SSW Stochastic Drought Groundwater Yield Assessment

Cambridge WRZ WRMP19

1 December 2017

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Contents

Glossary

AVPY	DYAA Potential Yield (see "PY")
AWS or AW	Anglian Water Services
BGS	British Geological Survey
BH	Borehole
CBO	Cam and Bedford Ouse (groundwater model area)
DAPWL	Deepest Advisable Pumping Water Level ((UKWIR and EA, 2002)
Deployable Output (DO)	The maximum rate of abstraction that can be maintained from a groundwater source, taking account of all relevant constraints (including pumps, treatment capacity, abstraction licence limits, etc), under a specified planning scenario.
DYAA	"Dry Year Annual Average" scenario for water resource planning
DYCP	"Dry Year Critical Period" scenario for water resource planning. Also referred to as "Peak" (period).
EA	Environment Agency
EONWN	Ely Ouse and North-West Norfolk (groundwater model area)
EBSD model	The "Economics of Balancing Supply and Demand" "least whole-life cost" model
Level of Service (LOS)	The predicted failure rate which accompanies any calculated water supply component, such as PY or DO. Here used in relation to drought yield failure, and typically specified as a frequency in years ("1 in 100", etc).
LPM	Lumped Parameter (groundwater) Model
l/s	Litres per second (unit of flow rate, PY or DO)
mAOD	Meters Above Ordnance Datum
Ml/d	Mega litres per day (unit of flow rate, PY or DO)
MODFLOW	Finite-difference groundwater flow modelling software used, for example, to build the EA's distributed regional groundwater models
NEAC	North-East Anglian Chalk (groundwater model area)
OBH	Observation Borehole
Peak	See "DYCP".
PDPY	DYCP (Peak) Potential Yield (see "PY")
Potential Yield (PY)	The maximum rate of abstraction that can be maintained from a groundwater source, as constrained only by the borehole performance aquifer properties and interference between boreholes, over a specified time period. For the DYAA scenario, this time period is taken to be the 200 days of lowest groundwater levels on record. For the DYCP scenario, the relevant time period is 7 days at a period of peak demand in a dry year.
PWL	Pumping Water Level
RWL	Rest (non-pumping) Water Level
SRO	"Source Reliable Output" methodology used to determine groundwater potential yield
SSW	South Staffordshire Water company
UKWIR	United Kingdom Water Industry Research,
USG	Unstructured Grid – used in relation to MODFLOW software
WRE	Water Resources East study
WRMP19	Water Resource Management Plan 2019
WRZ	Water Resource Zone: a geographic area specified at WRMP19 within which all properties and water resources are well connected, such that they all share the same risk of failure and level of service
WTW	Water Treatment Works

Executive summary

As part of its Water Resource Management Plan 2019 (WRMP19), South Staffordshire Water (SSW) is reviewing the impact of droughts more severe than those experienced in the historic record, on groundwater source potential yield in the Cambridge Water Resource Zone (WRZ). A yield assessment was undertaken, using 200 x 91-year stochastic time series of rainfall and temperature developed by the Met Office for the Water Resources East project.

The key advantage of the approach presented here is the high number of years' data that are utilised, as well as the use of groundwater models which, whilst lumped, capture key aspects in determining minimum groundwater levels, such as the importance of rainfall timing for recharge, cumulative storage response, groundwater/surface water interaction and aquifer boundary effects.

To determine the relevant drought yields, the first stage was to identify "severe drought" storage values from the stochastic series, using a ranking of minimum annual storage over the 18,200 years of stochastic data. We then plotted historical modelled LPM storage v observed groundwater level at key observation boreholes representative of each groundwater source, and used these to identify severe drought groundwater level responses, impacts on source PY and DO.

The approach suggests that nine groundwater sources in the Cambridge WRZ are at some risk of loss of DO under severe drought. The total potential loss of groundwater DYAA DO is estimated at 7.0 Ml/d, when allowing for constraints on DO such as abstraction licence limits and pump capacities. It is not possible to quantify DYCP severe drought impacts on yield with the current approach, but given that almost all groundwater droughts occur in late summer or autumn, these impacts are likely to be small.

The results presented here provide a pragmatic assessment of the impacts of stochastic drought on groundwater potential yield. Several technical limitations exist regarding evaluation of the response of groundwater yield to severe drought. For an improved understanding of the detailed response to specific droughts at each groundwater source, some of the modelling uncertainties could be addressed to a degree using updated techniques such using unstructured grid models (USG), and model refinement using the latest hydrogeological understanding. We propose a possible methodology for one such approach. It would also be worthwhile to check the accuracy of the LPM approach against modelling improved conceptual understanding of the groundwater flow to sources.

1 Introduction

As part of its Water Resource Management Plan 2019 (WRMP19), South Staffordshire Water (SSW) is reviewing the impact of droughts more severe than those experienced in the historic record, on groundwater source potential yield in the Cambridge Water Resource Zone (WRZ). A yield assessment was undertaken, using 200, 91-year stochastic time series of rainfall and temperature developed by the Met Office for the Water Resources East project.

1.1 Background

A meeting was held on the on 2nd October 2017 between Mott MacDonald and water company representatives including those from Anglian Water Services (AWS) and South Staffs Water (SSW) to discuss approaches to groundwater severe drought assessments. Following this meeting, SSW have reviewed their existing approach to severe drought assessments in the Cambridge region. SSW would like to extend their approach to consider the impact of 1:200 and 1:500-year droughts on their sources in the Cambridge Region for the purpose of WRMP reporting.

Mott MacDonald undertook a groundwater severe drought assessment for AWS in 2017 (Mott MacDonald for Anglian Water Services, 2017). This approach drew on the Water Resources East (WRE) simulator and applied 200 x 90-year stochastic weather timeseries to the simulator groundwater lumped parameter models (LPM) to define 1:200 and 1:500-year LPM storage values. These simulated storage levels (along with the historical simulated storage levels) were then used to define severe drought impacts at AWS's drought vulnerable sources.

