Update of the Blithe Hydrology

07 August 2017

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Contents

1 Introduction

Blithfield Reservoir, supported during dry periods by the River Blithe Pumpback, is a key component of the SSW supply system. The annual licence of the reservoir is 29,200Ml (equivalent to an average of 80Ml/d) and the recent average abstraction is around 60Ml/d. Drought conditions and demand saving measures are established and are based on stored volume relative to established control curves. Thus, the Level of Service of the whole system is derived from the simulation of this reservoir. Given this, it is essential that simulated inflow series to the reservoir and flow series downstream at the River Blithe Pumpback intake are as accurate as possible. This report describes the methodology followed and the results obtained in this hydrology update. The adopted period of simulation is 1882-2014.

The report is structured as follows:

- Modelling approach
- Available input data
- Calibration-validation process
- Simulation
- Summary

The conjunctive deployable output of the SSW supply system has been modelled with water resources allocation models since WRMP04. The inflow series was largely based on a single HYSIM model set up by earlier work in 1997. This HYSIM model was calibrated to the naturalised Upper Blithe flow sequence at Blithfield Reservoir and also applied to the Lower Blithe at the location of the pumpback by decomposition. The HYSIM model was progressively refined and extended in time for the Company's WRMP09 and WRMP14 submissions.

During the WRMP14 study work it became apparent that this modelling approach had some shortfalls. In particular, calibration to new flow gauging data on the Upper and Lower Blithe was poor and the model tended to overpredict the low flows observed during the 2011/12 drought. An alternative approach using a HYSIM model developed by Severn Trent Water produced an even higher system yield, and therefore, the WRMP14 submission was made using a hybrid flow series to determine baseline deployable output and the sensitivity of the DO to climate change using the STWL model.

As a consequence, for WRMP19, SSW needed a simulated flow series based on a robust calibration across the entire historic record. They required that the impact of significant upstream groundwater abstractions and discharges were explicitly modelled, and that both the reservoir and downstream catchments were separately simulated and calibrated. In addition to improving confidence in the baseline assessment of deployable output, this aimed to allow the simulation of series to study the impact of climate change and other scenarios.

2 Modelling approach

2.1 Requirements

Assessment of the yield or Deployable Output of a water resources system requires a long period of data (particularly river flows for a reservoir system) to allow the assessment to cover a wide range of climatic conditions. Flow data is rarely available for the length of period required. So models are used to simulate flows over longer periods, taking advantage of the fact that rainfall records are usually much more extensive than flow records.

The model selected for this purpose was HYSIM (Hydrological Simulation model).

2.2 HYSIM

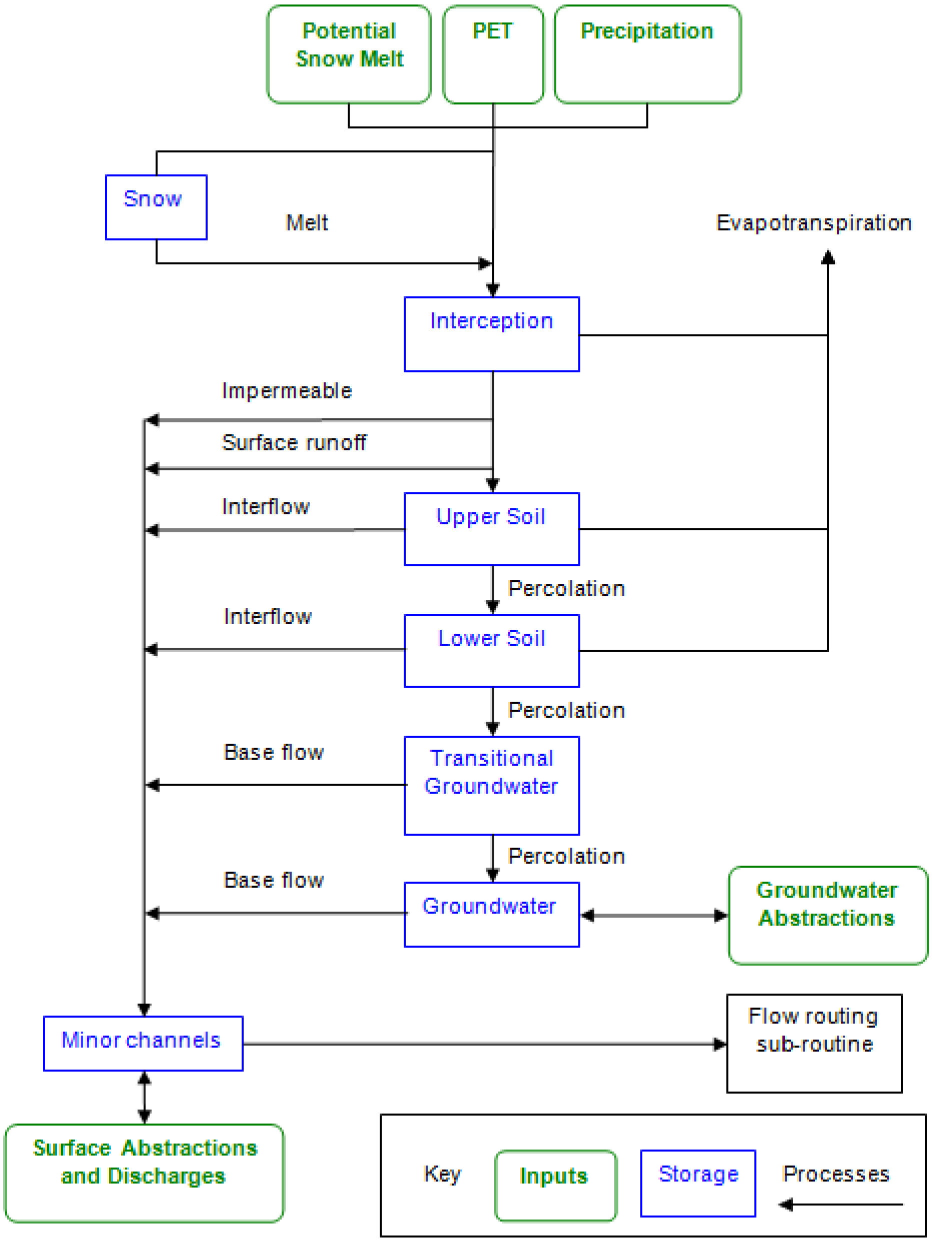
HYSIM is a lumped and conceptual rainfall-runoff model which was developed by Ron Manley (Water Resource Associates Ltd.) in the 1970s. It comprises a linked set of storages. The capacity of each storage, the maximum rate of transfer between them and equations which govern the transfer processes are all defined by time invariant parameters. Figure 5 shows a flow chart of the inputs, storage and processes that are defined in HYSIM. The key data inputs are rainfall and potential evapotranspiration (PET). The model also incorporates artificial influences (surface water abstractions and discharges, and groundwater abstractions), but in this study there are no sewage treatment works discharges, and abstractions are relatively minor.

Although HYSIM has since been refined and further developed, it remains a similar program now compared to the one used at the time of the creation of the original simulations. One of the advantages of HYSIM is its automated optimisation procedures which facilitate rapid calibration.

Although HYSIM has the option for inclusion of snowmelt it was decided not to include this element in this study. This was partly because of the lack of readily available temperature data sets but more particularly the fact that including snowmelt would have little or no effect on simulated low flows. Snowmelt may affect the timing of high flows but this is not a concern for this work.

Calibration involves a combination of manual adjustment and automatic optimisation. Some catchment parameters such as the area, reach and reach gradient are required by HYSIM, whilst others can be set as default values and altered as part of calibration. Within HYSIM there is the facility to subdivide the catchment in order to take account of varying geology, land use and drainage network. HYSIM also has the functionality to allow for the cascading of catchments through a system.

Figure 1: HYSIM flow chart



Source: R E Manley and Water Resource Associates Ltd (2006) A Guide to Using HYSIM

3 Available input data

3.1 Requirements

As in any hydrological simulation, some input data are required to generate streamflows, comprising:

- Rainfall and PET series during the whole simulation period to be transformed into runoff
- Recorded flow series for calibration and validation purposes
- Artificial influences modifying the natural flows

This chapter analyses the existing information in order to select the most suitable choice of data.

