PR19 Trading & Resources: peak demand model review

South Staffordshire Water plc.

6 October 2017

Contains *sensitive* information

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This document has 37 pages including the cover.

Document history

Document ref: 5151234-9.1-074

Revision	Purpose description	Originated	Checked	Reviewed	Authorised	Date
Rev 1.0	Draft for External Review	T Hedgeland	A Gill M Westbrook	G Jeal	B Arkell	14/08/17
Rev 2.0	Final Review	T Hedgeland	A Gill	A Gill	B Arkell	06/10/17

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1. Introduction

Atkins have previously assessed the peak week household demand (PWHH) for South Staffordshire Water (SSW) using the UKWIR peak demand approach[1]. This has involved assessment of PWHH, creation of a multiple linear regression (MLR) model of the variables affecting PWHH and application of this model to weather data back to 1971 to allow a more robust return period analysis. A PWHH demand model hereafter called the “Peak Demand Model”, was developed in 2007 and subsequently updated in 2013 Atkins (2007[2]; 2013[3]).

With five years of additional data now available, the model has been reviewed to ascertain the suitability of the 2013 Peak Demand Model in view of recent data and the impact of metering on PWHH. Atkins has been commissioned to undertake a review of the Peak Demand Model as follows:

a. Review peak demand model and identify the influence of different model variables on the demand estimates, including changes in metering coverage since the model was last developed.
b. Summarise the suitability of the current modelling approach for estimating peak demands, and identify alternative curve fit approaches if required.
c. Develop recommendations to refine the modelling approach where appropriate.

The main output of this project is this report, which outlines the findings of the review and identifies alternative curve fit approaches that could be applied to develop an improved PWHH. In addition, an updated Peak Demand Model spreadsheet also accompanies the report where the review calculations and assessments have been undertaken.

1.1. Structure of this report

This report is a concise review of the Peak Demand Model, and it is recommended that the original reporting (Atkins 2007; 2011) is read in conjunction with it. In addition to Section 1, this report includes the following components:

- Section 2 – Data Review
- Section 3 – Peak Demand Model Review
- Section 4 – Revised Peak Demand Model forecast
- Section 5 – Conclusions and Recommendations
- Appendices – Accompanying data and the model spreadsheet

[1] UKWIR (2006) *Peak Water Demand Forecasting Methodology* ISBN:- 1 84057 425 9
[2] Atkins (2007) *Peak Demand Analysis: South Staffordshire Water* Version 2.1 pp. 1-38
[3] Atkins (2013) *Peak Demand Forecast: Final Report: South Staffs Water* Revision 3 pp. 1-32

2. Data Review

Prior to the review of the Peak Demand Model structure, the input data to the model was reviewed and analysed to ascertain the influence of data variables on the demand estimates, including changes in metering coverage since the model was last developed.

2.1. Data Received

The following data-sets were received from SSW:

i. **Climate Data** – Adjusted Climate and Rainfall Data v3.xlsx – Date Received: 17/07/2017
ii. **Leakage Data** – Leakage Time Series v4 SSW.xlsx – Date Received: 16/07/2017
iii. **SSW Modified Regression Model (and any embedded data sets)** – Regression Model for SSW 280912 update Jul17.xlsx – Date Received: 16/07/2017
iv. **Population forecast** – Property and population forecasts for Peak model including split between meas and unmeas.xlsx – Date received 02/08/2017

Also obtained from the MetOffice:

v. **Shawbury Historic Weather Station Data** – shawburydata.txt – Date Received: 20/07/2017
vi. **Sutton Bonington Historic Weather Station Data** – suttonboningtondata.txt – Date Received: 20/07/2017

These can be found in Appendix A.

2.2. Data Reviewed

2.2.1. Peak Demand Model spreadsheet

The demand spreadsheet was initially provided by SSW, with relevant data entered and updated from the previous model produced in 2013. It was checked that this data was being correctly input into the regression model. A few minor adjustments were required to these inputs (Table 2-1).

Table 2-1 Corrections made to the peak demand model spreadsheet data

Sheet	Location	Corrections
Regression Model	Columns: H/I	Duplicated data – hidden to avoid confusion, and now auto updates the hidden column
Regression Model	Column: AZ	Summer Rainfall (May-Aug): Formula no longer pointing at correct column
Regression Model	Columns: BU-CN	Graph no longer showing correct calculations or values – the linear regression functions have been updated to include all new data provided by SSW, and regression with time variable displayed on graph
Regression Model	Columns CN onwards	Now defunct - removed
JR Data	Cell K43	Meter penetration value looked unrealistic (jump to 26% from 12%) – this has been changed to be an interpolation from surrounding values

2.2.2. Demand and Temporal Changes

2.2.2.1. Demand

Throughout both this model, and the 2013 Model, we have defined peak weekly household (PWHH) demand and household demand (HHD) using the following formulae:

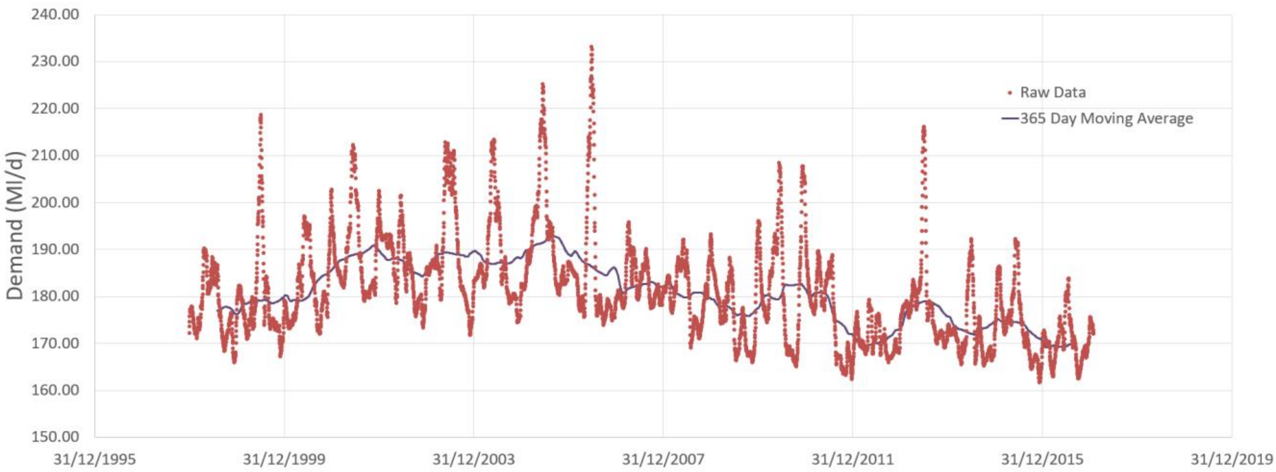
$$PWHH\ Demand = Maximum\ 7\ day\ rolling\ average\ of\ (Total\ Daily\ Demand\ minus\ Annual\ Average\ Non - household\ Demand\ (NHH)\ minus\ seasonally\ adjusted\ leakge)$$

$$HHD = DI\ minus\ Leakage\ minus\ NonHousehold\ Demand$$

The demand data given by SSW, now covers the period up to and including 1st March 2017 (Figure 2-1). Analysis of this time series, appeared to show two potential regimes of demand patterns, with a shift occurring around July 2006 (although the precise timing of the shift is a matter of interpretation), where an obvious reduction in the amplitude of peaks, and the average demand values, can be seen.

The 2013 model previously treated demand as one dataset. However, such a shift, could potentially suggest that a new model may be needed for the more recent dataset.

Figure 2-1 A timeseries of rolling 30 day household demand (Ml/d) in the SSW region, with annotation showing two possible separate regimes of demand



2.2.2.2. Metering and Population

To look at the potential causes in this change in demand, two major factors can be considered: meter penetration and population (Figure 2-2, Table 2-2). Meter penetration appears to show a steady increase throughout the time period, from 7% to 39%. Meter penetration has previously been considered likely to have an impact on the peak demand (Atkins 2011). Indeed, analysing the relationship between demand and meter penetration, a correlation does appear to be observed (Figure 2-3), where an increase in meter penetration leads to a reduction in peak weekly household (PWHH) demand. Given this variable's clear change throughout this period, it is important to investigate its possible impact. Meter penetration also appears to show an exceptionally strong covariance with time (as defined in the 2013 model; Figure 2-4), suggesting that a 'time variable' and a 'meter penetration' variable in any linear regression, would show very similar results.

Population (Figure 2-2) shows a similar increase throughout the period. Notably, over the 2011-2016 period, the gradient is increased dramatically, suggesting that the impact of population may have altered and therefore also important to consider such a factor when analysing the fit of the model.

Both population and meter penetration were considered in the 2013 model, being part of the 'catch-all' time variable. They were not disaggregated further due to the inability to separate the effects as stated in Atkins (2011):

"…It is not possible from the modelling to robustly disaggregate the impacts of metering from new properties and other time-related trends. This is because the new development and meter penetration variables are very closely correlated…as a result of the company's metering policy. This means that MLR cannot robustly distinguish between the two effects, especially with relatively few data points"

The previous analysis decided against using the *time* variable however, as including such a model in a linear regression led to no improvements in fit overall. However, the changes seen in these variables in Figure 2-2, suggests that a time variable should be re-considered.

Table 2-2 Proportion of changes in meter penetration and population between 1996 and 2017

	1996-2017	1996-2006	2007-2017
Meter Penetration	75.53%	56.37%	42.21%
Population	8.00%	3.04%	5.50%

Figure 2-2 Meter penetration and population values for the SSW region (1992-Present)

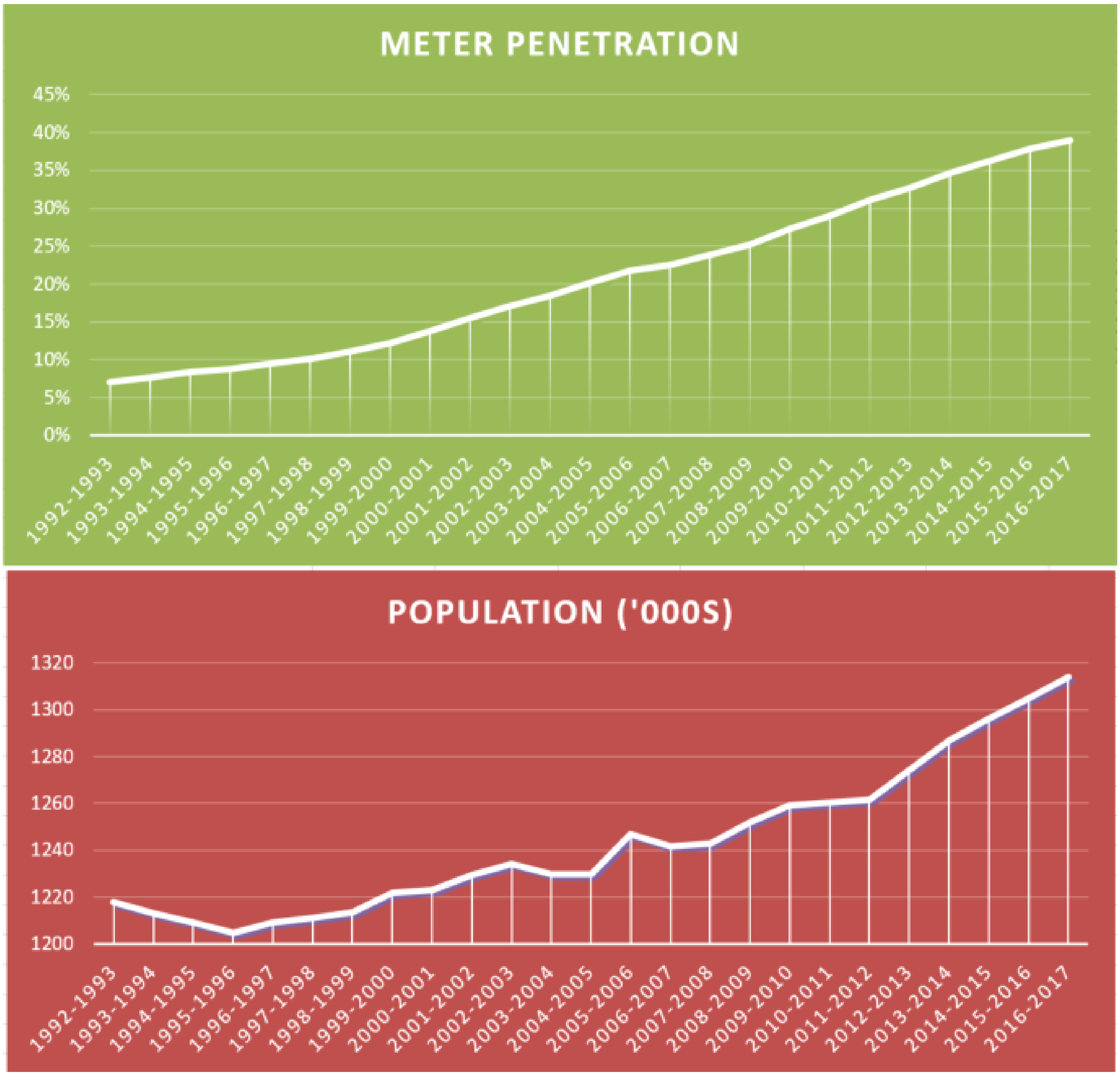


Figure 2-3 Relationship between measured peak week household demand (PWHH) and meter penetration between 1998 and 2016 in the SSW region

