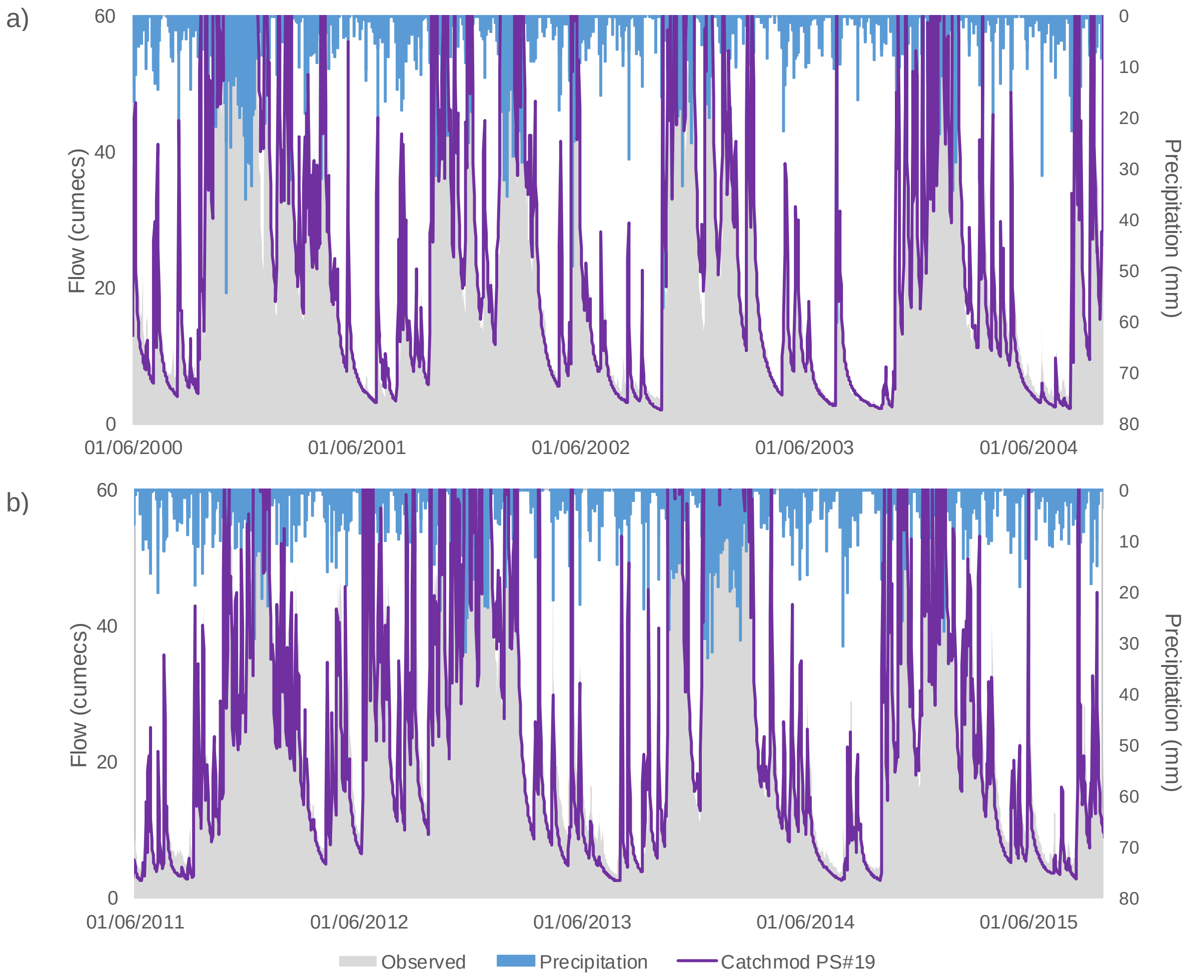

Figure 5.6 - Observed and simulated streamflow for Afon Teifi at Glanteifi with foccus on low flows for two time periods: a) June - December 2004; b) June 2012 - December 2013

Figure 5.7 shows the FDC for the observed and simulated streamflow and Figure 5.8 shows the volumetric fit. Both figures show good performance of Catchmod to simulate flow at Glanteifi.

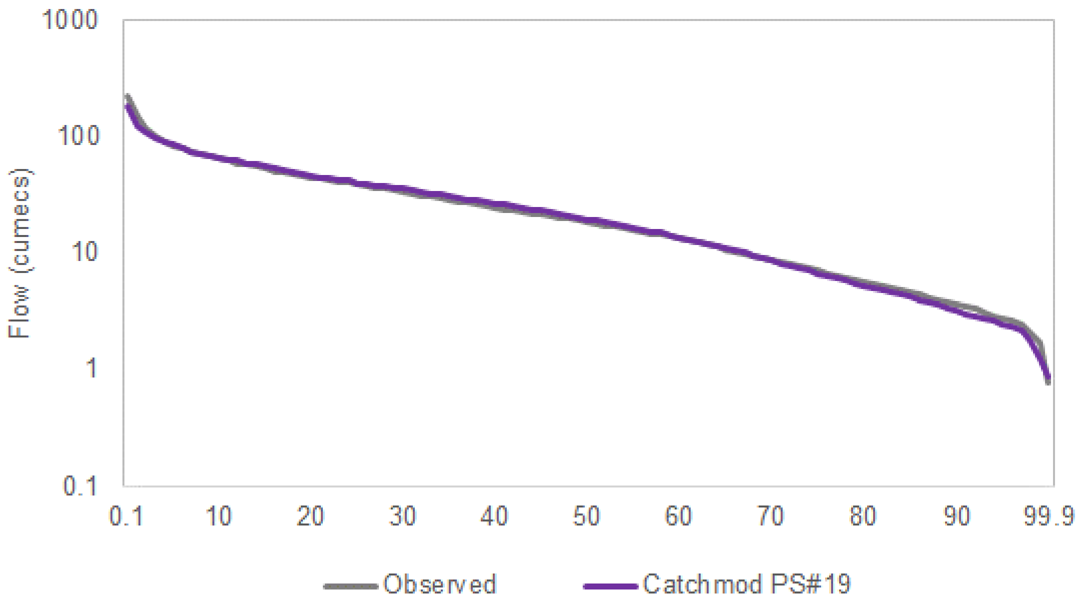

Figure 5.7 - Flow Duration Curves for observed flow and for the Catchmod calibration (for parameter set #19)

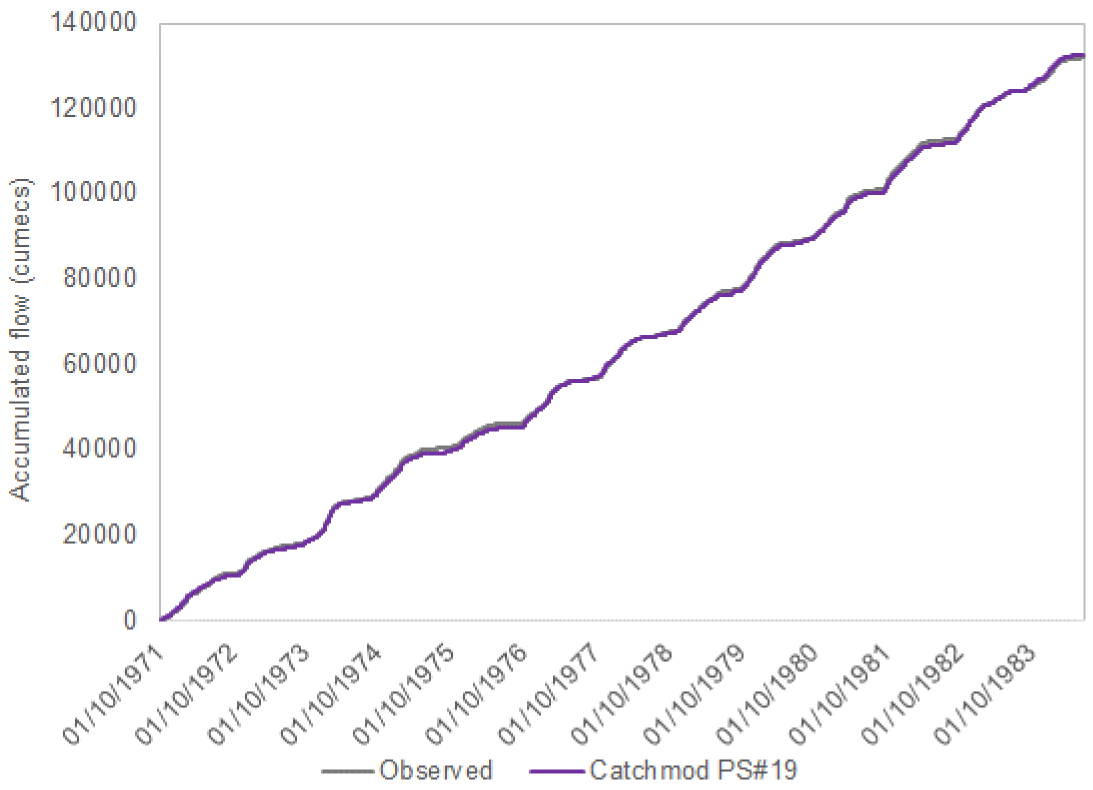

Figure 5.8 - Volumetric fit for Afon Teifi at Glanteifi

The parameter set obtained from the calibration of Catchmod at Glanteifi was then transposed to predict flow at Llechryd (Figure 5.9).

We also transposed observed flow at Glanteifi to Llechryd based on the area, as per the approach used by AFW (2017). For the period with missing data (April – September 1970) at Glanteifi, we infilled using: i) transposed observed flow at Wye at Ddol Farm (station 55026) based on ADF, as per AFW (2017); ii) transposed Catchmod from Glanteifi. Figure 5.9 shows that transposing based on observations at Ddol Farm gives very different results from transposing based on Catchmod.

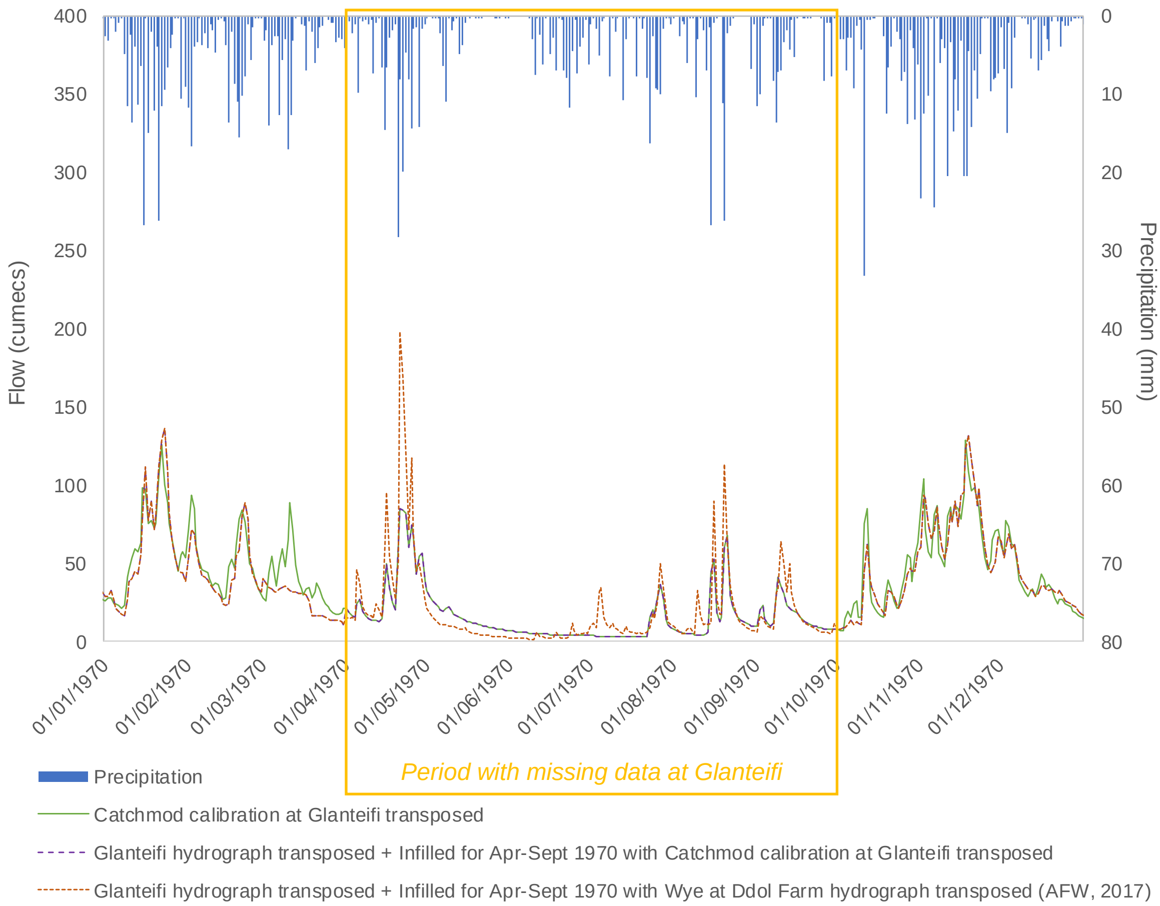

Figure 5.9 - Simulated flow at Llechryd by transposition of observed flow at Glanteifi and by transposing Catchmod calibrated at Glanteifi

While transposing observed flows at Glanteifi to estimate flow at Llechryd may give better results (as model uncertainty is not introduced in this process), when observations at Glanteifi are not available (01/04/1970-30/09/1970 and prior 1959) it is not possible to estimate flow at Llechryd. Wye at Ddol Farm may not be similar enough to Teifi to be used as a source of flows to transpose. In case of no observed data at Glanteifi, it may be more appropriate to infill using Catchmod transposed from Glanteifi.

5.2.3. Conclusions

A new Catchmod model has been developed for Afon Teifi at Llechryd. Precipitation was estimated based on CEH-GEAR dataset and PET based on CHESS-PE dataset. Catchmod was calibrated for Glanteifi and the best parameter set was transposed to Afon Teifi at Llechryd to simulate streamflow.

We recommend that modelled inflows for Afon Teifi at Llechryd are still obtained by transposing observed flows at Glanteifi when available, as per AFW (2017). However, for periods with missing data at Glanteifi, the newly developed Catchmod for Afon Teifi at Llechryd (Appendix A.3, that results from transposing parameters from Afon Teifi at Glanteifi) should be used, to avoid transposition from a not necessarily similar catchment (i.e. Wye at Ddol Farm). The model should also be used for future climate change assessments and, if required, exploration of hydrological uncertainty using stochastic datasets.

5.3. Teifi Pools

5.3.1. Introduction

The Teifi Pools reservoir group includes Llyn Teifi, Llyn Egnant and Pond y Gwaith (Figure 5.10). Abstractions are made from Llyn Teifi and Llyn Egnant. No abstractions are made directly from Pond y Gwaith, but water is transferred by gravity-fed pipe in to Llyn Teifi (AFW, 2017).

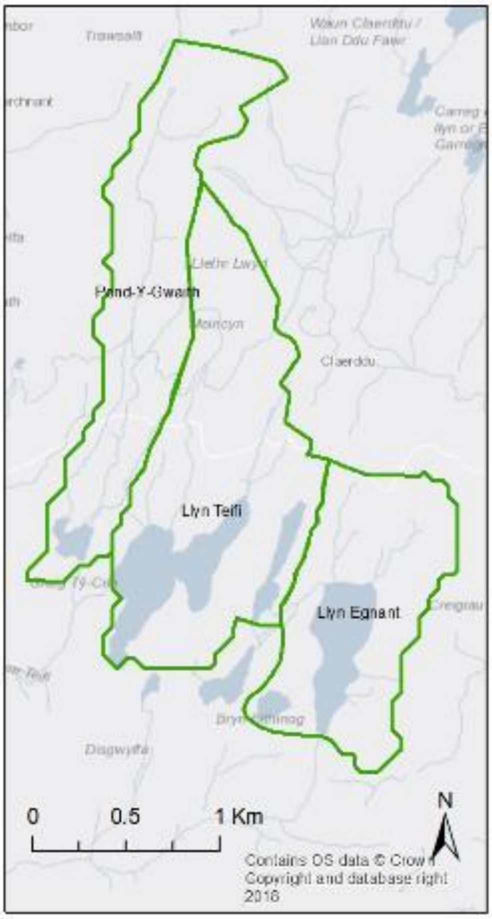

Figure 5.10 - Teifi Pools reservoir group: Llyn Teifi, Llyn Egnant and Pond y Gwaith

5.3.2. Model build

AFW (2017) developed a mass balance model for Teifi Pools. The model did not use the catchment area for all three reservoirs together, due to the lack of data for Pond y Gwaith. Instead only Llyn Teifi and Llyn Egnant were modelled, and a constant transfer rate of 3.11 Ml/d was assumed for the transfer from Pond y Gwaith to Llyn Teifi.

AFW (2017) scaled the flows by the ADF at Glanteifi (where a gauging station exists) to estimate flow at Teifi Pools. Other catchments were tested in AFW (2017) to be used as potential donors, namely Cothi at Felin Mynachdy, Wye at Ddol Farm, Ystwyth at Pont Llolwyn and Wyre Llanrhystud (this one also suggested by Thomas Elmitt, DCWW, pers comm). The fit of modelled to observed storage was reasonable, although the calculated performance metrics were relatively poor (AFW, 2017). AFW selected Glanteifi to be used as the donor for consistency with Afon Teifi Llechryd and because the fit of modelled data using Glanteifi was not worse than using any other tested donor catchment.

In an initial phase, we concluded that better results in terms of simulated storage could be obtained by calibrating Catchmod using the AFW mass balance model directly or by transposing parameters from Llanrhystud (Wyre) (see Appendix B for detailed results of the initial phase). However, it became clear that modelled inflows could be further improved through a better representation of the flow transferred from Pond y Gwaith, other than assuming a constant transfer of 3.11 Ml/d. Therefore, the project was extended to allow this work to be undertaken (Section 5.3.2.2).

5.3.2.1. Precipitation, PET and flow

The daily precipitation timeseries for Teifi Pools (Pond y Gwaith, Llyn Teifi and Llyn Egnant) and Wyre Llanrhystud were derived from CEH-GEAR (Tanguy et al., 2016) for 1950-2015. Figure 5.11 shows how the timeseries compare for the first six months of 2015 for the four catchments. The timeseries result from the averaging of 1km x 1km grid cells (Figure B.2). Given the small size and proximity of the catchments that comprise the Teifi Pools group, the differences between precipitation among these catchments are small, but differences can be seen between these and Wyre at Llanrhystud (Figure 5.11).

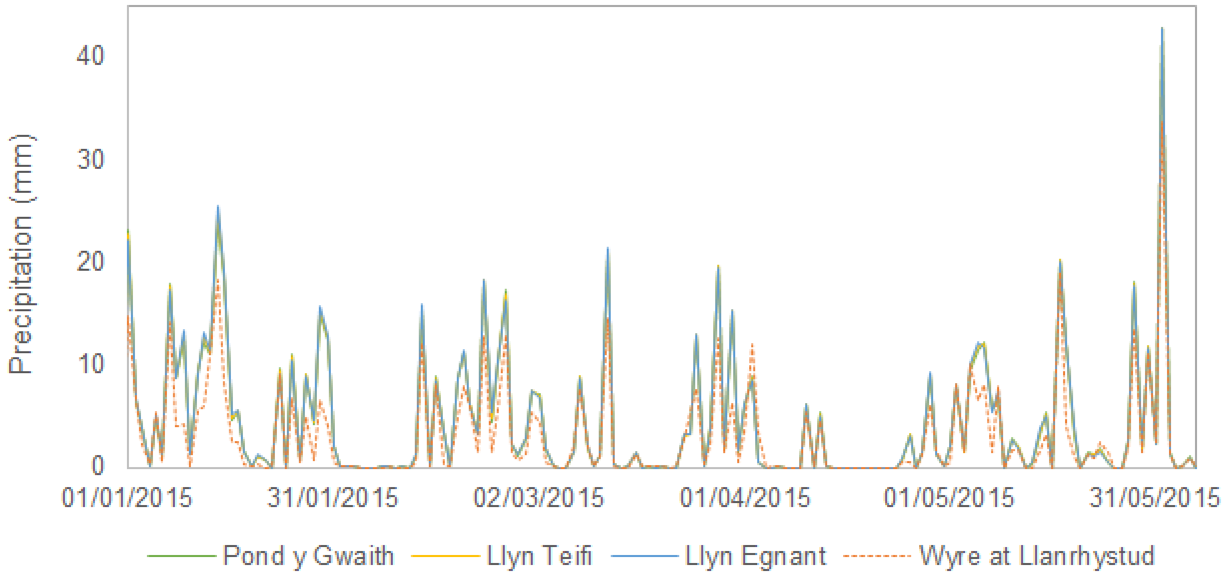

Figure 5.11 - Daily precipitation derived from CEH-GEAR for Teifi Pools and Wyre at Llanrhystud

In a similar way, we used the CHESS-PE dataset (Robinson *et al.*, 2016) to obtain daily PET timeseries (Figure 5.12). PET is only available from 1961 onwards.

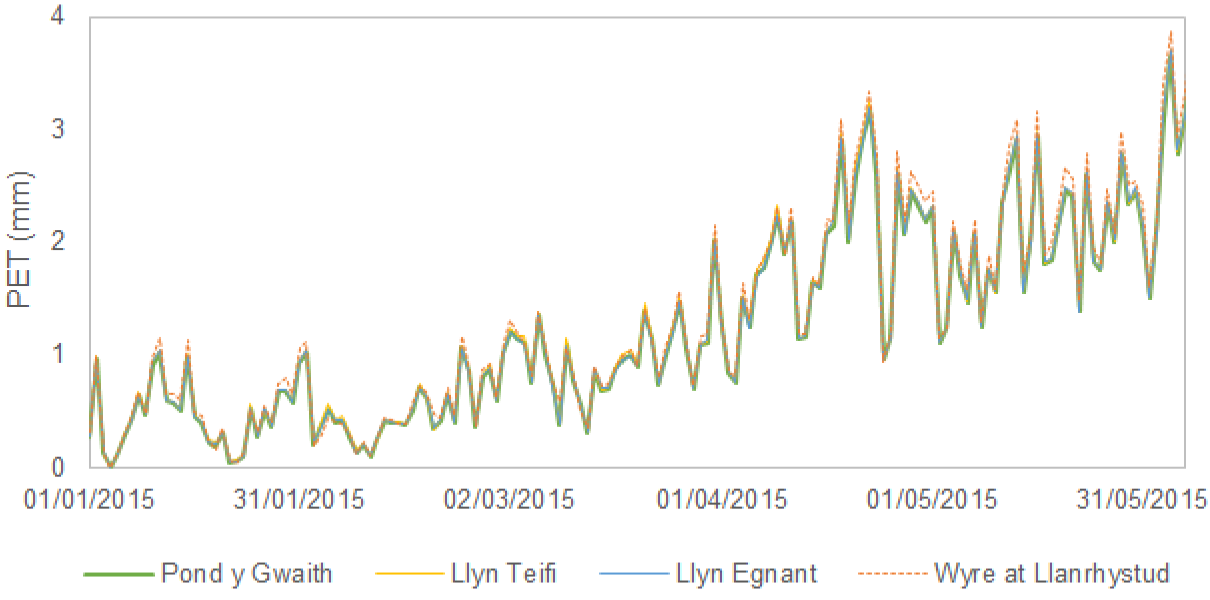

Figure 5.12 - Daily PET derived from CHESS-PE for Teifi Pools and Wyre at Llanrhystud

5.3.2.2. Streamflow simulation

We transposed the Catchmod parameters calibrated at Llanrhystud (Wyre) (Appendix B, Figure B.6 - Figure B.8) to Llyn Egnant to simulate flow. Additionally, we calibrated Catchmod at Llyn Egnant aiming at matching observed storage as well as possible, using a mass balance model. Observed storage and abstraction data (at strata inlet at WTW from Egnant) were available (storage from 09/2004 and abstraction from 01/2009), while compensation flows were only available for a very short period of time. For compensation flow it was assumed a constant value of 0.328 Ml/d corresponding to the mean of the available data. As spill from the reservoir is not recorded the mass balance model can only be used during drawdown periods. The resulting simulated storages are shown in Figure 5.13. Catchmod calibrated on the mass balance model gives better results in terms of modelled storage than Catchmod transposed from Llanrhystud (Wyre).

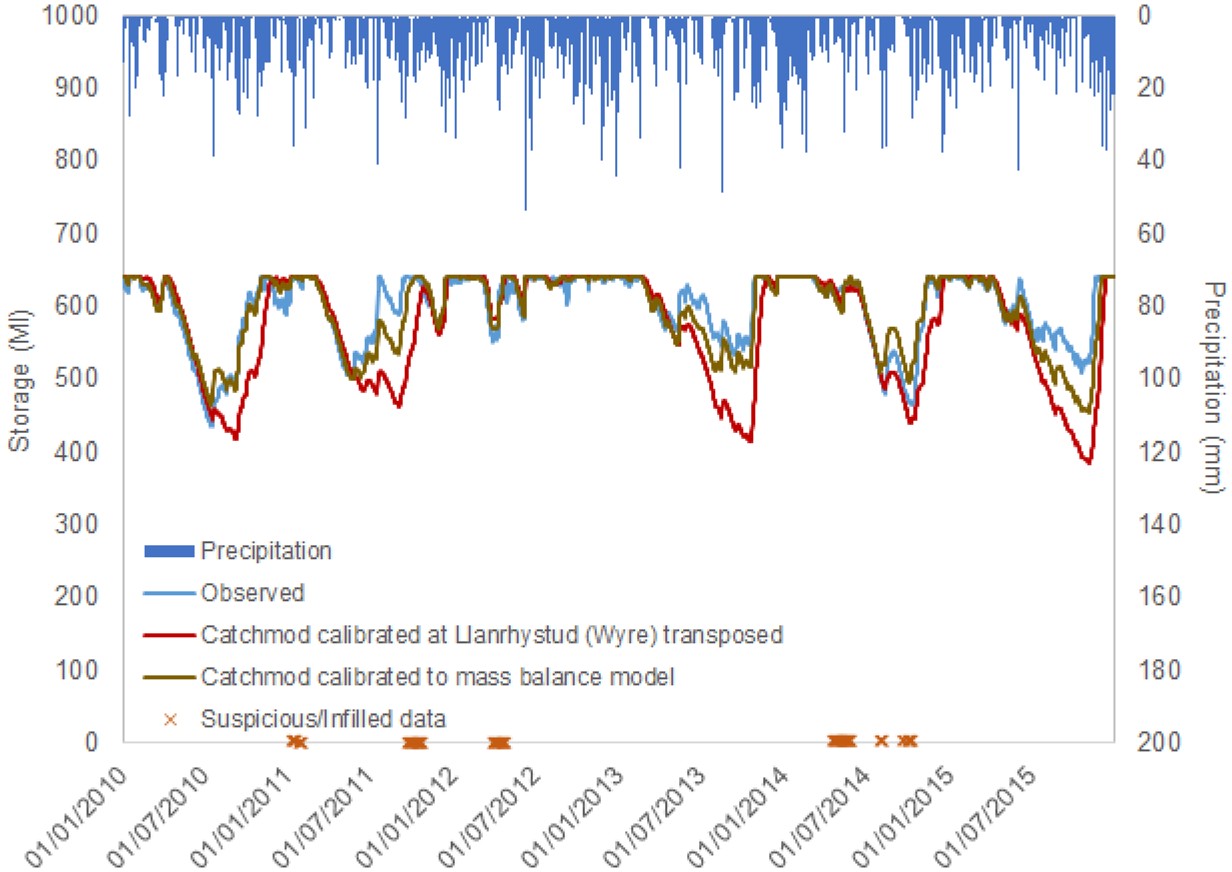

Figure 5.13 - Llyn Egnant observed and modelled storages

Giving the very limited data at Pond y Gwaith, the Catchmod parameter set calibrated to the mass balance model at Llyn Egnant was transposed to Pond y Gwaith (after adjusted for area differences) to simulate flow at this catchment. The simulated flow at Pond y Gwaith was then used to estimate the transfers from Pond y Gwaith to Llyn based on the DCWW mass balance model (Thomas Elmitt, DCWW, pers comms). This model assumes:

- Linear Head/Discharge relationship (Figure 5.14)
- Bore diameter 610 mm
- Pressure when Pond y Gwaith is full 1.16 m
- Length pipe 310 m
- Roughness 5
- No reduction in bore diameter

Figure 5.15 shows that the transfers from Pond y Gwaith to Llyn Teifi can differ substantially from the constant transfer of 3.11 Ml/d assumed in AFW (2017).