3.2 Rainfall

Daily rainfall data have been provided by the Environment Agency (EA) (Table 1) from the following rain gauges in the area of interest (see Figure 2):

Table 1: Rain gauge location and characteristics

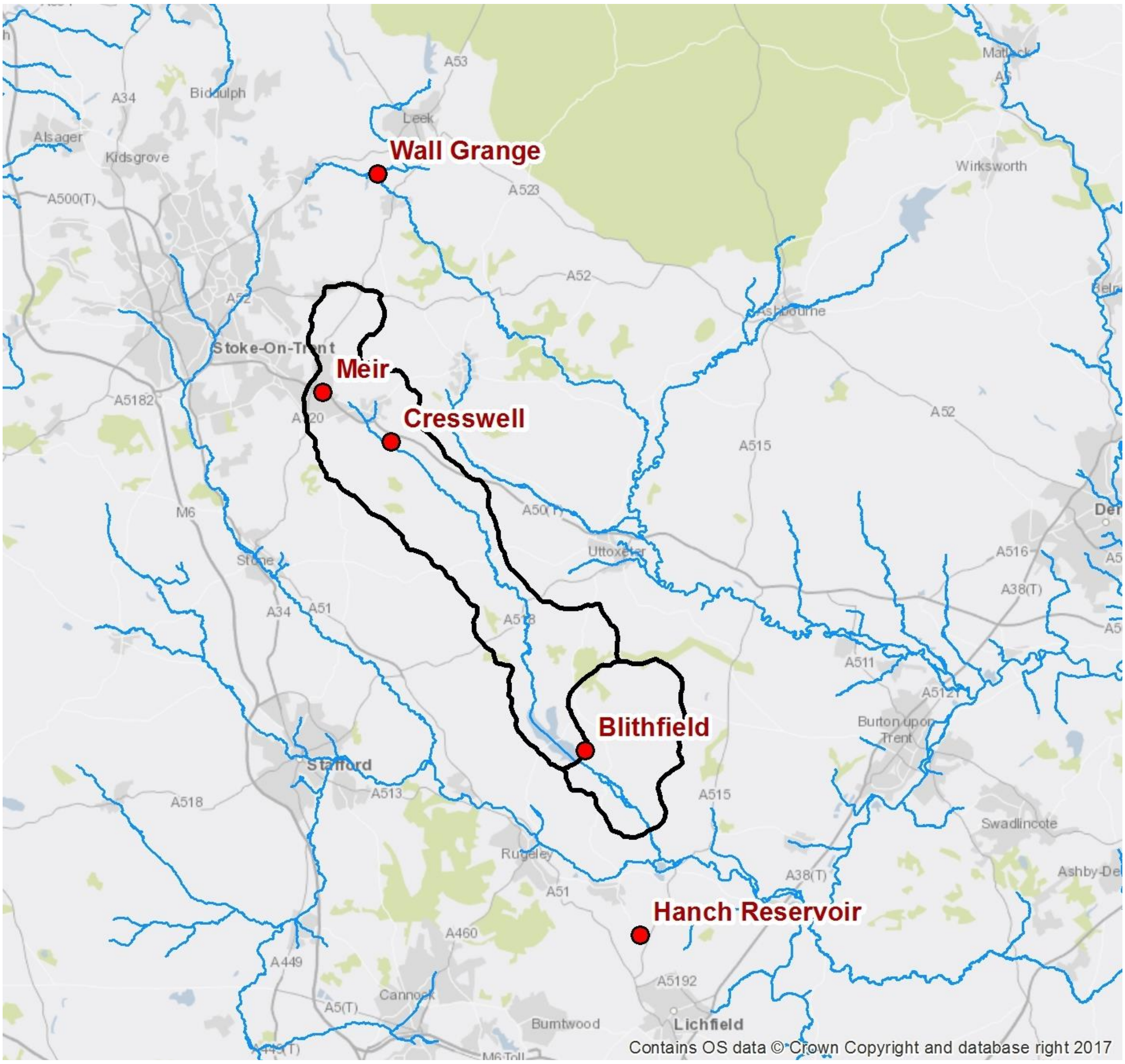
Gauge	NGR	AAR (mm)	Data Provider	Type	Period
Cresswell	SJ973395	891	EA	Storage	1961-1983
		871		Tipping Bucket	2000-2016
Hanch Reservoir	SK104136	691	EA	Storage	1918-2016
Blithfield	SK075233	714	EA	Storage	1961-2010
		676	SSW	Tipping Bucket	1974-2016
Meir	SJ937421	821	EA	Unknown	1882-1994
Wall Grange	SJ966536	909	EA	Storage	1882-2016

Notes: National Grid Reference (NGR), Annual Average Rainfall (AAR)

The information covers the period of study but is unevenly distributed. In the case of Blithfield, the two available series corresponding to different stations (TBR and the storage gauge) have a concurrent period from 1974 to 2010. A quality check found many months with zero rainfall in the 21st century for the storage gauge which does not match with the tipping bucket gauge or other stations. They are followed by a large rainfall value on the final day of the month, and therefore, they probably correspond to periods with no daily measurement that are summarised by a total at the end of the month. In a similar manner the Blithfield TBR is read every working day, so readings on Mondays (or the day following a public holiday) often show higher values as they are accumulated totals over three or more days.

In general, the storage gauge measures more rainfall than the TBR, with an average difference of 8%. Given that daily totals are usually more reliable when recorded by storage gauges, this series was kept while the TBR series was used to infill and extend the missing information. The accumulated weekend totals at Blithfield TBR will have some impact, but this is not considered significant.

Figure 2: Location of rain gauges and catchments of study



Source: Mott MacDonald

Based on the previous set of data, infilling and extension of rainfall series at each station for the period 1882-2014 was conducted as follows:

- A monthly correlation analysis was undertaken between each pair of stations from the original 5, for the period of overlapping data.
- Missing monthly values were infilled by using the derived relationship with the best-correlated station, with the assessment of "best" being undertaken for each month separately. Thus January and March might be infilled from station A, February from station B, April from station C, etc. A minimum correlation coefficient of 0.5 was required for the infilling.

- Infilled monthly values were apportioned on the basis of the recorded daily profile at the best-correlated station that had daily data.

The resulting average annual rainfall values are provided in Table 2.

Table 2: Average annual rainfall (AAR) for the extension of data covering 1882-2014

Gauge	AAR (mm)
Cresswell	863
Hanch Reservoir	672
Blithfield	699
Meir	822
Wall Grange	908

Based on the location of the stations, the influence of each rain gauge on the average catchment rainfall was obtained with a Thiessen polygons analysis (Table 3). Although two of the gauges (that lie outside the catchment) have not been used in compiling the catchment series, they did contribute to the infilling/extension process.

Table 3: Contributing gauges using the Thiessen polygon method

Gauge	Upstream Blithfield	Downstream Blithfield
Cresswell	45.1%	0
Hanch Reservoir	0	0
Blithfield	33.8%	100%
Meir	21.1%	0
Wall Grange	0	0

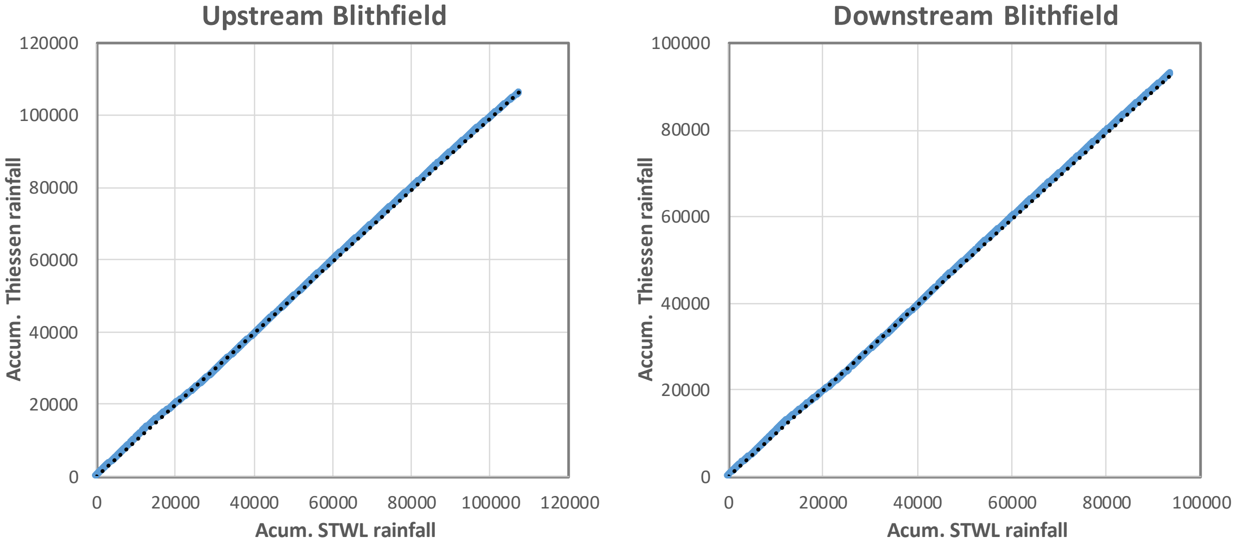
However, there is a clear positive trend towards the NW that agrees with the existing climatic pattern. Knowing this, a simple weighted average based on Thiessen polygons could result in an unreliable estimation of the catchment rainfall as a more complex spatial interpolation algorithm might be required. In this sense Severn Trent Water (STWL) has shared with SSW their spatial analysis of rainfall. It is based on a larger set of rain gauges for 1882-1957 (including information from the University of East Anglia Climatic Research Unit) and on the Met Office 5km grid data from 1958 onwards.