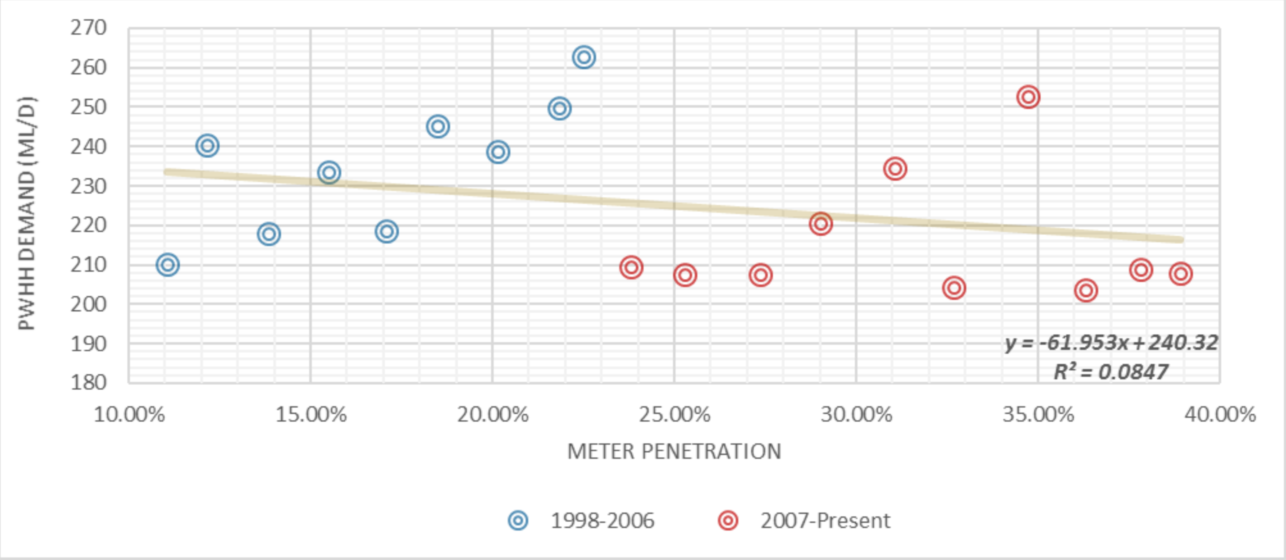
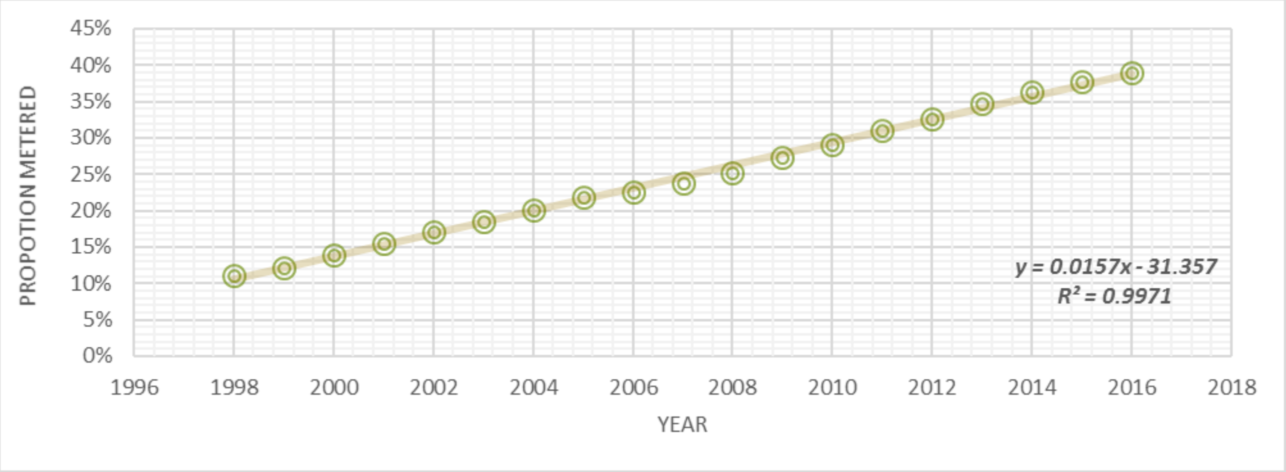


Figure 2-4 Relationship between time and meter penetration between 1998 and 2016 in the SSW region



2.2.3. Climate

2.2.3.1. Hysteresis analysis

Climate data from Shawbury (whose data was included in all three climate variables used in the original model), and Sutton Bonington (also within the SSW region), were compared to ensure that changes in any relationships with PWHH observed are not linked to major hysteresis in the record at Shawbury. Regression and double mass plot analysis was undertaken (Appendix B), to ascertain this. Both sets of analysis confirmed no significant hysteresis at the Shawbury climate station used in the Peak Demand Model. Example regressions and double mass plots undertaken on the clime data are shown in Figure 2-5 and Figure 2-6, respectively.

Figure 2-5 Relationship between May-September rainfall at two MetOffice gauging stations (Sutton Bonington and Shawbury)

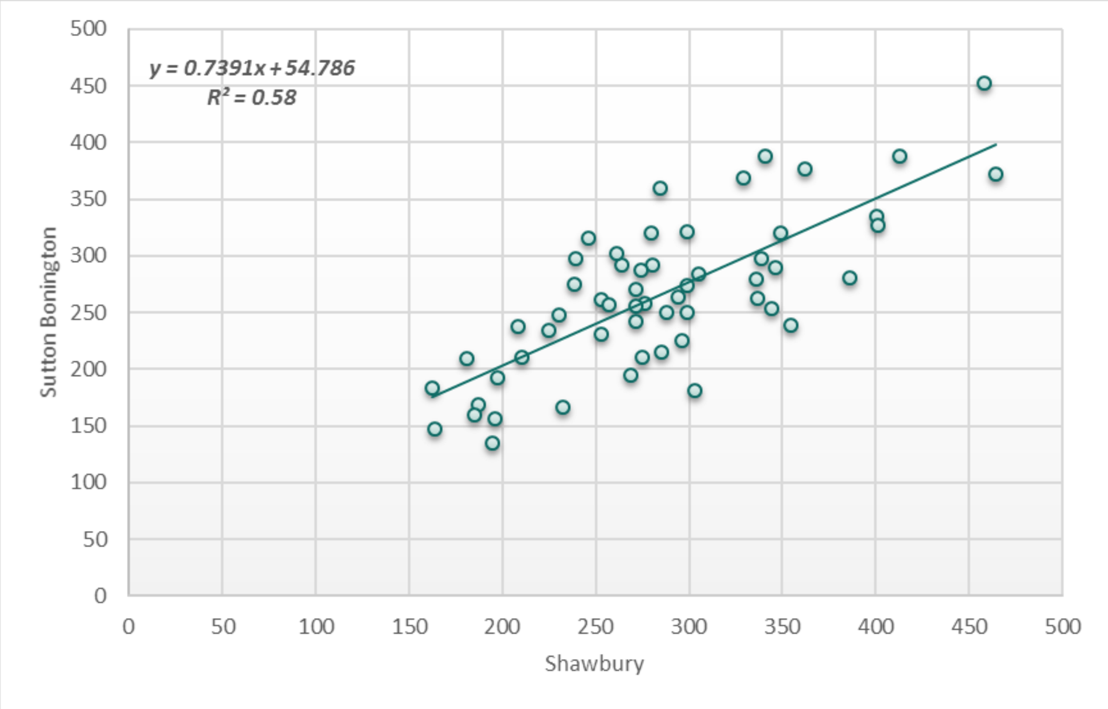
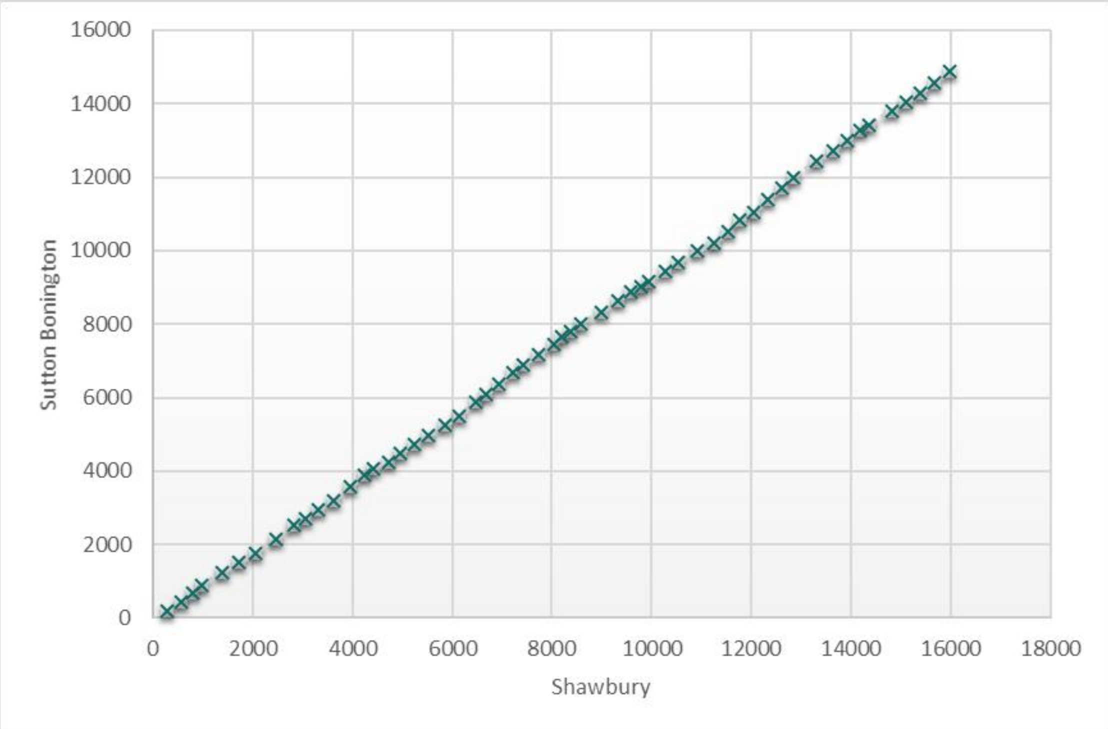


Figure 2-6 Cumulative relationship between May-September rainfall at two MetOffice gauging stations (Sutton Bonington and Shawbury)



2.2.3.2. Threshold Analysis

The 2013 model set thresholds for the climate variables, namely:

- Temperatures >21.5^{o}C;

- Rainfall >100mm; and
- Sunshine>6hours.

It is important to consider whether or not these threshold values are still appropriate given the extended dataset. This was done by plotting the daily data, and looking for inflection points around values suggesting peak demand (Figure 2-7, Figure 2-8, Figure 2-9 and Figure 2-10).

Although thresholds are defined as a hard and fast boundary, in reality they exist over a range of values, where two different behaviour regimes overlap – this can mean that defining a precise location can be exceptionally difficult. Overall, the previous thresholds appear broadly correct, although there may be some room for refinement (e.g.: 30 Day Mean Sunshine Hours threshold could be at a lower value if present at all, and the threshold for 30 Day Max Temp doesn't appear to be exactly on the inflection point, for the 2007-Present dataset).