Mott MacDonald also undertook source drought vulnerability work for SSW in 2016 (Mott MacDonald for Cambridge Water Company, 2016). This work included the creation of spreadsheet models to link precipitation timeseries to observation borehole (OBH) water levels through multi-regression analysis. Hind-cast precipitation timeseries were then used in these spreadsheet models to estimate the worst 20th century historical drought impacts at each OBH. These worst drought OBH water levels were then used in updated source summary diagram spreadsheets, as per the standard UKWIR method (UKWIR and EA, 2002), to estimate the resulting yield impact at 13 drought vulnerable SSW sources. SSW would like to build on this existing drought work but include consideration of 1:200 and 1:500-year drought impacts on source potential yield.

To do so requires a stochastic approach. The chosen option was to use existing stochastic data analysis from the AWS severe drought work for the Cams Bedford Ouse (CBO) and the Ely Ouse Northwest Norfolk (EONWN) LPM models. The EONWN LPM is calibrated as a subset model of the North East Anglia Chalk (NEAC) regional groundwater model. For both LPMs, a stochastic weather generator (calibrated against historical observations) was used to produce 200 x 90 year weather time series for analysis.

The key advantage of the approach presented here is the high number of years' data that are utilised, as well as the use of groundwater models which, whilst lumped, capture key aspects in determining minimum groundwater levels, such as the importance of rainfall timing for recharge, cumulative storage response, groundwater/surface water interaction and aquifer boundary effects.

1.2 Objectives

The objectives of the project were to:

- define 1:200 y and 1:500 y drought groundwater levels at the key observation boreholes for 25 sources in the Cambridge region
- use the source summary diagrams for the 25 sources to return 1:200 y and 1:500 drought potential yield values for each source
- provide a short technical report summarising the project outcomes.

1.3 Report structure

This report gives an overview of the project methodology and the work undertaken to meet the requirements of the Brief. We describe the methodology involving: ranking of stochastic annual LPM storage minima and identification of severe drought storage values; plotting historical lumped parameter model (LPM) storage against observed groundwater levels, to estimate potential severe drought water level declines at key observation boreholes across the region; and applying the standard UKWIR 2002 methodology to determine likely source yields under severe drought.

The results of the yield analysis are compiled and tabulated. Lastly, we make recommendations for further work to address current limitations and gaps in modelling methods for evaluating severe drought impacts on groundwater source yield.

1.4 Supporting reports

The LPM modelling approach is described in (Atkins for Anglian Water, 2017), the LPM recharge model in (Mott MacDonald, 2017). The development of the groundwater severe drought approach is outlined in more detail in (Mott MacDonald for Anglian Water Services, 2017). The previous hindcasting approach to assessing 20th century droughts is described in (Mott MacDonald for Cambridge Water Company, 2016). The UKWIR SRO analysis approach for source yield can be found in (UKWIR and EA, 2002).