The resulting average annual rainfall for the period 1882-2014 obtained from the two sets of data is presented in Table 4. As can be seen there is a good correspondence between the methods, which confirms in this case the goodness of the Thiessen procedure. A double mass analysis (see Figure 3) reinforces this conclusion. However, in order to show consistency to the EA given the interrelationship between STWL and SSW supply systems, the STWL rainfall data was used for the calibration and simulation of the Blithe.

Table 4: Annual average rainfall for 1882-2014

Origin	Upstream Blithfield	Downstream Blithfield
EA data + Thiessen	799	699
STWL spatial data	809	705

Figure 3: Double mass plots for monthly rainfall (1882-214) obtained from STWL and the Thiessen analysis



3.3 Potential Evapotranspiration

PET series for the upstream and downstream catchments were received from STWL. They are a combination of monthly MOSES data supplied by the EA for the 40km by 40km No. 115 square during the period 1961-2014 (distributed evenly across the month) and PET data obtained from the original HYSIM models for the period from 1918 to 1960, which were scaled by a monthly factor to match the MOSES profile (based on comparison of overlapping data from 1961 to 1996). For 1882-1917 typical annual PET profiles (dry, normal and wet) were assigned as a function of the annual rainfall.

The resulting average annual PET for the period 1882-2014 is 493mm. In WRMP14, MORECS data were used instead, leading to 566mm. However, they were later scaled with a factor of 0.64 in order to match the observed runoff. Therefore, the use of a lower PET coming from MOSES, which is generally considered to be more accurate than MORECS, was considered appropriate.

3.4 Hydrometry

Several flow and stage series for gauging stations were received from the EA or retrieved from the National River Flow Archive (NFRA). Spot flow measurements were also provided for stage stations so that a rating curve could be built and applied to convert stage into flow.

The River Blithe at Hamstall Ridware station is particularly relevant for the current hydrology update as it reflects the behaviour of the whole Blithe catchment. The gauged series retrieved from the National River Flow Archive (NRFA) comprises a period before (up to 1952) and after the construction of Blithfield. Originally the station was formed by a side contracted flume with pilot tube tapping. In 1994 a permanent non-standard, broad crested weir was installed. This weir is by-passed at high flows (over 13.3m^3/s) but provides accurate flows at lower levels. In fact, a good rating is considered only post 1994. Given this, the observed series before 1952 should be used only for validation. The average annual runoff is 317mm.

There are also two naturalised series for Hamstall Ridware. One was generated by the EA by decomposition and covers the period post-Blithfield until 1998. The series has many negative values and is deemed of poor quality. The average runoff for the period 1956-1998 is 288mm, which is lower than for the previous period. The second series was produced by Wallingford Hydrosolutions using a rainfall-runoff model (CERF). It covers the period from 1962 to 2007 with an estimated runoff of 343mm. Its quality is considered better than the decomposition series. However, as it is the product of a simulation, it cannot be used for calibration purposes.

There are other stage gauging stations on the Blithe. The River Blithe Pumback is located just downstream from Hamstall Ridware, and therefore, does not add any more relevant information, while the following stations measure water level for relatively small draining surfaces upstream of Blithfield (Blithfield catchment area is 120.9km^2):

- Blythe Bridge: 15.6km^2
- Caverswall: 12.9km^2
- Cresswell: 32.8km^2
- Roughcote Bridge: 9.3km^2

As the interest of the hydrological simulation relied on the inflows to Blithfield and a lumped model was applied, any calibration attempt at these stations would have been difficult to transfer to the reservoir, so that the accuracy of estimated flows would be doubtful. Cresswell was used, however, to contrast the runoff of the whole reservoir catchment with an upper one, and for validation purposes. The available series starts in June 2000 and indicates an average annual runoff for the 2001-2014 period of 359mm, which is coherent with the higher rainfall recorded in the upper part of the catchment.

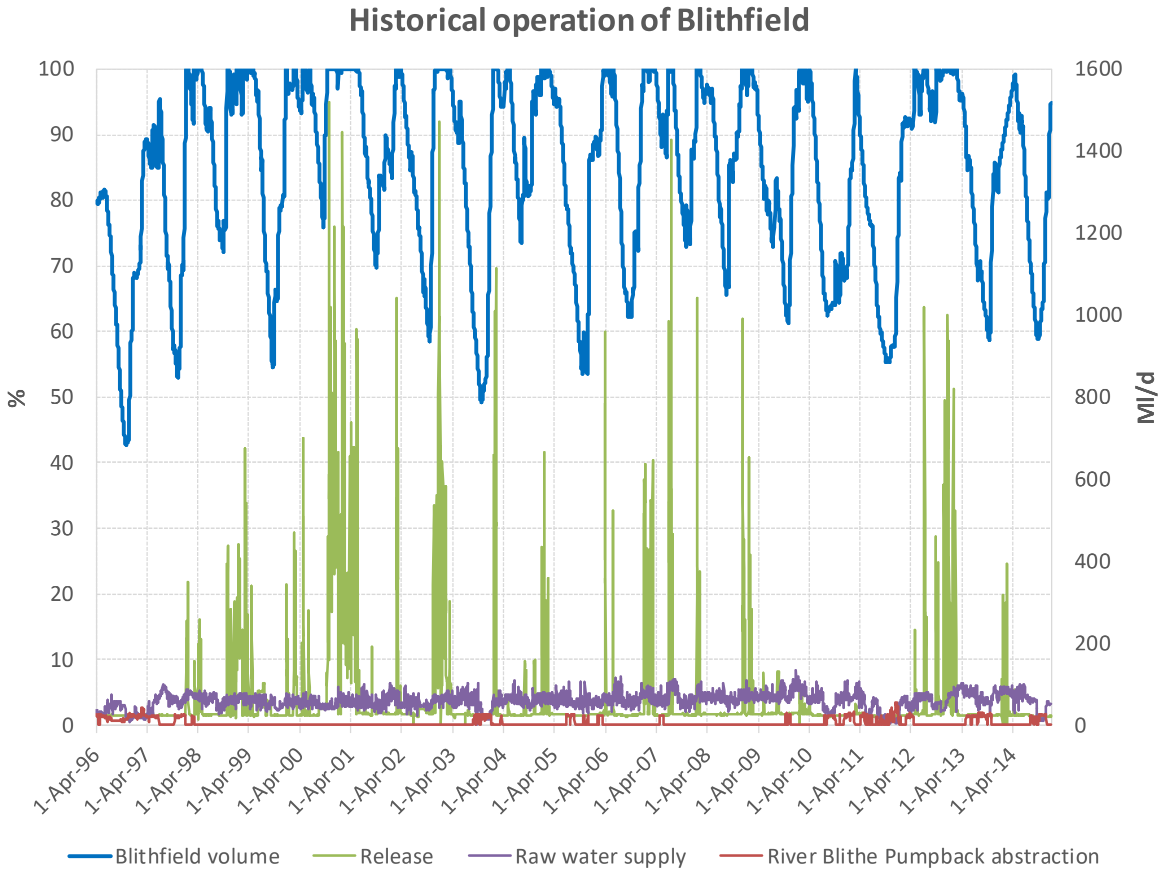
Data from a recent stage gauging station at Newton Bridge, measuring roughly 95% of the inflow to Blithfield were provided by SSW. The series starts in 2012 and a rating curve has been constructed based on spot flow gaugings. Although the estimated flow series is still rather short to allow a proper calibration, and there is some uncertainty in the existing rating curve, it was used to check the suitability of the derived inflows by reservoir balance as described below.

In order to calibrate the hydrological model for the upstream catchment, data from Apr-96 to Nov-16 regarding the water balance in Blithfield were provided by SSW (Figure 4). They comprised daily values of:

- Blithfield Level (%)
- Blithfield Volume (Ml)
- River Blithe pumping back to Blithfield (Ml)
- Raw Water Supply from Blithfield (Ml)
- Compensation Release from Blithfield (Ml)

The level-surface-volume curves were also made available, allowing the inflow values to be inferred by reservoir water balance calculations.

Figure 4: Existing record of Blithfield operation



A preliminary derived inflow series was calculated but it was of poor quality, with numerous negatives and sharp oscillations due to the low accuracy of the water level meter, and possibly to some inconsistencies in other data. However, the estimated annual runoff is 353mm, which is consistent with the Cresswell value.