Figure 2-7 Threshold analysis of 30 Day Max Temp Against PWHH Demand

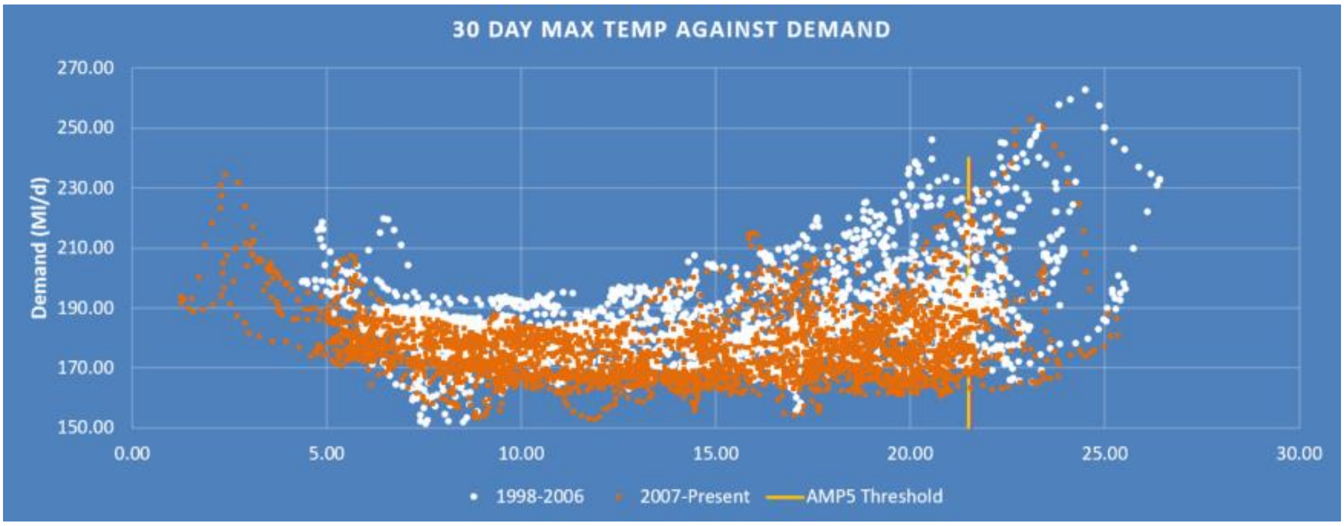


Figure 2-8 Threshold analysis of 30 Day Mean Sunshine Hours Against PWHH Demand

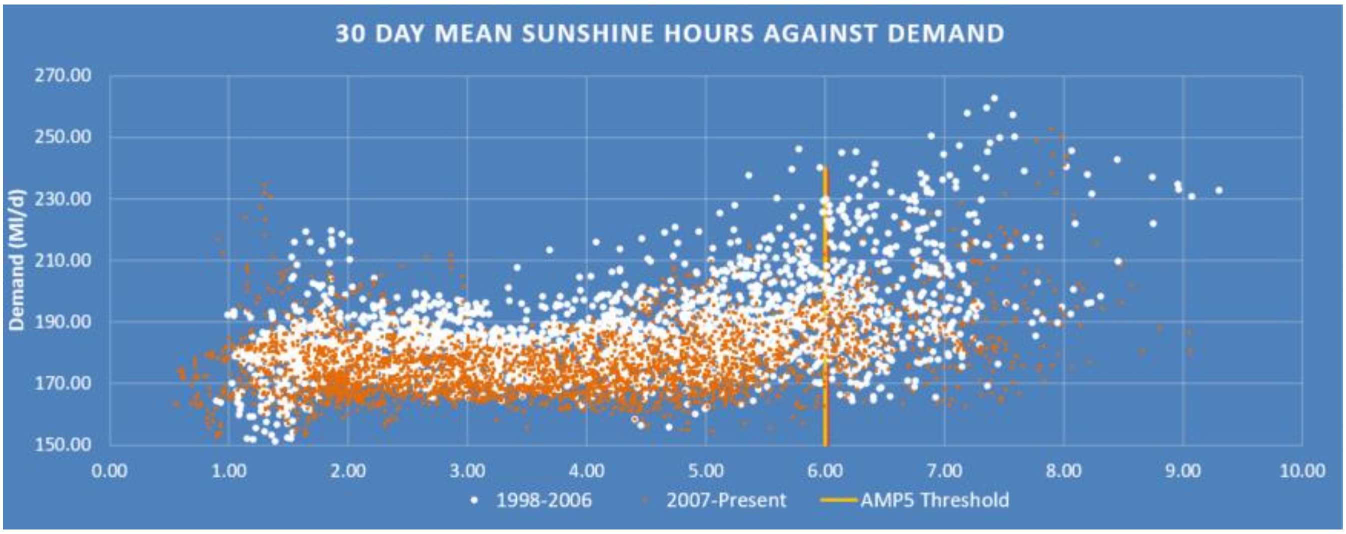


Figure 2-9 Analysis of 30 Day Mean Rainfall Against PWHH Demand

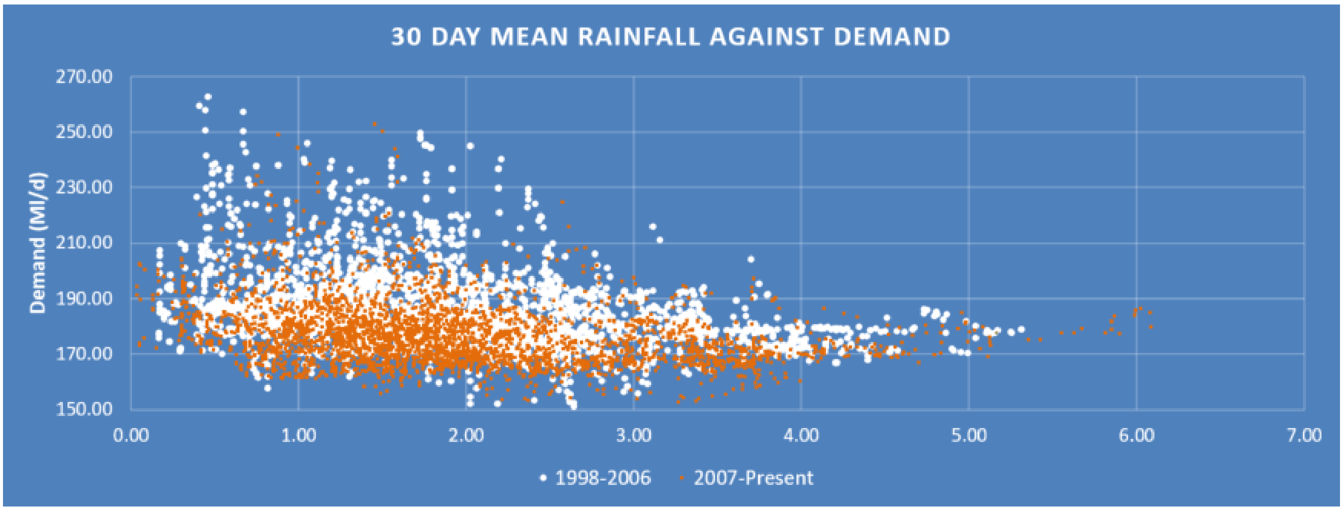
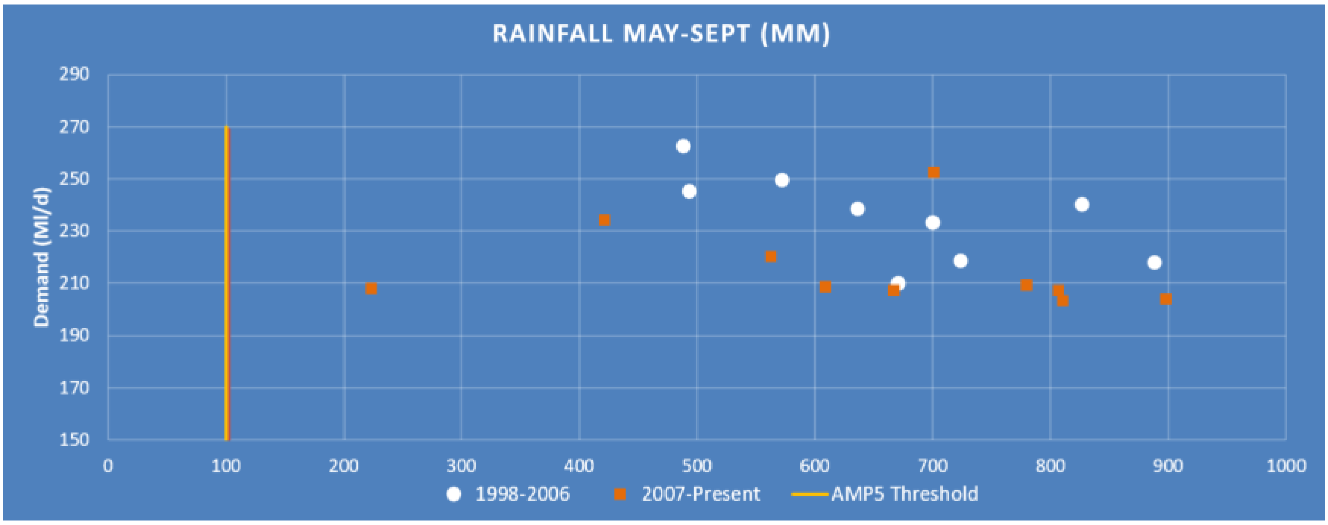


Figure 2-10 Threshold analysis of Rainfall (May-Sept) Against PWHH Demand



2.2.3.3. The impact of climate on PWHH Demand

As was discussed for both population and meter penetration, it is important to check that there is an apparent relationship between the selected climate variables and PWHH demand, in light of the expanded dataset (Figure 2-11, Figure 2-12, Figure 2-13). The r^2 values here are far greater than that seen in either metering or time variables (Section 2.2.2.2); the impact of climatic variables is more important to representing PWHH demand therefore, than either meter penetration or time.

Figure 2-11 Relationship between measured peak week household demand (PWHH) and 30 Day Max Temperature > 21.5 Degrees Celcius between 1998 and 2016 in the SSW region

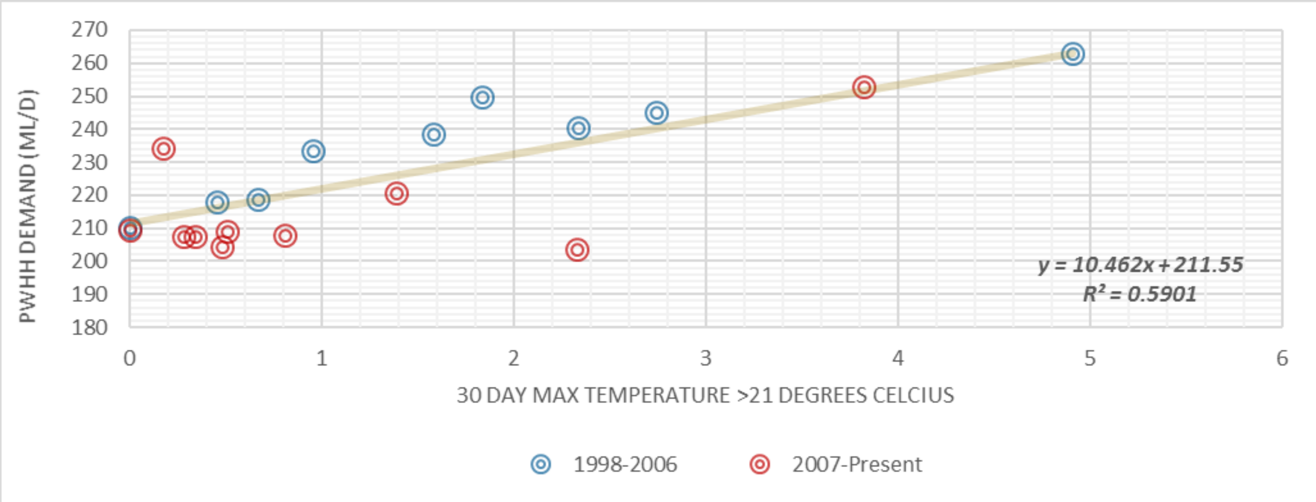


Figure 2-12 Relationship between measured peak week household demand (PWHH) and Max 30 Day Sun Hours >6hrs between 1998 and 2016 in the SSW region