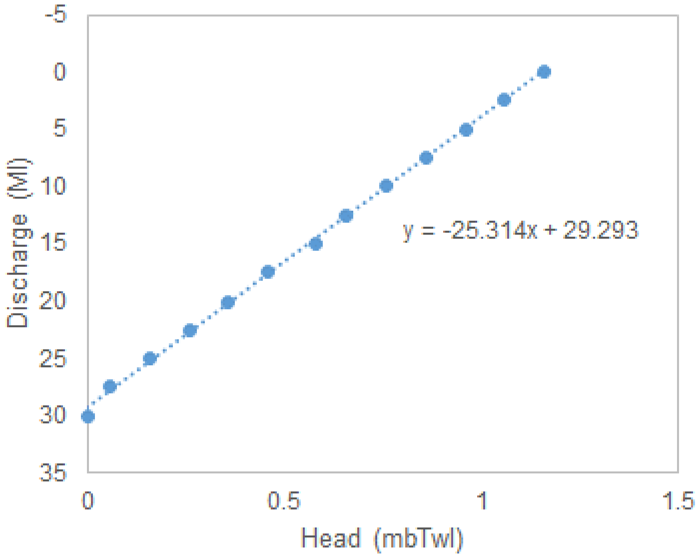

Figure 5.14 - Head/Discharge relationship for Pond y Gwaith (plot provided by DCWW)

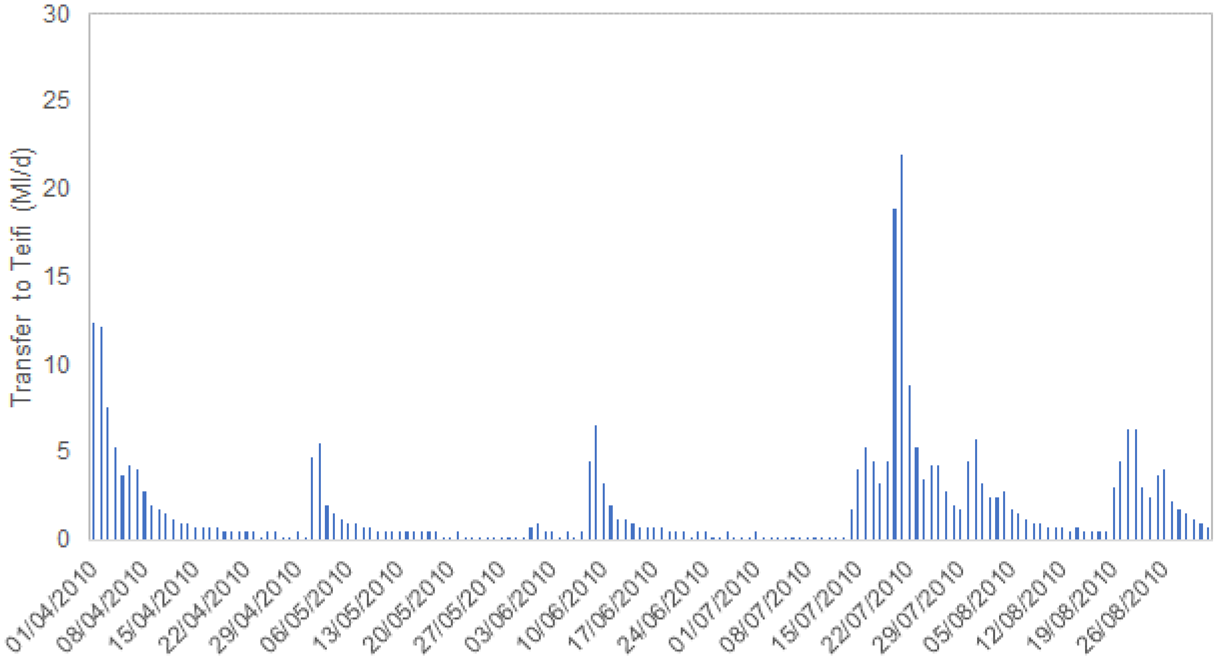

Figure 5.15 - Transfer from Pond y Gwaith to Llyn Teifi from April 2010 to September 2010 (data/plot provided by DCWW)

For Llyn Teifi we transposed the Catchmod parameters calibrated at Llanrhystud (Wyre) (Appendix B, Figure B.6 - Figure B.8) to simulate flow. We also tried to calibrate Catchmod at Llyn Teifi aiming at matching observed storage, but results in terms of storage were not better than when using Catchmod parameters calibrated at Llanrhystud (Wyre) transposed (adjusted for differences in area). Figure 5.16 shows observed and modelled storage for Llyn Teifi. Note that simulated storage, accounts for the transfer from Pond y Gwaith. The drawdown in early 2011 is assumed to be for operational reasons.

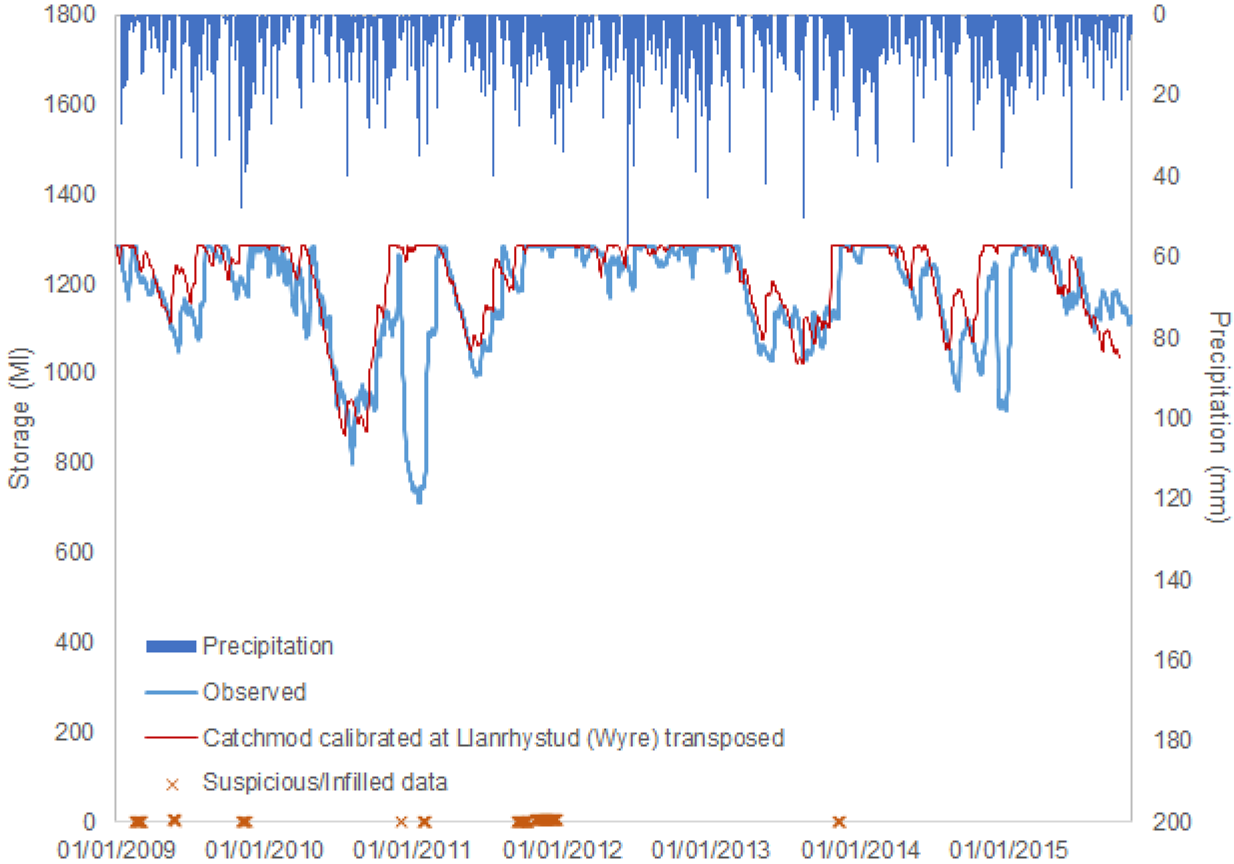

Figure 5.16 - Llyn Teifi observed and modelled storages for 01/2009-10/2015

5.3.3. Conclusions

Three new Catchmod models have been developed for Llyn Egnant, Llyn Teifi and Pond y Gwaith. The Catchmod model for Llyn Egnant was developed based on a mass balance model (Figure A.6), while the Catchmod models for Pond y Gwaith and Llyn Teifi were based on parameters transposed from Llyn Egnant (Figure A.7) and Llanrhystud (Wyre) (Figure A.8), respectively. Precipitation was estimated based on CEH-GEAR dataset and PET based on CHESS-PE dataset.

Whilst performance against the mass balance model was much improved, when the new Teifi Pools inflow series was used in the WRAPSim model, the level of drawdown was much lower than previously simulated. This can be seen below in Figure 5.17 (1976) by comparing the orange (Catchmod) and blue (HYSIM) storage lines. Given the scale of these differences, the decision was taken to retain the previous inflows for the DVF assessment, but schedule a follow-up investigation.

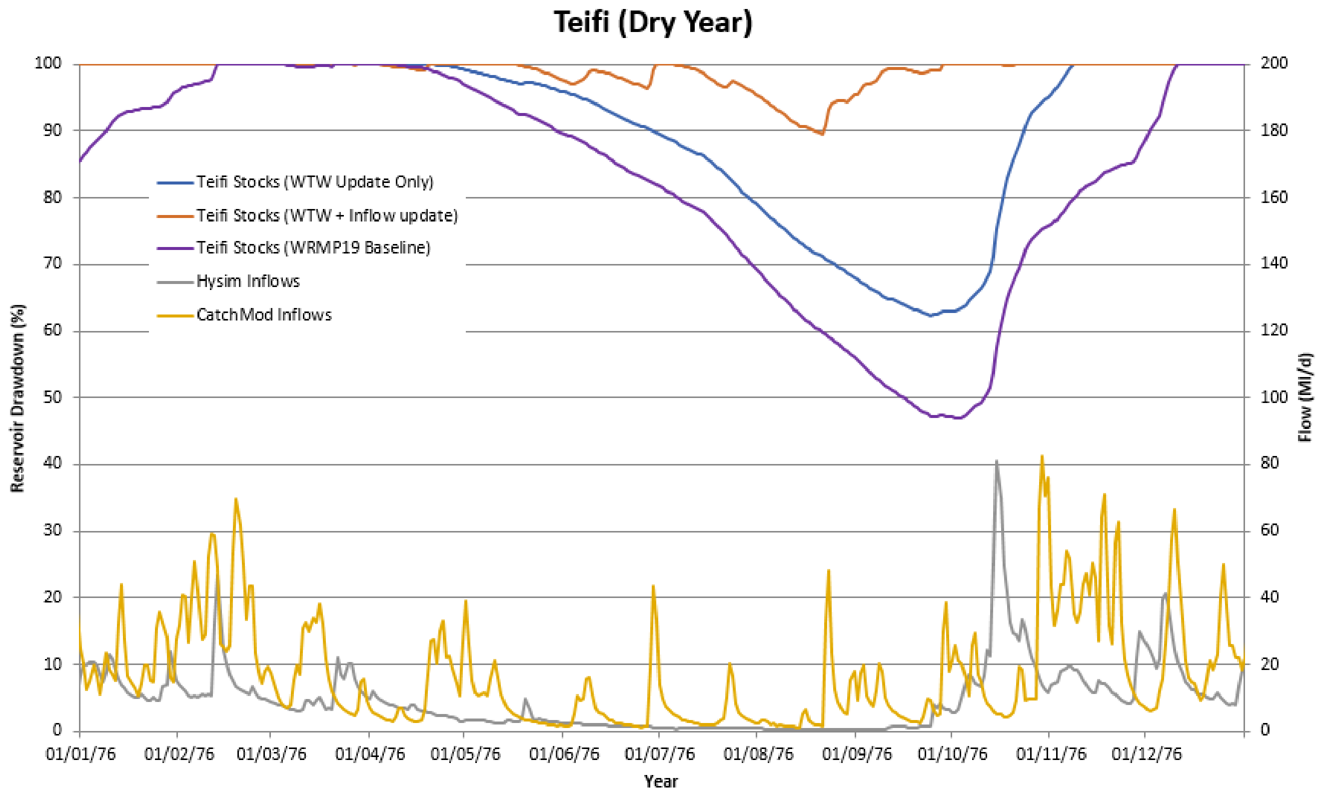

Figure 5.17 - Teifi Pools WRAPSim inflows and simulated storage in 1976, showing existing Hysim-based inflows and updated Catchmod-based inflows.

6. North Eryri Ynys Môn

6.1. Overview of the zone

The North Eryri Ynys Môn (NEYM) WRZ consists of five raw water storage reservoirs (Figure 6.1), two of which are located on Anglesey and the remaining three on the mainland.

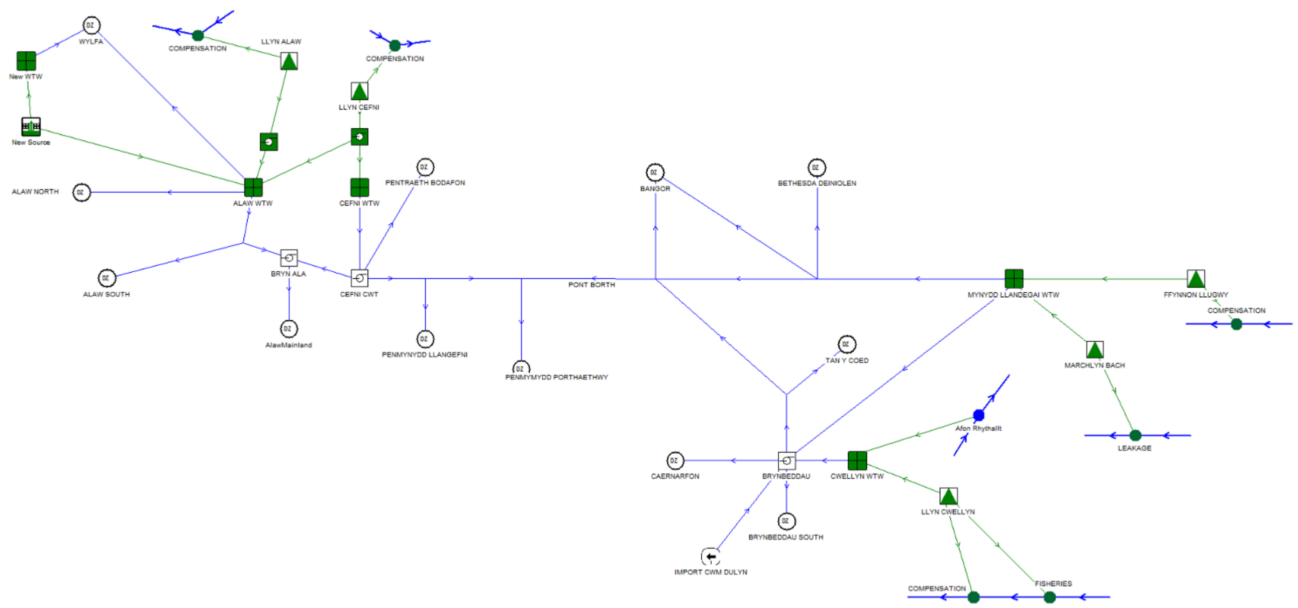

Figure 6.1 - WRAPsim NEYM schematic

The five sources modelled using Catchmod in this zone are:

- Llyn Alaw – an impounding reservoir on Anglesey;
- Llyn Cefni – an impounding reservoir on Anglesey;
- Ffynnon Llugwy – an impounding reservoir in Snowdonia;
- Marchlyn Bach – an impounding upland reservoir on the edge of Snowdonia; and
- Llyn Cwellyn – an impounding reservoir in Snowdonia - simulated using the Catchmod model for Glaslyn river.

Figure 6.2 shows the location of the study catchments, whilst Table 6.1 outlines the hydrological catchment characteristics of each catchment extracted from the LFE. Table 6.2 shows the hydrological data available for comparison with the Catchmod simulations, showing that only three catchments have observed gauging station data, with the remainder containing water balance back calculated flows. Due to the un-reliability of generating back calculated flows from reservoir storage, the Catchmod calibration work focused on the use of reservoir mass balance analysis and LFE outputs as a means of calibration instead of the back calculated flows.

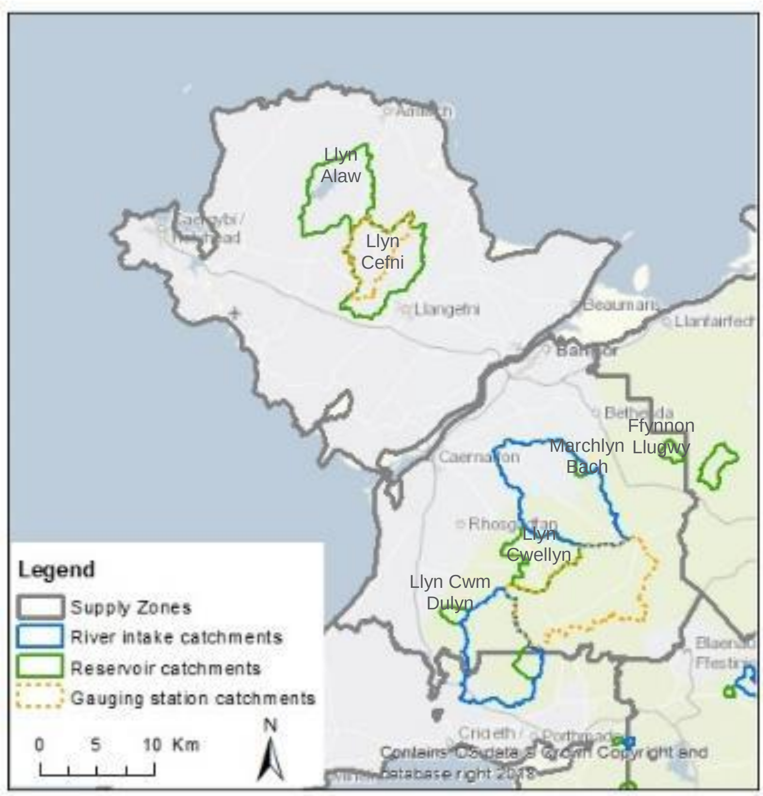

Figure 6.2 - NEYM zone: catchment areas of inflows

Table 6.1 - LFE catchment characteristics of Llyn Alaw, Llyn Cefni, Ffynnon Llugwy, Marchlyn Bach and Glaslyn catchments

Catchment	Catchment area (km^2)	BFI HOST	Mean flow (m^3/s)	Q95 (m^3/s)
Llyn Alaw	33.39	0.42	0.51	0.061
Llyn Cefni	40.7	0.47	0.72	0.042
Ffynnon Llugwy	2.26	0.32	0.19	0.024
Marchlyn Bach	1.02	0.28	0.08	0.007
Glaslyn	20.82	0.37	1.55	0.14

Table 6.2 - Hydrological data available for comparison against the Catchmod simulations

Name	Type	Description	Period of record	Percent complete (%)	Limitations
Llyn Alaw	Back calculated	The available observed data includes change in storage and raw water abstractions.	01/01/1989 – 31/12/2012	>99%	Small errors in reading reservoir levels (e.g. as a result of wave effects and wind fetch) can lead to large flow uncertainties.
Llyn Cefni, Cefni at Bodffordd	NRW gauging station	Weir rated at medium to high flows by current meter. Full range station. Weir susceptible to blockage and accumulation of debris which may affect the intake, particularly in the summer/autumn. Some gravel accumulation and clearance. Missing data 12-23/09/2009 due to repair work on weir.	10/10/1988 – 30/09/2015	>99%	Issues with measuring flows across the flow range.
Ffynnon Llugwy	Back calculated	The available observed data includes change in storage, abstraction and compensation data.	16/03/1995 – 15/11/2011	84%	Small errors in reading reservoir levels (e.g. as a result of wave effects and wind fetch) can lead to large flow uncertainties. The back-calculated inflows are clearly too low in the period 1999-2004.
Marchlyn Bach	Back calculated	The available observed data includes change in storage data, leakage and abstraction.	13/01/1995 – 25/12/2011	98%	Small errors in reading reservoir levels (e.g. as a result of wave effects and wind fetch) can lead to large flow uncertainties.
Glaslyn at Beddgelert	NRW gauging station	Gravel removal may have produced abrupt level changes in the past but careful management and regular clearance now allows a more stable rating to be maintained. Station bypassed at high flows. Rating tends to be insensitive at low flows due to subtle movements in the natural bed control, but the non-standard stone section control improves stability.	01/12/1961 – 30/09/2015	>99%	Issues with measuring flows across the flow range.

6.2. Model build

As the catchments in NEYM WRZ have relatively low base flow indices, ‘flashy’ responses and relatively rapid response to recharge events, a generalised format for the Catchmod models was adopted, based on principles generally recommended by the Environment Agency and used in the United Utilities Catchmod models. Each Catchmod model was separated into three ‘area elements’, which reflect the slow (storage), fast (general catchment response) and very fast (rapid runoff following non-trivial rainfall) elements of the catchment response. Effectively each sub-model provides a different Soil Moisture Deficit and storage-response to rainfall and PET and empirically reflects the underlying processes in the catchment. The relative proportion of each was initially set up based on baseflow separation, whereby the slow element upper bound was set to equal the baseflow proportion of the flow timeseries. The separation between ‘fast’ and ‘very fast’ was primarily based on the size of observable responses during summer spate events.

The HYSIM 2016 models developed by Atkins have already been re-calibrated to improve the catchment hydrological fits and reservoir storage fits (where appropriate). The calibration using Catchmod sought to further improve the hydrological models in comparison to HYSIM. In particular the multiple storage and release parameters contained within Catchmod, provided visibility of the behaviour of slow rapid and very rapid runoff, which was used to try and improve the recession and recovery responses that were observed in the reservoirs. The calibration process therefore consisted of two stages:

1. Hydrological calibration against ‘observed’ flow timeseries (typically transposed or back-calculated flow timeseries, rather than actual direct observations) and the LFE FDCs.
2. Validation and iterative calibration improvement based on observed versus simulated reservoir storage responses.

For Marchlyn Bach, the large data uncertainties in the back calculated flow record (due to leakage) meant that a slightly amended process was used, whereby parameters were initially set to be the same as for Ffynnon Llugwy, and then adjusted to generate the best reservoir plot fit across the observed time period.

6.2.1. Model calibration

For the first element of the calibration, Table 6.3 compares the original HYSIM 2011 simulation by Amec (2012), the revised HYSIM 2016 simulations by Atkins and Catchmod simulations with available flow data. This demonstrates statistical improvements in nearly all catchments. The only exception to this is Marchlyn Bach, which, as referred previously, relies on a highly uncertain back-calculated time series for the ‘observed’ data. In this catchment, some ‘goodness of fit’ on flow timeseries was therefore sacrificed to make the calibration for the reservoir better and ensure that catchment parameters were similar to the neighbouring Ffynnon Lllugwy catchment.

The calibration of the Catchmod models did not only focus on statistical fit but also volumetric (Appendix C.1), flow duration, contribution to flow by area and hydrograph fit and analysis. Flow duration, contribution to flow by area and hydrograph fits are shown in Figure 6.3 to Figure 6.17. These no longer contain the original HYSIM modelling carried out in 2011, which were notably improved upon during the HYSIM 2016 re-calibration, particularly for Alaw and Ffynnon Llugwy inflows, which were made less flashy to reflect the hydrological regime more accurately. In both catchments, the HYSIM 2011 calibrations led to the catchment drying out during low flow periods. Similarly, Cefni inflows (in the Catchmod model) were increased to better reflect the flows from the entire inflow catchment (41 km^2). It is understood that the original work (Amec, 2012) calibrated the model to the gauging station (21.1 km^2) catchment area. The Catchmod models calibrated the hydrological response to the Bodffordd gauging station timeseries but increased the flow volumes to be closer to the LFE output for the entire catchment. This calibration was balanced with achieving a satisfactory water balance fit at Cefni reservoir.