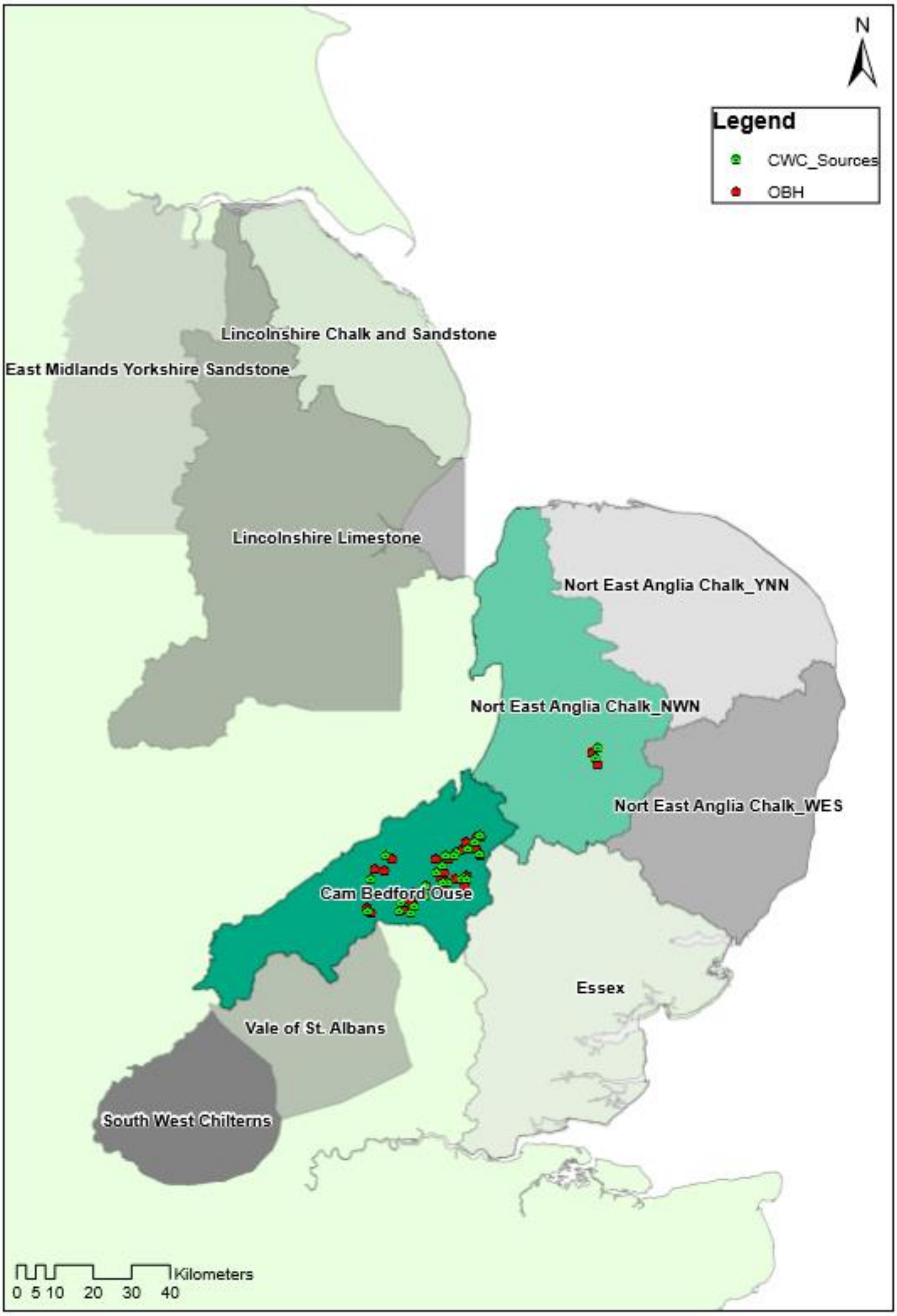
2 Methodology

The Met Office produced 200 sets of 91-year, stochastically generated, time series of rainfall and temperature for Water Resources East (Mott MacDonald, 2017). These droughts use the historic climate as a basis, but then vary certain weather-related indices, such as sea surface temperatures, the East Atlantic Index and the North Atlantic Oscillation, to create artificial weather events which could have happened over the 20th century. All 200 of these were run through the WRE Simulator (Atkins for Anglian Water, 2017) to establish modelled aquifer storage levels, and likely impact on the supply system, in terms of level of service response. The WRE simulator is a regional-scale water resource model, which includes a number of lumped parameter groundwater models (LPMs), each of which calculates time series of storage from spatially average recharge, determined from precipitation and temperature (Mott MacDonald, 2017). The geographic distribution of the models and corresponding source locations is shown in Figure 1.

A summary of the key data analysis steps in the study is as follows:

1. Determine minimum annual LPM storage for every year in each stochastic time-series. Rank series-years by minimum storage and create frequency distribution plots of minimum annual storage for every series. Identify “1 in 200 year” (“severe drought”) and “1 in 500 year” minimum storage value for each LPM.
2. Plot monthly historical LPM groundwater storage v observed groundwater level at each key observation borehole in the Cambridge WRZ. Determine linear regression line and standard deviation.
3. Use storage v level regression in combination with the severe drought LPM storage value for each LPM to determine a potential severe drought response to groundwater level for each key observation borehole.
4. Translate this severe drought groundwater level impact across to the relevant source reliable output summary diagrams(s) using the accepted “curve shifting” methodology. Determine a potential severe drought yield for each source using the adjusted bounding curve intersection with deepest advisable pumping water level, along with expert knowledge regarding source response to drought (groundwater quality and quantity).
5. Compare this severe drought yield to deployable output (DO) at each source and determine the potential DO impacts of severe drought

Figure 1: Lumped parameter model (LPM) locations and Cambridge Water sources. Relevant LPM to Cambridge Water Sources highlighted: CBO and EONWN.



Source: Mott MacDonald WRE

3 Results

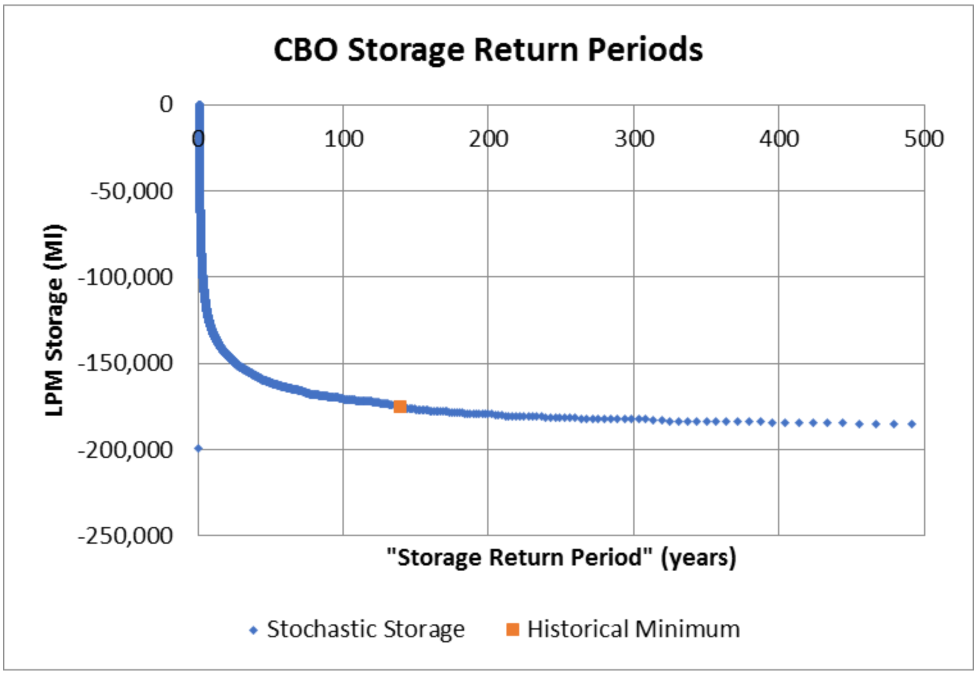
3.1 Determining LPM Storage under Severe Drought