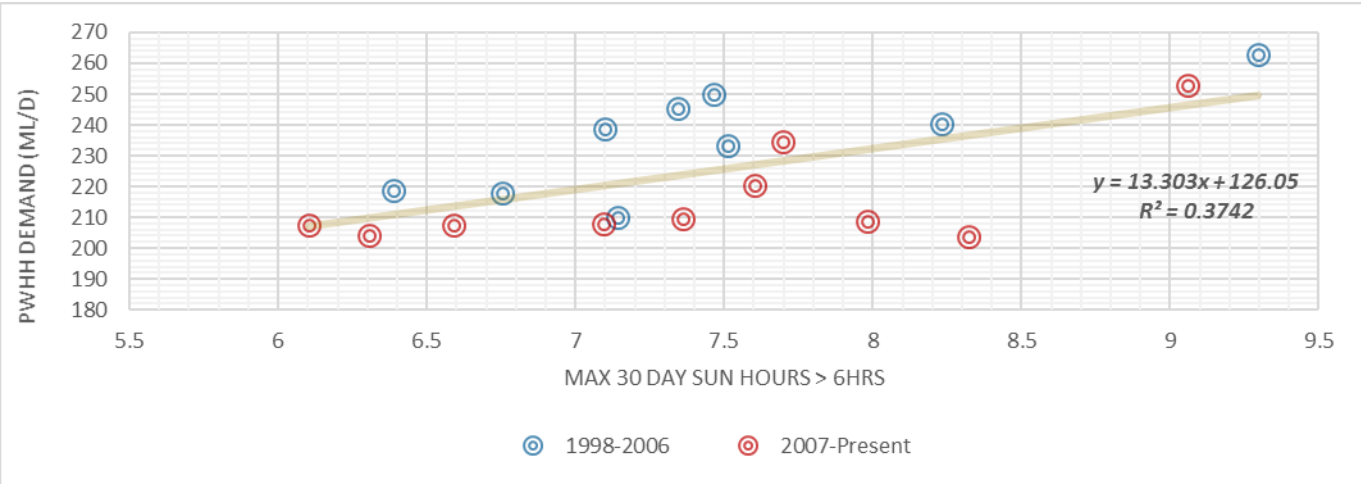
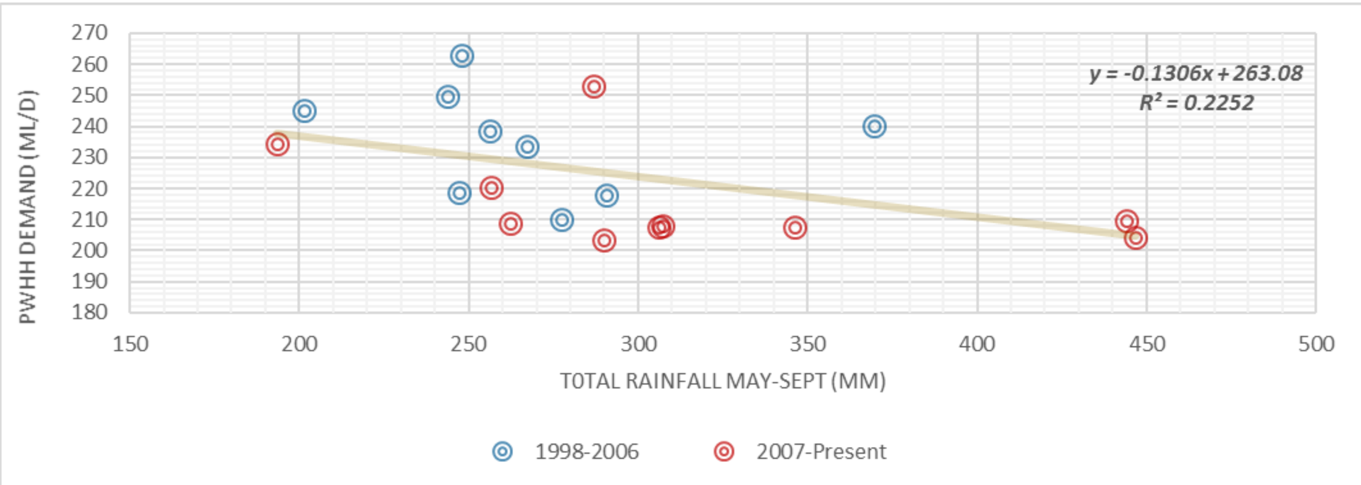


Figure 2-13 Relationship between measured peak week household demand (PWHH) and Total Rainfall (May-Sept) between 1998 and 2016 in the SSW region



2.3. Data Input summary

Analysis of the input data suggests the following:

1. The climate data used in the Peak Demand Model was confirmed to show no significant hysteresis.
2. The climatic thresholds used in the Peak Demand Model still appear suitable, however further work could be undertaken to explore these further (beyond the scope of this study)
3. Of the four key variables explored independently (Table 2-3), meter penetration is the weakest explanatory variable, confirming that weather (temperature, sunshine, rainfall) drives the main PWHH demand response in the historical series.
4. There are noticeable changes in demand from 2006 onwards, suggesting the need to look at a Peak Demand Model which uses data from 2007 onwards only (2006 was ignored, to avoid potentially including any data from the older behaviour regime).
5. A time variable (year or meter penetration) should be reconsidered in refining the current Peak Demand Model approach
6. Metering and population show strong covariance, and therefore normalisation of the demands should be explored in refining the current Peak Demand Model approach

Items 3 to 6 are taken forwards in Section 3 to explore alternative Peak Demand models.

Table 2-3 Linear regression correlation coefficients showing the strength of different relationships with PWHH

Variable	R^2
Temperature	0.59
Sunshine	0.37
Rainfall	0.23
Meter Penetration	0.09

3. Peak Demand Model review

3.1. Original Model

The **'original model'** refers to the model co-efficients given in the SSW Modified Regression Model. It was produced using a multi-linear regression model: using the assumption that the demand was linearly related to a number of variables, multiple combinations of different variables were fitted to create a function to represent the PWHH demand seen in the 1998-2011 period (Table 3-1). These results were incorporated into a linear equation as follows:

$$y = \sum_{1}^{n} k_i . x_i + c = k_1 . x_1 + \cdots + k_i . x_i + \cdots k_n . x_n + c$$

In this case this produced the following equation for estimating PWHH:

$$Demand = -0.076 * Summer\ Rainfall + 6.77 * Sun\ Hours + 7.00 * Max\ T + 191.42$$

Table 3-1 The 'Original Model'

	Summer rainfall (May-Sept)	Max 30 day mean sun hours	30day Max Temp >threshold °C	Constant
Value	-0.076	6.7656	7.000	191.419
standard error	0.035	4.365	2.641	30.053
R2	0.839	8.076		
F	17.404	10		
Ssreg	3405.416	652.197		
T-test	-2.151	1.550	2.649	6.369

The *time* variable was considered to not have a significant relationship with demand, so was not included in the original model. Because no time component was included, the equation could be considered to 'auto-normalise,' meaning that no normalisation was necessary in this process.

Figure 3-1 shows the values plotted using this model, up to 2016. The model appears to be overestimating multiple peaks (e.g.: 2006, 2013), and overestimating other values (2014-16). Analyses (Figure 3-2) were carried out to check the 2014 values in particular, to see if any of the explanatory variables evaluated were unusual in that year – however, 2014 appeared a fairly standard year for all four explanatory variables tested, asides from a slightly higher maximum temperature.

Whilst the model appears to have produced fairly realistic results of peaks in the past, this decreased accuracy is becoming an increasing problem in the present, suggesting that refinement of the model is required.

Figure 3-1 The Original Model compared to the Rolling PWHH Demand between 1998 and 2016

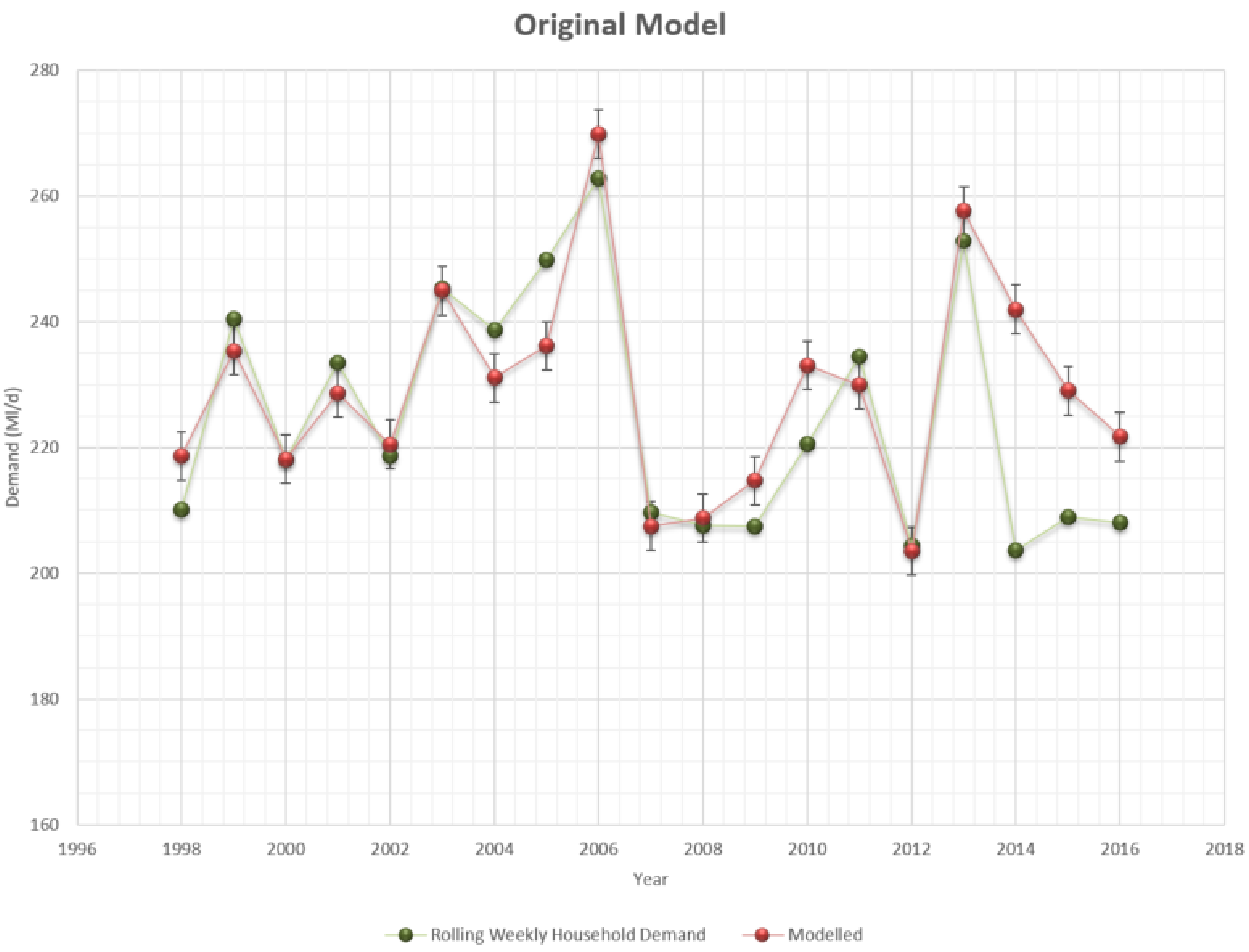
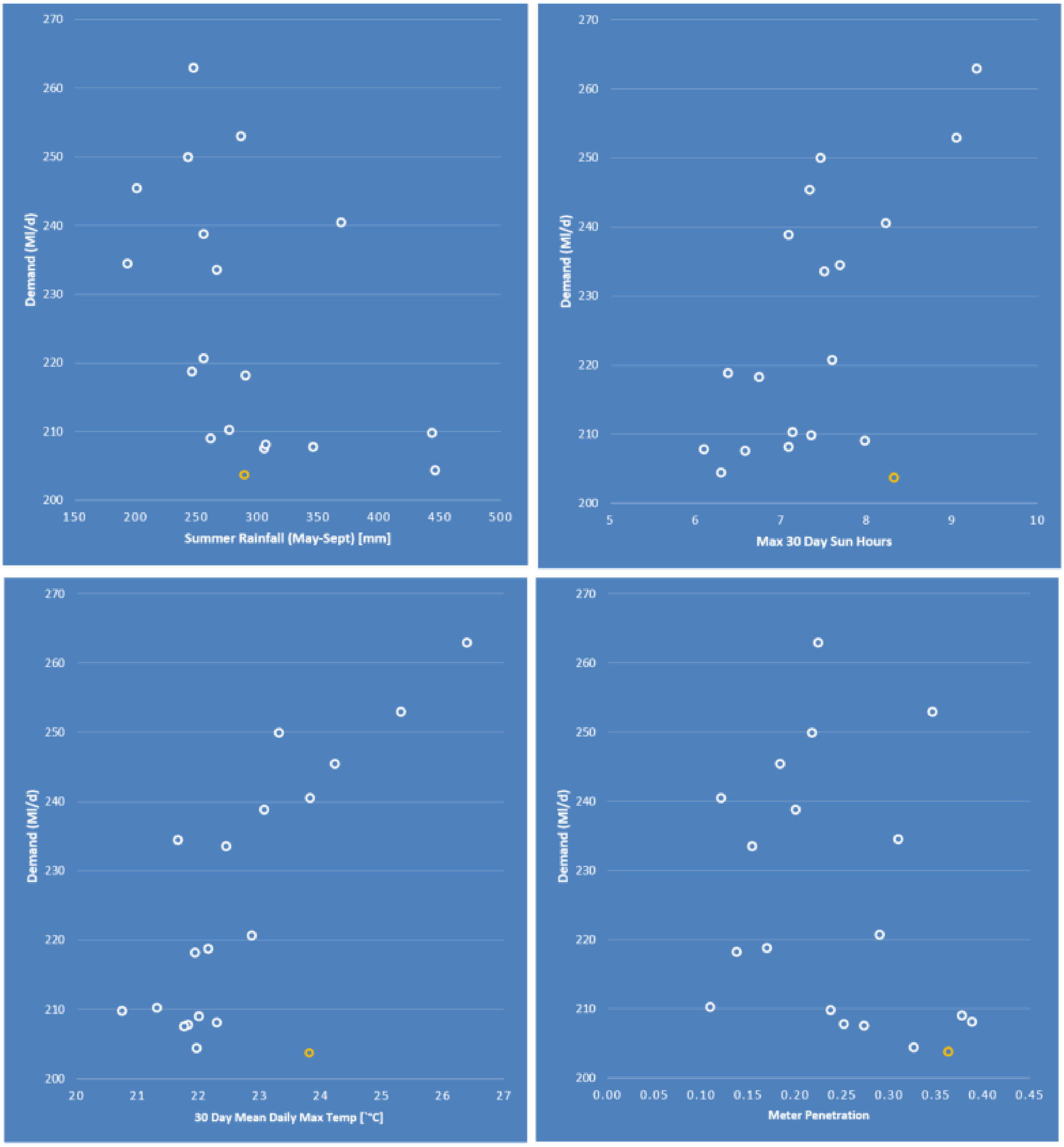


Figure 3-2 Explanatory variables plotted against demand (2014 highlighted in gold) (Clockwise, from top-right: Max 30 Day Sun Hours; Meter Penetration; 30 Day Mean Daily Max Temperature; Summer Rainfall (May-Sept)



3.2. Revised models

To try and address the issue of the poorer fit in the most recent years, revisions to the model were undertaken, to determine if they could improve the fit. In addition to the 'Original Model', four further models were defined (and the co-efficients calculated using multiple linear regression techniques). Based on the 2 potential demand regimes observed (Section 2.2.2.1), it was decided to also use the same models, but alter the years of data used to calculate the co-efficients, to represent only the most recent regime (2007 – Present) – these models have been suffixed with an '*a*'.