The decision to use Catchmod for this project rather than the existing Hysim models was made in order to improve the reservoir mass balance performance (see Section 6.2.2) with some improvements made in other hydrological indicators. These are summarised as follows:

1. For Alaw, there was a clear issue with the over-estimation of inflows in the calculated ‘observed’ record, which did not provide a good fit against observed reservoir data. The HYSIM 2016 and Catchmod outputs were very similar for most of the flow range, with the biggest differences at higher flows and in the spate flow behaviour during drought events, which were more frequent during dry winters (such as 1996), but avoided responding as much to late summer/autumn spate events.
2. For Cefni, the low flow end of the FDC now plots much closer to the historic and LFE estimates, and the log Coefficient of determination (R^2) is also greatly improved. The volumetric match is over-estimated by 7%, but as shown in Section 6.2.2, the reservoir drawdown response for this timeseries provides a significantly improved fit, which does require appropriate spate response to achieve this.
3. The volumetric and lower flows fit (as evidenced by the log R^2) were both improved for Ffynnon Llugwy. There was a slight increase in mid-range flows on the FDC, bringing that part of the FDC closer to the LFE values.
4. For Marchlyn Bach there is an apparent deterioration in the fit, but as noted previously there is a very large uncertainty in the back-calculated ‘observed’ record in this case. The reservoir fit improved and the catchment characteristics were maintained at values that are close to Ffynnon Llugwy. The catchment is hydrologically very similar to Ffynnon Llugwy and only ~8km away.
5. For Glaslyn the fit was only slightly improved, but there was a notable improvement in the overall volumetric fit, and a much better fit at low flows.

Appendix D.1 provides example lower flow timeseries details for drought events. The most notable difference shown is for Llyn Cefni, which has a much better fit during the latter half of the 1995/96 event, as reflected in the reservoir storage calibration.

Table 6.3 - Summary of HYSIM 2011 original simulation, HYSIM 2016 revised simulation and Catchmod simulation fits against available flow data

Catchment	Parameter set	R^2	R^2(ln)	Σ Calc Q/ Σ Q Obs	Parameter files
Llyn Alaw	HYSIM 2011	0.166*	0.38*	1.733*	Alaw_updated2012_v1.par
Llyn Alaw	HYSIM 2016	0.604	0.649	0.716	Alaw_updated2016_v3.par
Llyn Alaw	Catchmod	0.932	0.917	0.880	Appendix A.4
Llyn Cefni	HYSIM 2011	0.696	0.856	1.052	Cefni_updated2012_v2.par
Llyn Cefni	HYSIM 2016	0.742	0.798	0.97	Cefni_updated2016_v2.par
Llyn Cefni	Catchmod	0.69	0.88	1.07	Appendix A.4
Ffynnon Llugwy	HYSIM 2011	0.326*	0.319*	2.100*	Ffynnon_updated2012_v1.par
Ffynnon Llugwy	HYSIM 2016	0.69*	0.78*	0.92*	Llugwy_updated2016.par
Ffynnon Llugwy	Catchmod	0.70*	0.84*	0.98*	Appendix A.4
Marchlyn Bach	HYSIM 2011	0.657*	0.699*	1.910*	Marchlyn_updated2012_v1.par
Marchlyn Bach	HYSIM 2016	0.569*	0.601*	1.916	Marchlyn_updated2016_v2.par
Marchlyn Bach	Catchmod	0.44*	0.55*	1.90	Appendix A.4
Glaslyn	HYSIM 2011	0.794	0.842	1.117	Glaslyn_updated2012_v1.par
Glaslyn	HYSIM 2016	0.790	0.835	1.117	Glaslyn_updated2012_v1.par
Glaslyn	Catchmod	0.790	0.85	1.00	Appendix A.4

* Note: Simulation compared to back calculated flows

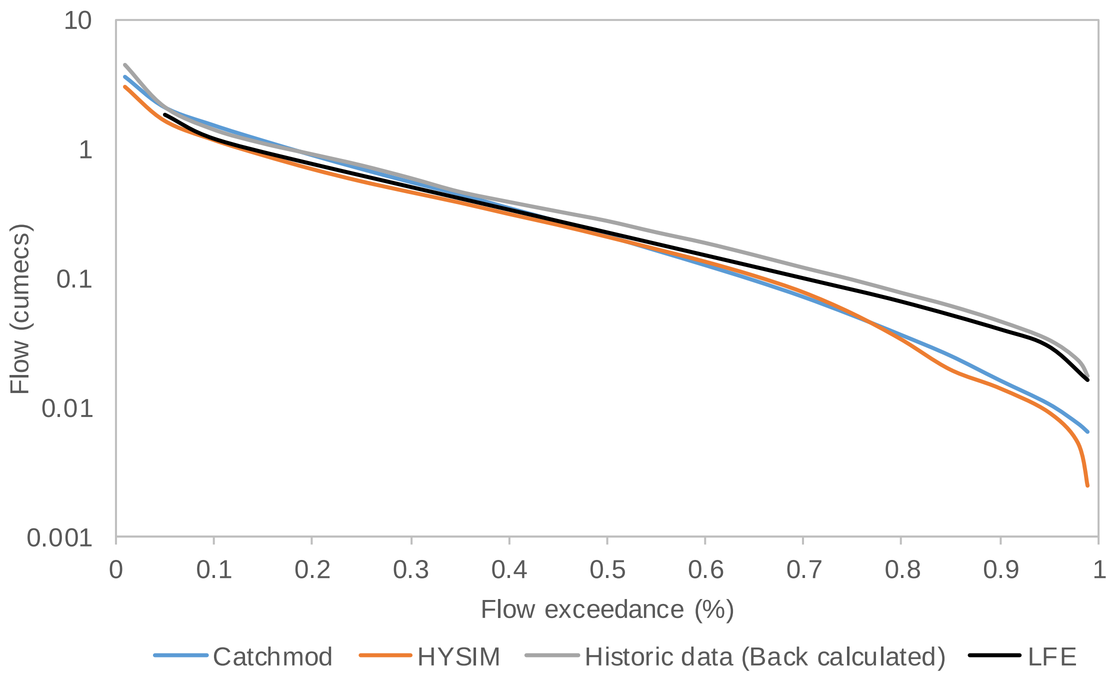

Figure 6.3 - Flow Duration Curves at Llyn Alaw for Catchmod, HYSIM 2016, historic data (back-calculated) and from LFE.

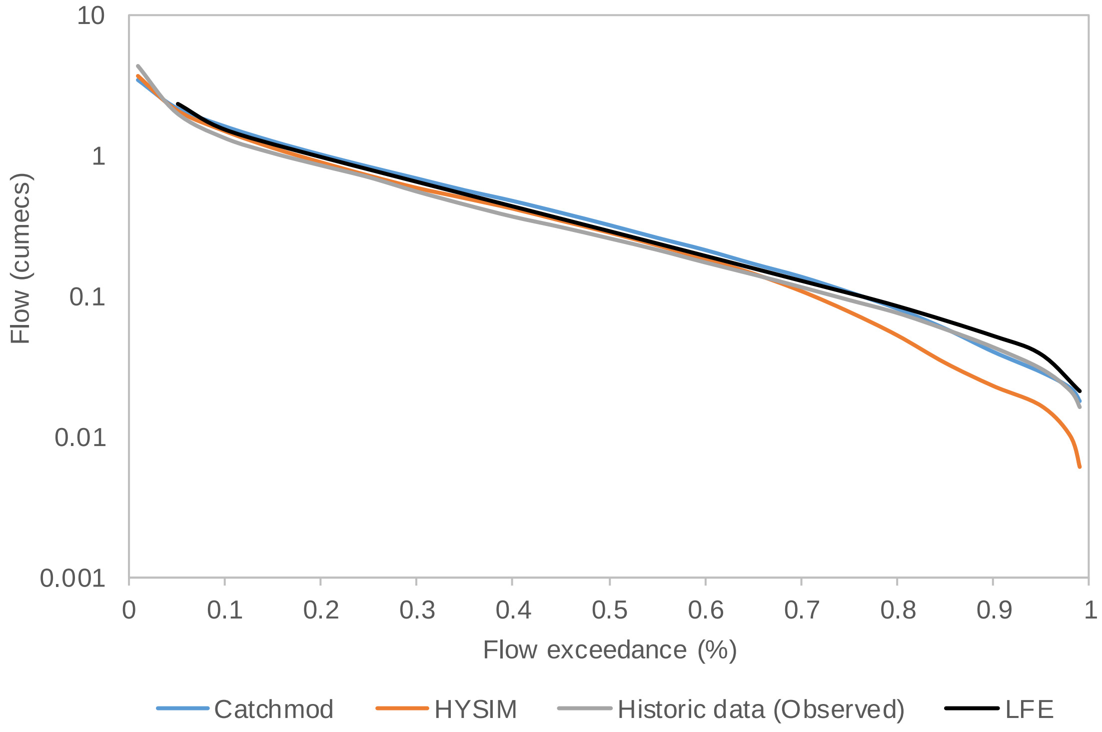

Figure 6.4 - Flow Duration Curves at Llyn Cefni for Catchmod, HYSIM, historic data (observed) and from LFE.

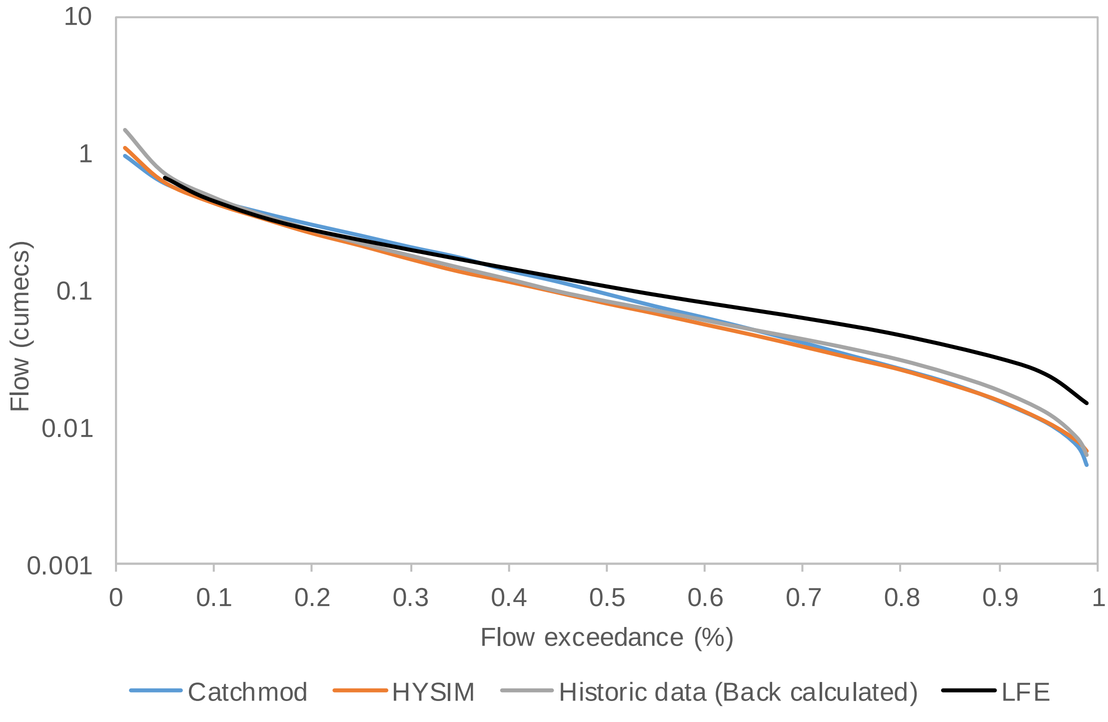

Figure 6.5 - Flow Duration Curves at Ffynnon Llugwy for Catchmod, HYSIM, historic data (back-calculated) and from LFE.

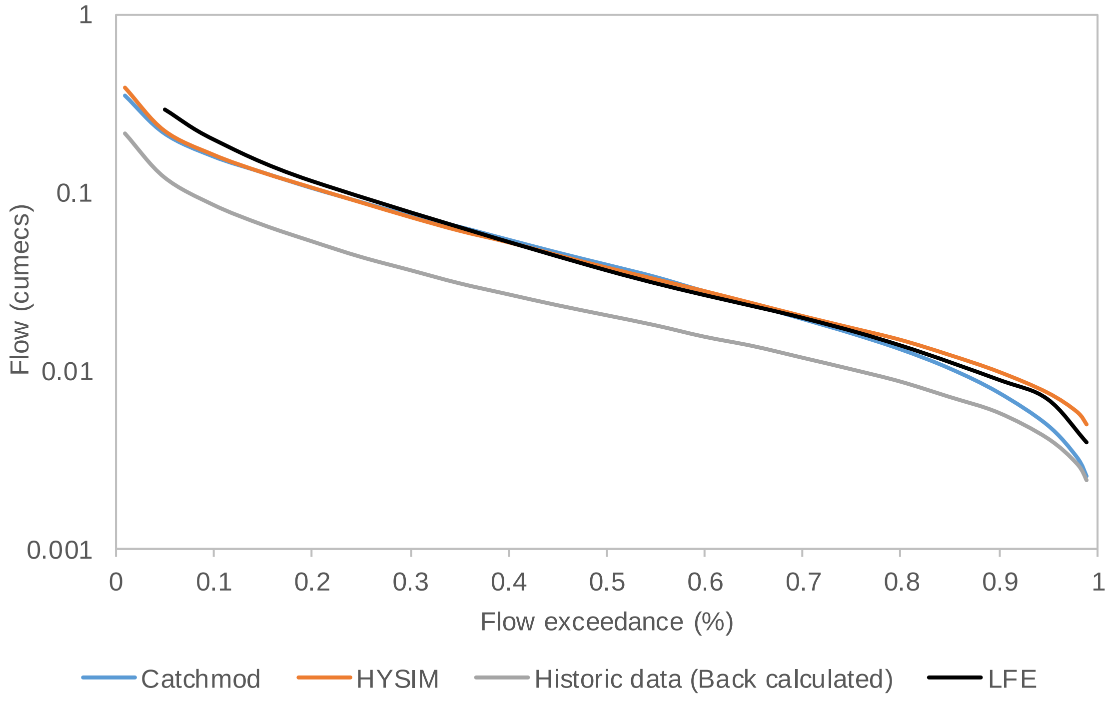

Figure 6.6 - Flow Duration Curves at Marchlyn Bach Llugwy for Catchmod, HYSIM, historic data (back-calculated) and from LFE.

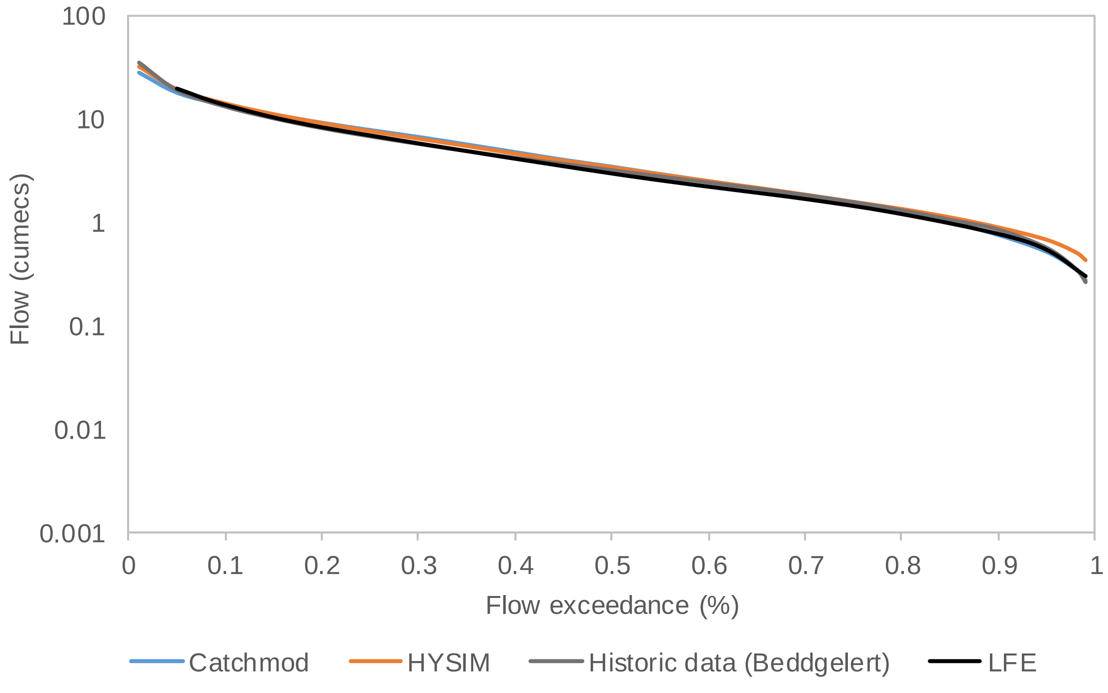

Figure 6.7 - Flow Duration Curves at Glaslyn for Catchmod, HYSIM, historic data (observed) and from LFE.

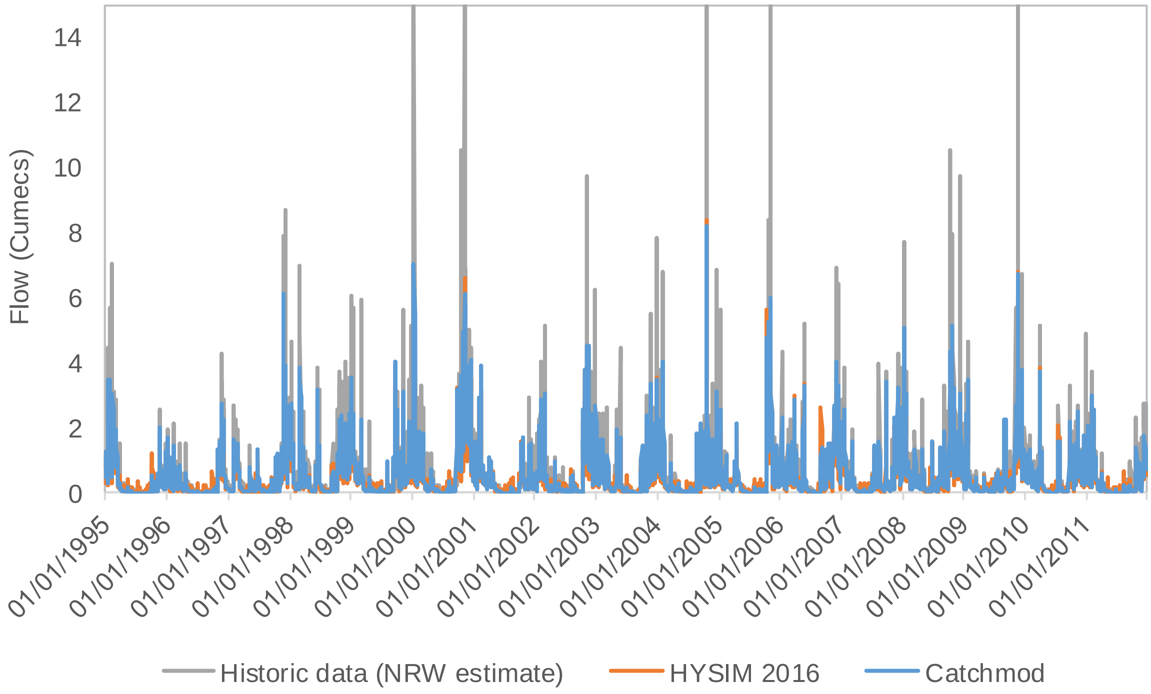

Figure 6.8 - Observed and simulated (HYSIM 2016 and Catchmod) flows for Llyn Alaw

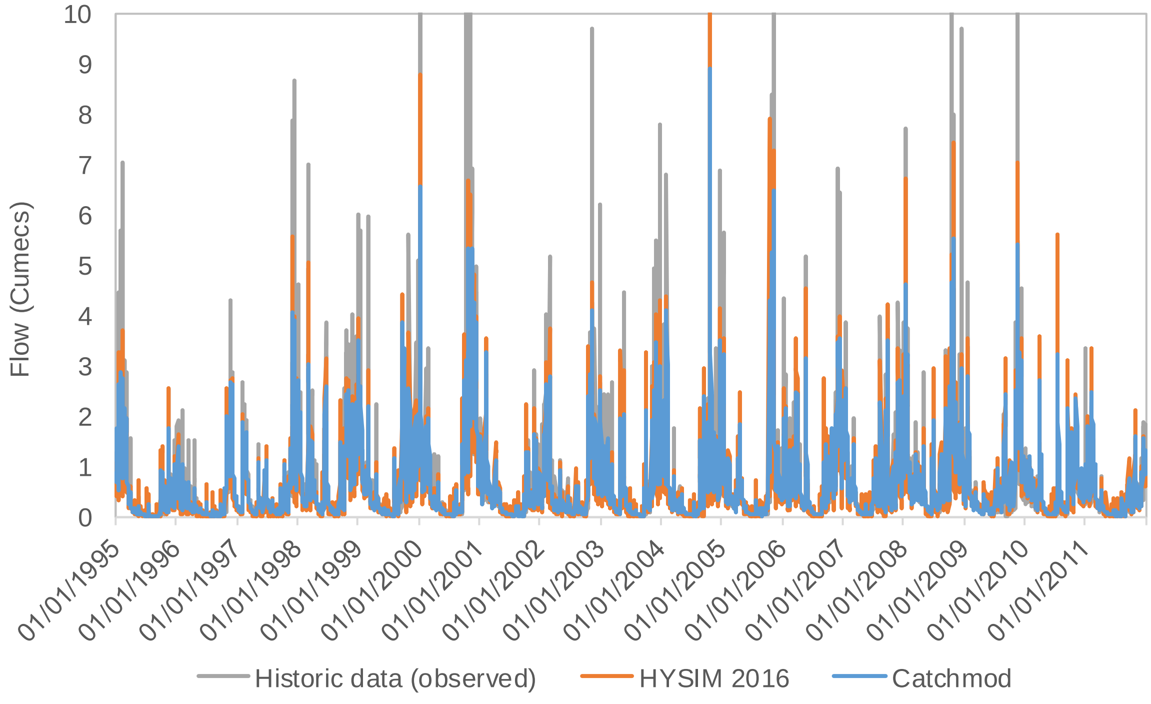

Figure 6.9 – Observed and simulated (HYSIM 2016 and Catchmod) flows for Llyn Cefni

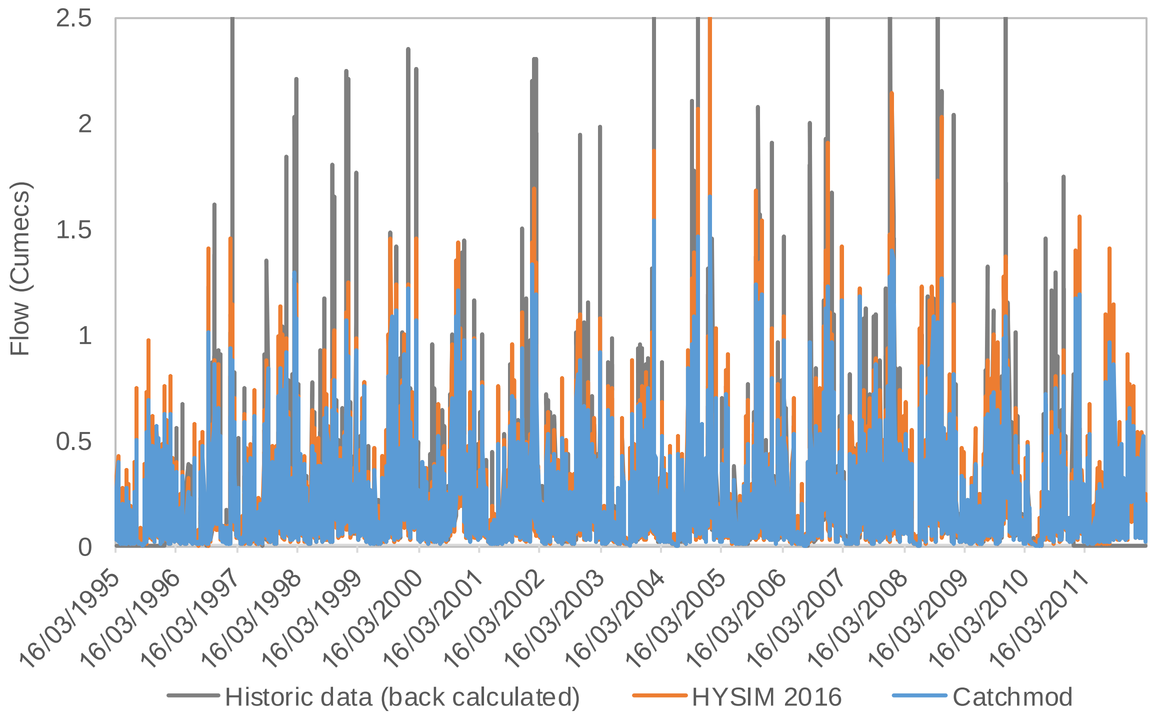

Figure 6.10 – Observed and simulated (HYSIM 2016 and Catchmod) flows for Ffynnon Llugwy

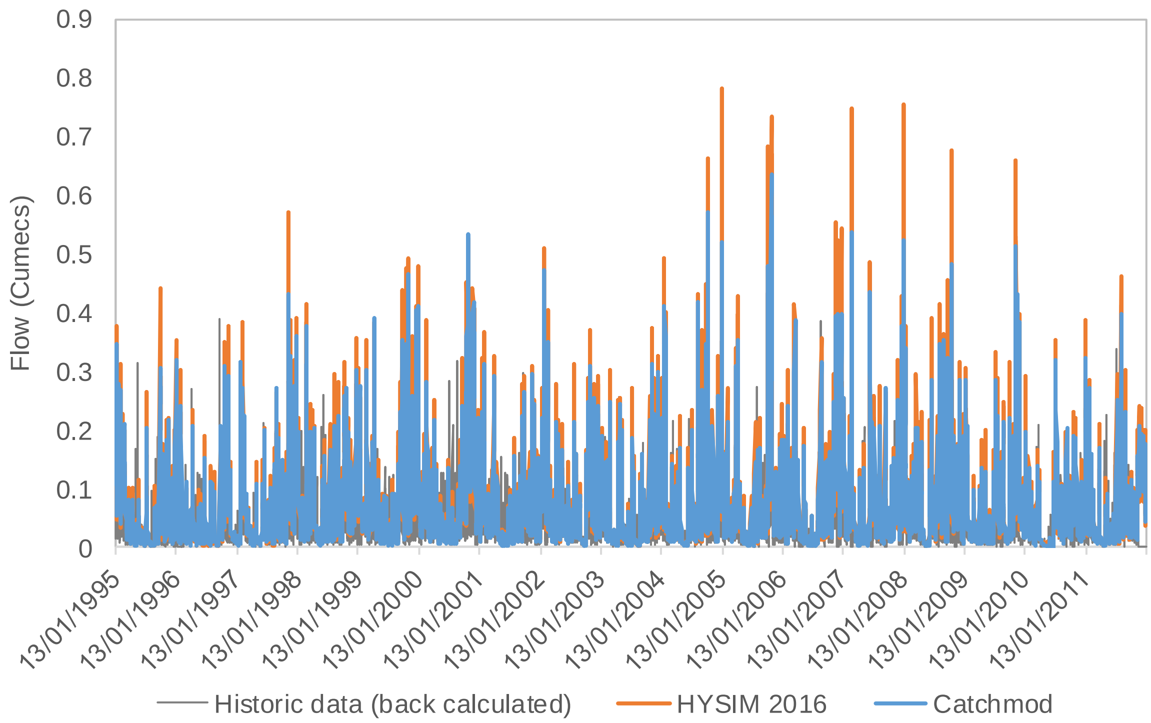

Figure 6.11 - Naturalised (back-calculated) and simulated (HYSIM 2016 and Catchmod) flows for Marchlyn Bach

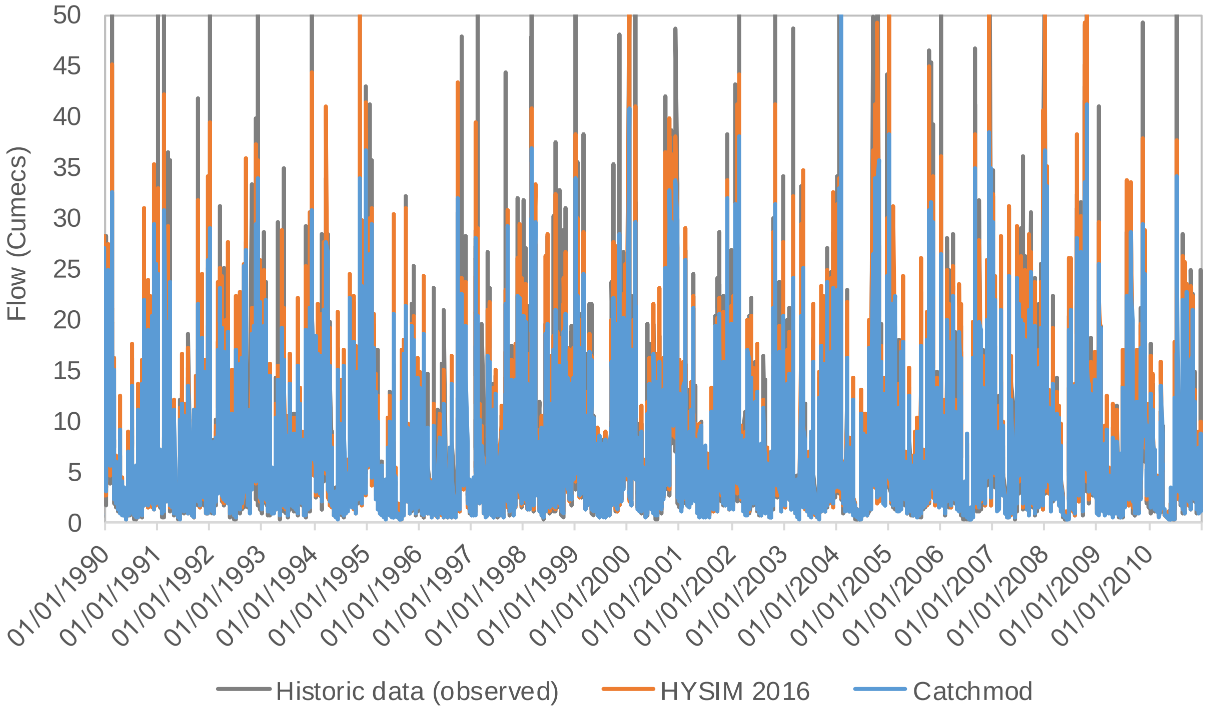

Figure 6.12 – Observed and simulated (HYSIM 2016 and Catchmod) flows for Glaslyn.