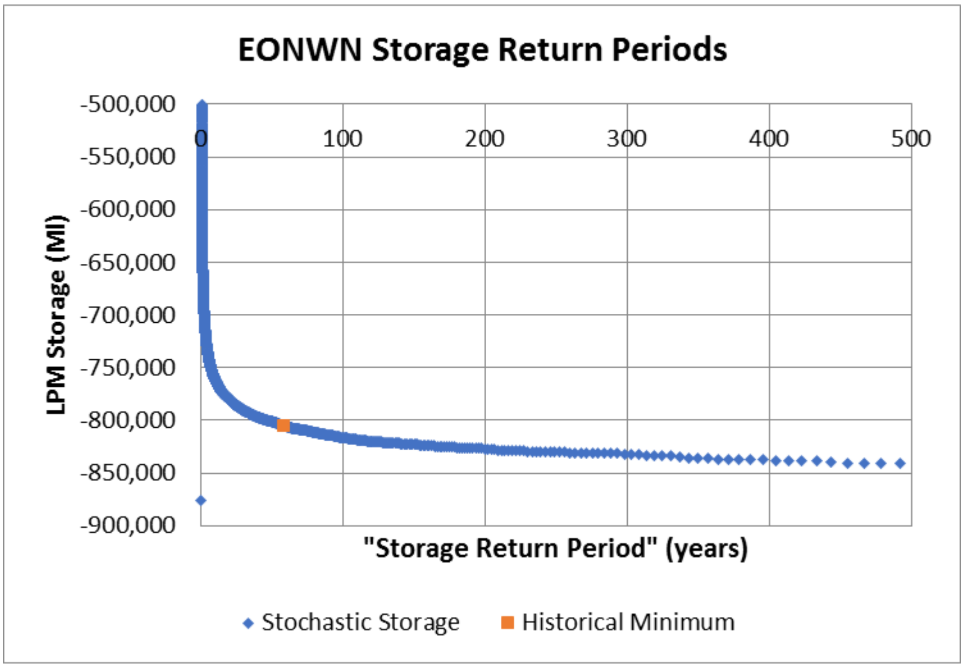
The 200 x 91-year series of stochastic storage value allow an estimate of severe drought storage value based on the frequency distribution of annual minimum storage values. The principle behind this is that the lowest recorded stochastic storage level might be expected to occur only once every 18,200 years; the 10th lowest annual minimum storage to occur once every 1,820 years; the 100th lowest to occur once every 182 years, etc. Figure 2 shows the corresponding scatter plots for the two LPMs relevant to Cambridge WRZ: CBO and EONWN.

Each plot also shows the position of the historical minimum storage level, ranked against all the stochastic years. This gives an indication of the level of service to which sources in a given model area have their yield assessed. It is only an indication because the relationship between groundwater level and LPM storage is not perfectly correlated, as shown in Figure 3 in Section 3.2.

An important point is that the historical minimum for all three LPMs occurs below the asymptote of the line of best fit. This is significant and means that, at a regional scale, historical groundwater droughts are not much less severe than groundwater Severe Droughts (as defined here). Also of note is the fact that “1 in 500 year” events are not predicted to be significantly worse than “1 in 200 year” events. Given the uncertainty in other aspects of the UKWIR yield analysis approach, no attempt is made here to distinguish between 1 in 200 or 1 in 500 year events. The severe drought yields and DO presented here are considered representative of PY for any return period within this range.

Figure 2: Charts showing the “return period” (inverse frequency) of minimum annual LPM storage based on the 200 x 91-year series of stochastic weather





Source: Mott MacDonald "Stochastic Drought Storage Ranking"

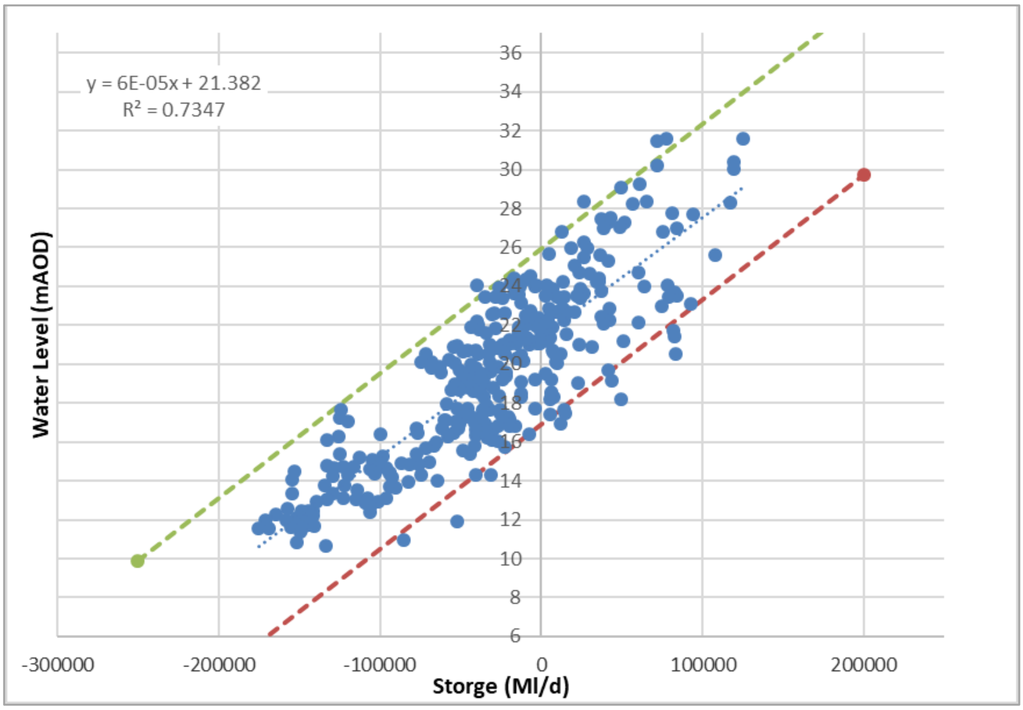
In order to specify a severe drought potential yield for each source, we take the "1 in 200" year storage value from the plots in Figure 2, and read off the corresponding "worst case" groundwater level from the OBH v LPM storage scatter plots, as described below.