A summary of the model set ups is provided in Table 3-2, whilst the full list of calculated co-efficients can be found in Appendix C. A normalisation approach was applied to a model including meter penetration using the following formula:

$$Demand_{Normalised} = Demand_i * \frac{Population\ in\ 2016}{Population\ in\ year\ i}$$

Table 3-2 Model revisions[4]

Model No.	Model description	Years of data used	Year	Metering	Normalisation	R2
1	The 'Original' model	1998-2011				0.63
2	Revised Model with no time variable	1998-2016				0.66
3	Revised Model with time variable	1998-2016	✓			0.75
4	Revised Model with metering variable calculated	1998-2016		✓		0.75
5	Revised Model with metering variable calculated, normalised	1998-2016		✓	✓	0.53 (norm.)
2a	Revised Model with no time variable	2007-2016				0.63
3a	Revised Model with time variable	2007-2016	✓			0.67
4a	Revised Model with metering variable calculated	2007-2016		✓		0.69
5a	Revised Model with metering variable calculated, normalised	2007-2016		✓	✓	0.61(norm.)

Once the models were produced and the results calculated (Appendix C), it was important to assess the 'goodness of fit' of each of the models. Whilst the r^2 values are provided in Table 3-2, these do not necessarily show how well the models fit the given peaks in the peak PWHH demand, but simply the distribution of data. To analyse this, plots were produced (Figure 3-3 and Figure 3-4) and statistics calculated (Table 3-3 and Table 3-4).

From analysing the r^2 values and the fit of the curves, it is apparent that the time varying models provide a closer fit than those without any time varying components (reflecting the correlation seen in Figure 2-3) for both the 1998-2016 and the 2007-2016 datasets. This suggests that given the new data, including a time component marginally improves the fit. The correlation coefficients suggest that the time variable models explain 9% more variability in the observed data but visually there is not much change in the fit, especially at peak values.

Normalising the data appears to not significantly improve the fit, suggesting that the recent changes in population are not necessarily significant enough to include in the model to accurately predict the peak demand, and indeed creating a more complex model adds extra complications that are not fully encompassed by simply normalising demand against population. Applying Ocham's Razor (that the simplest principle that produces the best result, is the best solution), it is sensible to discard Model 5 as an option.

Overall, the benefits of calibrating the co-efficients against a larger dataset (Models 2-5) appear to outweigh the benefits of only using the most recent data (Models 2a-5a), with the former consistently achieving more

[4] Revised models use new co-efficients based on the new data

significant r^2 values than the latter. In addition, the use of post 2006 data only for model calibration excludes the key dry year 2005 in the calibration series, which is likely to impact modelling capabilities for drier periods in the record. This suggests, for the moment at least, it is beneficial to use a non-abridged dataset, rather than fine-tuning to recent changes.

Table 3-3 Statistics comparing the % difference in calculated and assimilated PWHH Demand[5]

Year	Model 1	Model 2	Model 3	Model 4	Model 5
Mean	1.8%	0.0%	0.0%	0.0%	0.0%
Median	4.7%	1.5%	2.6%	2.5%	3.1%
95th Percentile	2.7%	-0.1%	0.5%	0.7%	0.4%
5th Percentile	1.4%	0.0%	-0.6%	-0.4%	1.1%
Standard Error	-10.9%	-18.6%	-13.4%	-13.2%	-11.5%
Peakiest Demand	2.7%	-0.1%	0.5%	0.7%	0.4%
2nd Peakiest Demand	1.9%	-1.5%	-2.5%	-2.5%	-0.2%

Table 3-4 Statistics comparing the % difference in calculated and assimilated PWHH Demand [6]

Year	Model 2a	Model 3a	Model 4a	Model 5a
Mean	0.0%	0.0%	0.0%	0.0%
Median	3.7%	2.0%	1.9%	2.5%
95th Percentile	-4.9%	-4.6%	-4.6%	-4.6%
5th Percentile	-0.4%	-2.0%	-1.9%	-2.1%
Standard Error	-30.4%	-22.8%	-22.9%	-23.0%
Peakiest Demand	-6.2%	-5.3%	-5.3%	-5.3%
2nd Peakiest Demand	-3.2%	-3.7%	-3.6%	-3.7%

[5] Models 1-4 were compared against the PWHH Demand, whilst Model 5 was compared against the Normalised PWHH Demand
[6] Models 2a-4a were compared against the PWHH Demand, whilst Model 5a was compared against the Normalised PWHH Demand

Figure 3-3 The model predictions using the 1998-2016 data compare to the PWHH Demand and PWHH Demand (normalised)

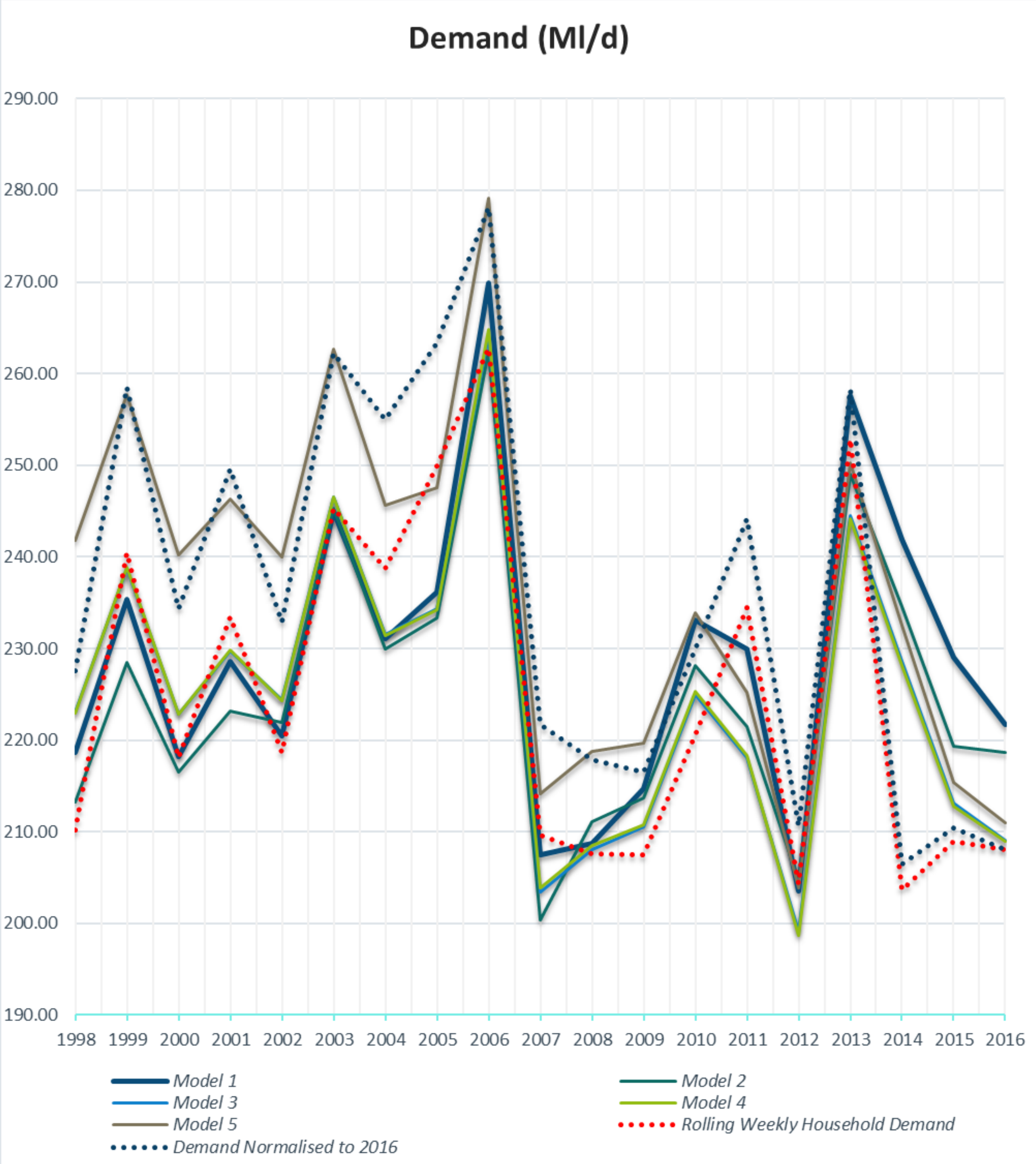


Figure 3-4 The model predictions using the 2007-2016 data compare to the PWHH Demand and PWHH Demand (normalised)

3.3. Model Review summary

The model review has demonstrated that:

1. A time variable marginally improves the Peak Demand Model fits to observed PWHH, by 9% according to Pearson's r^2 analysis.

2. Of the two models incorporating a time variable (year or meter penetration), both provide a similar fit to observed PWHH.

3. Simple normalisation of demand data does not improve the fit to observed (normalised) PWHH, and therefore does not justify the need to apply it.

4. Some years are still not satisfactorily modelled with the revised models

4. Revised Peak Demand Model forecast

As the Peak Demand Model with a time variable improves the model performance – a revised peak demand forecast has been developed using a time variable model. Whilst a "catch all" year variable provides a similar level of explanatory performance to a metering variable, at the request of SSW (Pers. Comm, 17/07/2017), we have focussed on the metering penetration model (model 4) going forward, to allow us to assess the impacts of future metering forecasts.

Using a metering only variable does provide a more practical result, allowing the impacts of metering to be included in forecasting. Due to the strong co-linearity between year and metering (Figure 2-4), it would be unwise to include both variables on the same model. The remainder of this section applies the original and selected mode (model 4) to develop PWHH estimates for a 1:20 and 1:40 return period.

4.1. Return Period Analysis approach

It is possible to estimate the corresponding base year equivalent peak volume for a given return period by producing a cumulative frequency distribution of the range of base year equivalent PV values obtained from rebasing the historical peaks. To achieve this, a histogram covering the range of values is plotted, together with its cumulative distribution. Normal, Lognormal and Box-Cox cumulative distribution functions (CDFs) can be calculated to compare with the actual cumulative distribution of the data. The distribution of base year equivalent PV often has a right-hand skew.

Where this is the case, the normal distribution would not generally be expected to provide a good estimate. The lognormal distribution could be more suitable for a right-hand skew, as could the Box-Cox distribution, which attempts to remove the skew and normalise the data.

4.2. Return period analysis results

4.2.1. Present

Using this return period analysis approach, it is possible to predict the demand for 1 in 20 and 1 in 40 year events (Table 4-1, Figure 4-1, Figure 4-2). This in turn allows hindcasting of what may have happened under similar climatic conditions to that recorded (Figure 4-3 and Figure 4-4). Notably both models give similar values for the 1995 drought, yet the new model produces a lower demand for the 1976 demand, and overall a reduced amplitude of both the peaks and troughs.