Adopting a moving average smooths the series but considerably reduces the high peaks which are more likely to be true than the low values. In order to enable its application for calibration, several techniques were tested:

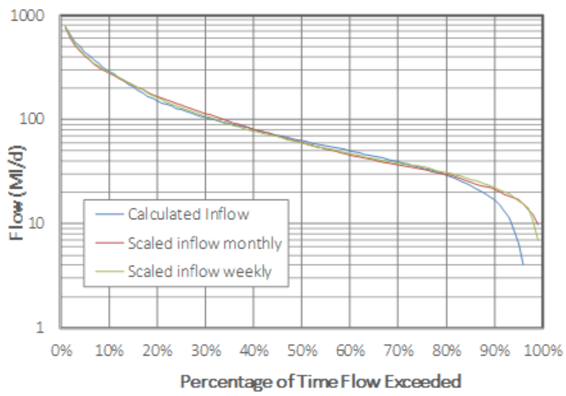
- Introduction of direct rainfall and evaporation from the reservoir surface. Daily surface values were calculated based on the level and a polynomial equation obtained from the digitised bathymetry. The infilled storage rain gauge and MOSES PET series without factoring were applied to obtain daily gains and losses. This reduced the magnitude of the negative values. The new average runoff from 1996 to 2014 was 356 mm.
- Correction by interpolation of suspicious level data in Oct-01, Oct-05 and Sep-08, removed three very large negatives.
- Determination of a first revised inflow series by scaling the simulated flow series provided by STWL to match the monthly or weekly volume as estimated by reservoir balance. The average runoff remained the same. Note that STWL has also produced an updated modelled flow series in WRMP19 for the Blithe using HYSIM. As this is for the purpose of assessing

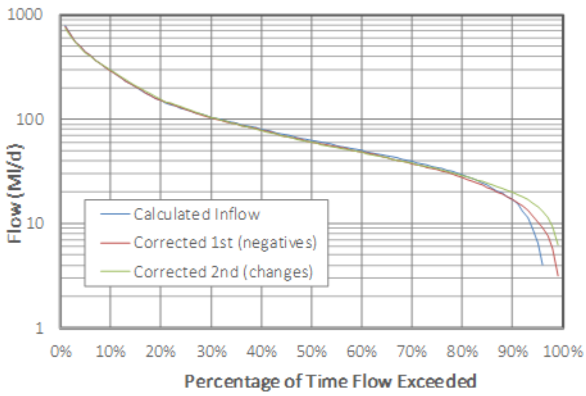
downstream River Trent flows, it includes a lower degree of detail than adopted here and, as evidenced by the WRMP14 work, tends to overestimate Blithfield DO values.

- Determination of a second revised inflow series by, first, removal of negative values, and second, smoothing of unrealistic flow decreases. In the first step, starting with the lowest negative, the wrong value was substituted by the 7-days moving average, and the adjacent 6 flow values were modified accordingly to maintain the volumetric balance. 440 iterations were needed to remove all values lower than 1Ml/d. In the second step, starting with the largest negative change between two consecutive days, the suspicious value was substituted by the 3-days moving average. In the case of a recession, the previous flow was reduced accordingly, whereas if the suspicious value constitutes a local minimum, the two adjacent flows were reduced equally. 792 iterations were needed to remove negative changes greater than 150%. This threshold was obtained as the maximum negative change in the simulated series provided by STWL. The resulting series was more natural while maintaining the average runoff.

The effect these techniques had on the Flow Duration Curve (FDC) can be seen in Figure 5 and Table 5. Scaling the simulated flow series affects the whole range of flows, while the correction modifies mainly the low range.

Figure 5: Effect of differing improvement techniques on the derived inflow FDC





An additional comparison was made from 2012 to 2014 with the recorded flow series at Newton Bridge resulting in the correlation and Nash-Sutcliffe (NSCC) coefficients shown in Table 5.

Table 5: Correlation and NSCC of the scaled and corrected inflow series

	Scaled inflow monthly	Scaled inflow weekly	Corrected 1st (negatives)	Corrected 2nd (changes)
Correlation	0.78	0.79	0.83	0.84
NSCC	0.55	0.57	0.63	0.65

As can be seen, there is a better correspondence with the corrected inflow series, which does not involve any previous simulation that can prejudice the subsequent calibration. Therefore, this series was selected for calibration.

3.5 Artificial influences

Information about abstraction licences in the Blithe was provided by the EA. The GW licences that were active during the calibration period in the upstream catchment are outlined in Table 6. These licences operate during the whole year. The maximum total annual abstraction is 340l/s or 29.4Ml/d. However, actual abstraction volumes from these sources were provided by SSW from 1994 to 2010, ranging between 23.1Ml/d in 1996 and 11.8Ml/d in 2008 with an average value of 16.7Ml/d. A proportion of this water may potentially belong to catchments adjacent to the Blithe, although this is uncertain. Given this, the recorded annual series was used in the calibration process, whereas a value of 15.6Ml/d (average of the last 5 years) was considered for 2011-2014 during the calibration and for the whole period of long-term simulation.

Table 6: Blithe abstraction licence information

Date Effective from	Purpose Description	Daily licensed volume	Annual licensed volume
01/02/1966	Water Supply	7046	2578946
31/01/1966	Water Supply	4319	1580644
31/01/1966	Water Supply	13638	4977870
07/02/1966	Industrial, Commercial & Public Services	27	8183
31/03/1974	Water Supply	3273	1194689
22/07/1974	Agriculture	27	9983
10/07/2003	Industrial, Commercial & Public Services	1500	385000

Source: Environment Agency

In the downstream catchment, there are several surface water abstractions for agricultural purposes (Table 7).

Table 7: Agricultural abstraction licences on the Blithe

Date Effective from	Purpose Description	Daily licensed volume	Annual licensed volume
14/02/1966	Agriculture	136	2728
20/10/1976	Agriculture	650	25000
03/11/1978	Agriculture	455	9092
25/05/1984	Agriculture	750	22700
08/09/1997	Agriculture	1080	25000
28/04/1999	Agriculture	506	20900
28/04/1999	Agriculture	506	20900

Source: Environment Agency

These licences operate from April to September/October. The maximum average abstraction assuming 6 months of operation is approximately 8 l/s. Given this reduced amount, which is unlikely to affect the calibration/simulation process, this artificial influence was not considered in the analysis.

Finally, there is no significant discharge of water (for example from sewage treatment works) within the catchment.

4 Calibration-validation process

4.1 Approach

Given the nature of the available information, as described in chapter 3, the following calibration-validation process was followed:

- The calibration of the upstream catchment was conducted with the corrected inflow series from 1996 to 2014.
- The calibration of the downstream catchment was undertaken with the recorded series at Hamstall Ridware from 2005 to 2014 by considering the releases from Blithfield and the streamflow from the intermediate catchment.
- A validation exercise was carried out for the whole naturalised catchment between 1933 and 1952 at Hamstall Ridware, and for a portion of the upstream catchment at Cresswell from 2001 to 2014.

4.2 Model building

Two independent catchments were set up in HYSIM (BL-UPS and BL-DWS), with the downstream one receiving the releases from Blithfield. This scheme is suitable for producing the flow series required by Aquator (the water resources model used for assessing deployable output). Based on a 50m grid Digital Terrain Model, the catchments were delimited and the features of the main river network were obtained:

Table 8: Catchment characteristics

	BL-UPS	BL-DWS
Area [km^2]	117.8*	42.4
Main river length [km]	34.3	5.8
Main river slope [m/m]	0.003	0.003
Number of tributaries	1	2
Average time to peak for minor channels [hr]	2	3.5

Note: * Without taking into account the surface of the reservoir as the effect of rainfall and evaporation on it was already considered while obtaining the derived inflow series or in running Aquator.

According to the Corine Land Cover 2012 dataset, the distribution of land uses in the two catchments is outlined in Table 9.

Table 9: Land use distribution

Land use	BL-UPS	BL-DWS
Urban	7.3%	0.7%
Agricultural	12.9%	40.6%
Grasslands	73.3%	54.2%
Forest	4.0%	4.4%
Water bodies (Blithfield)	2.4%	0.0%

Note: In this table BL-UPS includes the reservoir surface
Source: Corine Land Cover

The impermeable proportion parameter of HYSIM can be estimated as 25% of the proportion of urban surface, whereas given the predominance of grassland and crops, an interception storage of 2 mm and a soil rooting depth of 1,000mm were initially adopted.

According to the European Soil Database, the type and abundance of soils in the two catchments of study is outlined in Table 10.

Table 10: Soil characteristics

Catchment	FAO soil	USDA texture	Abundance
BL-UPS	Dystric Gleysol	Sandy Clay Loam	0.7%
	Gleyic Luvisol	Sandy Clay Loam	80.7%
	Cambic Arenosol	Loamy Sand	12.5%
	Dystric Cambisol	Loam	4.4%
	Eutric Cambisol	Sandy Clay Loam	1.8%
BL-DWS	Stagno-Gleyic Luvisol	Sandy Clay Loam	82.9%
	Eutric Cambisol	Sandy Clay Loam	17.1%

Taking into account this distribution and the typical properties of the different soil textures, average HYSIM initial parameters were set as per Table 11.