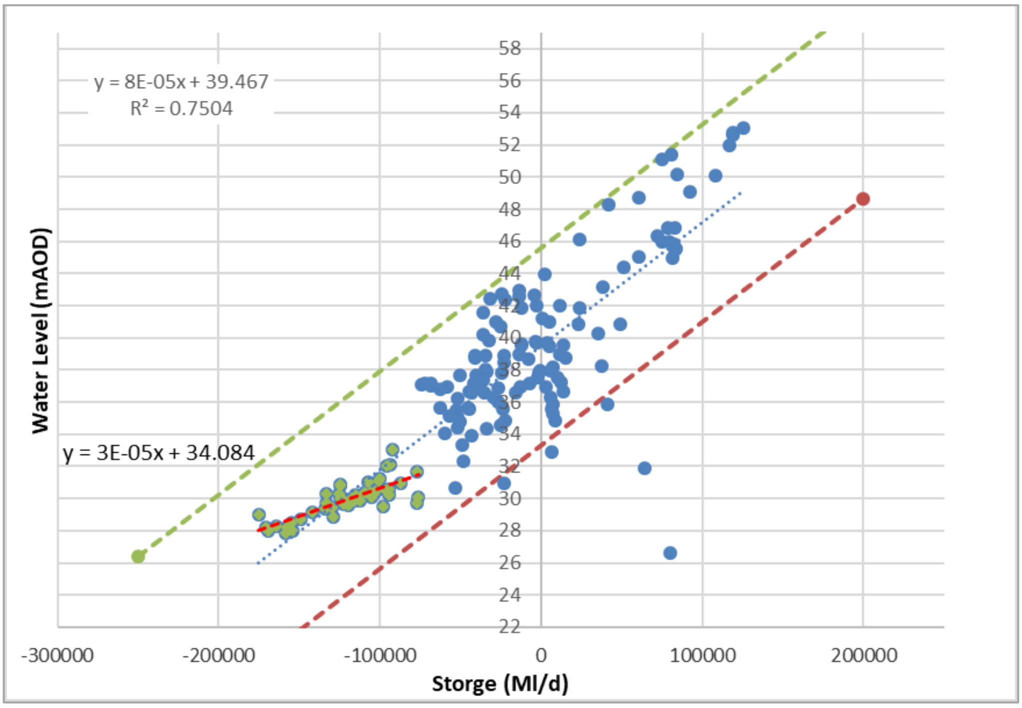
3.2 Relationship between LPM storage and Groundwater levels

In order to quantify possible severe drought impacts, the next stage was to plot historical modelled LPM storage v observed groundwater level at a number of key observation boreholes across the region, chosen to be representative of water level changes at all sources in aquifers potentially vulnerable to drought. Figure 3 shows examples for two of the sources, at Dullingham and Lowerfield. A "storage v level" bounding line is determined for every OBH as equal to the linear regression line of best fit, shifted vertically downwards by one standard deviation of the data: red dashed line on the charts.

Where this bounding line intersects the LPM-modelled severe drought storage value, the groundwater level is interpreted as the minimum feasible level under severe drought. The vertical difference between this and the minimum historical observed level is the severe drought water level decline used to estimate possible yield impacts at each source using the UKWIR (2002) "SRO diagram" approach.

Figure 3: Key observation borehole groundwater level v LPM storage for example locations at Dullingham (top) and Lowerfield (bottom)





Note that for Lowerfield, there are signs of a “levelling out” of groundwater levels at low storage (points shown in green). For the results presented below, we have used the GW level decline trendline determined for the full data-set to infer groundwater level declines. This is deliberately precautionary and may somewhat over-estimate impacts.

The results in Figure 3 and Appendix A show the significant variation in groundwater level that may accompany a given change in regionally modelled groundwater storage. Neither LPM storage nor regional groundwater model levels (200m grid resolution) adequately represent local groundwater level effects to use for detailed analysis of source potential yield under conditions significantly more severe than the historical record. Applying the lower bounding curve on the storage v groundwater level plots for each key observation borehole is intentionally precautionary. Recommendations for a more detailed analysis are provided in section 4.2

3.3 Groundwater Yield Results

The “plausible worst case” impacts on water levels under severe droughts were translated to the relevant source reliable output summary diagram of each source in the aquifer, and used to estimate a severe drought yield. The resultant PY is compared to the Dry Year Annual Average (DYAA) DO and the potential DO loss determined.

Examples of SRO summary diagrams used for severe drought yield analysis are presented in Figure 4 and **Error! Reference source not found.** below. Figure 4 is an example where source DO is constrained by PY, such that severe drought impact on PY is equal to the impact on DO. In **Error! Reference source not found.**, the source DO is constrained by licence at present, but there is a risk that a severe drought could reduce yield below the licence: the potential impact on DO is less than the impact on PY. A full set of diagrams are presented in Appendix B.

Figure 4: Example of UWKIR Source Reliable Output Summary Diagram with Severe Drought adjustment for Dullingham, DYAA conditions.