Table 4-1 Results of return period analysis for the 'Original Model' and Model 4

	Original Model (Ml/d)		**Model 4 (Ml/d)**	
Method	1 in 20 year	1 in 40 year	1 in 20 year	1 in 40 year
Percentile	271	275	269	284
LogNormal	**266**	**273**	**265**	**275**
Box-Cox	**266**	**273**	**264**	**275**
Skew	Right-hand (Figure 4-1)		Mild right-hand (Figure 4-2)	
Suggested value	LogNormal/Box-Cox		LogNormal/Box-Cox	

Figure 4-1 Histogram and Cumulative Distribution Function of Original Model

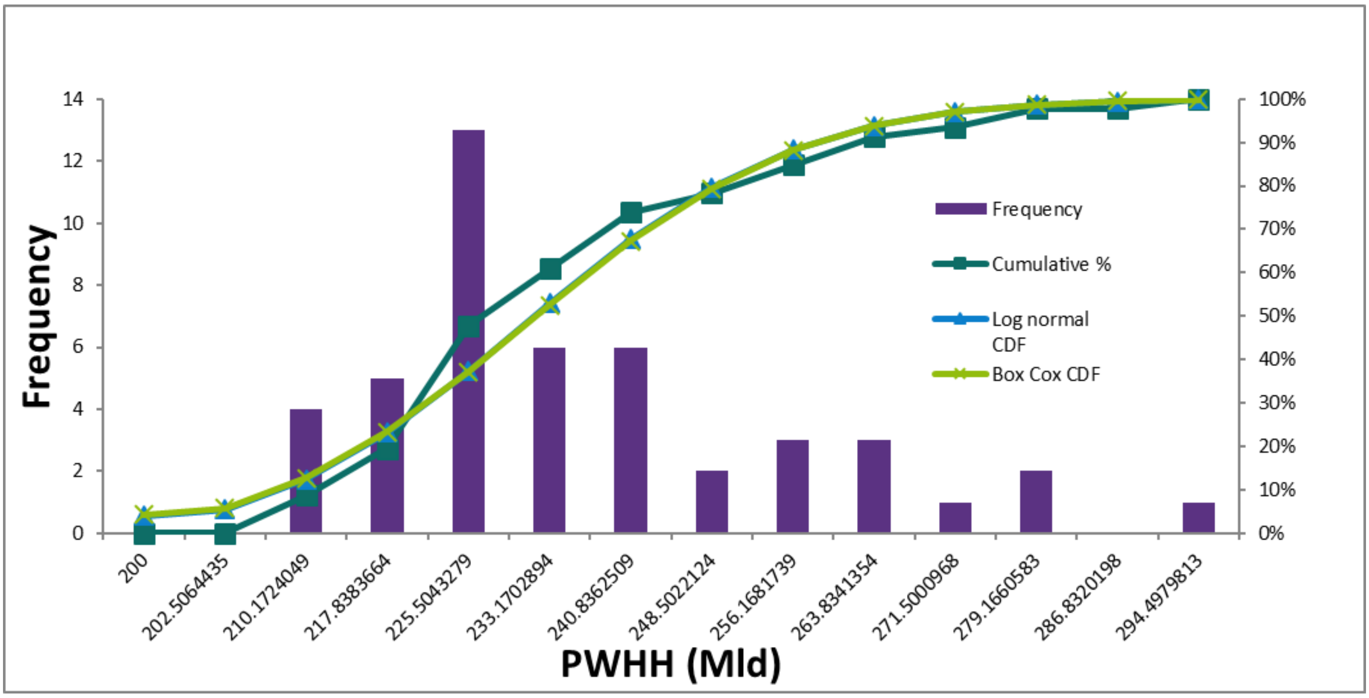


Figure 4-2 Histogram and Cumulative Distribution Function of Model 4

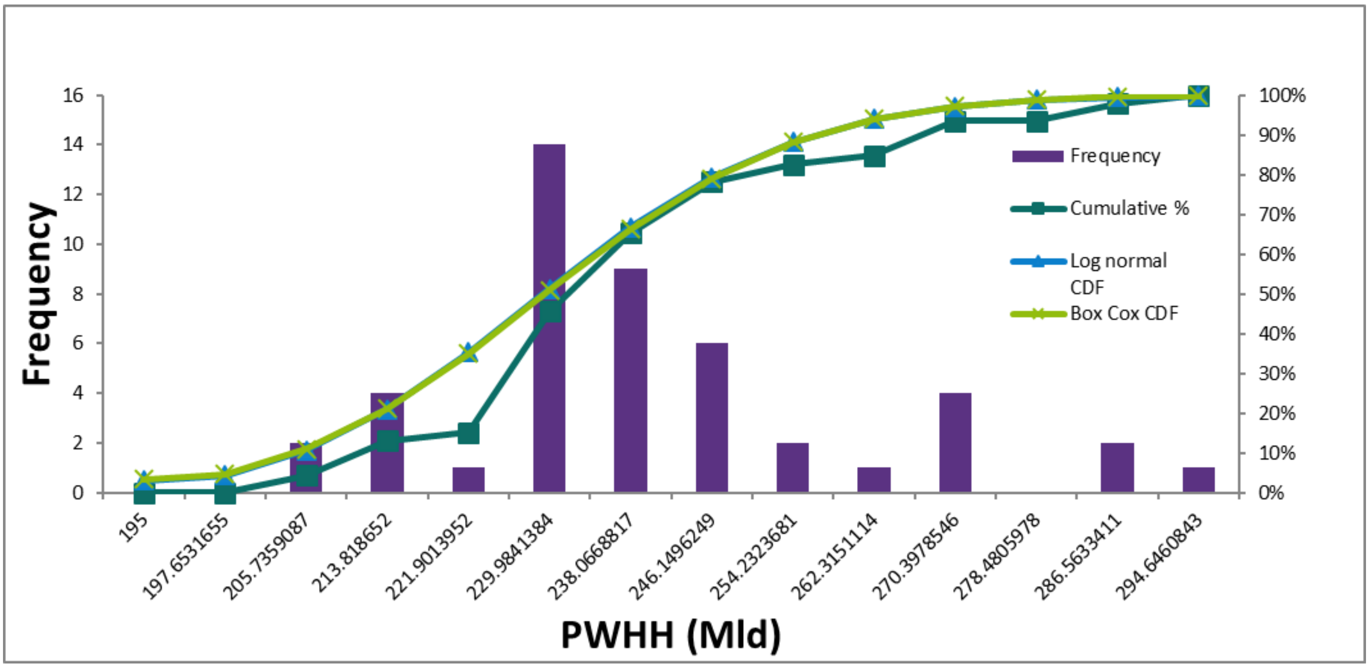


Figure 4-3 Backcast PWHH Demand values, based on the Original Model

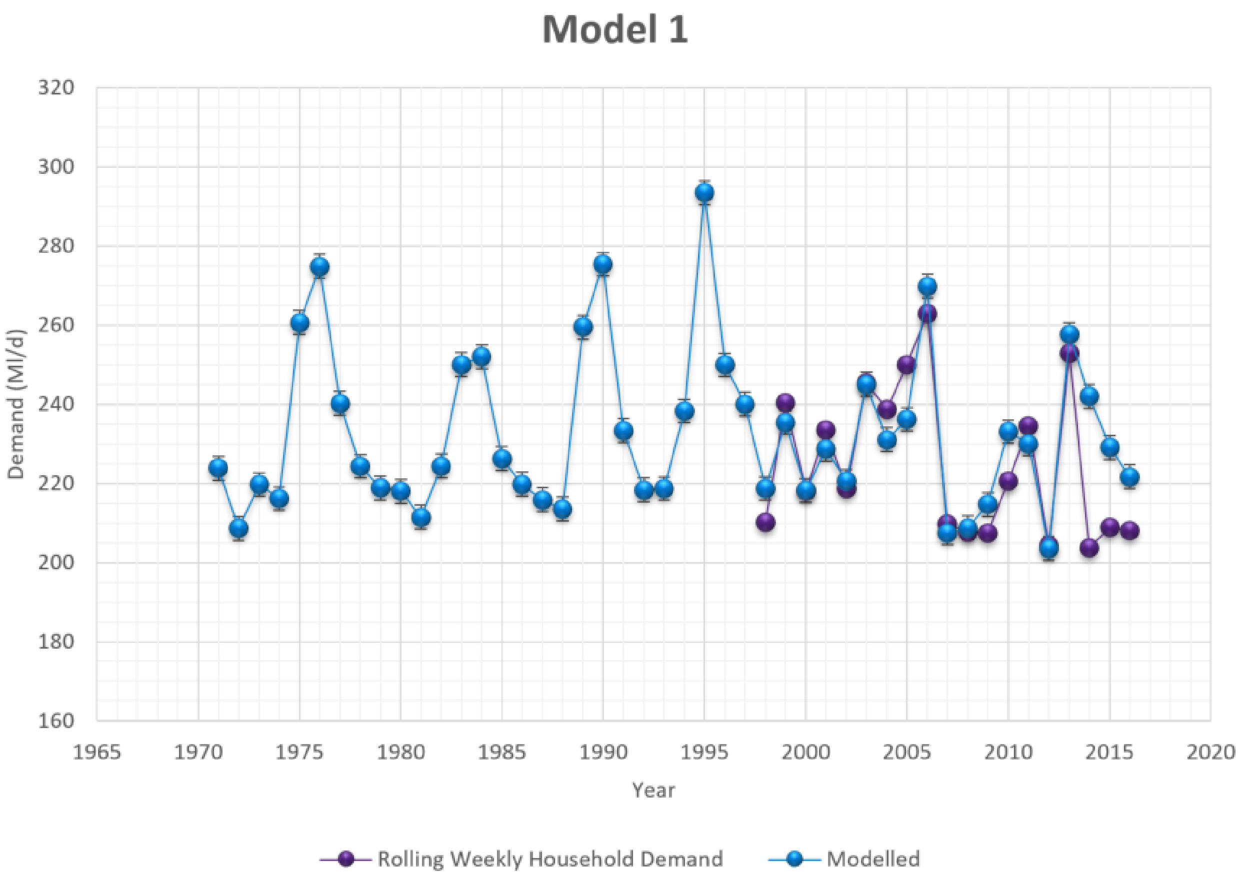
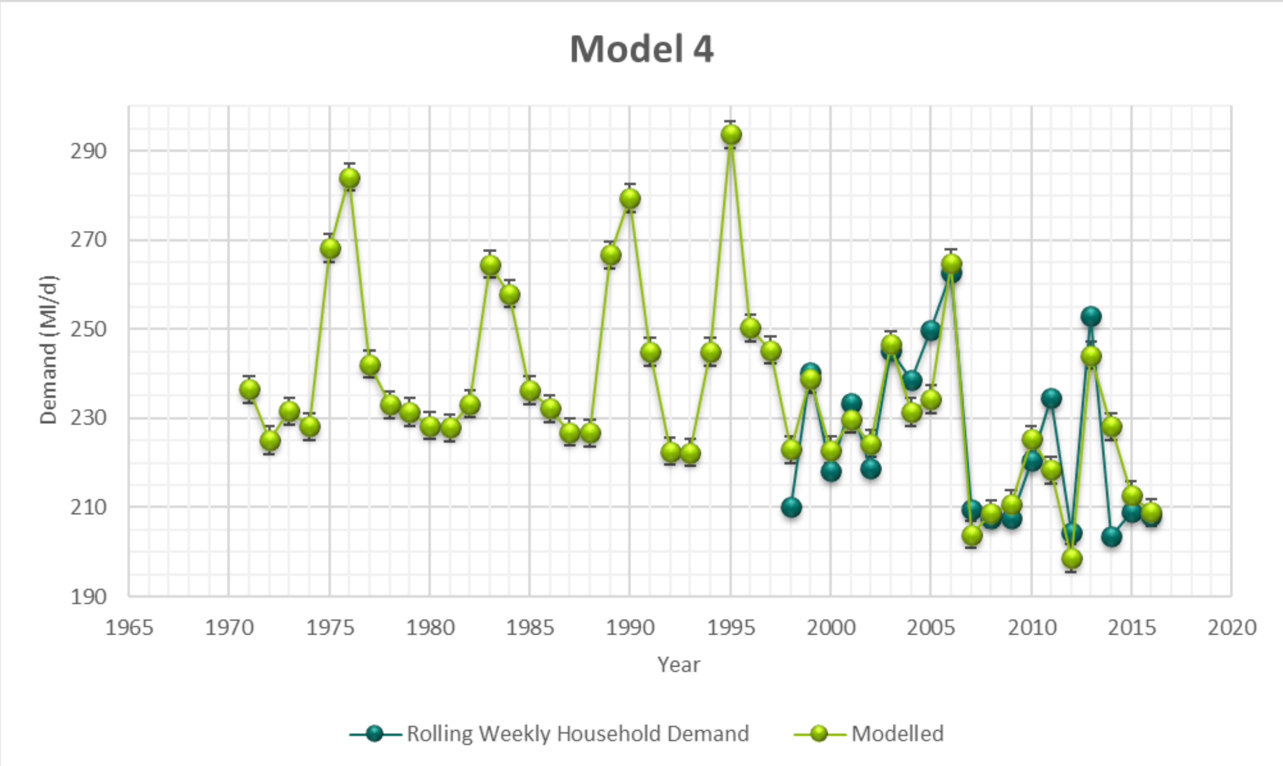