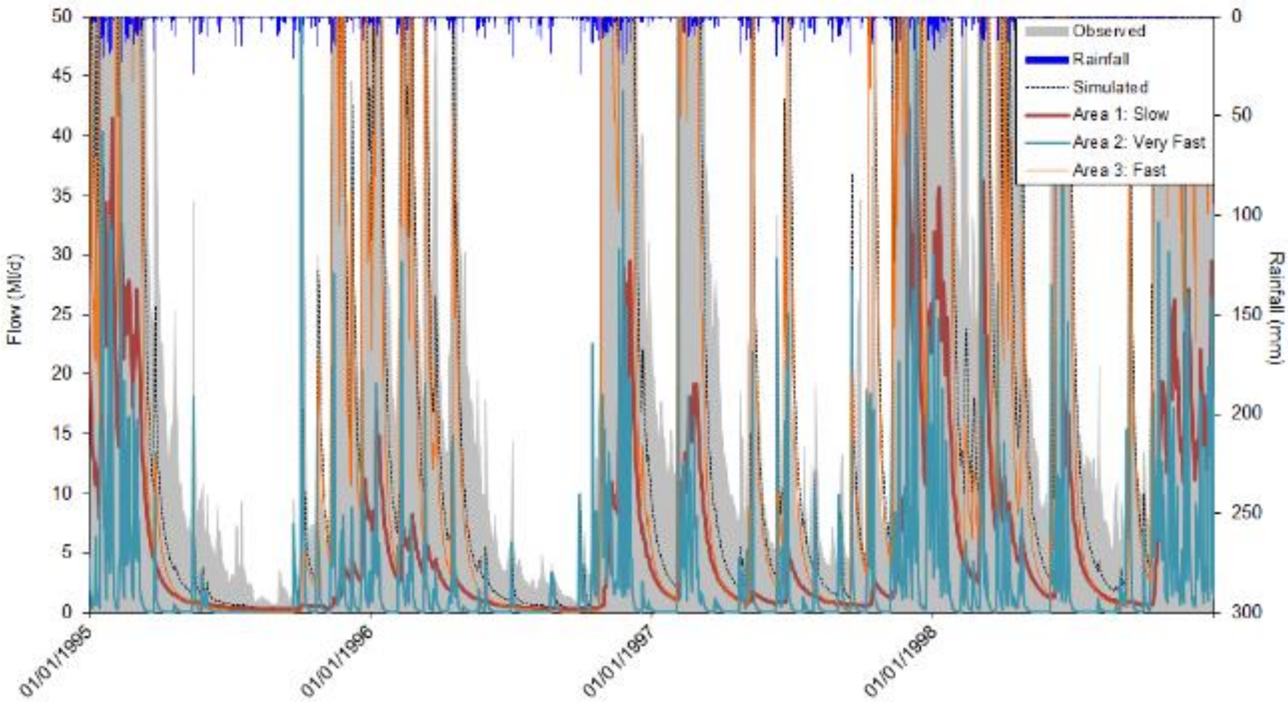

Figure 6.13 - Contribution to flow by area for Alaw catchment using Catchmod simulated flows (1990s detail).

It is noted that the above calibration appears to under-represent recession flows and spates in comparison to the ‘observed’ record. However, as noted in previous reports, the observed record does not reconcile well with either the LFE or the reservoir mass balance observations, and the generated flows need to under-estimate in order to provide a meaningful water resource calibration. For Alaw, the validation and iterative calibration against the reservoir storage behaviour was a key part of the process (see Section 6.2.2).

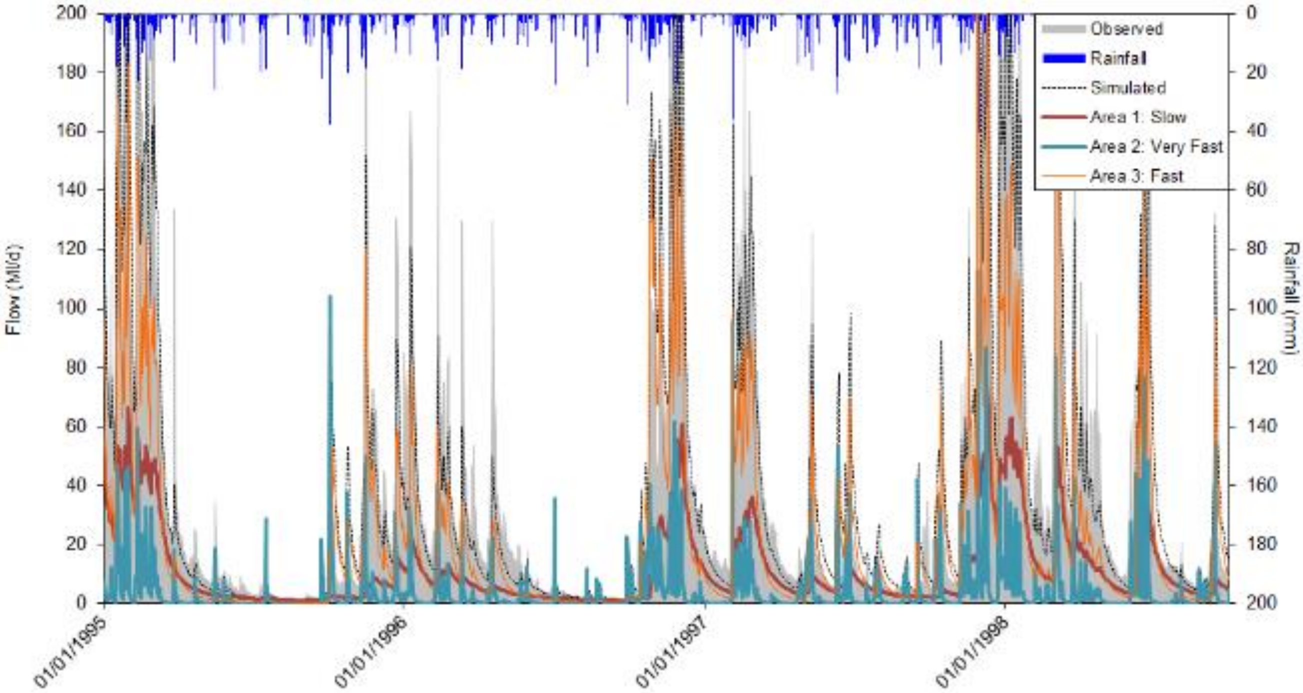

Figure 6.14 - Contribution to flow by Area for Cefni catchment using Catchmod simulated flows (1990s detail)

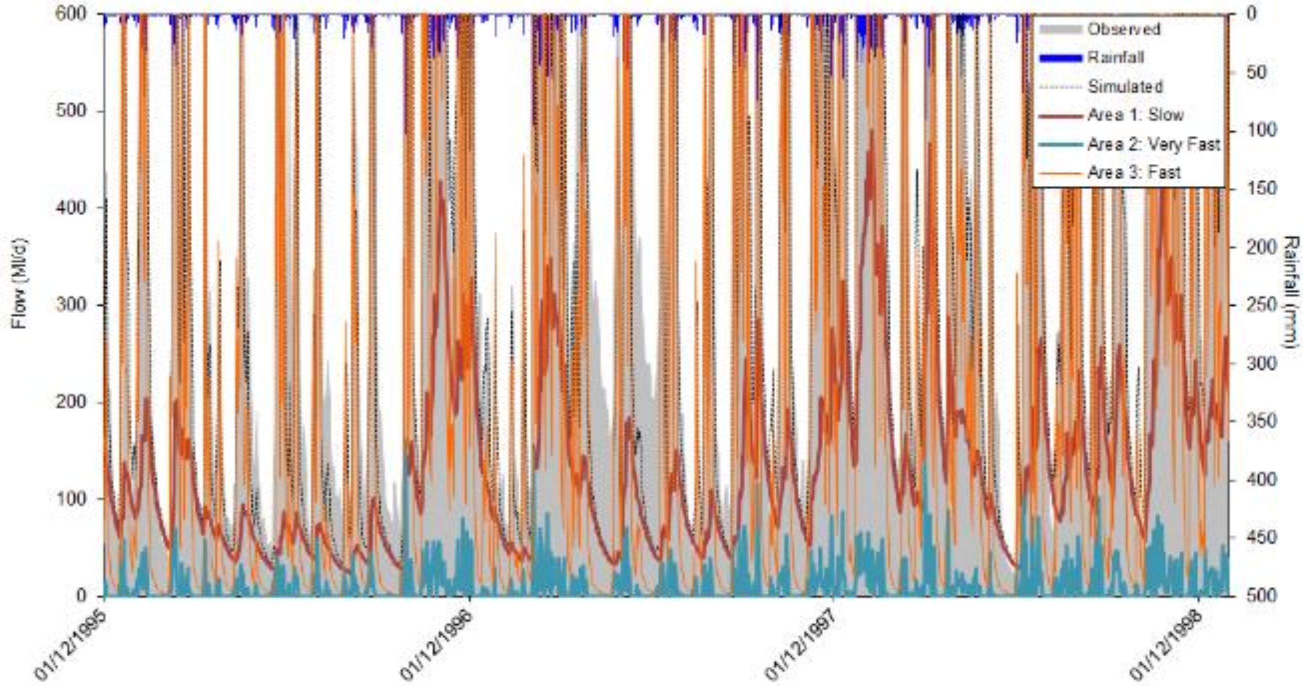

Figure 6.15 - Contribution to flow by Area for Glaslyn catchment using Catchmod simulated flows (drought detail)

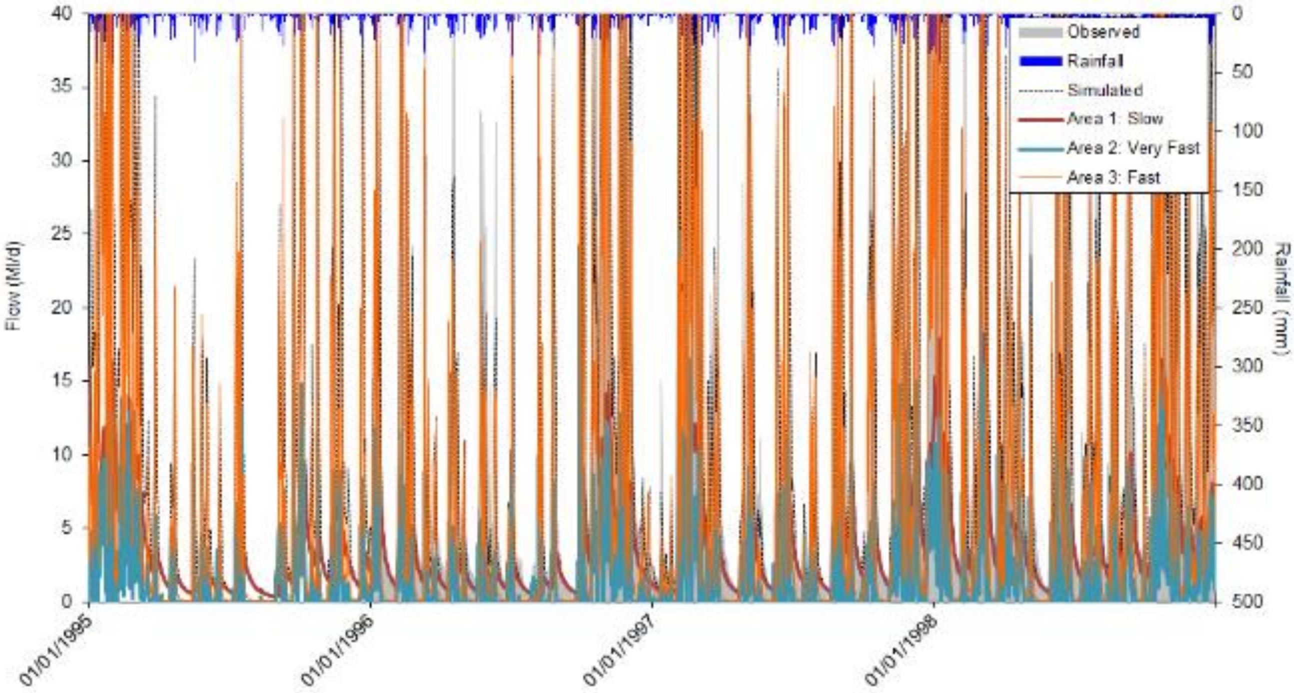

Figure 6.16 - Contribution to flow by area for Llugwy catchment using Catchmod simulated flows (drought detail)

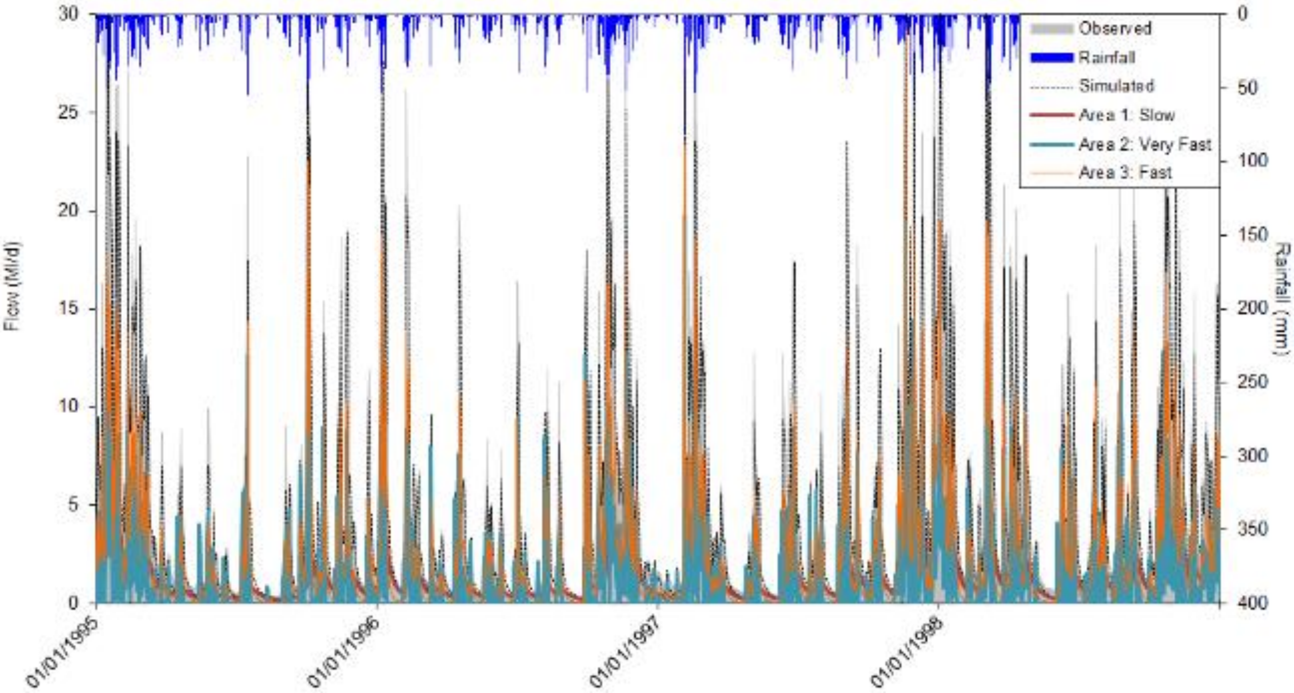

Figure 6.17 - Contribution to flow by area for Marchlyn Bach catchment using Catchmod simulated flows (drought detail)

6.2.2. Reservoir water balance fits

The Catchmod outputs were assessed against the observed reservoir storage using mass balance models.

Table 6.4 and Figure 6.18 to Figure 6.21 provide the reservoir storage fits for the reservoir water balances, showing notable improvements in all the reservoir storage fits except at Marchlyn Bach, where there was relatively little change. The fit for Llyn Alaw improved significantly, and crucially the drought response during the 1995/96 event now follows the drawdown and recharge observed during that sequence. Details of responses to the 1995/96 drought event at all reservoirs are provided in Appendix D.1 of this report.

It must be noted that scour releases are generally not measured by DCWW operational staff. These are particularly relevant to Marchlyn Bach reservoir, which has been managed for dam safety purposes over the last few years. This will partly explain the water balance fit achieved at this reservoir (Figure 6.21) and might explain some of the unusual observed drawdowns for individual years at Cefni (Figure 6.19) and Alaw (Figure 6.18).

Table 6.4 - Coefficient of determination (R^2) of observed and simulated reservoir storage

Reservoir	HYSIM 2011	HYSIM 2016	Catchmod	Comments
Alaw reservoir	0.81	0.77	0.91	Major improvements in response behaviour and a significantly improved hydrological fit.
Cefni reservoir	0.70	0.78	0.87	Overall better water balance fit and the re-calibration improves the 1995 to 1996 drought response.
Ffynnon Llugwy	0.59	0.61	0.65	Significantly improves the 1995 and 1996 drought response. Overall, better water balance fit.
Marchlyn Bach	0.63	0.77*	0.78*	Where real leakage data is not available, an average value equal to 0.65 Ml/d leakage has been set. When evaluating model fit, the rainfall for the 2001 simulated data, as 2001 had the only summer in which two consecutive months were well below the nearest Met Office gauge.

* Calibration values exclude year 2000 data

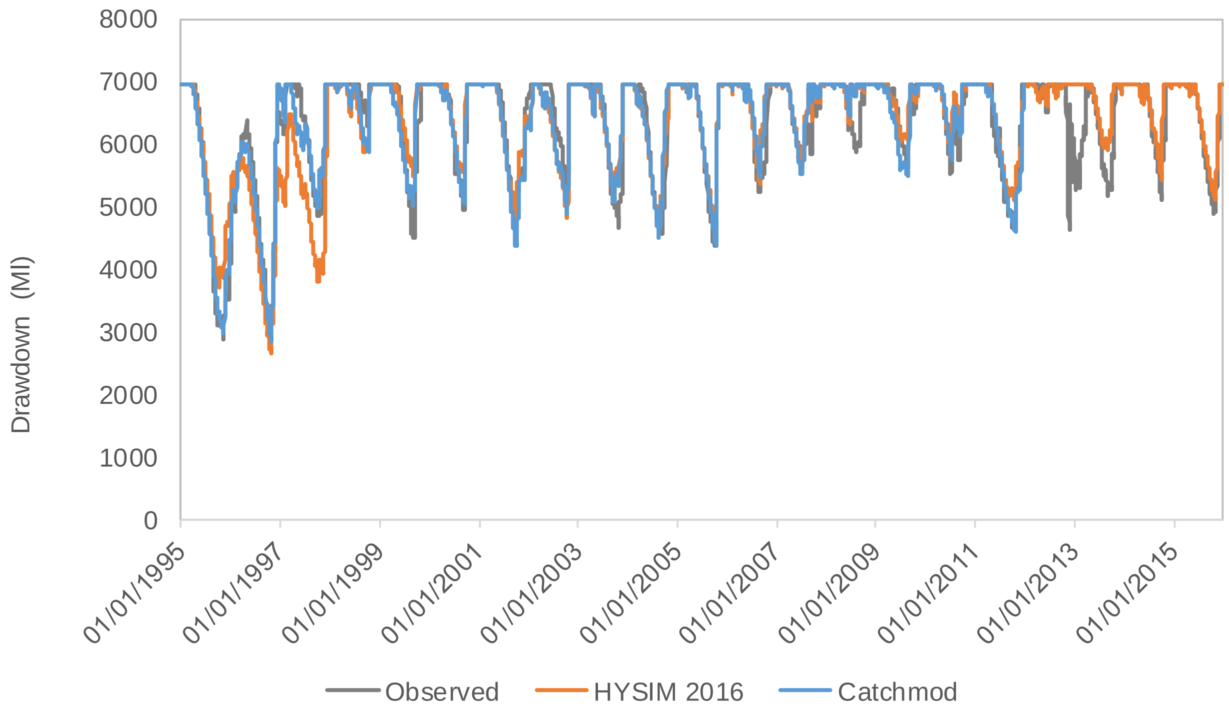

Figure 6.18 - Water balance fit for Alaw reservoir (Observed, Catchmod simulation and HYSIM 2016 simulation)

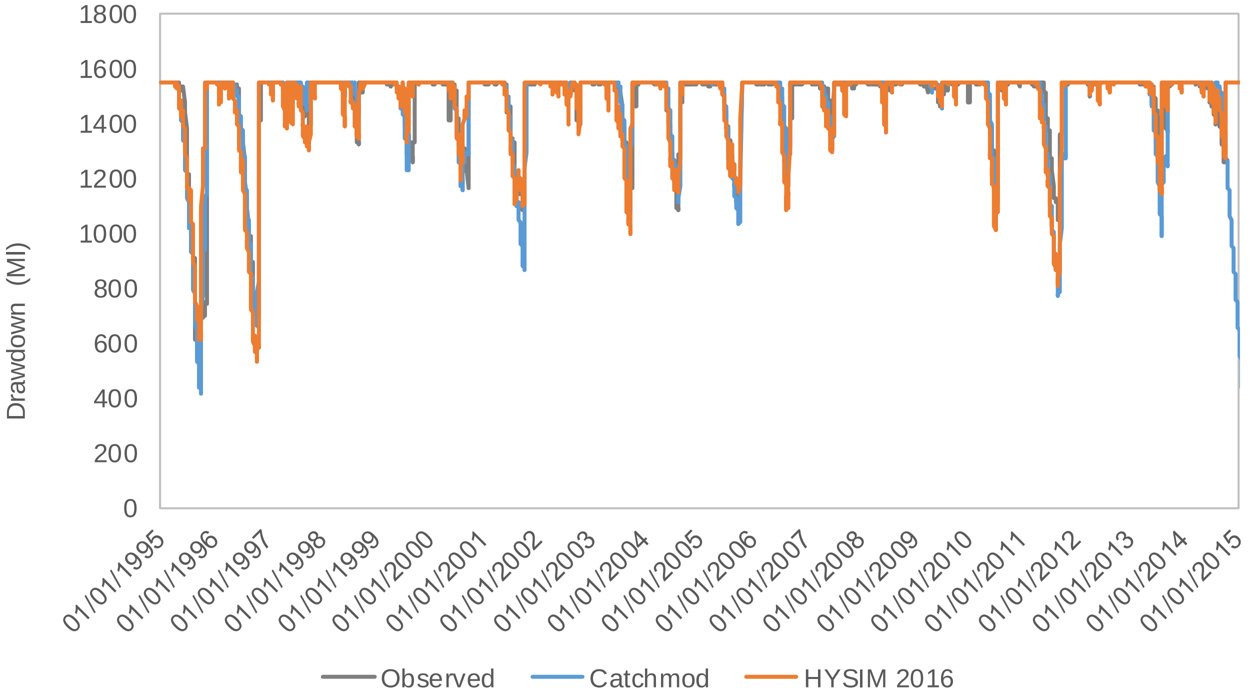

Figure 6.19 - Water balance fit for Cefni reservoir (observed, Catchmod simulation and HYSIM 2016 simulation)

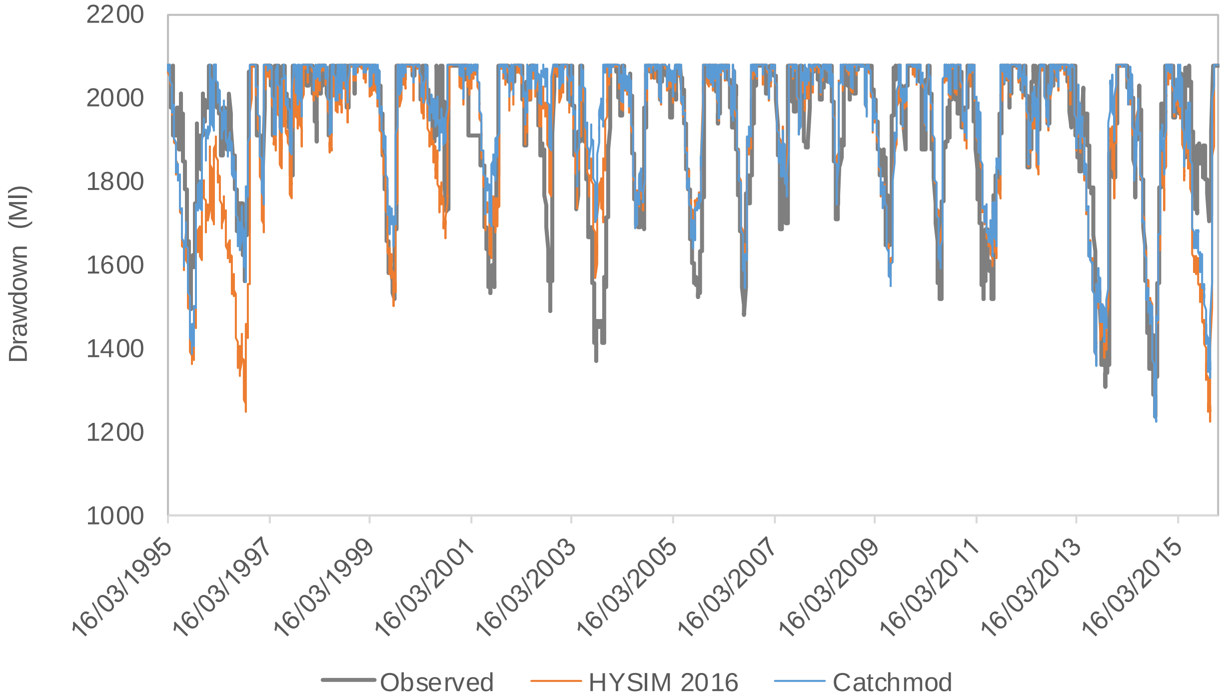

Figure 6.20 - Water balance fit for Ffynnon Llugwy (observed, Catchmod simulation and HYSIM 2016 simulation)

Note: In Figure 6.20, the poor fit from 2014 onwards is attributed to suspect measured compensation flows, which are circa 1 Ml/d higher the historic compensation flow values. Applying the historic values improves the fit from 2014 onwards.