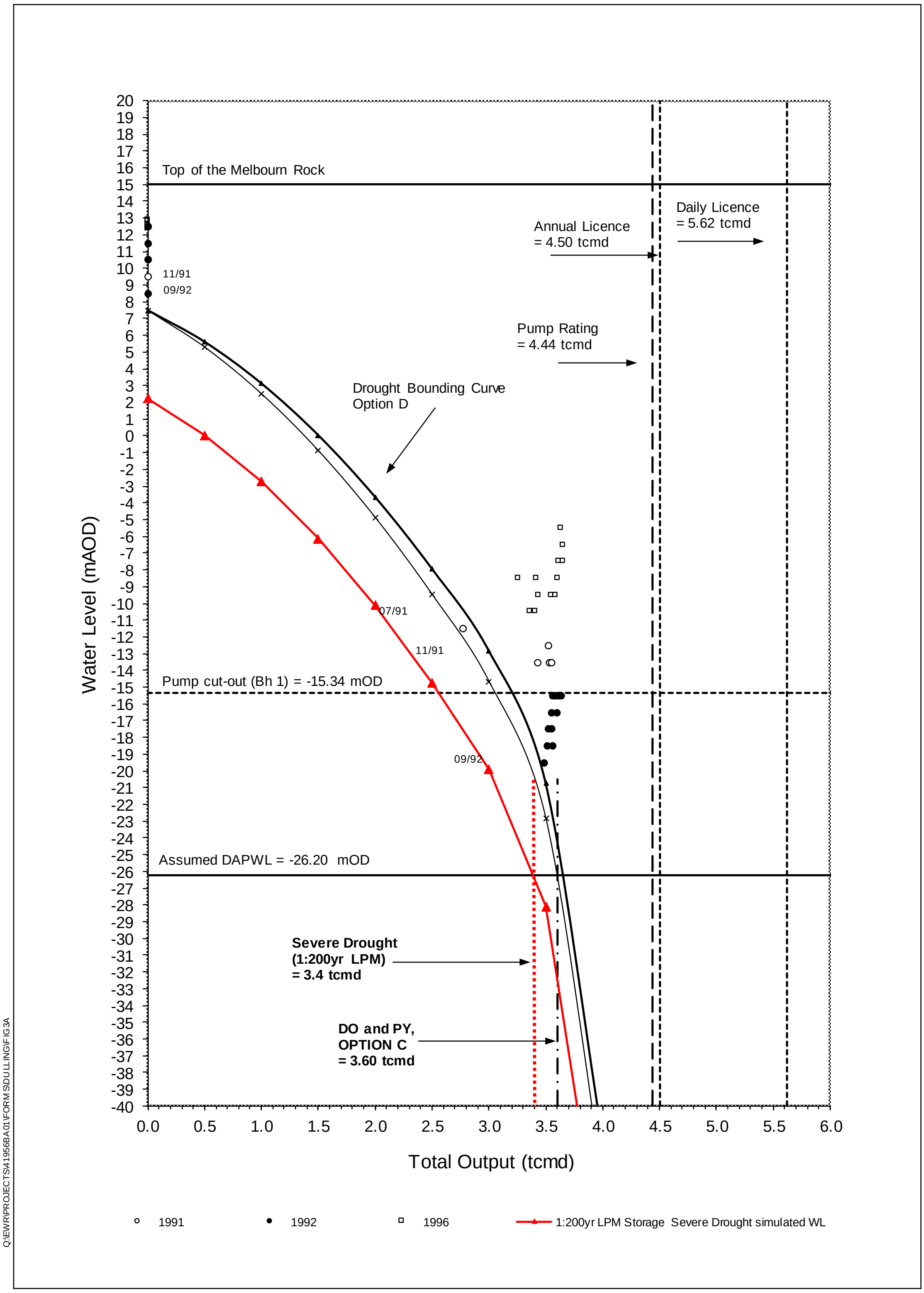


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Figure 5: Example of UWKIR Source Reliable Output Summary Diagram with Severe Drought adjustment for Lowerfield, DYAA conditions.