Figure 4-4 Backcast PWHH Demand values, based on Model 4



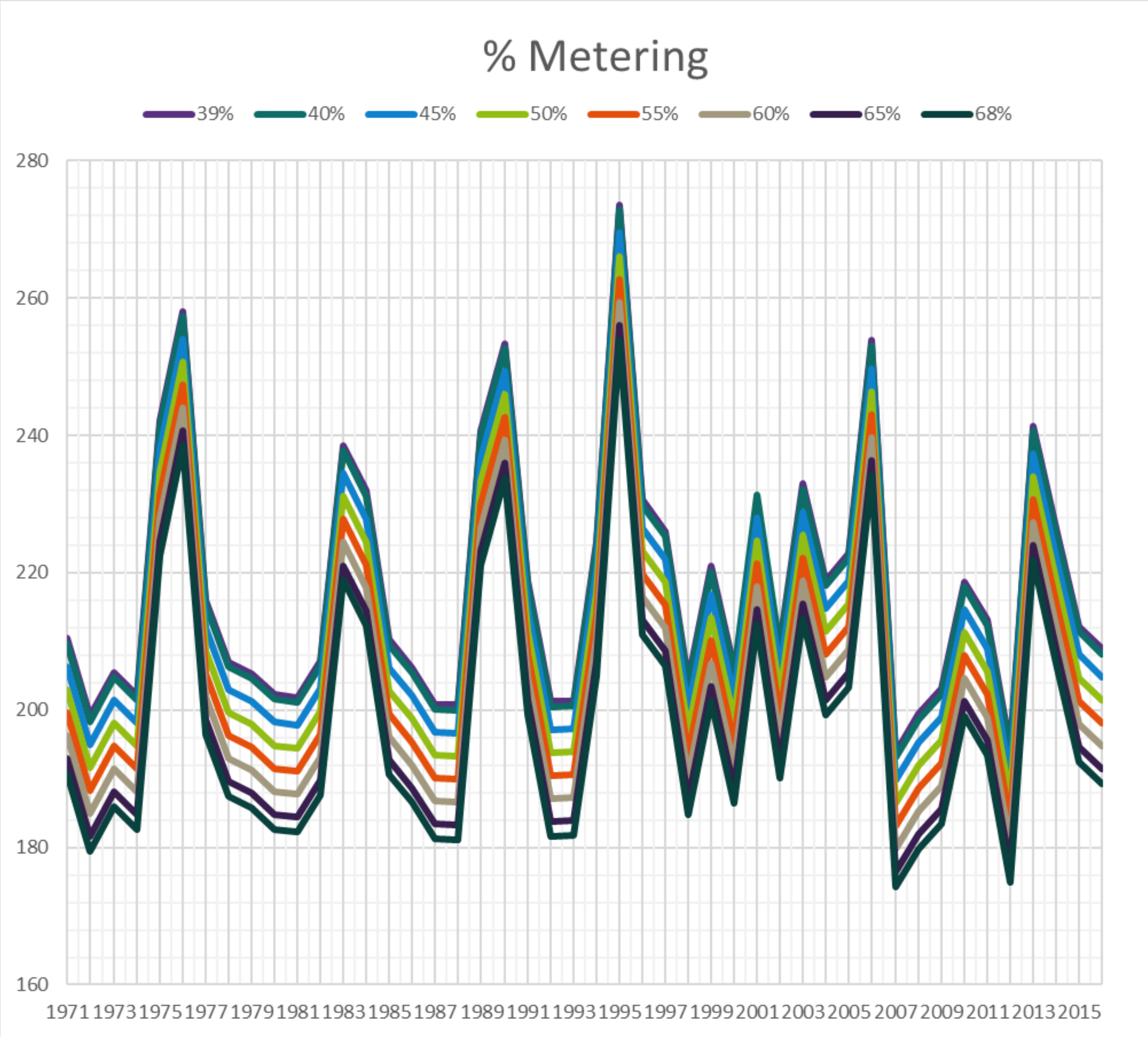
4.2.2. Possible Forecasting Approaches

The development of a relationship between meter penetration and peak demand in Model 4 permits the potential utilisation of Option H in UKWIR 2006 (i.e. Forecast peak demands using projected changes in numbers of each customer type and modelling the demand impacts of metering). The effects of future changes in meter penetration can be investigated using Model 4 (Table 4-2 and Figure 4-5). It is apparent that increasing the metering from the current value of 39% to 68% (the forecast for 2045), produces a considerable reduction in peak demand, by up to 19Ml/d over the period. Such figures should be treated with a degree of caution however, as the further the model is used beyond its calibrated data range, the greater the potential uncertainty.

Table 4-2 Future metering effects on PWHH demand using Model 4 (Ml/d)

Metering	Return Period	Percentile	LogNormal	Box-Cox
39%	1in 20	253	249	249
	1in 40	258	255	255
40%	1in 20	253	249	249
	1in 40	257	256	256
45%	1in 20	249	246	246
	1in 40	253	252	252
50%	1in 20	246	253	252
	1in 40	250	249	249
55%	1in 20	243	239	239
	1in 40	247	246	246
60%	1in 20	239	236	236
	1in 40	243	243	242
65%	1in 20	236	233	232
	1in 40	240	239	239
68%	1in 20	234	230	230
	1in 40	238	237	237

Figure 4-5 Forecasting the effects of metering on PWHH Demand (Ml/d)



5. Conclusions and Recommendations

The original peak demand model was reviewed confirming that climate variables are the main explanatory variables influencing PWHH. However, a time variable (year or metering) is also shown to have some influence with the peak demand model fits improving with the incorporation of a year or meter penetration variable. The meter penetration variable was incorporated into a revised Peak Demand Model and applied to the return period analysis, showing reductions in PWHH as metering increases.

Despite the revisions to the model and inclusion of new data, the overall improvements in simulating the highest PWHH is only moderately improved. This suggests that an alternative model structure could be required to further improve the simulation of PWHH.

It is recommended that further refinements to the modelling of PWHH could include investigating the timing (and thresholds) of peak weather events and peak demands to establish if there has been a change in this pattern over time. This could be addressed through the development of sub-annual models (weekly or monthly). The application of micro-component analysis could also be explored to ascertain the data-availability and quality to undertake it.

Appendices

Contains *sensitive* information

Appendix A. Data received

A.1. SSW data

Adjusted Climate and Rainfall Data v3.:

Leakage Time Series v4 SSW.xlsx

property and population forecasts

Regression Model for SSW 280912 upda

A.2. Met Office data

suttonboningtondata.txt

shawburydata.txt

Appendix B. Weather Station Comparisons

30 Day Mean Sunlight [Hours]

Figure B-1 A scatter plot showing the relationship between 30 Day Mean Sunlight Hours at two MetOffice gauging stations (Sutton Bonington and Shawbury)

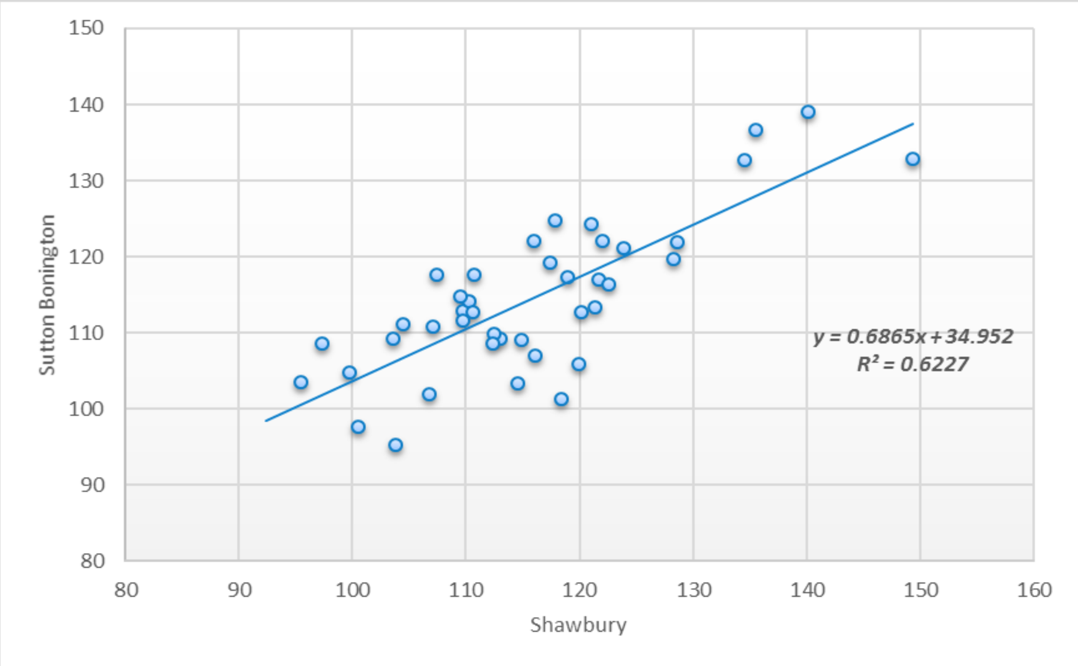
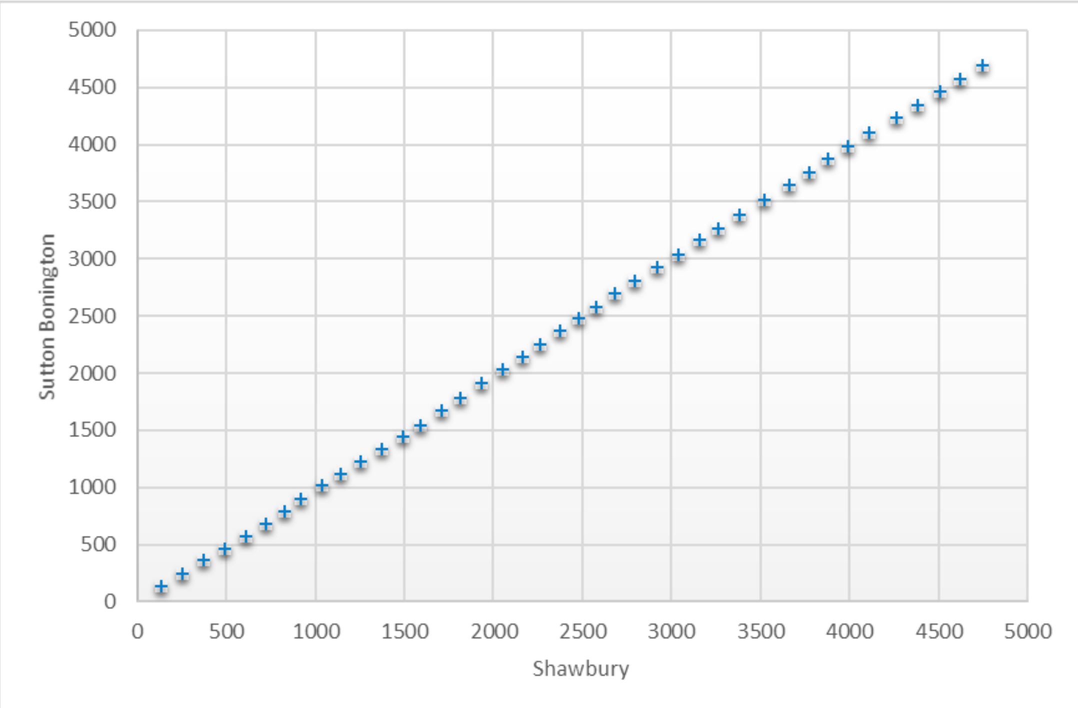


Figure B-2 A double mass plot showing the cumulative relationship between 30 Day Mean Sunlight Hours at two MetOffice gauging stations (Sutton Bonington and Shawbury)



30 Day Max T>21.5ºC

Figure B-1 A scatter plot showing the relationship between 30 Day Max Temperature >21.5 Degrees Celcius at two MetOffice gauging stations (Sutton Bonington and Shawbury)