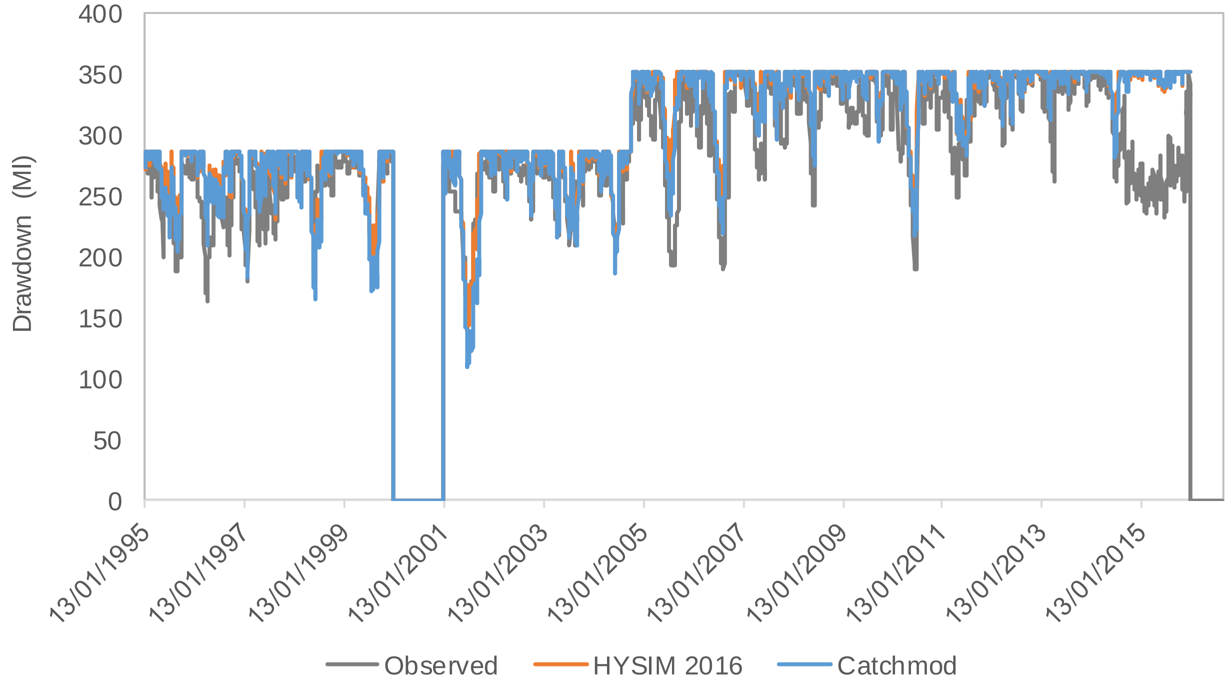

Figure 6.21 - Water balance fit for Marchlyn Bach (observed, Catchmod simulation and HYSIM 2016 simulation)

Note: Revised rainfall timeseries significantly improves the fit in 2001 for Marchlyn Bach. The observed data from 2013 onwards at Marchlyn Bach are as a result of managing the reservoir to lower levels due to safety concerns. 2000 is excluded due to inconsistencies in the rainfall data set.

6.3. Conclusions

The hydrological models in the NEYM WRZ were translated from HYSIM into the Catchmod modelling platform, and calibrated and then validated using the historic flow timeseries and reservoir drawdown responses. The revised work has shown significant improvements in hydrological fits, particularly where the original work was calibrating too closely to unreliable estimates of reservoir inflows. Water balance fits on observed data from reservoirs were generally improved by the re-calibration process, with a particular improvement in the pattern of response to the 1995/1996 drought event on Anglesey and in Ffynnon Llugwy.

7. Final Recommendations

The HYSIM precipitation timeseries are based on Met Office 5 km by 5 km gridded data. However, to model river flows accurately at the catchment level a finer resolution is desirable. Therefore, we would recommend spatial rainfall fields with higher resolution than 5 km to be used to perform hydrological modelling. Examples of gridded rainfall datasets at 1 km resolution, include CEH-GEAR (Tanguy *et al.*, 2016) and the Met Office HadUK-Grid (Met Office, 2018), which will supersede the UKCP09 gridded observation. As the optimisation of model parameters tend to compensate for measurements errors (both for input data and calibration flow data), it is essential that new parameterisation is sought if a different input dataset is used.

In addition to the uncertainty in the input data, namely precipitation and PET, there are large uncertainties in the observed flow data. To improve model calibration, it is essential that observational uncertainty is reduced as much as possible. As a starting point, we would recommend that any observations (including storage, abstraction, compensation and spill data) to be reviewed. Flow measurements would also be desirable to improve the calibration. It has been shown that even a reduced number of spot measurements can significantly improve model calibration (Seibert and Beven, 2009; Pool, Viviroli and Seibert, 2018).

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Appendices

Appendix A. Catchmod Parameters

A.1. Barmouth

CATCHMOD (VBA Version 4.11) **Input Parameter Sheet** **Catchment Name: Bodlyn**

			Area Number		
Soilmoisture store parameters	**Units**	**Comments**	**1**	**2**	**3**
Area Type		For reference/labelling purposes only (Chalk, Clay, Urban etc)	Slow	Very Fast	Fast
Slope of Drying Curve		Usually 0.3 for most zones, zero for urban (paved) areas	0.3	0.3	0.3
Drying Constant (mm)	mm	Finite storage of upper soil moisture store. Typically 30 to 150 (0 for urban).	12	0	5
Direct Percolation (%)	%	% bypassing soil moisture store. Typically 15 to 25 for aquifers, 0 for others.	20	10	15
Upper Zone (one) Deficit	mm	Has a maximum value equal to the drying constant	0	0	0
Lower Zone (two) Deficit	mm	Lower zone is effectively infinite	0	0	0
Catchment Storage Parameters					
Area	km^2	Effective Catchment Area	1.1	1.5	1.06
Cr	days	First (linear) storage constant. Typically 0 to 30	0	0	0
Cqu	cumec.days^2/km^2	Second (non-linear) storage constant. Typically 0 to 5000	5	0.15	1
R1	mm/d	Initial output of first storage	0	0	0
Q1	m^3/s	Initial output of second storage	0.05	0	0

Figure A.1 - Catchmod parameter set for Llyn Bodlyn catchment

A.2. Lleyn Harlech

CATCHMOD (VBA Version 4.11) **Input Parameter Sheet** **Catchment Name: Cwm Dulyn**

			Area Number		
Soilmoisture store parameters	**Units**	**Comments**	**1**	**2**	**3**
Area Type		For reference/labelling purposes only (Chalk, Clay, Urban etc)	Lumped		
Slope of Drying Curve		Usually 0.3 for most zones, zero for urban (paved) areas	0.3		
Drying Constant (mm)	mm	Finite storage of upper soil moisture store. Typically 30 to 150 (0 for urban).	0.05		
Direct Percolation (%)	%	% bypassing soil moisture store. Typically 15 to 25 for aquifers, 0 for others.	15		
Upper Zone (one) Deficit	mm	Has a maximum value equal to the drying constant	0		
Lower Zone (two) Deficit	mm	Lower zone is effectively infinite	0		
Catchment Storage Parameters					
Area	km^2	Effective Catchment Area	2.5		
Cr	days	First (linear) storage constant. Typically 0 to 30	0		
Cqu	cumec.days^2/km^2	Second (non-linear) storage constant. Typically 0 to 5000	15		
R1	mm/d	Initial output of first storage	0		
Q1	m^3/s	Initial output of second storage	0.06		

Figure A.2 - Catchmod parameter set for Llyn Cwm Dulyn catchment

CATCHMOD (VBA Version 4.11) **Input Parameter Sheet** **Catchment Name: Cwmystradllyn**

			Area Number		
Soilmoisture store parameters	**Units**	**Comments**	**1**	**2**	**3**
Area Type		For reference/labelling purposes only (Chalk, Clay, Urban etc)	Lumped		
Slope of Drying Curve		Usually 0.3 for most zones, zero for urban (paved) areas	0.3		
Drying Constant (mm)	mm	Finite storage of upper soil moisture store. Typically 30 to 150 (0 for urban).	1		
Direct Percolation (%)	%	% bypassing soil moisture store. Typically 15 to 25 for aquifers, 0 for others.	25		
Upper Zone (one) Deficit	mm	Has a maximum value equal to the drying constant	0		
Lower Zone (two) Deficit	mm	Lower zone is effectively infinite	0		
Catchment Storage Parameters					
Area	km^2	Effective Catchment Area	5		
Cr	days	First (linear) storage constant. Typically 0 to 30	0		
Cqu	cumec.days^2/km^2	Second (non-linear) storage constant. Typically 0 to 5000	5		
R1	mm/d	Initial output of first storage	0.1		
Q1	m^3/s	Initial output of second storage	0.2		

Figure A.3 - Catchmod parameter set for Llyn Cwmystradllyn catchment

CATCHMOD (VBA Version 4.11)   Input Parameter Sheet   Catchment Name: Dwfor

Soilmoisture store parameters	Units	Comments	Area Number 1	2	3
Area Type		For reference/labelling purposes only (Chalk, Clay, Urban etc)	Slow	V Rapid	Rapid
Slope of Drying Curve		Usually 0.3 for most zones, zero for urban (paved) areas	0.3	0.3	0.3
Drying Constant (mm)	mm	Finite storage of upper soil moisture store. Typically 30 to 150 (0 for urban).	35	0.01	15
Direct Percolation (%)	%	% bypassing soil moisture store. Typically 15 to 25 for aquifers, 0 for others.	15	0	0
Upper Zone (one) Deficit	mm	Has a maximum value equal to the drying constant	0	0	0
Lower Zone (two) Deficit	mm	Lower zone is effectively infinite	0	0	0

Catchment Storage Parameters	Units	Comments	1	2	3
Area	km^2	Effective Catchment Area	13.8	16	19.8
Cr	days	First (linear) storage constant. Typically 0 to 30	0	0	0
Cqu	cumec.days^2/km^2	Second (non-linear) storage constant. Typically 0 to 5000	300	0.09	1
R1	mm/d	Initial output of first storage	1	0	0
Q1	m^3/s	Initial output of second storage	2	0.05	0

Figure A.4 - Catchmod parameter set for Dwfor at Dolbenmaen catchment

A.3. Mid & South Ceredigion

CATCHMOD (VBA Version 4.11)   Input Parameter Sheet   Catchment Name: Llechryd

Soilmoisture store parameters	Units	Comments	Area Number 1	2	3
Area Type		For reference/labelling purposes only (Chalk, Clay, Urban etc)	Slow	Fast	V. Fast
Slope of Drying Curve		Usually 0.3 for most zones, zero for urban (paved) areas	0.3	0.3	0.3
Drying Constant (mm)	mm	Finite storage of upper soil moisture store. Typically 30 to 150 (0 for urban).	30	10	10
Direct Percolation (%)	%	% bypassing soil moisture store. Typically 15 to 25 for aquifers, 0 for others.	15	0	0
Upper Zone (one) Deficit	mm	Has a maximum value equal to the drying constant	0	0	0
Lower Zone (two) Deficit	mm	Lower zone is effectively infinite	0	0	0

Catchment Storage Parameters	Units	Comments	1	2	3
Area	km^2	Effective Catchment Area	424.9	202.3	280.8
Cr	days	First (linear) storage constant. Typically 0 to 30	0	0	0
Cqu	cumec.days^2/km^2	Second (non-linear) storage constant. Typically 0 to 5000	60	5	0.1
R1	mm/d	Initial output of first storage	2	1	0
Q1	m^3/s	Initial output of second storage	2	1	0

Figure A.5 - Catchmod parameter set for Teifi at Llechryd catchment

CATCHMOD (VBA Version 4.11)   Input Parameter Sheet   Catchment Name: Llyn Egnant

Soilmoisture store parameters	Units	Comments	Area Number 1	2	3
Area Type		For reference/labelling purposes only (Chalk, Clay, Urban etc)	Slow	Rapid	V Rapid
Slope of Drying Curve		Usually 0.3 for most zones, zero for urban (paved) areas	0.3	0.3	0.3
Drying Constant (mm)	mm	Finite storage of upper soil moisture store. Typically 30 to 150 (0 for urban).	5	5	5
Direct Percolation (%)	%	% bypassing soil moisture store. Typically 15 to 25 for aquifers, 0 for others.	10	0	0
Upper Zone (one) Deficit	mm	Has a maximum value equal to the drying constant	0	0	0
Lower Zone (two) Deficit	mm	Lower zone is effectively infinite	0	0	0

Catchment Storage Parameters	Units	Comments	1	2	3
Area	km^2	Effective Catchment Area	0.45	0.32	0.32
Cr	days	0	0	0	0
Cqu	cumec.days^2/km^2	Second (non-linear) storage constant. Typically 0 to 5000	5	0.5	0.05
R1	mm/d	Initial output of first storage	0	0	0
Q1	m^3/s	Initial output of second storage	0	0	0

Figure A.6 - Catchmod parameter set for Llyn Egnant

CATCHMOD (VBA Version 4.11) **Input Parameter Sheet** **Catchment Name: Pond Y Gwaith**

Soilmoisture store parameters	Units	Comments	Area Number 1	2	3
Area Type		For reference/labelling purposes only (Chalk, Clay, Urban etc)	Slow	Rapid	V Rapid
Slope of Drying Curve		Usually 0.3 for most zones, zero for urban (paved) areas	0.3	0.3	0.3
Drying Constant (mm)	mm	Finite storage of upper soil moisture store. Typically 30 to 150 (0 for urban).	5	5	5
Direct Percolation (%)	%	% bypassing soil moisture store. Typically 15 to 25 for aquifers, 0 for others.	10	0	0
Upper Zone (one) Deficit	mm	Has a maximum value equal to the drying constant	0	0	0
Lower Zone (two) Deficit	mm	Lower zone is effectively infinite	0	0	0
Catchment Storage Parameters					
Area	km^2	Effective Catchment Area	0.522	0.371	0.371
Cr	days	0	0	0	0
Cqu	$cumec.days^2/km^2$	Second (non-linear) storage constant. Typically 0 to 5000	5	0.5	0.05
R1	mm/d	Initial output of first storage	0	0	0
Q1	m^3/s	Initial output of second storage	0	0	0

Figure A.7 - Catchmod parameter set for Pond y Gwaith (transposed from Llyn Egnant adjusted for area difference)

CATCHMOD (VBA Version 4.11) **Input Parameter Sheet** **Catchment Name: Llyn Teifi**

Soilmoisture store parameters	Units	Comments	Area Number 1	2	3
Area Type		For reference/labelling purposes only (Chalk, Clay, Urban etc)	Slow	Fast	V. Fast
Slope of Drying Curve		Usually 0.3 for most zones, zero for urban (paved) areas	0.3	0.3	0.3
Drying Constant (mm)	mm	Finite storage of upper soil moisture store. Typically 30 to 150 (0 for urban).	50	30	30
Direct Percolation (%)	%	% bypassing soil moisture store. Typically 15 to 25 for aquifers, 0 for others.	10	0	0
Upper Zone (one) Deficit	mm	Has a maximum value equal to the drying constant	0	0	0
Lower Zone (two) Deficit	mm	Lower zone is effectively infinite	0	0	0
Catchment Storage Parameters					
Area	km^2	Effective Catchment Area	0.74	0.49	0.49
Cr	days	0	0	0	0
Cqu	$cumec.days^2/km^2$	Second (non-linear) storage constant. Typically 0 to 5000	25	5	0.1
R1	mm/d	Initial output of first storage	0	0	0
Q1	m^3/s	Initial output of second storage	0	0	0

Figure A.8 - Catchmod parameter set for Llyn Teifi (transposed from Wyre Llanrhystud adjusted for area difference)

A.4. North Eryri Ynys Môn

CATCHMOD (VBA Version 4.04) **Input Parameter Sheet** **Catchment Name: Alaw**

Soilmoisture store parameters	Units	Comments	Area Number 1	2	3
Area Type		For reference/labelling purposes only (Chalk, Clay, Urban etc)	Slow	Very Fast	Fast
Slope of Drying Curve		Usually 0.3 for most zones, zero for urban (paved) areas	0.3	0.2	0.33
Drying Constant (mm)	mm	Finite storage of upper soil moisture store. Typically 30 to 150 (0 for urban).	25	3	9
Direct Percolation (%)	%	% bypassing soil moisture store. Typically 15 to 25 for aquifers, 0 for others.	5	0	0
Upper Zone (one) Deficit	mm	Has a maximum value equal to the drying constant	0	0	0
Lower Zone (two) Deficit	mm	Lower zone is effectively infinite	0	0	0
Catchment Storage Parameters					
Area	km^2	Effective Catchment Area	6	2.19	25.2
Cr	days	First (linear) storage constant. Typically 0 to 30	0	0	0
Cqu	$cumec.days^2/km^2$	Second (non-linear) storage constant. Typically 0 to 5000	10	0.1	1.5
R1	mm/d	Initial output of first storage	0	0	0
Q1	m^3/s	Initial output of second storage	0.0	0.0	0.2

Figure A.9 - Catchmod parameter set for Alaw catchment

CATCHMOD (VBA Version 4.04) **Input Parameter Sheet** **Catchment Name: Cefni**

Soilmoisture store parameters	Units	Comments	Area Number 1	2	3
Area Type		For reference/labelling purposes only (Chalk, Clay, Urban etc)	Slow	Very Fast	Fast
Slope of Drying Curve		Usually 0.3 for most zones, zero for urban (paved) areas	0.3	0.2	0.3
Drying Constant (mm)	mm	Finite storage of upper soil moisture store. Typically 30 to 150 (0 for urban).	20	2	8.5
Direct Percolation (%)	%	% bypassing soil moisture store. Typically 15 to 25 for aquifers, 0 for others.	10	0	0
Upper Zone (one) Deficit	mm	Has a maximum value equal to the drying constant	0	0	0
Lower Zone (two) Deficit	mm	Lower zone is effectively infinite	0	0	0
Catchment Storage Parameters					
Area	km^2	Effective Catchment Area	11	3	21
Cr	days	First (linear) storage constant. Typically 0 to 30	0	0	0
Cqu	$cumec.days^2/km^2$	Second (non-linear) storage constant. Typically 0 to 5000	20	0.1	3
R1	mm/d	Initial output of first storage	0	0	0
Q1	m^3/s	Initial output of second storage	0.2	0.1	0.4

Figure A.10 - Catchmod parameter set for Cefni catchment

CATCHMOD (VBA Version 4.04) **Input Parameter Sheet** **Catchment Name: Glaslyn**

Soilmoisture store parameters	Units	Comments	Area Number 1	2	3
Area Type		For reference/labelling purposes only (Chalk, Clay, Urban etc)	Slow	Very Fast	Fast
Slope of Drying Curve		Usually 0.3 for most zones, zero for urban (paved) areas	0.3	0	0.3
Drying Constant (mm)	mm	Finite storage of upper soil moisture store. Typically 30 to 150 (0 for urban).	30	0	2
Direct Percolation (%)	%	% bypassing soil moisture store. Typically 15 to 25 for aquifers, 0 for others.	12	0	0
Upper Zone (one) Deficit	mm	Has a maximum value equal to the drying constant	0	0	0
Lower Zone (two) Deficit	mm	Lower zone is effectively infinite	0	0	0
Catchment Storage Parameters					
Area	km^2	Effective Catchment Area	22	1.6	45
Cr	days	First (linear) storage constant. Typically 0 to 30	0	0	0
Cqu	$cumec.days^2/km^2$	Second (non-linear) storage constant. Typically 0 to 5000	50	0	0.3
R1	mm/d	Initial output of first storage	0	0	0
Q1	m^3/s	Initial output of second storage	4.2	0.3	8.5

Figure A.11 - Catchmod parameter set for Glaslyn catchment

CATCHMOD (VBA Version 4.04) **Input Parameter Sheet** **Catchment Name: Llugwy**

Soilmoisture store parameters	Units	Comments	Area Number 1	2	3
Area Type		For reference/labelling purposes only (Chalk, Clay, Urban etc)	Slow	Very Fast	Fast
Slope of Drying Curve		Usually 0.3 for most zones, zero for urban (paved) areas	0.3	0.2	0.33
Drying Constant (mm)	mm	Finite storage of upper soil moisture store. Typically 30 to 150 (0 for urban).	30	3	15
Direct Percolation (%)	%	% bypassing soil moisture store. Typically 15 to 25 for aquifers, 0 for others.	10	0	0
Upper Zone (one) Deficit	mm	Has a maximum value equal to the drying constant	0	0	0
Lower Zone (two) Deficit	mm	Lower zone is effectively infinite	0	0	0
Catchment Storage Parameters					
Area	km^2	Effective Catchment Area	0.65	0.3	1.4
Cr	days	First (linear) storage constant. Typically 0 to 30	0	0	0
Cqu	$cumec.days^2/km^2$	Second (non-linear) storage constant. Typically 0 to 5000	20	0	0.1
R1	mm/d	Initial output of first storage	0	0	0
Q1	m^3/s	Initial output of second storage	0.1	0.0	0.1

Figure A.12 - Catchmod parameter set for Llugwy catchment

CATCHMOD (VBA Version 4.04) **Input Parameter Sheet** **Catchment Name: Marchlyn**

Soilmoisture store parameters	Units	Comments	Area Number 1	2	3
Area Type		For reference/labelling purposes only (Chalk, Clay, Urban etc)	Slow	Very Fast	Fast
Slope of Drying Curve		Usually 0.3 for most zones, zero for urban (paved) areas	0.3	0.2	0.33
Drying Constant (mm)	mm	Finite storage of upper soil moisture store. Typically 30 to 150 (0 for urban).	30	2	10
Direct Percolation (%)	%	% bypassing soil moisture store. Typically 15 to 25 for aquifers, 0 for others.	10	0	0
Upper Zone (one) Deficit	mm	Has a maximum value equal to the drying constant	0	0	0
Lower Zone (two) Deficit	mm	Lower zone is effectively infinite	0	0	0
Catchment Storage Parameters					
Area	km^2	Effective Catchment Area	0.25	0.25	0.48
Cr	days	First (linear) storage constant. Typically 0 to 30	0	0	0
Cqu	cumec.days^2/km^2	Second (non-linear) storage constant. Typically 0 to 5000	30	0	1
R1	mm/d	Initial output of first storage	0	0	0
Q1	m^3/s	Initial output of second storage	0.1	0.1	0.1

Figure A.13 - Catchmod parameter set for Marchlyn Bach catchment

Appendix B. Teifi Pools modelled for a constant transfer from Pond y Gwaith

AFW (2017) developed a mass balance model for Teifi Pools. The model did not use the catchment area for all three reservoirs together, due to the lack of data for Pond y Gwaith. Instead only Llyn Teifi and Llyn Egnant were modelled, and a constant transfer rate of 3.11 Ml/d was assumed for the transfer from Pond y Gwaith to Llyn Teifi.

AFW (2017) scaled the flows by the ADF at Glanteifi (where a gauging station exists) to estimate flow at Teifi Pools. Other catchments were tested in AFW (2017) to be used as potential donors, namely Cothi at Felin Mynachdy, Wye at Ddol Farm, Ystwyth at Pont Llolwyn and Wyre Llanrhystud (this one also suggested by Thomas Elmitt, DCWW, pers comm). The fit of modelled to observed storage was reasonable, although the calculated performance metrics were relatively poor (AFW, 2017). AFW selected Glanteifi to be used as the donor for consistency with Afon Teifi Llechryd and because the fit of modelled data using Glanteifi was not worse than using any other tested donor catchment. Here, we also use Glanteifi as donor, but instead of transposing the hydrograph based on ADF, we will assess if better results can be achieved by transposing Catchmod calibrated at Glanteifi to Teifi Pools. Further methods assessed here, not tested previously, include:

- Transposing Catchmod model parameters calibrated at Wyre Llanrhystud to Teifi Pools;
- Transposing Catchmod model parameters calibrated at Llanfair to Teifi Pools; and
- Calibrate Catchmod using AFW (2017) mass balance model.