Table 11: HYSIM initial parameters

Catchment	PSDI	Bubbling pressure (mm)	Permeability (mm/hr)	Porosity
BL-UPS	0.15	283	90	0.42
BL-DWS	0.14	300	23	0.42

Finally, by analysing the recession curves recorded at Hamstall Ridware during dry periods without considering compensation releases, the GW recession constant was established at 0.85. Other parameters were initially assigned their default values. An initial correction factor for rainfall of 1.04 is adopted due to the usual underestimation of actual rainfall as measured by rain gauges.

Although some parameters were modified later on during the calibration process, a good estimation of initial values was relevant for establishing reliable rainfall and PET correction factors afterwards.

4.3 Calibration

There is not a unique way of conducting the calibration process but a usual approach implies:

- A first multi-parameter optimisation of saturated permeability (at the horizon boundary, controlling the infiltration rate, and at the base of the lower horizon, controlling the percolation rate) and interflow rate (from the upper and lower horizons, controlling the quickness of dewatering process, and thus, of the response of the catchment). The optimization is conducted to minimise the Extreme Error of Estimate statistic, which gives a greater weight to the extremes be they high or low flows.
- A second manual refinement of:
  - Impermeable run-off factor in order to match summer peaks corresponding to small short storms with mainly direct runoff.
  - Total soil storage to match the response at the beginning of the winter and summer conditions.
  - Proportion of soil storage in the upper horizon to match summer peaks corresponding to major storms.
  - Recession rates and the proportion of GW storage contributing to run-off to match the flows in dry periods.

- A final verification of the water balance.

Following this approach, the final optimal parameter sets for both catchments are outlined in Table 12.

Table 12: Optimal HYSIM parameters

Parameter	BL-UPS	BL-DWS
Interception storage (mm)	2	2
Impermeable proportion	0.018	0.002
Time to peak (hours)	2	3.5
Rooting depth (mm)	1400	1960
Pore size distribution index	0.15	0.14
Permeability - horizon boundary (mm/hour)	125.9	39.4
Permeability - base lower horizon (mm/hour)	74.6	41.5
Interflow - upper (mm/hour)	59.6	31.9
Interflow - lower (mm/hour)	87.0	2.4
Groundwater recession (per month)	0.95	0.85
Precipitation factor	1.04	1.04
PET factor	0.96	1.22

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

- Examination of the daily flow chart to confirm if the model matches the low flow periods, has a similar rate of recession, and matches summer and winter storm peaks. Not every feature can be replicated with a model, but this assessment provides an adequate representation of the hydrograph shape and how this might vary in key years or stages in the calibration period.
- Examination of the FDC to help identify how good the fit is for lower flows and higher flows. Although the aim is to achieve a good fit over the whole record, the fit at lower flows is almost always most important for water resource assessments. The use of a log curve to display FDCs accentuates the lower part of the FDC allowing, at a glance, the goodness of the fit at low flows to be assessed.
- Comparison of the mean flows, Q50 and Q95 statistics provide further evidence as to the goodness of fit both over the whole record and at low flows. These statistics alone are not enough to determine a good fit, but it is important that they support the above two assessments.
- The root mean squared error (RMSE) is a good statistical measure that has been used in assessing the performance of simulations. It is calculated as the square root of the mean of the squared difference between the observed (Oi) and simulated (Pi) flows. RMSE was calculated separately for the full range of flows and the low (Q50-Q95) flows. To standardise comparisons of RMSE, this was calculated as a percentage of Q50. Broadly speaking both RMSE statistics follow the same trend.
- The Nash-Sutcliffe correlation coefficient (NSCC), which is a normalised statistic that determines the relative magnitude of the model's residual variance compared with the reference data variance, has also been calculated and reported for the calibration period. The NSCC is sometimes referred to as the Nash Sutcliffe model efficiency coefficient. The NSCC is calculated by reference to the mean of observed flows ($\overline{Q_o}$) and the daily time

series of observed (o) and modelled flows (m). An NSCC value of 1 corresponds to a perfect match between observed flows and modelled flows.

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

- a Q95 percentage error of less than 5%;
- a mean flow percentage error of less than 5%;
- a RMSE (all flows) of less than 100%;
- a RMSE (Q95-Q50) of less than 50%; and
- a NSCC greater than 0.7.

In the case of a derived inflow series to a reservoir or a recorded series largely affected by one, as is the case here, the above conditions cannot usually be met due to problems in characterising the influence of the reservoir. The performance indicators obtained after calibration are outlined in Table 13.

Table 13: Performance indicators obtained after calibration

	BL-UPS			BL-DWS		
	Rec. (m^3/s)	Sim. (m^3/s)	Diff (%)	Rec. (m^3/s)	Sim. (m^3/s)	Diff (%)
Mean flow	1.353	1.351	0	0.793	0.793	0
Q50	0.696	0.879	26	0.436	0.435	0
Q95	0.167	0.158	-6	0.275	0.278	1
	BL-UPS			BL-DWS		
RMSE	1.16			0.87		
RMSE (Q50 - Q95)	0.48			0.07		
RMSE (as a % of Q50)	167%			199%		
RMSE Q50 to Q95 (as a % of Q50)	69%			17%		
Nash-Sutcliffe Correlation Coefficient	0.58			0.56		

A comparison of the FDC is presented in Figure 6 and Figure 7.

Figure 6: Comparison of FDCs in the upstream catchment (1996-2014)

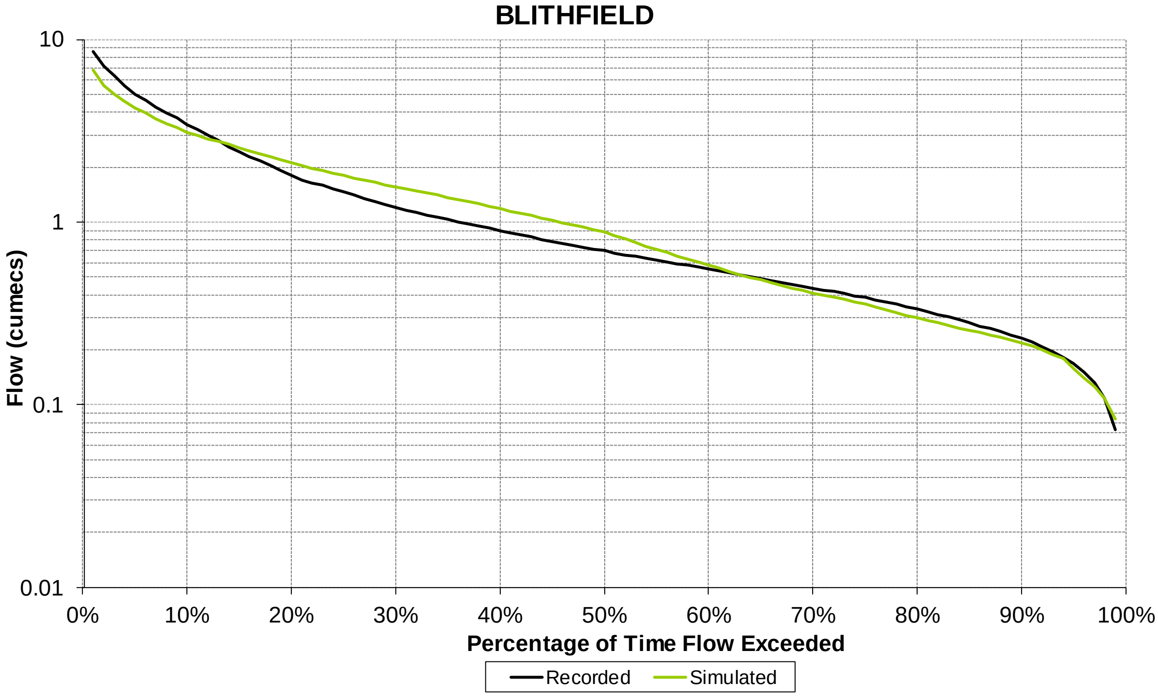
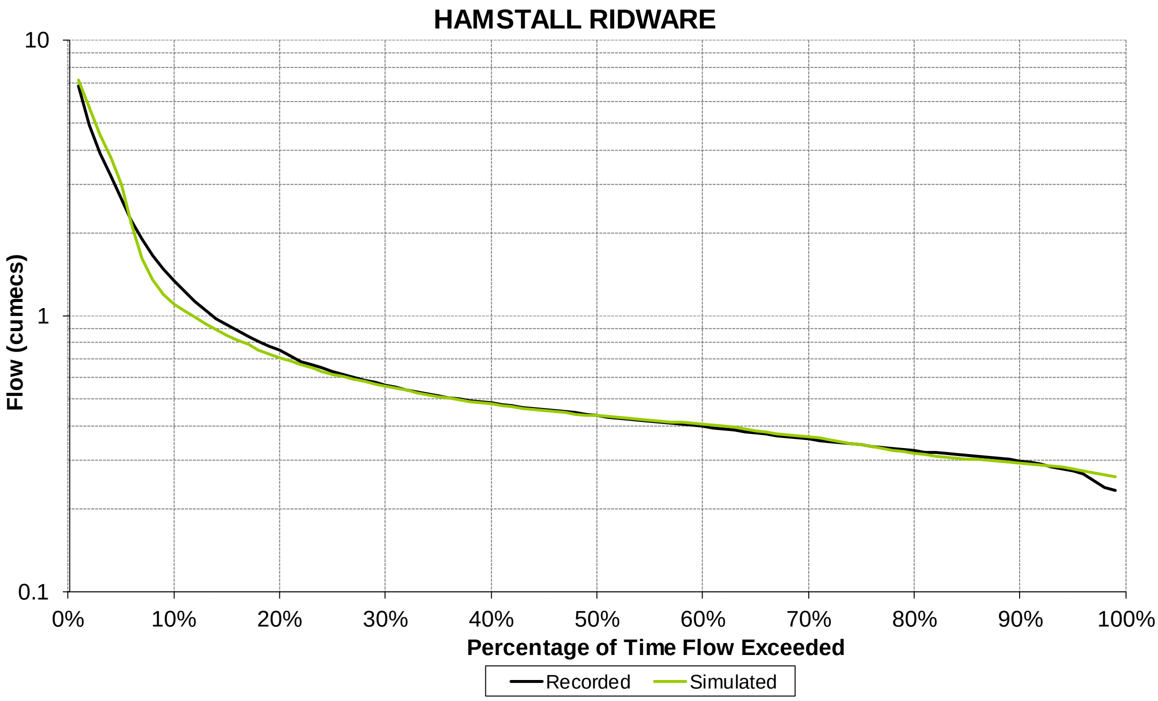