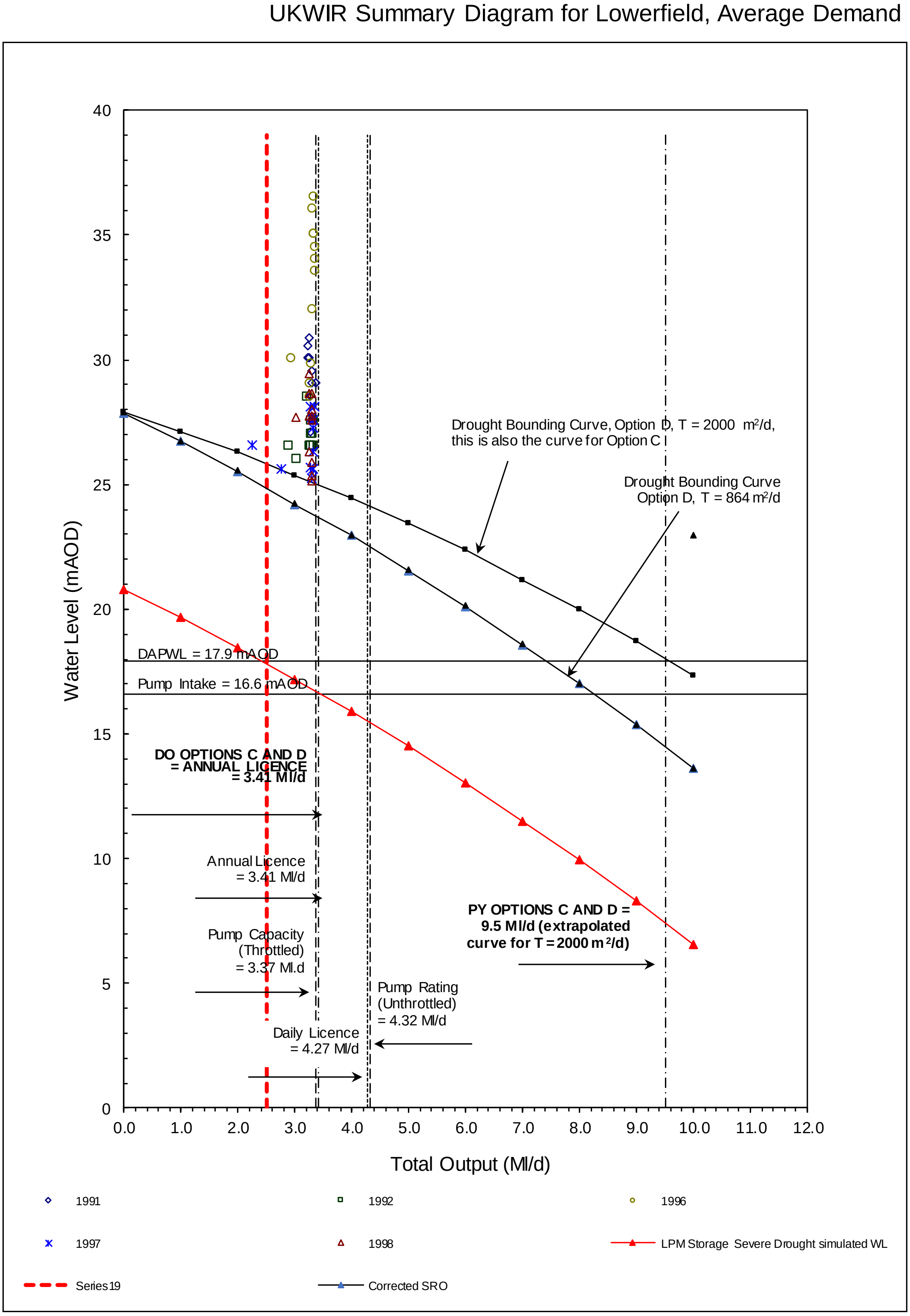


Table 1: Potential Yield Results

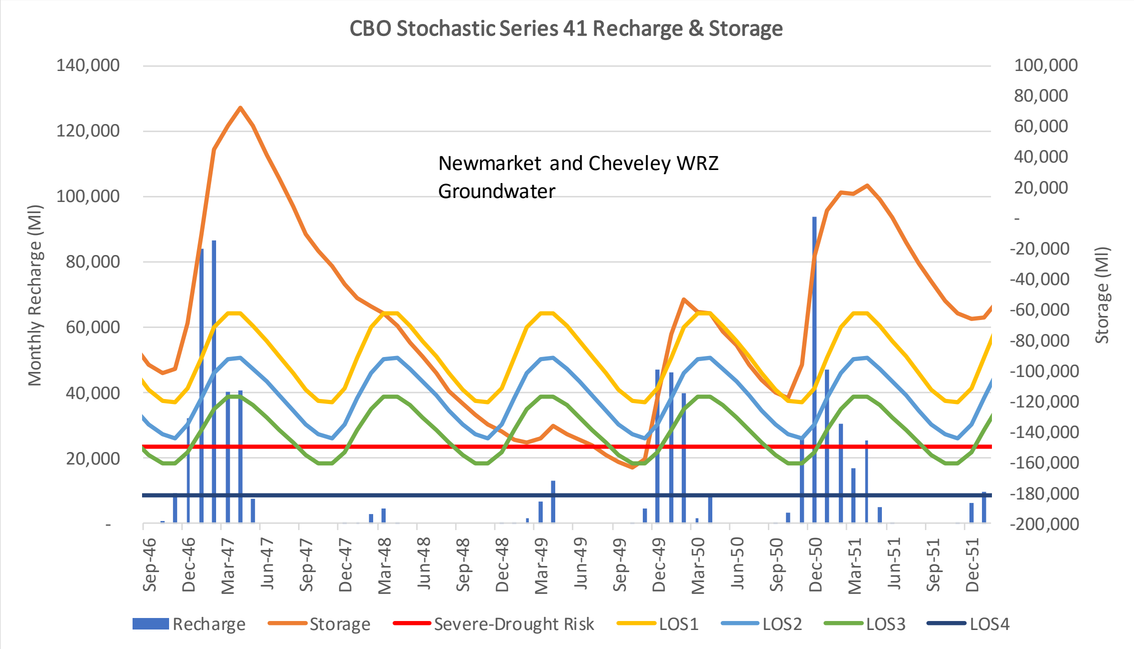
Source (ABH)	OBH	Simulated Water Level Difference	Current PY	Severe Drought PY	DYAA DO	DO loss
Abington Park	TL54_074	0.34	18.00	18.00	1.00	**0.00**
Babraham	TL45_017	0.47	9.09	9.09	9.09	**0.00**
Brettenham	TL88_013	0.41	15.00	15.00	8.43	**0.00**
Croydon	TL35_001	-1.67	2.50	2.50	N/s	**-**
Dullingham	TL65_043	5.26	3.60	3.40	3.60	**0.20**
Duxford Airfield	TL44_048	0.88	4.56	4.56	4.56	**0.00**
Duxford Grange	TL44_240	3.42	3.25	3.05	3.41	**0.36**
Euston	TL97_014	0.73	10	10	8	**0.00**
Fleam Dyke (12")	TL55_005	0.22	3.25	3	N/s	**-**
Fleam Dyke (main)	TL55_005	0.22	12.3	12.2	12.3	**0.10**
Fowlmere	TL44_293	-5.27	7.35	7	3.6	**0.00**
Fulbourn	TL45_017	0.47	1.88	1.6	1.49	**0.00**
Great Chishill	TL44_234	7.94	1.056	1.02	1.06	**0.04**
Great Wilbraham	TL55_005	1.15	-	-	5.67	**-**
Heydon	TL44_238	6.19	1.97	1.8	1.13	**0**
Hinxton Grange	TL54_102	1.65	-	-	5.77	**-**
Horseheath	TL54_101	2.55	-	-	1.7	**-**
Kingston	TL35_003	-0.11	-	-	-	**0.00**
Linton	TL54_001	3.40	-	-	0	**0.00**
Lord's Bridge	TL35_004	-1.43	-	-	-	**0.00**
Lowerfield	TL38_048	7.06	9.5	2.5	3.41	**0.91**
Melbourn	TL44_427	2.84	7.94	7.2	7.95	**0.75**
Morden Grange	TL34_007	1.84	1.5	1.3	1.5	**0.20**
Rivey	TL54_113	1.33	-	-	1	**-**
Westley	TL55_009	1.15	11.39	7.8	11.4	**3.60**
Weston Colville	TL65_042	9.78	2.7	2.05	2.92	**0.87**
					TOTAL DO LOSS:	**7.03**