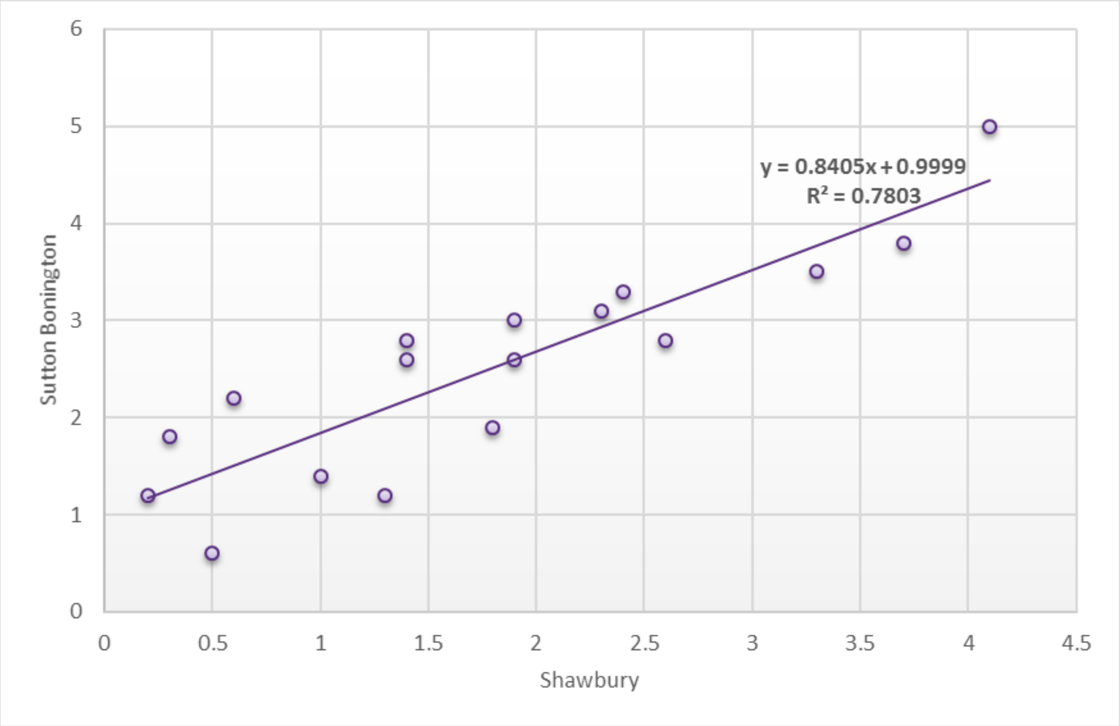
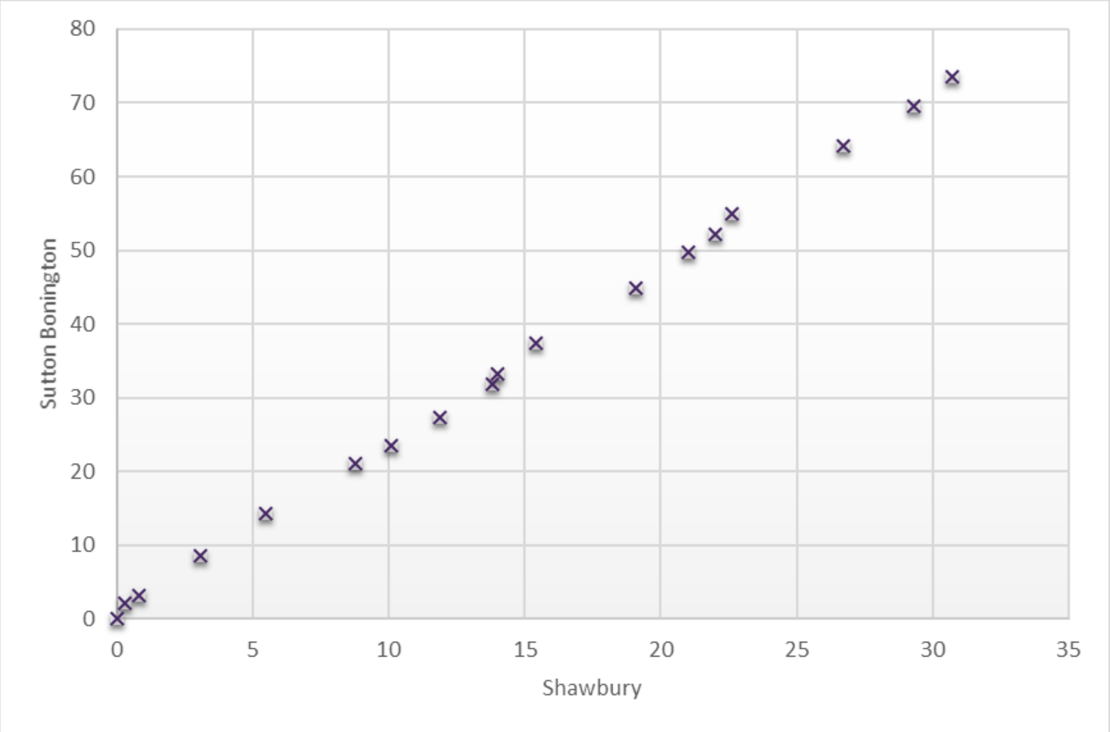


Figure B-2 A double mass plot showing the cumulative relationship between 30 Day Max Temperature >21.5 Degrees Celcius at two MetOffice gauging stations (Sutton Bonington and Shawbury)



Appendix C. Peak Demand Models

Model 1

Table C-1 Calculated Multiple Linear Regression for Model 1

	Summer rainfall (May-Sept)	Max 30 day mean sun hours	30day Max Temp >threshold°C	constant
Value	-0.0760012	6.765579	6.9976581	191.419042
standard error	0.035335068	4.364657	2.6412354	30.0525081
R2	0.839265757	8.075874		
F	17.40483223	10		
Ssreg	3405.415946	652.1974		
T-test	-2.15087183	1.550083	2.6493883	6.3694864

Model 2

Table C-2 Calculated Multiple Linear Regression for Model 2

	Summer rainfall (May-Sept)	Max 30 day mean sun hours	30day Max Temp >threshold°C	constant
Value	-0.07755653	0.082278	9.5206942	234.193212
standard error	0.04314768	5.212391	3.3435751	38.9106005
R2	0.662032082	12.03184		
F	9.794303659	15		
Ssreg	4253.621875	2171.477		
T-test	-1.79746692	0.015785	2.8474593	6.01875091

Model 2a

Table C-3 Calculated Multiple Linear Regression for Model 2a

	Summer rainfall (May-Sept)	Max 30 day mean sun hours	30day Max Temp >threshold°C	constant
Value	-0.04966177	4.685237	4.3643952	192.21607
standard error	0.069085494	8.789415	6.0683864	73.926152
R2	0.484086034	14.07838		
F	1.87661535	6		
Ssreg	1115.840685	1189.206		
T-test	-1.79746692	0.015785	2.8474593	6.01875091

Model 3

Table C-4 Calculated Multiple Linear Regression for Model 3

	Year	Summer rainfall (May-Sept)	Max 30 day mean sun hours	30day Max Temp >threshold°C
constant	-1.03755339	-0.065622	2.8358552	8.43010227
standard error	0.467728284	0.038793	4.804153	3.01737962
R2	0.749928294	10.71293		
F	10.49598563	14		
Ssreg	4818.363765	1606.736		
T-test	-2.21828232	-1.691599	0.5902924	2.79384874

Model 3a

Table C-5 Calculated Multiple Linear Regression for Model 3a

	Year	Summer rainfall (May-Sept)	Max 30 day mean sun hours	30day Max Temp >threshold°C
constant	-2.03493737	-0.066247	5.8675614	5.45400974
standard error	1.723271439	0.068379	8.5726946	5.95023302
R2	0.596590717	13.63728		
F	1.848590071	5		
Ssreg	1375.169179	929.877		
T-test	-2.21828232	-1.691599	0.5902924	2.79384874

Model 4

Table C-6 Calculated Multiple Linear Regression for Model 4

	Metering	Summer rainfall (May-Sept)	Max 30 day mean sun hours	30day Max Temp >threshold°C
constant	-66.889349	-0.067013	3.005827	8.34672206
standard error	29.53493899	0.038491	4.7927921	3.00583634
R2	0.752651769	10.65443		
F	10.65009108	14		
Ssreg	4835.86236	1589.237		
T-Test	-2.26475325	-1.74101	0.6271557	2.7768385

Model 4a

Table C-7 Calculated Multiple Linear Regression for Model 4a

	Metering	Summer rainfall (May-Sept)	Max 30 day mean sun hours	30day Max Temp >threshold°C
constant	-117.807209	-0.065829	6.1070239	5.47566559
standard error	100.9908585	0.068514	8.6231009	5.97028237
R2	0.594455336	13.67333		
F	1.832274555	5		
Ssreg	1370.247027	934.7992		
T-Test	-1.16651359	-0.9608	0.7082167	0.9171535

Model 5

Table C-8 Calculated Multiple Linear Regression for Model 5

	Metering	Summer rainfall (May-Sept)	Max 30 day mean sun hours	30day Max Temp >threshold°C
constant	-128.12029	-0.071223	2.8050289	8.93343367
standard error	32.32433843	0.042126	5.2454428	3.28971972
R2	0.783718437	11.66068		
F	12.68260915	14		
Ssreg	6897.891391	1903.6		
T-Test	-3.96358583	-1.69072	0.5347554	2.7155607

Model 5a

Table C-9 Calculated Multiple Linear Regression for Model 5a

	Metering	Summer rainfall (May-Sept)	Max 30 day mean sun hours	30day Max Temp >threshold°C
constant	-198.90551	-0.071121	6.6719337	5.37056991
standard error	107.6698709	0.073045	9.1933882	6.36512593
R2	0.593419615	14.57761		
F	1.824422789	5		
Ssreg	1550.808109	1062.533		
T-Test	-1.84736462	-0.97366	0.7257317	0.8437492

Results

Table C-10 Results of Models 1-5 and PWHH Demand

Year	Rolling Weekly Household Demand	Demand Normalised to 2016	Model 1	Model 2	Model 3	Model 4	Model 5
1998	210.15	227.56	218.66	213.26	223.08	222.96	241.74
1999	240.41	258.52	235.37	228.43	238.77	238.81	257.67
2000	218.14	234.39	218.18	216.51	222.85	222.82	240.18
2001	233.45	249.55	228.65	223.20	229.76	229.78	246.35
2002	218.68	232.87	220.51	221.90	224.40	224.25	240.01
2003	245.33	262.17	244.97	245.27	246.56	246.57	262.69
2004	238.72	255.04	231.04	229.98	231.47	231.40	245.64
2005	249.87	263.34	236.20	233.33	234.38	234.26	247.59
2006	262.83	278.13	269.84	262.48	264.23	264.76	279.10
2007	209.68	221.70	207.48	200.37	203.44	203.93	214.14
2008	207.66	217.92	208.76	211.06	208.10	208.54	218.72
2009	207.48	216.52	214.69	213.64	210.56	210.79	219.72
2010	220.59	229.99	233.05	228.10	224.98	225.29	233.87
2011	234.42	244.18	230.00	221.47	218.14	218.32	225.19
2012	204.31	210.68	203.51	204.65	199.14	198.65	203.91
2013	252.89	258.25	257.65	249.06	244.55	244.17	250.27
2014	203.63	206.44	241.95	234.54	228.62	228.19	232.57
2015	208.96	210.46	229.05	219.35	213.11	212.84	215.41
2016	208.05	208.05	221.69	218.62	209.10	208.91	210.98
Mean	**225.01**	**236.09**	**229.01**	**225.01**	**225.01**	**225.01**	**236.09**
Median	**218.68**	**232.87**	**229.05**	**221.90**	**224.40**	**224.25**	**240.01**
95th Percentile	**262.83**	**278.13**	**269.84**	**262.48**	**264.23**	**264.76**	**279.10**
5th Percentile	**203.63**	**206.44**	**203.51**	**200.37**	**199.14**	**198.65**	**203.91**
Standard Error	**4.22**	**4.94**	**3.76**	**3.43**	**3.65**	**3.66**	**4.37**
Peakiest Demand	**262.83**	**278.13**	**269.84**	**262.48**	**264.23**	**264.76**	**279.10**
2nd Peakiest Demand	**252.89**	**263.34**	**257.65**	**249.06**	**246.56**	**246.57**	**262.69**

Table C-11 Results of Models 2a-5a and PWHH Demand

Year	Rolling Weekly Household Demand	Demand Normalised to 2016	Model 2a	Model 3a	Model 4a	Model 5a
1998	210.15	227.56	211.90	238.56	235.31	258.86
1999	240.41	258.52	222.63	249.55	247.38	269.91
2000	218.14	234.39	211.39	233.79	231.26	252.21
2001	233.45	249.55	218.33	240.53	238.24	258.34
2002	218.68	232.87	212.78	231.63	229.24	247.56
2003	245.33	262.17	228.58	249.55	247.80	265.55
2004	238.72	255.04	219.66	236.13	234.40	250.51
2005	249.87	263.34	223.07	238.41	236.82	251.79
2006	262.83	278.13	244.89	263.66	263.83	278.95
2007	209.68	221.70	204.65	210.49	210.64	223.08
2008	207.66	217.92	205.09	209.40	209.53	220.55
2009	207.48	216.52	209.11	212.55	212.35	222.17
2010	220.59	229.99	221.14	225.78	225.91	235.11
2011	234.42	244.18	219.42	221.86	221.60	229.65
2012	204.31	210.68	201.68	196.58	196.21	200.78
2013	252.89	258.25	237.09	239.50	239.46	244.45
2014	203.63	206.44	226.95	224.77	224.66	228.07
2015	208.96	210.46	218.81	212.67	212.67	215.00
2016	208.05	208.05	213.71	204.06	204.63	205.31
Mean	**225.01**	**236.09**	**218.47**	**228.39**	**227.47**	**239.89**
Median	**218.68**	**232.87**	**218.81**	**231.63**	**229.24**	**244.45**
95th Percentile	**262.83**	**278.13**	**244.89**	**263.66**	**263.83**	**278.95**
5th Percentile	**203.63**	**206.44**	**201.68**	**196.58**	**196.21**	**200.78**
Standard Error	**4.22**	**4.94**	**2.44**	**3.92**	**3.80**	**4.95**
Peakiest Demand	**262.83**	**278.13**	**244.89**	**263.66**	**263.83**	**278.95**
2nd Peakiest Demand	**252.89**	**263.34**	**237.09**	**249.55**	**247.80**	**269.91**

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