Figure 7: Comparison of FDCs in the downstream catchment (2005-2014)



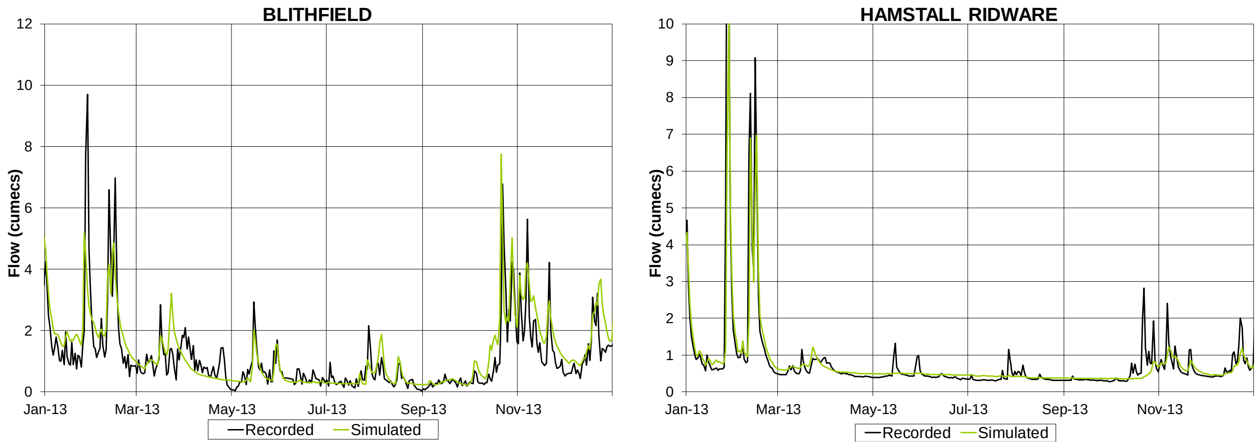
As can be seen there is a good match between the simulated and recorded FDCs at Hamstall Ridware for low and medium flows. Given that the flows from the downstream catchment will be used in Aquator to establish if there is enough water on the Blithe for pumping back into

Blithfield, this calibration was considered fit for purpose. Major discrepancies are located only for high flows, when the pump back may not be required (if the reservoir is spilling). These discrepancies have a major influence on the RMSE and the Nash-Sutcliffe coefficient (despite this NSCC is still close to 0.6). However, high flows are affected by the spills from Blithfield, whose reliability is discussed below.

In the upstream catchment, the simulated FDC only matches the observed one for low flows. The model overestimates medium flows and underestimates high ones, although the average flow is fitted. The difficulties of calibrating the model to the derived inflow series can be a consequence of some inaccuracy in the information about releases. While compensation flows are easier to control and measure, spills can be difficult to estimate depending on the reliability of the level transducer. A comparison of the simulated and recorded inflow series shows that while the autumn peaks are better simulated, the winter ones are systematically underestimated (Figure 8). However, most of these winter high flows are obtained when the reservoir is full and spilling. If the actual spills were lower than stated, the derived inflows would be closer to the simulated ones. Likewise, the simulated flows at Hamstall Ridware would be lower and would fit better with the recorded ones (Figure 8).

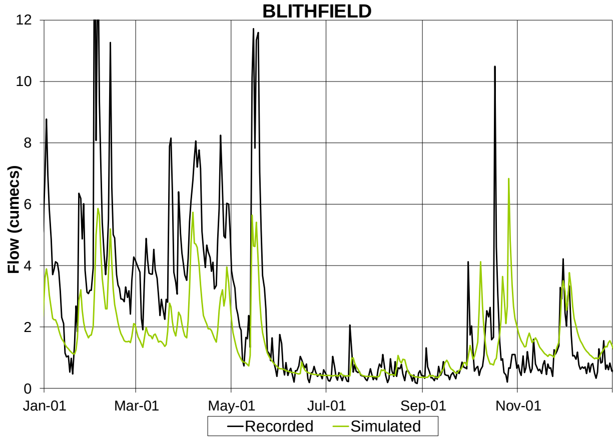
To test this hypothesis, the information at Newton Bridge was used. In January 2013, there was a recorded peak of 9.7 m^3/s, coinciding with an estimated spill of 9.5m^3/s. However, the simulated flow is 5.2m^3/s, while the estimated flow at Newton Bridge is 6.6 m^3/s.

Figure 8: Comparison of recorded and simulated flows in 2013



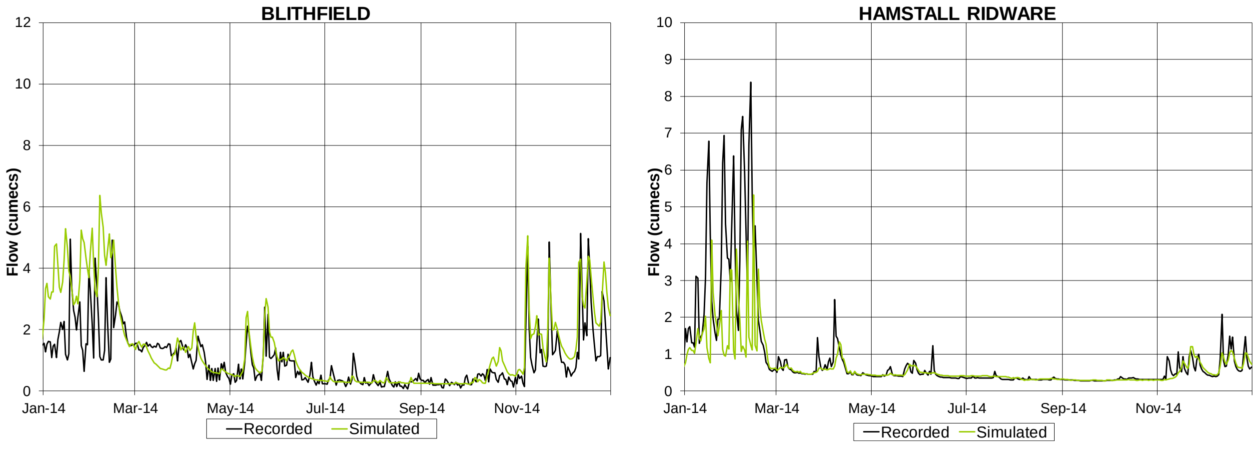
In addition, during winter 2001, when spills were substantial, rainfall was 189mm, PET 32mm and the deduced runoff into Blithfield 285mm, which is clearly overestimated, implying that spills could be overstated too (Figure 9).

Figure 9: Comparison of recorded and simulated flows in 2001



Nevertheless, there are also cases, where this trend is the opposite. In winter 2014, there are several peaks that are overestimated in the model at Blithfield and underestimated at Hamstall Ridware (Figure 10). However, Newton Bridge points towards higher inflow values than the ones obtained from the reservoir balance, and similar to the simulated ones. If releases were higher in this case than stated, the model would offer better fit at both Blithfield and Hamstall Ridware.