The daily precipitation timeseries for Teifi Pools (excluding Pond y Gwaith), Afon Teifi at Llanfair, Afon Teifi at Glanteifi and Wyre Llanrhystud were derived from CEH-GEAR (Tanguy et al., 2016) and the daily PET timeseries were obtained from CHESS-PE dataset (Robinson *et al.*, 2016). Figure B.1 shows how the timeseries compare for the first six months of 2015 for the four catchments. The timeseries result from the averaging of 1km x 1km grid cells, and therefore for days with high precipitation variability (example 01/06/2015, Figure B.2), the precipitation amount can be very different between catchments (Figure B.1).

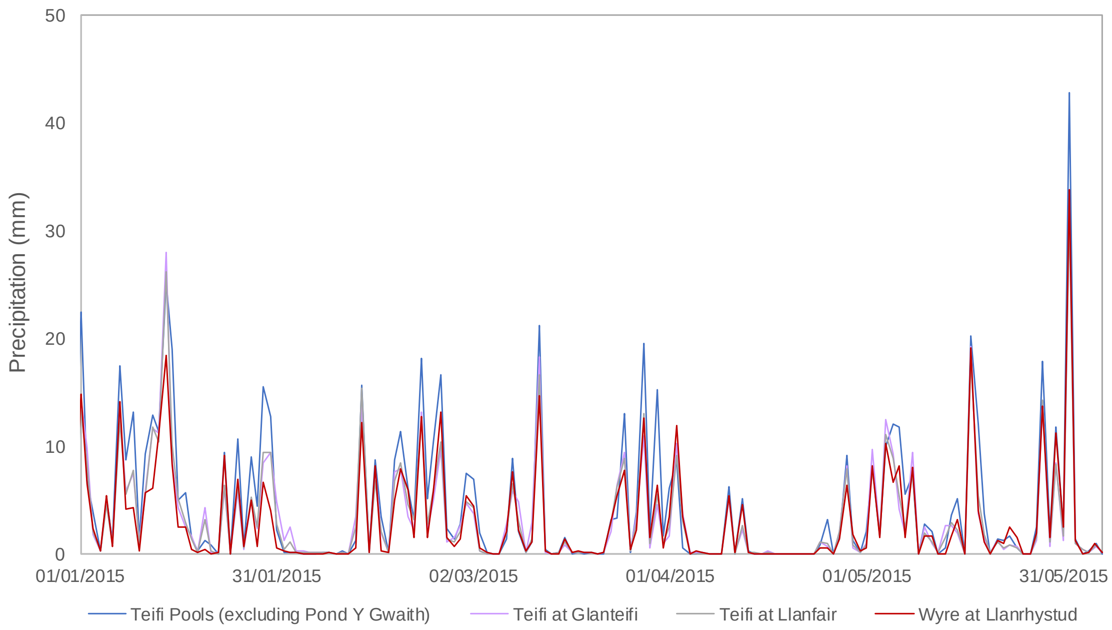

Figure B.1 - Daily precipitation time series derived from CEH-GEAR for Teifi Pools (excluding Pond y Gwaith), Teifi at Glanteifi, Teifi at Llanfair and Wyre at Llanrhystud

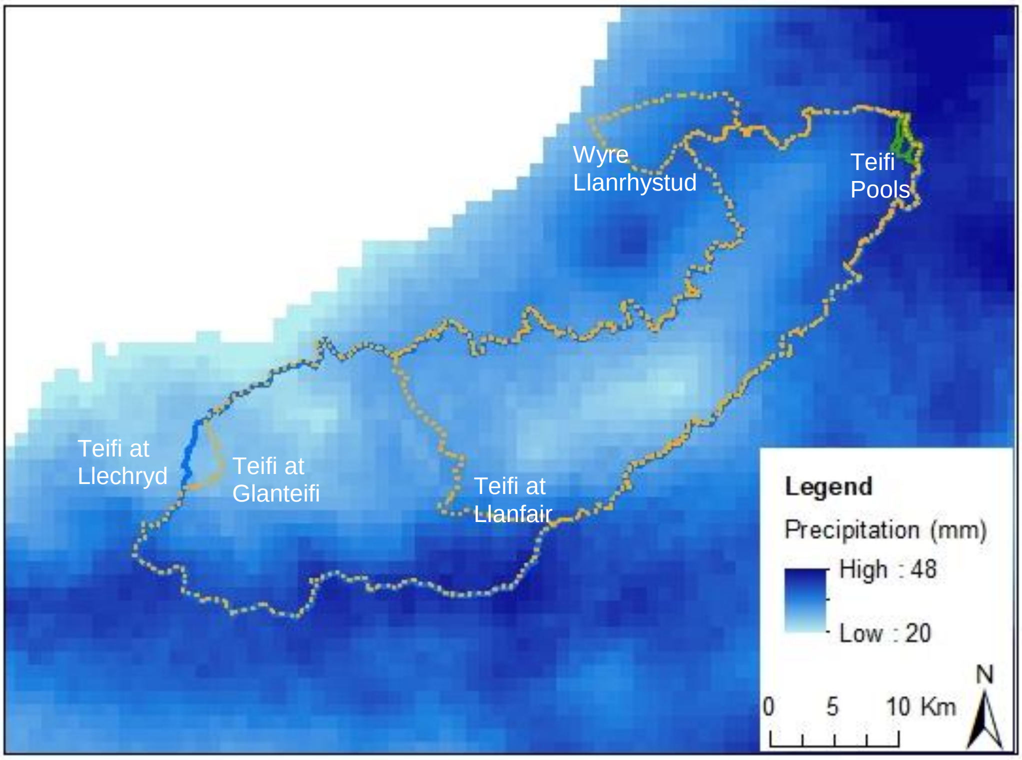

Figure B.2 - CEH-GEAR precipitation on 01/06/2015

We transposed the Catchmod parameters calibrated at Glanteifi (Sect. 5.2) to Teifi Pools (excluding Pond y Gwaith) to simulate flow. Additionally, we calibrated Catchmod at Llanfair and at Llanrhystud (Wyre) and transposed the parameters to Teifi Pools (excluding Pond y Gwaith). The Llanfair gauging station and Wyre at Llanrhystud are closer to Teifi Pools, than Glanteifi gauging station.

Firstly we calibrated Catchmod at Llanfair using data between 12/04/2002 and 31/12/2015 (note that we had already calibrated a model for Glanteifi as outlined in Sect. 5.2). There is data prior to 1982 (the gauging station at Llanfair closed on 01/11/1982 and re-opened again on 12/04/2002), but 13 years of data was considered a long enough period to achieve a robust model parameterisation. A warm up period of 160 days was used. For Teifi Pools, minor agricultural abstractions and Tregaron bog (10 km^2) have a partial effect on flows, but nonetheless this is a sensibly natural flow regime catchment. Figure B.3 shows how the Catchmod simulated flow compares with the observed flow for two distinct time periods.

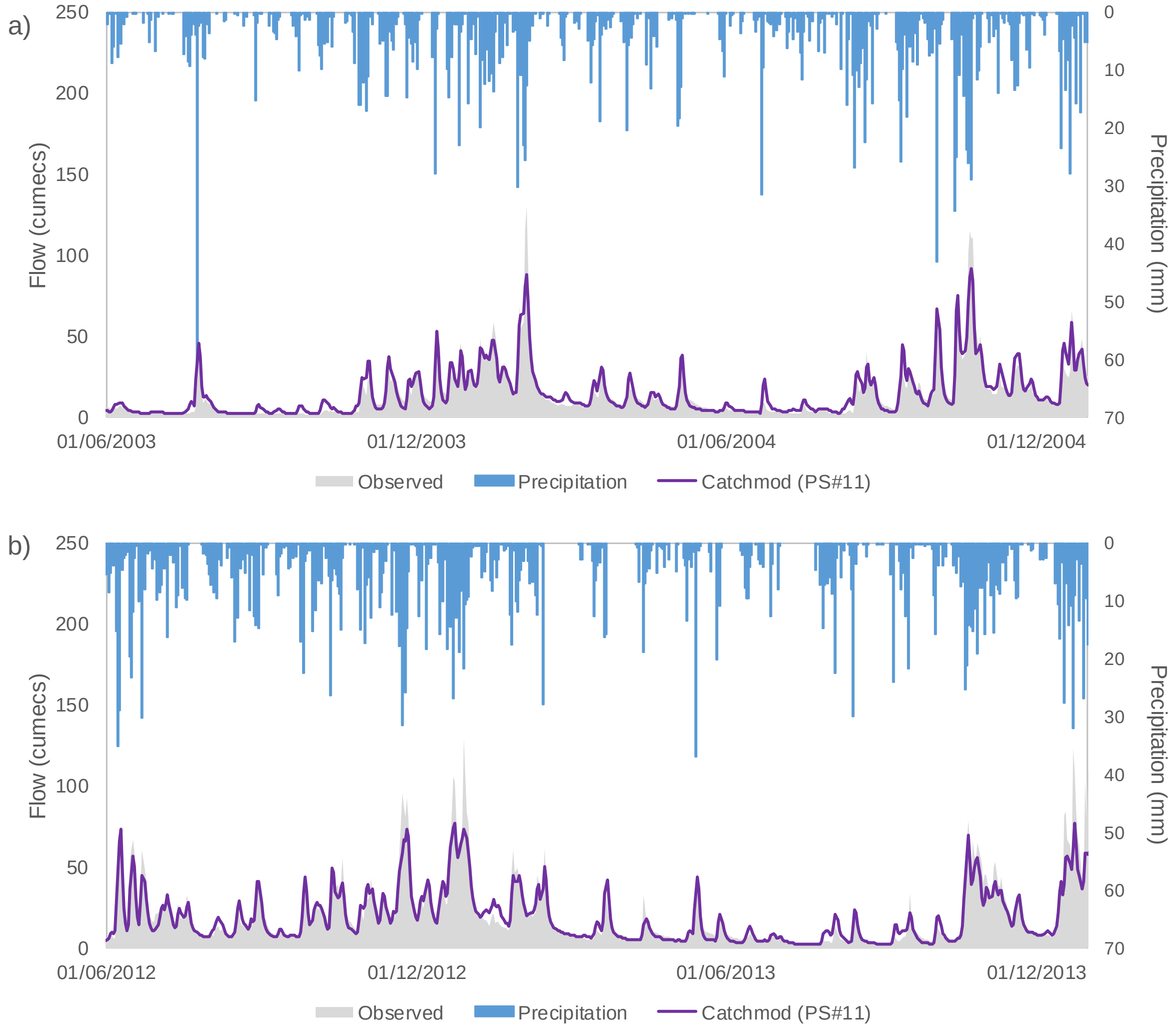

Figure B.3 - Llanfair observed and simulated streamflow for a) 06/2003-12/2004; b) 06/2012-12/2013

shows the FDC for the observed and simulated streamflow and Figure B.5 shows the volumetric fit. Both figures show good performance of Catchmod to simulate flow at Llanfair.

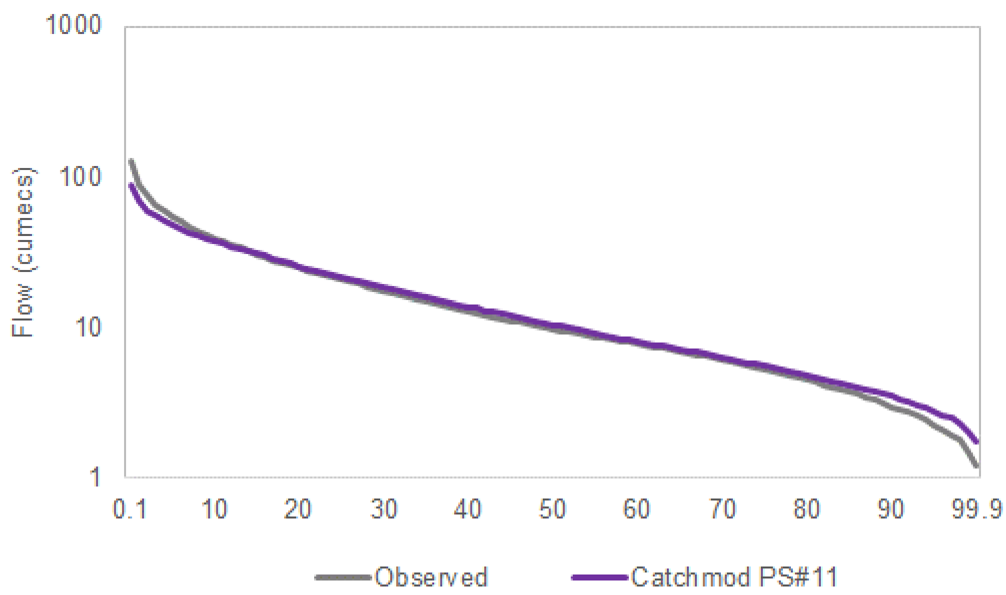

Figure B.4 - Llanfair FDC for observed flow and FDC for the Catchmod calibration (for parameter set #11)

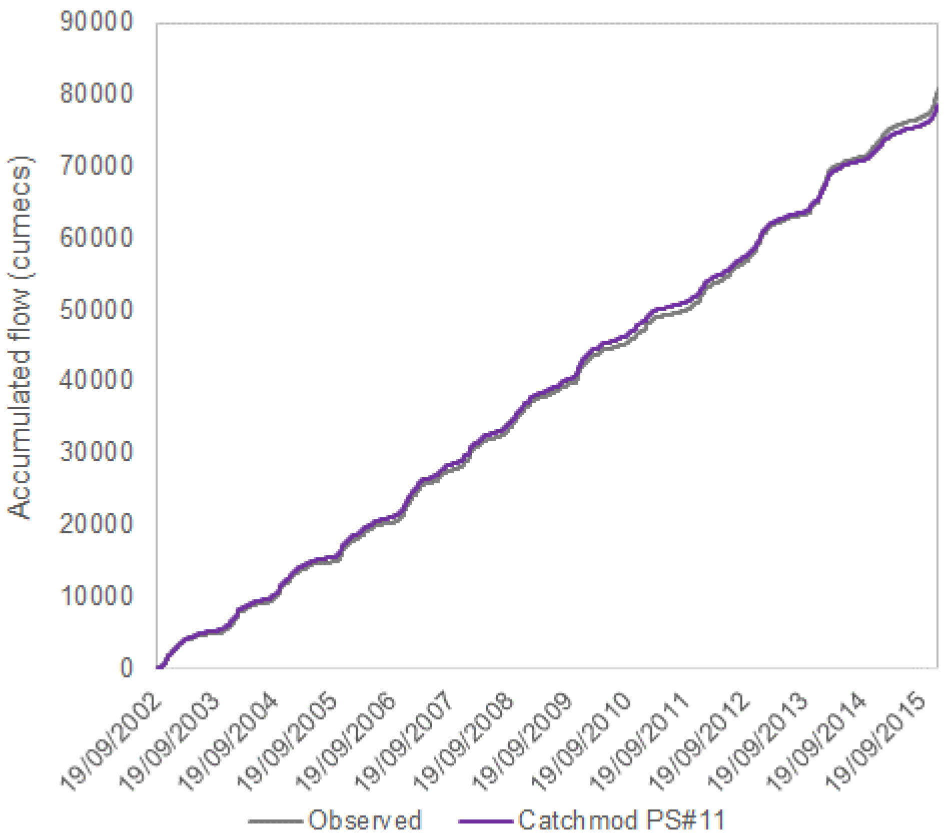

Figure B.5 - Volumetric fit for Teifi at Llanfair. Missing data 22/05/2005-08/06/2005

We also calibrated Catchmod for Wyre at Llanrhystud using data between 01/10/1999 and 31/12/2014, as this time period has nearly no missing flow data and it is long enough to achieve a robust model parameterisation. However, we needed to be careful between 24/12/2011 and 23/01/2012 as during this time period flow data was estimated from gauging station 63001 (NRFA, 2018). Flowdata were also suspicious in January 2005 and 2011 (NRFA, 2018). Wyre at Llanrhystud has no known artificial influences and is considered a natural flow regime catchment (NRFA, 2018). Figure B.6 shows how the Catchmod simulated flow compares with the observed flow for two distinct time periods.

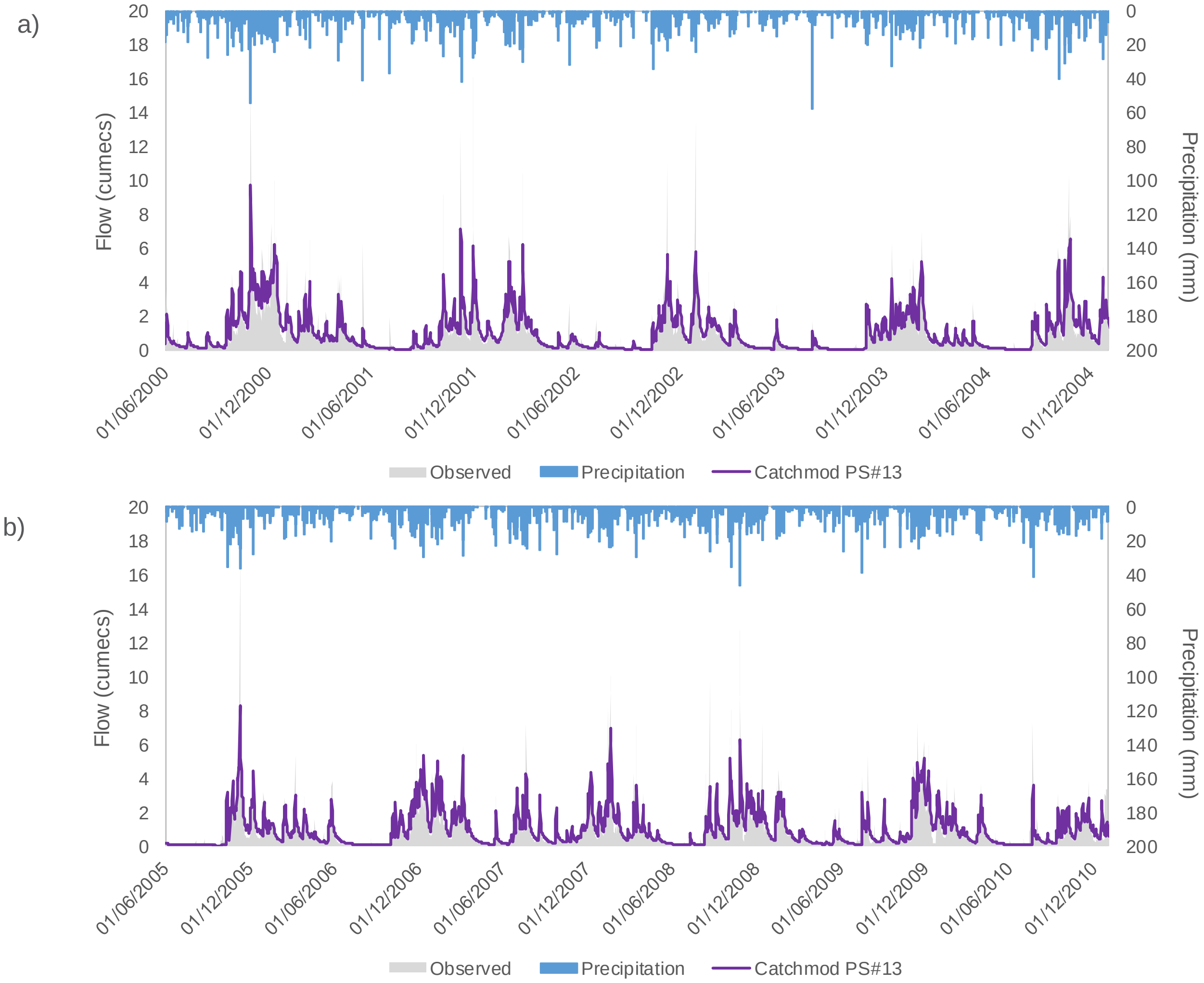

Figure B.6 - Llanrhystud observed and simulated streamflow for a) 06/2003-12/2004; b) 06/2012-12/2013

Figure B.7 shows the FDC for the observed and simulated streamflow and Figure B.8 shows the volumetric fit. Figure B.7 shows a reasonable fit in terms of FDC and Figure B.8 shows a good performance in terms of volumetric fit.

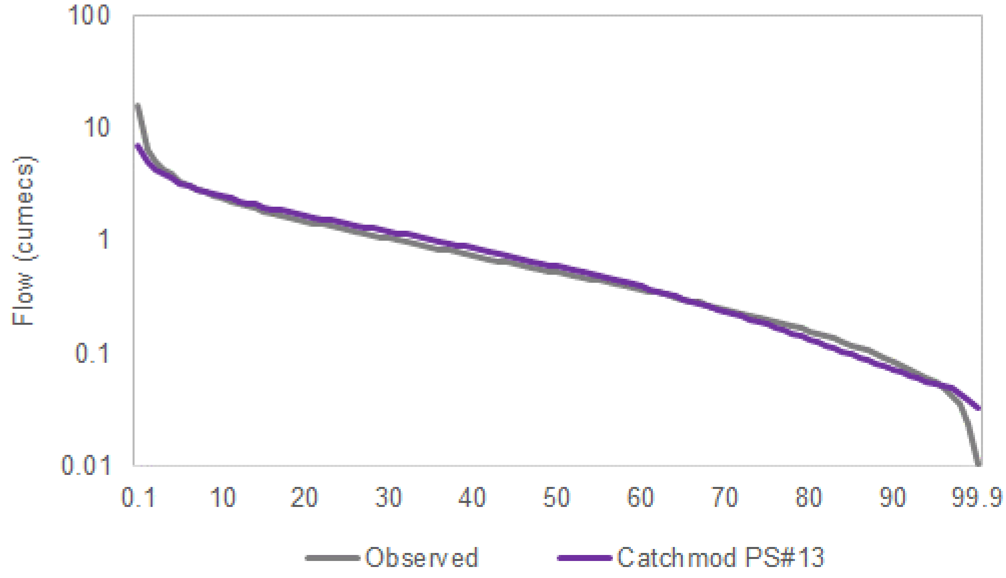

Figure B.7 - Llanrhystud FDC for observed flow and FDC for the Catchmod calibration (for parameter set #13)

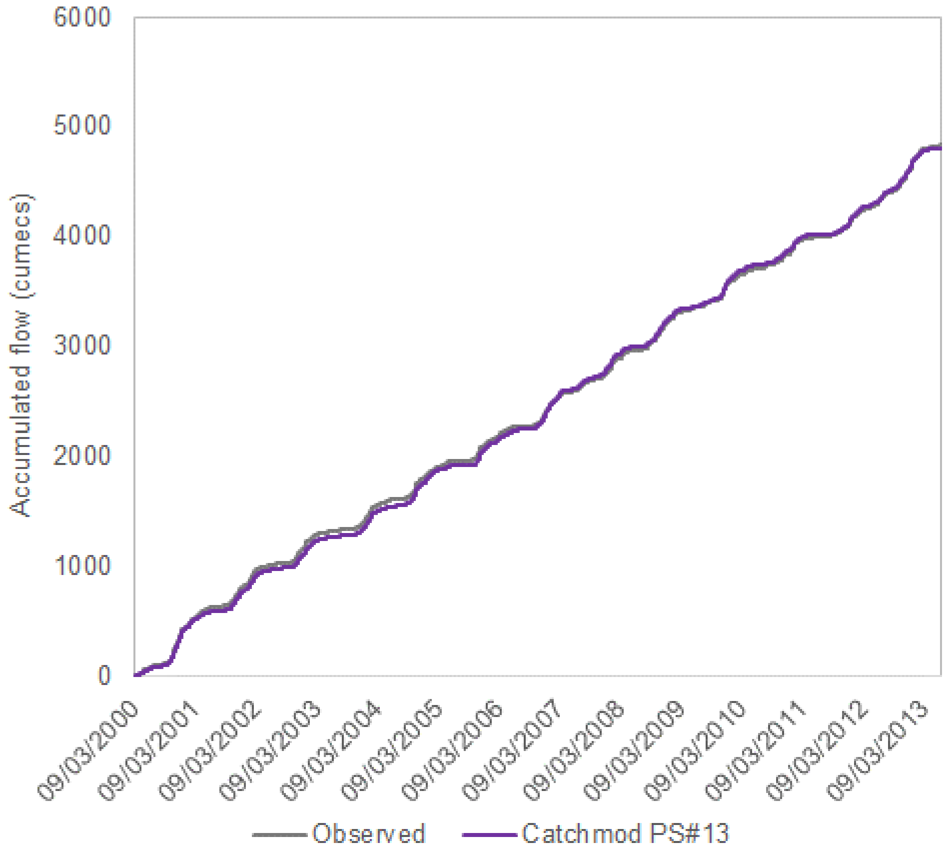

Figure B.8 - Volumetric fit for Wyre at Llanrhystud

The parameter sets obtained from: i) calibration of Catchmod at Llanfair; ii) calibration of Catchmod at Glanteifi; and iii) calibration of Catchmod at Llanrhystud (Wyre), were transposed to predict flow at Teifi Pools. Additionally, we calibrated Catchmod aiming at matching the storage as well as possible, using the AFW mass balance model.

The resulting simulated flows as a FDC are shown in Figure B.9**Error! Reference source not found.**. Figure B.9 shows how these three methods compare with the FDC from LFE (upscaled as the file we were given by

DCWW was for a catchment with area equal to 1.025 km^2) and to the FDC obtained by AFW (2017) (result of transposing the hydrograph at Glanteifi).

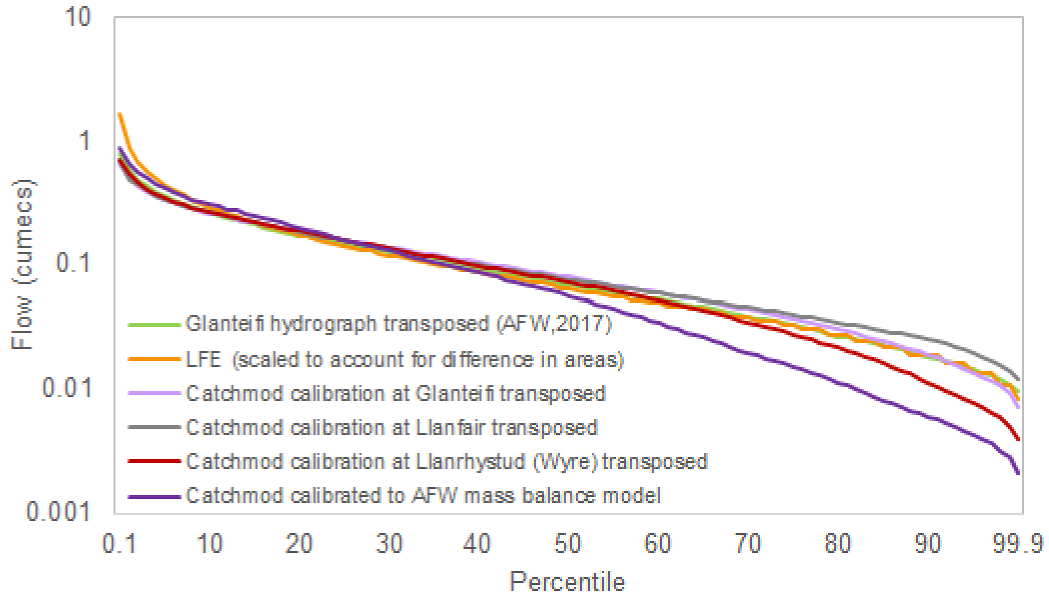

Figure B.9 - Flow Duration Curves from the LFE, for the Catchmod calibration transposed from Llanfair, Glanteifi and Llanrhystud (Wyre), for the Catchmod calibration using the mass balance model (parameter set #9) and for Glanteifi hydrograph transposed.