Figure 10: Comparison of recorded and simulated flows in 2014



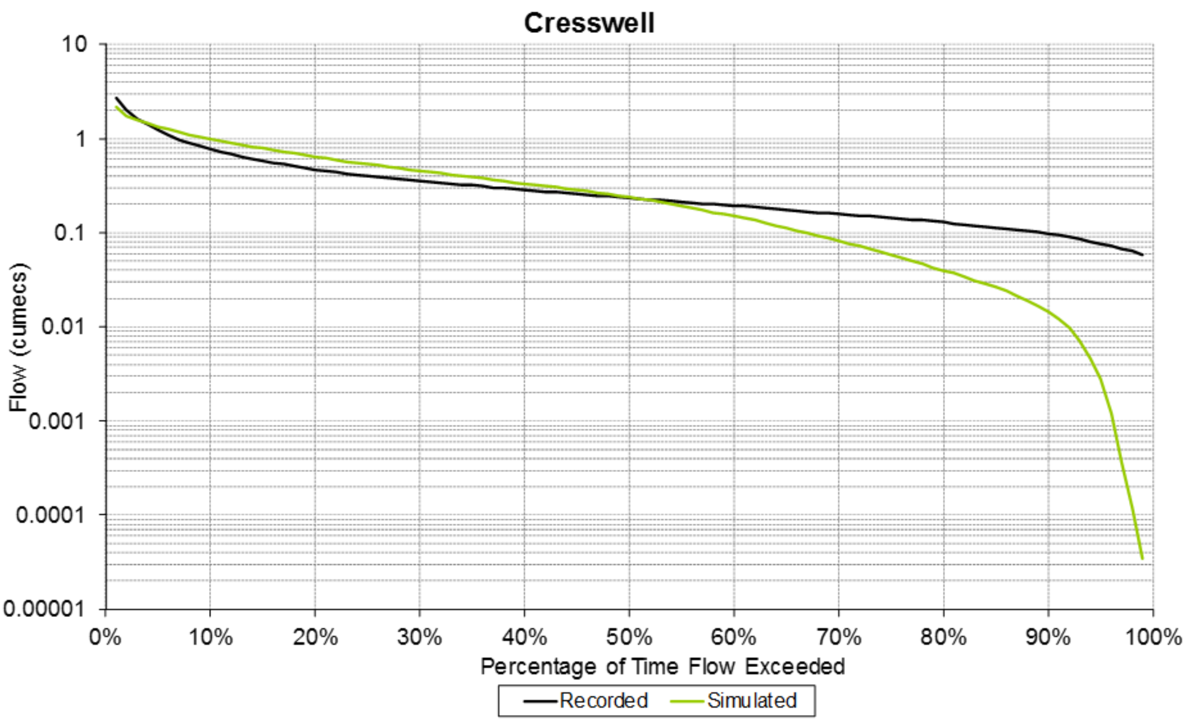
4.4 Validation

In order to assess the suitability of the calibrated model to represent the hydrology of the Blithe, a validation exercise was conducted at the upstream Creswell gauging station. In this case the parameters calibrated at Blithfield were maintained, while the drainage area was reduced to 32.8km^2. Rainfall was increased by 10% to take into account the higher values recorded in the upper part of the catchment. Blacklake, Fulford and Mossgate GW abstractions were taken out from the analysis as they are located outside the Cresswell drainage area. The results are outlined in Table 14 and Figure 11.

Table 14: Results of validation against Cresswell

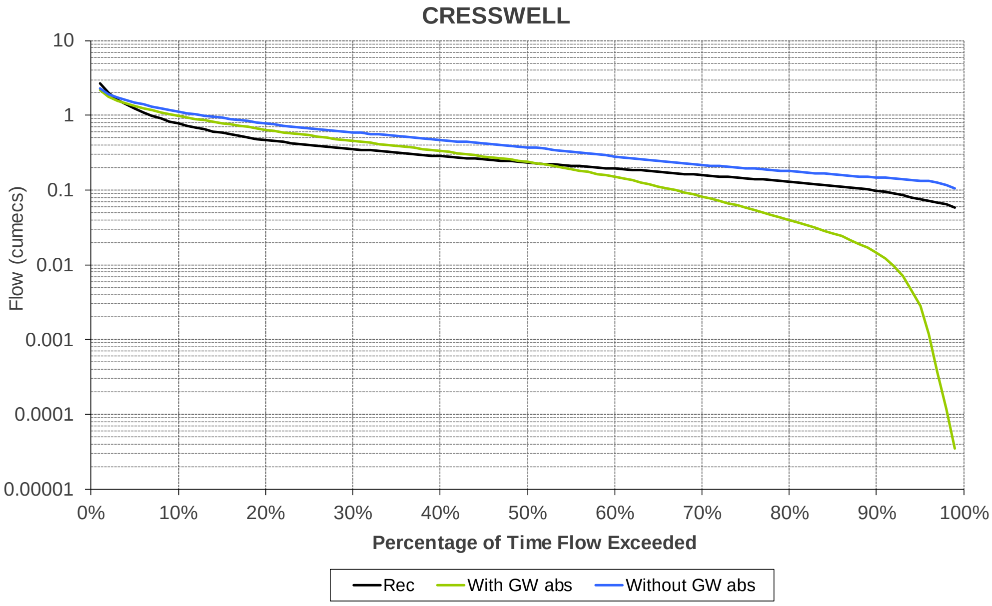
	BL-CRE		
	Rec. (m^3/s)	Sim. (m^3/s)	Diff (%)
Mean flow	0.391	0.392	0
Q50	0.232	0.240	3
Q95	0.076	0.003	-96
	BL-CRE		
RMSE	0.36		
RMSE (Q50 - Q95)	0.10		
RMSE (as a % of Q50)	143%		
RMSE Q50 to Q95 (as a % of Q50)	43%		
Nash-Sutcliffe Correlation Coefficient	0.63		

Figure 11: Comparison of FDCs at Cresswell (2011-2014)



In this case, the model underestimates low flows, whereas medium flows are overestimated. The pattern resembles that of Blithfield but with a poorer representation of low flows. Having this sharp recession might be related to the way HYSIM accounts for GW abstractions. This volume is subtracted from the lower tank of the model, which is responsible for producing baseflow. Consequently, in dry periods, GW abstractions can effectively reduce streamflow to almost zero, as they end up in fact being subtracted from the streamflow. In reality, depending on the degree of connectivity between the aquifer from which water is abstracted and the river, this might not be the case. The sensitivity of low flows to the groundwater abstractions is illustrated in Figure 12, which includes a simulation without any GW abstraction.

Figure 12: Effect of GW abstraction on FDCs at Cresswell (2011-2014)



Mean annual flows at Cresswell were well estimated, which gives confidence in the simulated Blithfield flow series as it is going to be used in Aquator to feed a reservoir.

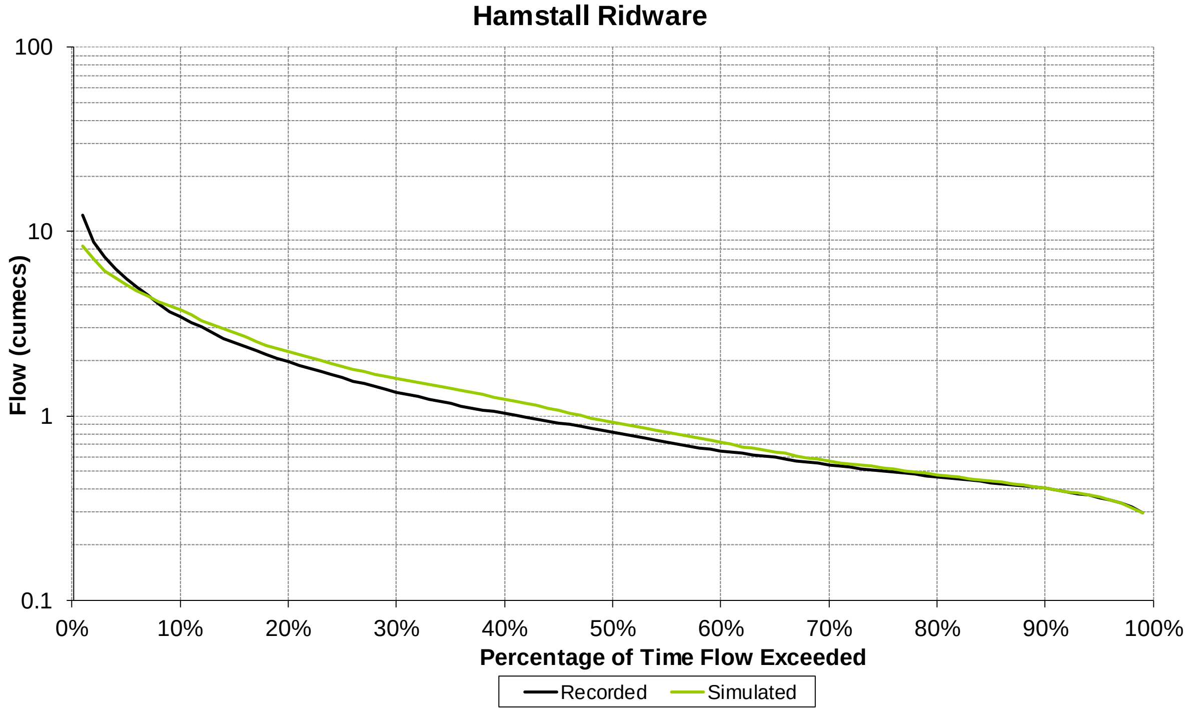
Likewise, estimated flows at Newton Bridge, which comprise around 95% of the drainage area to Blithfield, were also used to check the validity of the simulated series from 2012 to 2014, yielding a Nash-Sutcliffe coefficient of 0.66.

Finally, a comparison of the naturalised simulated flows (without Blithfield) at Hamstall Ridware with the available recorded flows during 1937-52 was undertaken. Even though the quality of the observed series is questionable, the comparison was quite satisfactory, adding more confidence to the goodness of the model. The results are outlined in Table 15 and Figure 13.

Table 15: Comparison of the naturalised simulated flows (1937-1952)

	BL-DWS		
	Rec. (m^3/s)	Sim. (m^3/s)	Diff (%)
Mean flow	1.590	1.588	0
Q50	0.815	0.925	13
Q95	0.360	0.363	1
RMSE	1.51		
RMSE (Q50 - Q95)	0.58		
RMSE (as a % of Q50)	185%		
RMSE Q50 to Q95 (as a % of Q50)	71%		
Nash-Sutcliffe Correlation Coefficient	0.59		

Figure 13: Comparisons of FDCs in the downstream catchment (1937-1952)



5 Simulation

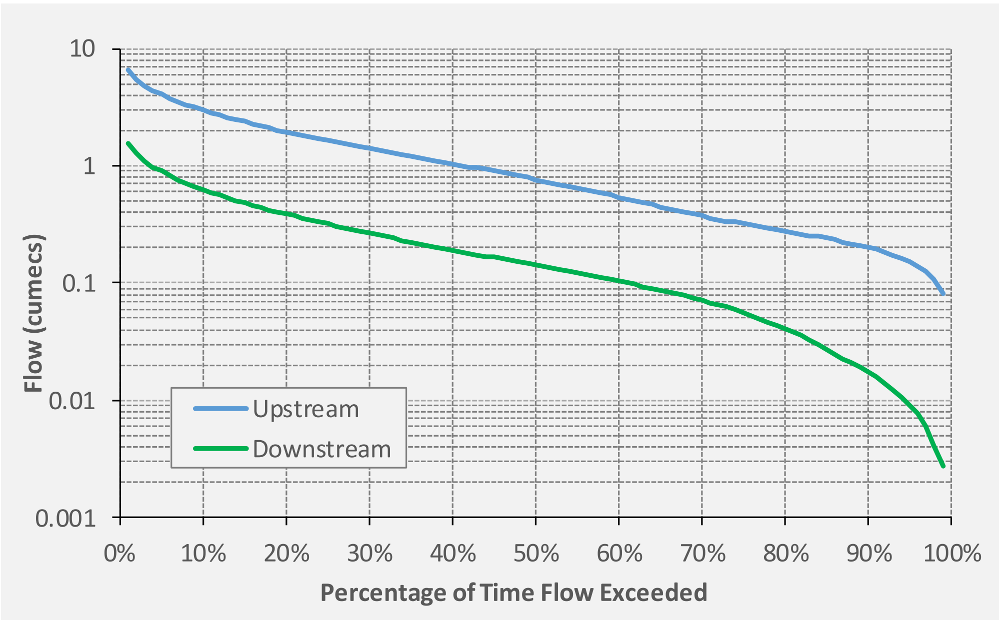
Once the HYSIM model was calibrated it was used to produce daily flow series for the whole period from 1882 to 2014. The simulation was conducted for the upstream and downstream catchments independently and without taking into account the presence of Blithfield, as the operation of the reservoir is modelled within Aquator.

Groundwater abstractions in the upstream catchment were fixed at their recent actual value (15.6Ml/d) with no seasonal variation. The downstream catchment was extended by increasing the drainage area to 47.9km^2 and the related river network, while keeping the parameters calibrated at Hamstall Ridware. For both catchments, initial groundwater storage was defined so that there are no long-terms effects on the simulated flows and so that the warm-up period could be limited to 1882-1883. These results are provided in Table 16, Figure 14 and Figure 15.

Table 16: HYSIM model simulation results

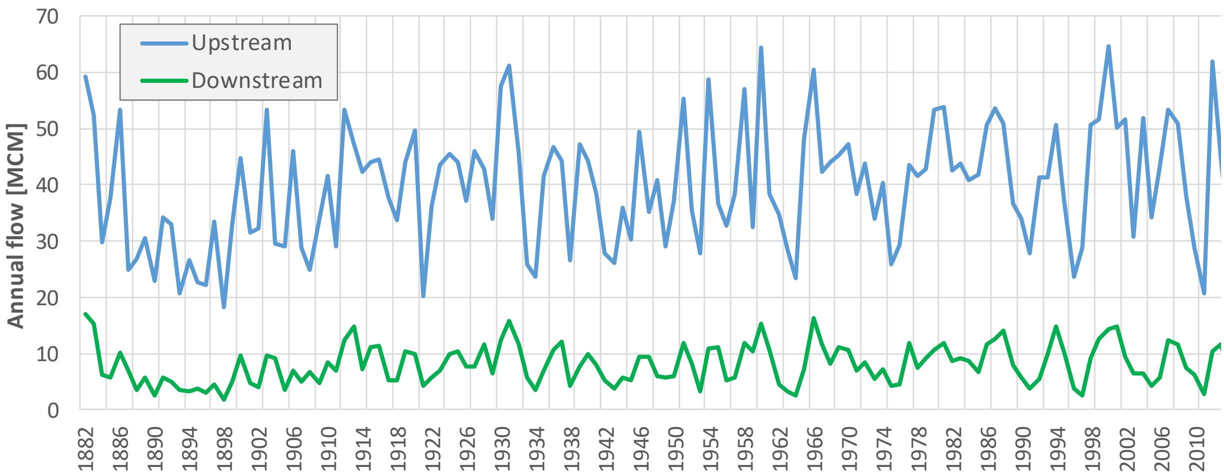
	Upstream	Downstream
Mean	1.257	0.255
Standard Deviation	1.413	0.331
Q50	0.766	0.143
Q95	0.153	0.009

Figure 14: Simulated FDCs (1882-2014)



A notable feature of Figure 15 is the extended period of below average flows in the late 19th century. However, annual flows do not necessarily identify critical drought periods in terms of reservoir operation – for example, 1975 and 1976 upstream flows are below average, but not even within the worst ten years of the record, yet the 1975/76 drought was certainly very severe for Blithfield. The drought lasted from early summer 1975 to late summer 1976, but the early months of 1975 and the end of 1976 were both very wet.

Figure 15: Simulated annual flows (1882-2014)



6 Summary

The hydrology of the River Blithe has been updated based on an improved knowledge of rainfall, potential evapotranspiration, flows and artificial influences. The rainfall-runoff model HYSIM has been used to generate streamflows at Blithfield and the River Blithe Pumpback. This model has been calibrated and validated before being used for simulations, providing a good fit to the existing flow record, both inferred from the historic evolution of the stored volume in Blithfield and gauged at the NRFA Hamstall Ridware station. Validation checks at stations upstream of the reservoir have also helped to confirm the suitability of the model. The work has also benefitted from recent modelling work undertaken for Severn Trent Water Limited (STWL), thanks to the agreement between SSW and STWL to collaborate on aspects of data and modelling scenarios.

The model provides a significant improvement over the series used for WRMP14, demonstrated by the improved fit of the flow duration curve of reservoir inflows (**Error! Reference source not found.**). The previous series had low flows approximately double the observed, and was above the observed for all except the highest 15% of flows. The revised series is also below the observed for the top 15% of flows, but over the remaining 85% it is much closer to the observed, and shows a rough balance between periods above and below. The downstream catchment has been explicitly modelled, whereas previously the model applied a factor to the reservoir inflow series.

The new series also cover a longer period (131 years rather than 90). The extension incorporates two additional notable drought events, one fortuitous (the 2011 event that occurred after the data period available to the previous study) and one by design (the series were extended back to the 1880s because of historic reports of drought conditions in the late 19^{th} century).

The data extension and modelling improvements provide greater confidence to SSW in deployable output estimates derived from using these flow series in the Aquator water resources model.

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