Figure B.10 and Figure B.11 show the simulated storage using the AFW mass balance model. Simulated storage using i) inflows predicted based on Catchmod calibrated to AFW mass balance model (**----** in Figure B.10 and Figure B.11) and ii) inflows predicted based on Catchmod calibration at Llanrhystud (Wyre) transposed (**----** in Figure B.10 and Figure B.11) give the best results. While in years like 2003 and 2006 there are significant differences between simulated and observed storage, it is important to note that the shape of the modelled storage curves seem to closely follow the shape of the observed storage curve. In paraticular, the shape of the two best simulated storage curves, match much more closely the shape of the observed storage compared to the results obtained by AFW (2017) using Glanteifi transposed hydrograph (**----** in Figure B.10 and Figure B.11).

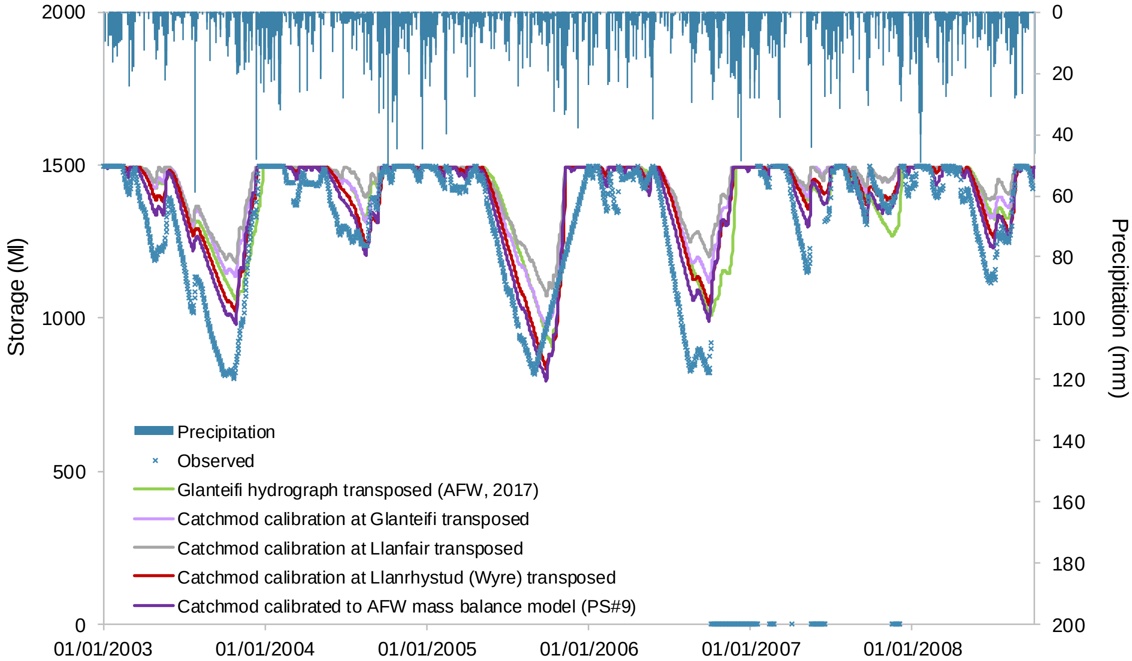

Figure B.10 - Observed and modelled storages for Teifi Pools for 01/2004-09/2008

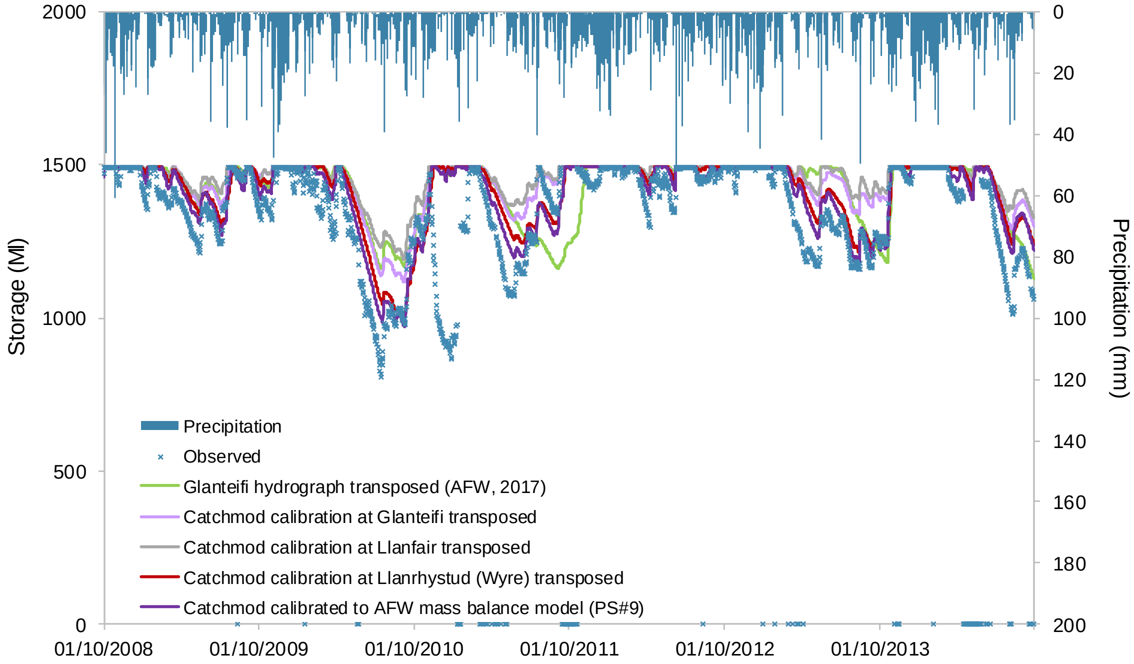

Figure B.11 - Observed and modelled storages for Teifi Pools for 10/2008 – 09/2014

The reason why in years like 2003 and 2006 the simulated storage is significantly different from the observed storage, may be because the assumed constant transfer from Pond y Gwaith of 3.11 Ml/d is not realistic in those years. Pond y Gwaith storage is 67 Ml and catchment area is 1.27 km2 (Table 5.1) so sustaining a 3.11 Ml/d transfer throughout a dry period seems unlikely (Thomas Elmitt, DCWW, pers comms). If, for example, a constant transfer of 2.00 Ml/d is assumed throughout 2003, a much better fit is achieved (Figure B.12). Clearly, more accurate data on water transferred from Pond y Gwaith is essential to better model drawdowns at Teifi Pools.

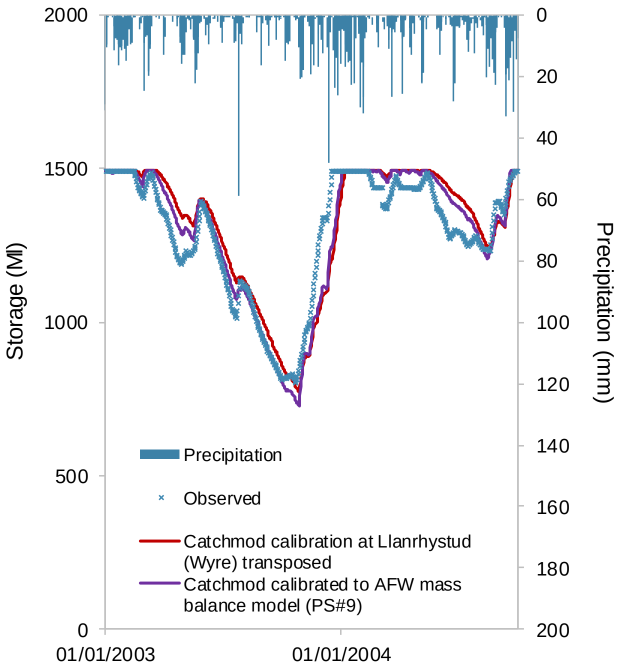

Figure B.12 - Observed and modelled storages for Teifi Pools for 01/2003-09/2004, using a constant transfer from Pond y Gwaith of 2.00 Ml/d throughout 2003, and 3.11 Ml/d during the rest of the time.

From these results it was agreed that DCWW, as per Thomas Elmitt pers comm, was to look at whether the Pond y Gwaith transfer could be linked to a flow series that reduced the contribution from 3.11 Ml/d to a more realistic transfer during dry periods (Thomas Elmitt pers comm).

Appendix C. Volumetric fit plots

C.1. North Eryri Ynys Môn

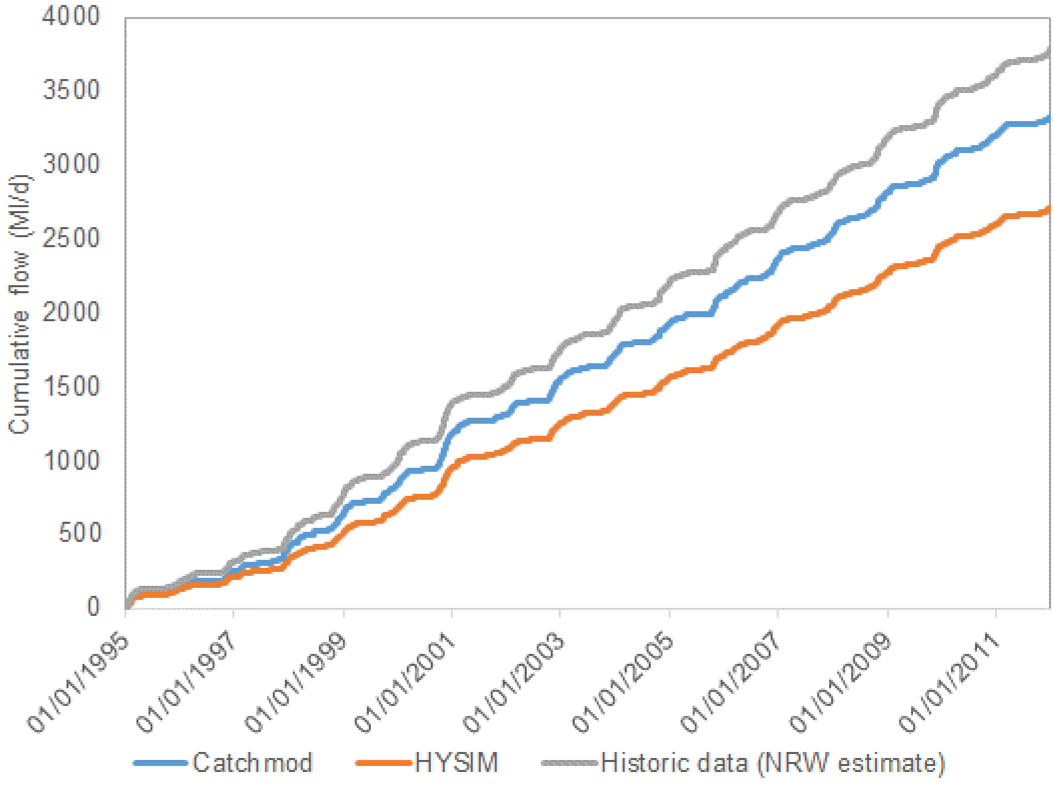

Figure C.1 - Volumetric fit for Llyn Alaw

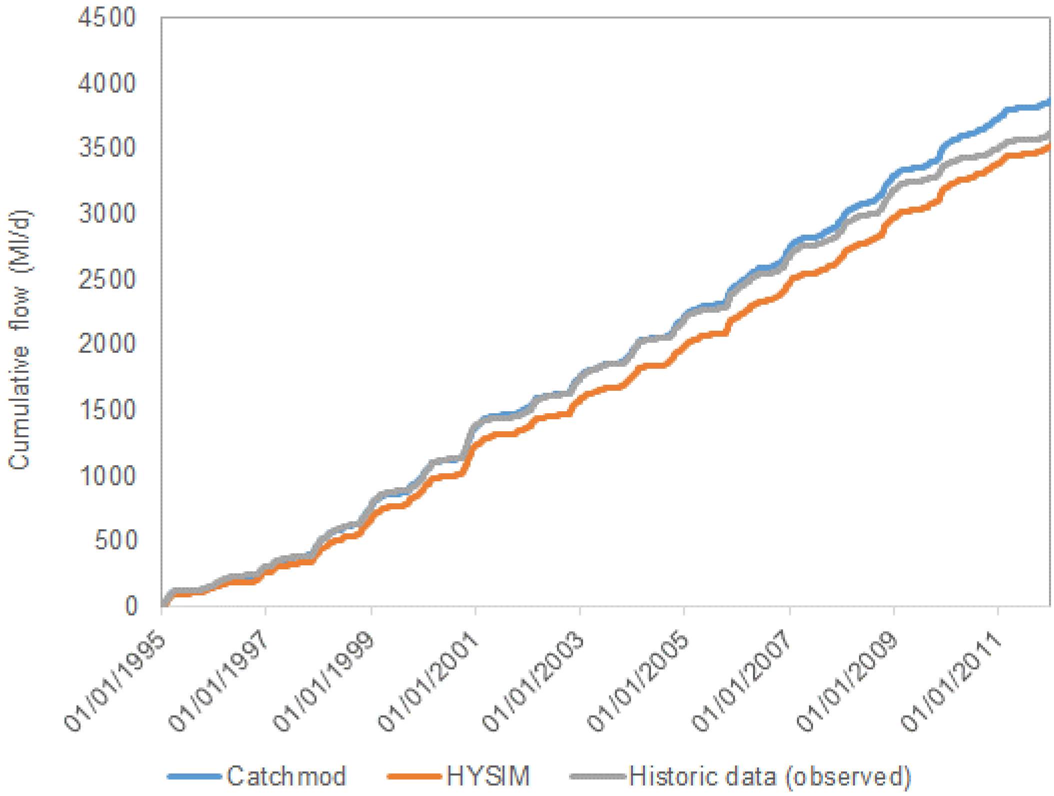

Figure B.2 - Volumetric fit for Llyn Cefni

Note – In Figure B.2 the revised inflows have a higher cumulative fit compared with the gauging station since they represent the inflow sequence into the entire catchment rather than just the flow measured at the gauging station.

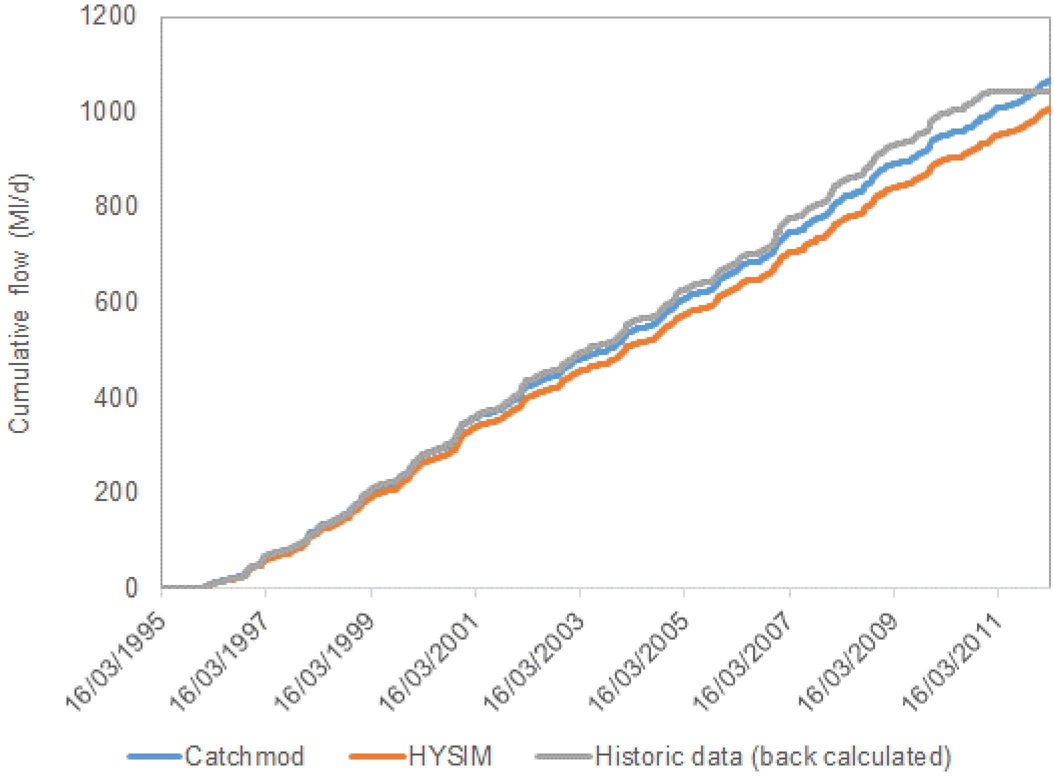

Figure B.3 - Volumetric fit for Ffynnon Llugwy

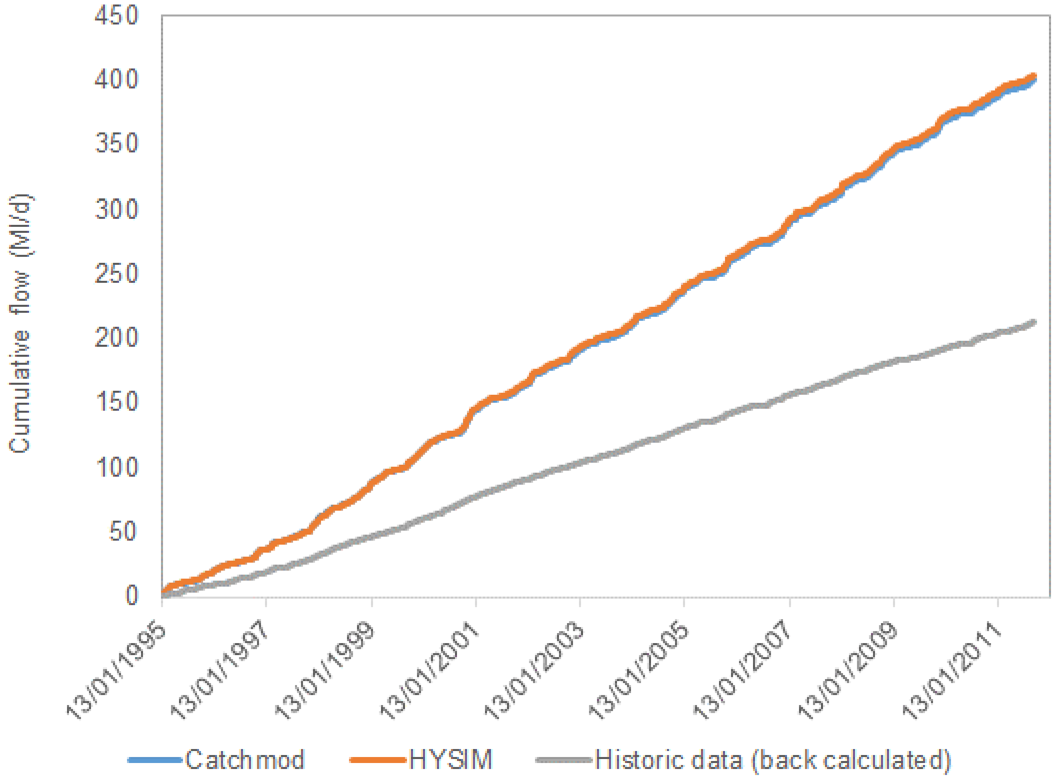

Figure B.4 - Volumetric fit for Marchlyn Bach

The 'observed' flows at Marchlyn Bach have been back calculated by mass balance but there is considerable leakage/ dam safety releases that aren't accurately measured. The 'observed' flows are therefore significantly underestimated.

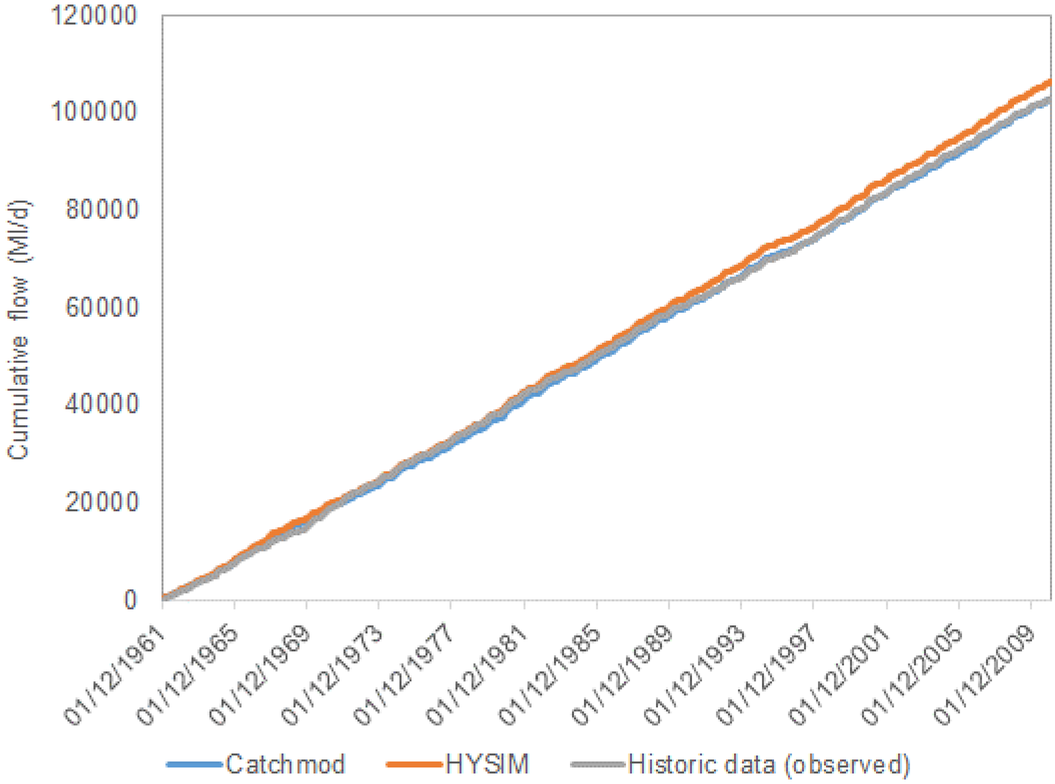

Figure B.5 - Cumulative fit for Glaslyn

Appendix D. Detailed plots for selected drought events

D.1. North Eryri Ynys Môn

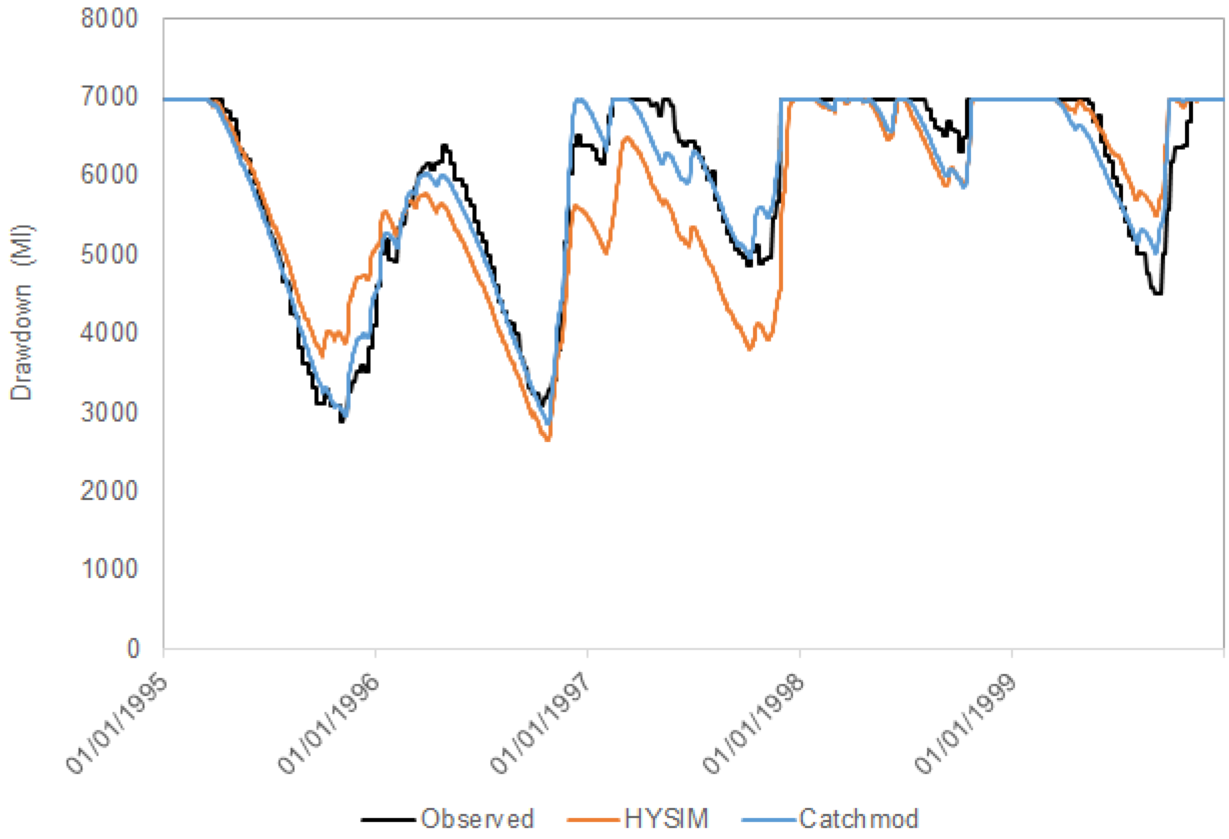

Figure D.1 - Reservoir Storage for Llyn Alaw

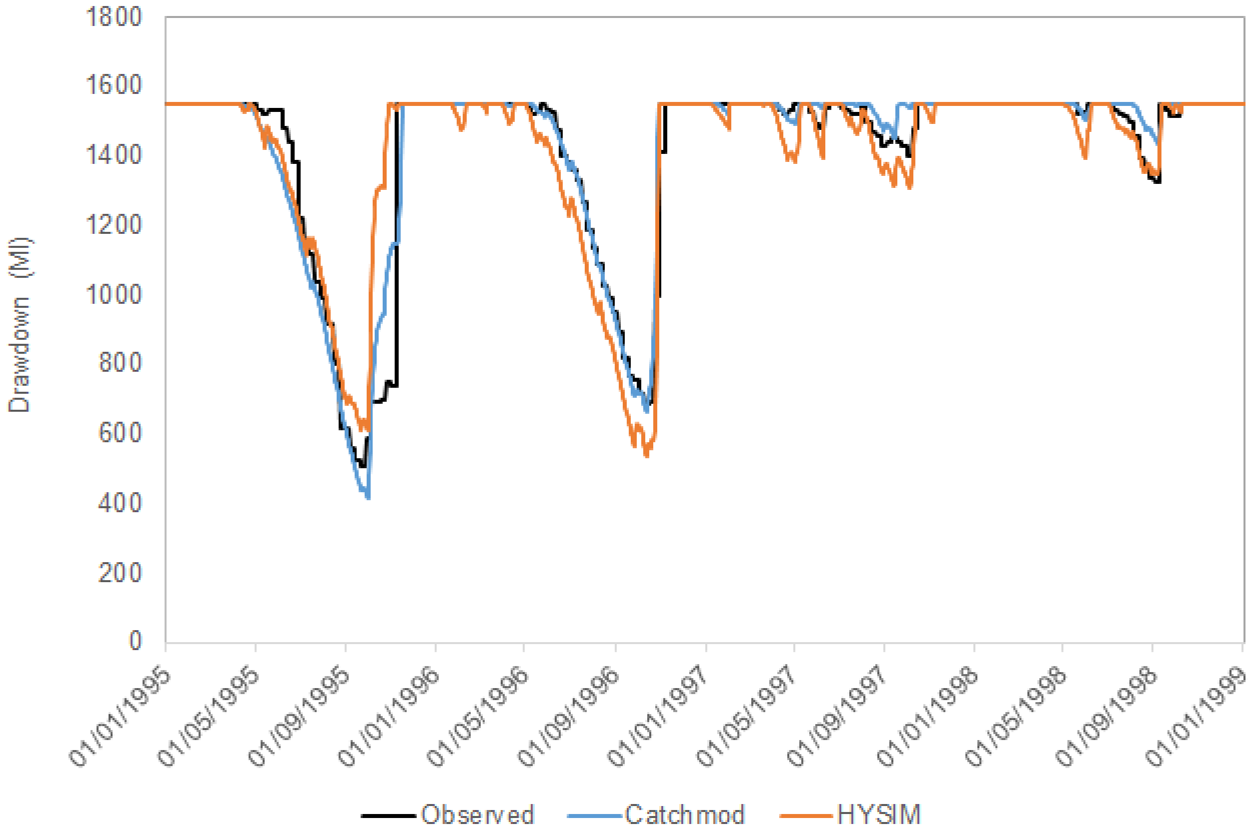

Figure D.2 - Reservoir Storage for Llyn Cefni

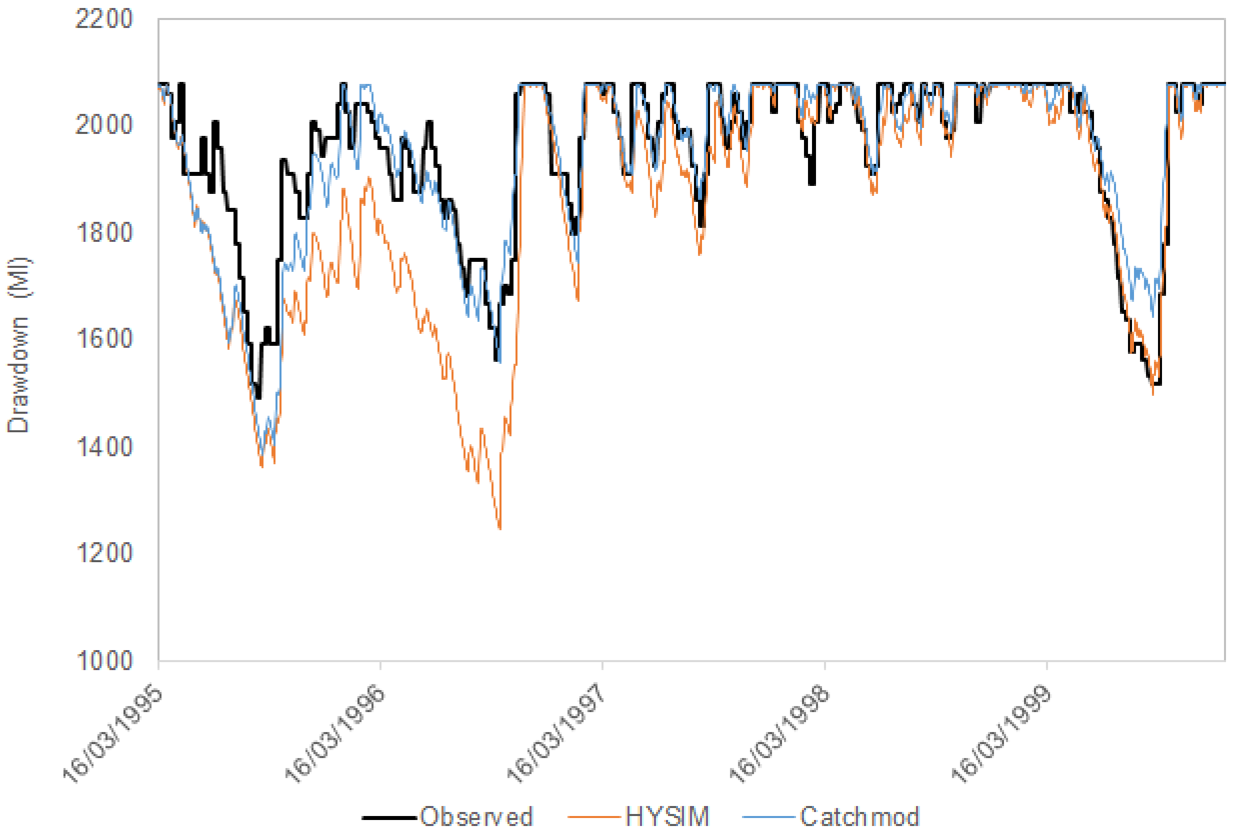

Figure D.3 - Reservoir Storage for Ffynnon Llugwy

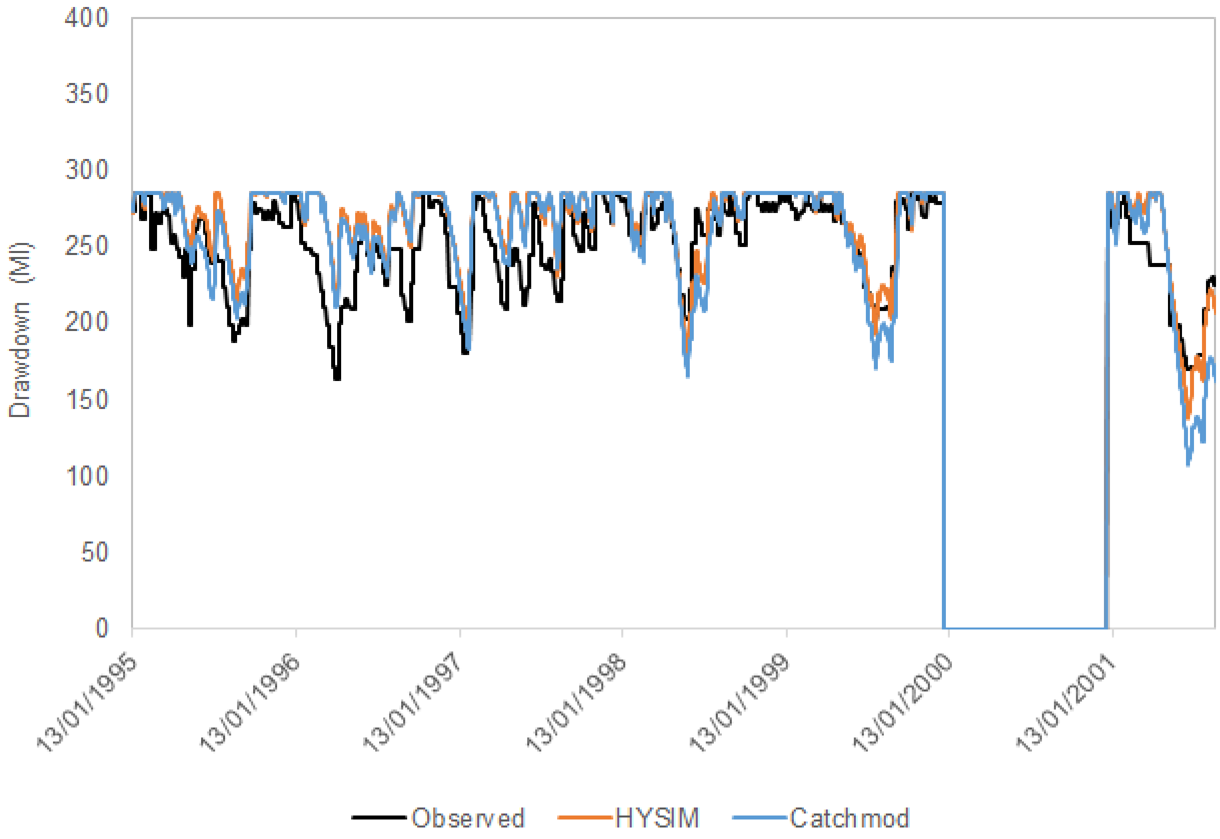

Figure D.4 - Reservoir Storage for Marchlyn Bach.

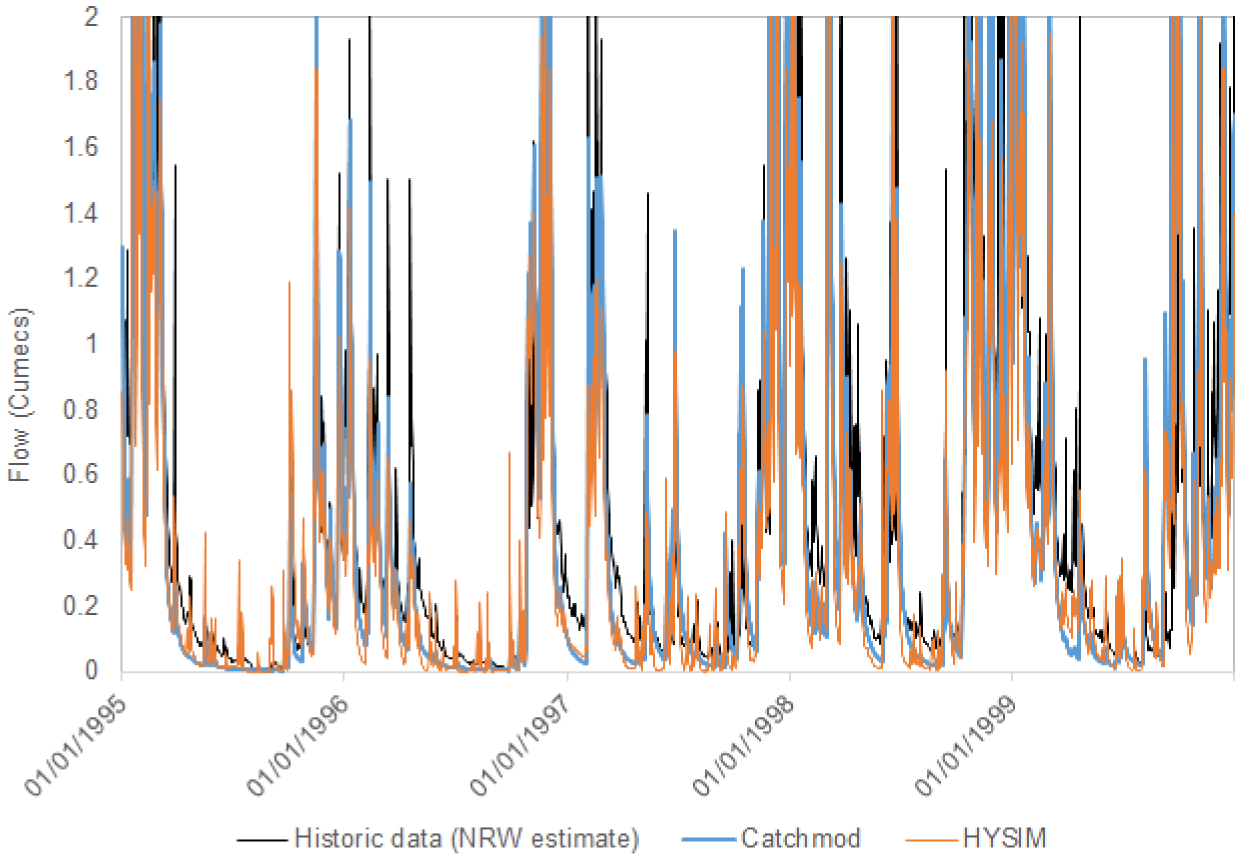

Figure D.5 - Flow timeseries for Llyn Alaw.

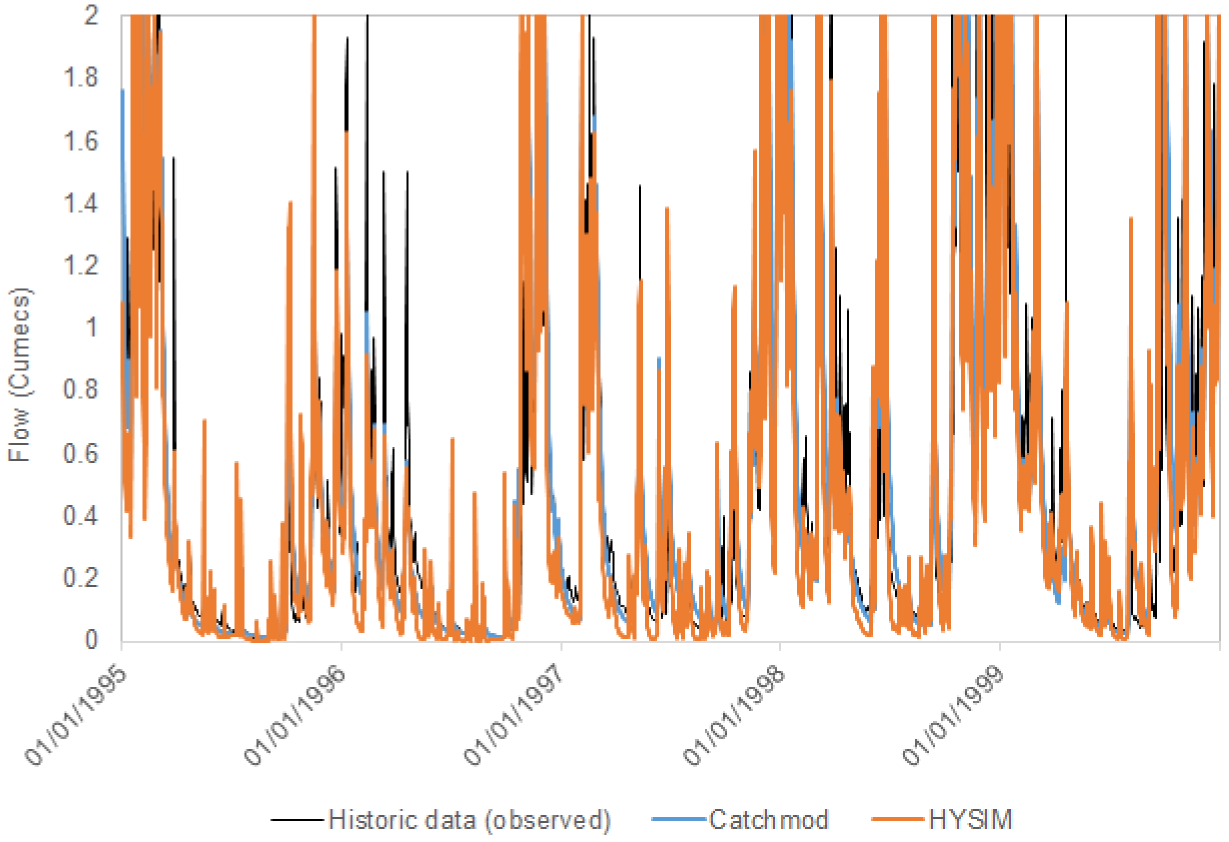

Figure D.6 - Flow timeseries for Llyn Cefni

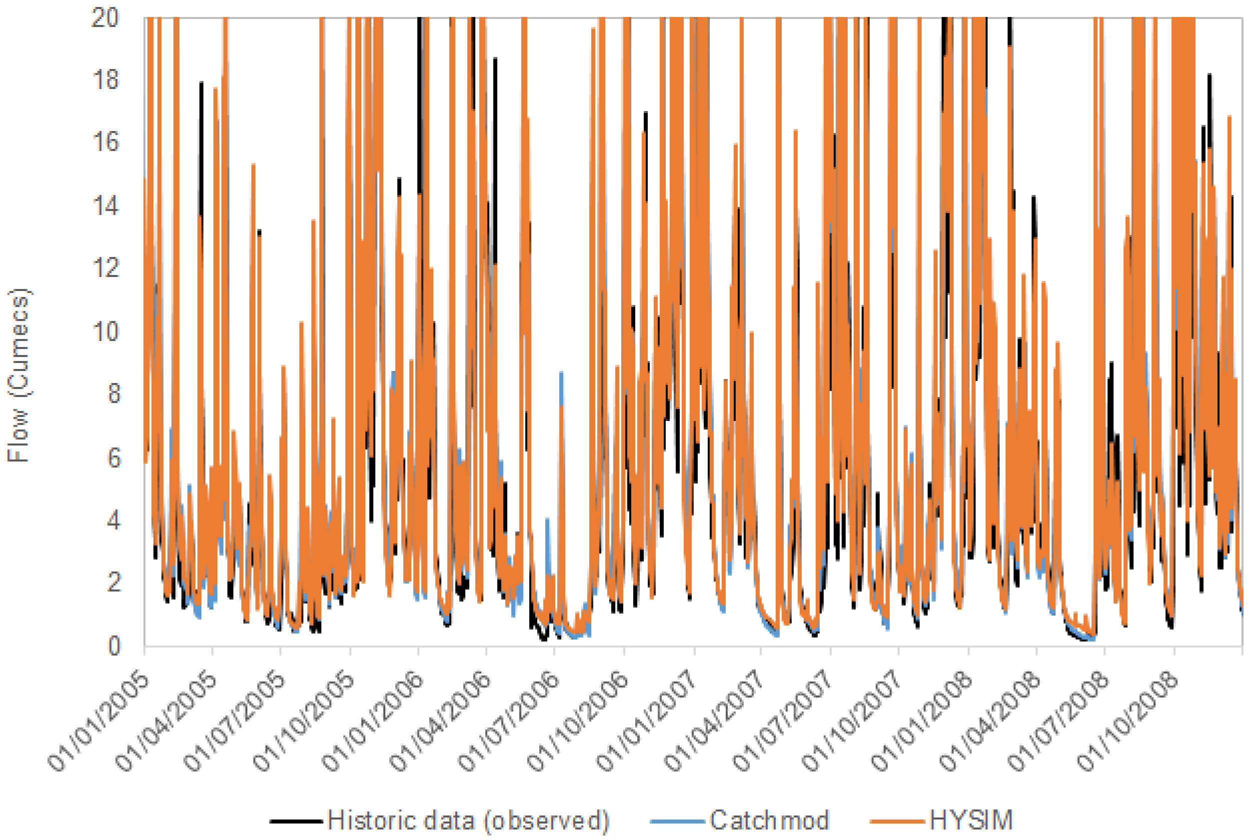

Figure D.7 - Flow timeseries for Glaslyn

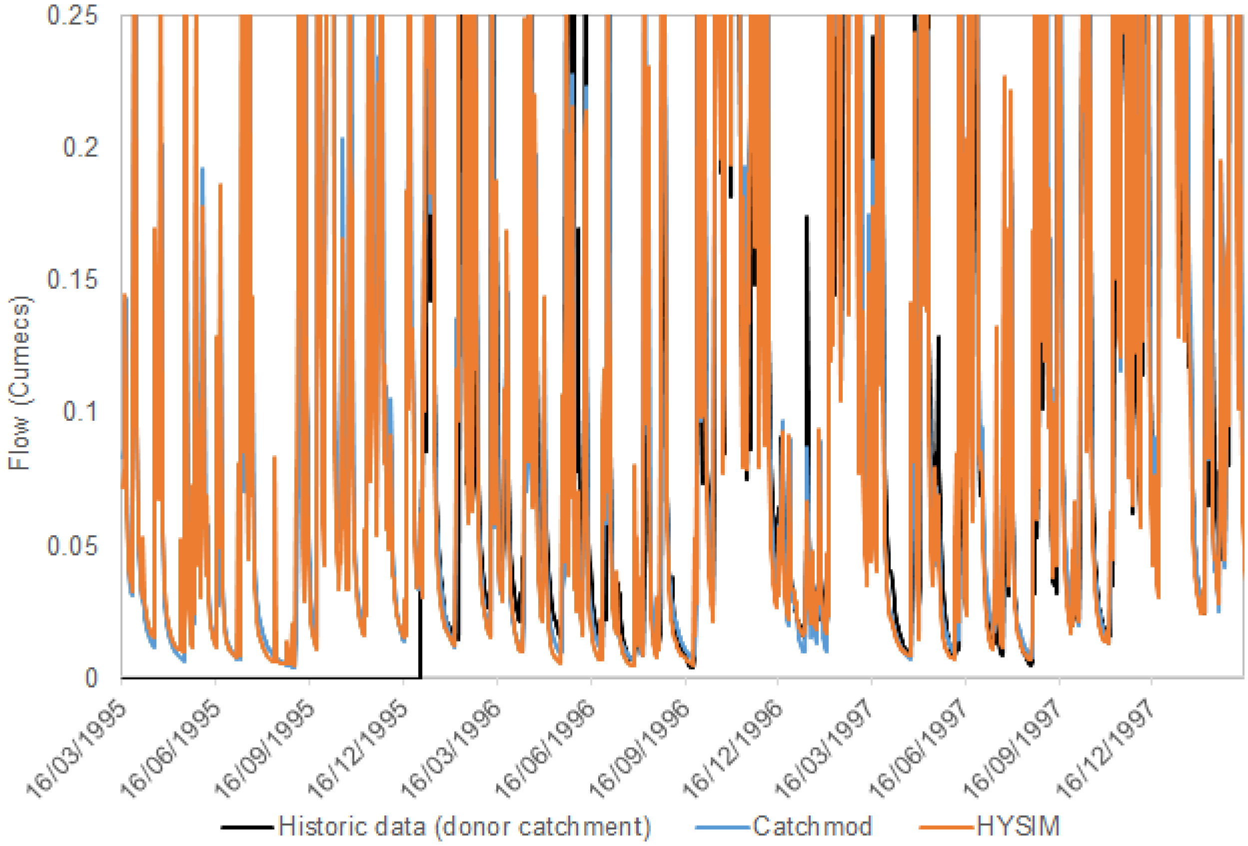

Figure D.8 - Flow timeseries for Ffynnon Llugwy

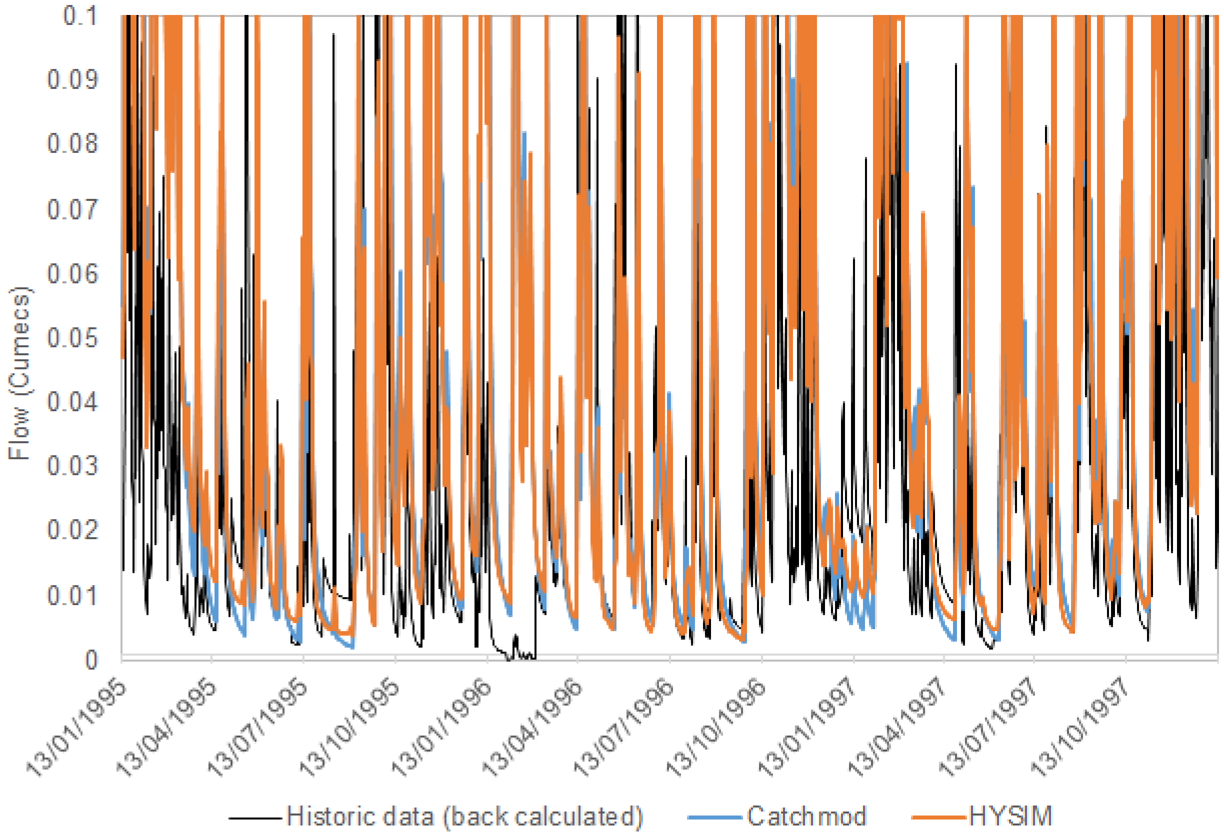

Figure D.9 - Flow timeseries for Marchlyn Bach

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