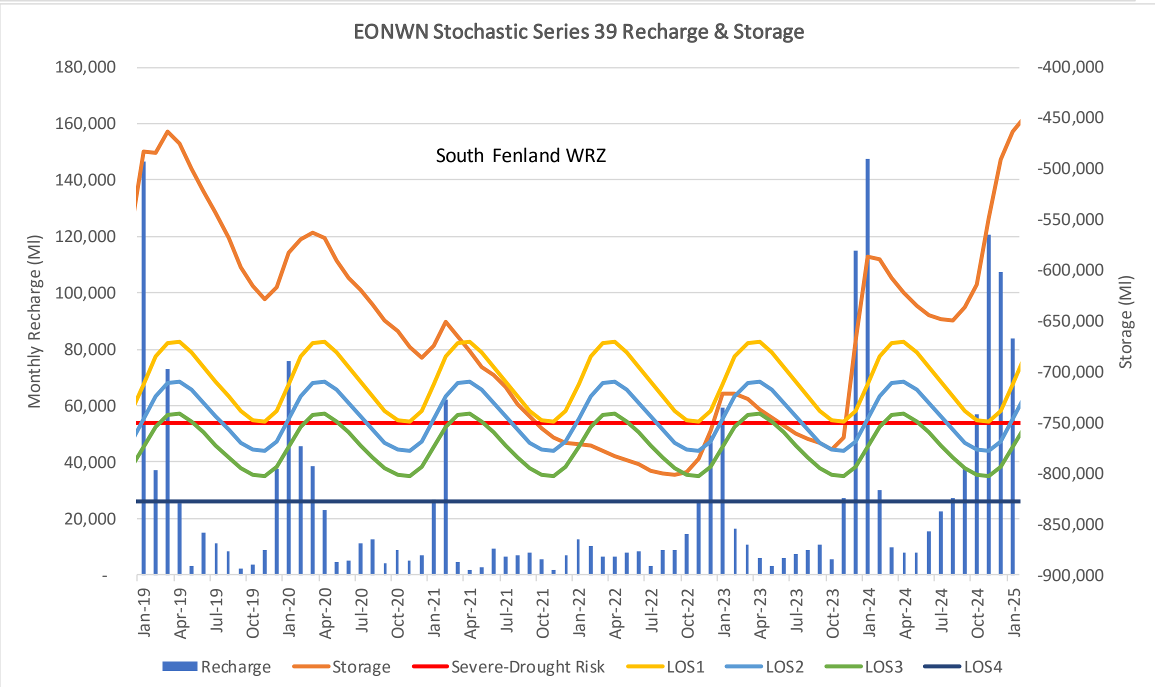
Table 1 shows the results of the analysis, including: the selected OBH for each source; the simulated water level difference under severe drought; the existing DYAA PY; the predicted severe drought PY; existing DYAA DO; and the predicted maximum DO loss at each source.

The total DO loss in a severe drought scenario across all sources is estimated at 7.0 Ml/d, with the most significant loss simulated at Westley (3.6Ml/d). Further significant DO loss impacts (>0.5 Ml/d) are simulated at Lowerfield, Weston Colville and Melbourn. DO impacts are observed to a lesser extent (<0.5 Ml/d) at Dullingham, Duxford Grange, Morden Grange and Great Chishill, which are deemed low risk sources. Croydon, Euston and Fowlmere sources exhibit a change in PY but are still constrained by daily licence, so there is no corresponding loss in DO.

It should be noted that whilst the DO impacts are specified as under DYAA conditions, groundwater minima across almost all stochastic droughts occur during the late summer or autumn. An example is shown in Figure 6 below, with control curves defined at WRE, based on historical record return periods. The horizontal severe drought risk line is source-specific, and accurate determination is beyond the scope of this study. The lines shown here are as an example only, but it indicate that for much of the year, potential yield would be higher than the severe drought value.

Figure 6: Times series of LPM recharge and storage with WRE control curves and severe drought risk thresholds





Source: Mott MacDonald "EONWN CBO Monthly Storage Recharge Plots"

The fact that the groundwater minima occur in the autumn, outside of the dry year critical period (DYCP) month, means that no attempt is made to estimate DYCP severe drought impacts on DO, which are likely to be minimal.

One final point is that the severe drought yield analysis is based on historical climate conditions (pre-1990). Climate change could interact with severe drought to alter the magnitude, duration or spatial extent of droughts. No attempt is made here to quantify these effects, but climate change/severe drought effects are unlikely to be additive. In general, severe drought yield impacts may be assumed to include any effects of climate change where they occur.

4 Conclusions

4.1 Summary

To understand the impact of severe droughts on groundwater resource deployable output, a yield assessment was undertaken, using 200 stochastic time series of rainfall and temperature developed by the Met Office for the Water Resources East project. These were run through a lumped parameter model (LPM) for the CBO and EONWN areas, to output time series of LPM groundwater storage which could then be used to estimate stochastic drought groundwater yields.

To determine the relevant drought yields, the first stage was to identify "severe drought" storage values from the stochastic series. We then plotted historical modelled LPM storage v observed groundwater level at key observation boreholes representative of each groundwater source, and used these to identify severe drought groundwater level responses, impacts on source PY and DO.

Nine groundwater sources in the Cambridge WRZ are at some risk of loss of DO under droughts more severe than historic. The total potential loss of groundwater DYAA DO is estimated at 7.0 Ml/d, when allowing for constraints to DO such as abstraction licence limits and pump capacities. It is not possible to quantify DYCP severe drought impacts on yield with the current approach, but given that almost all groundwater droughts occur in late summer or autumn, these impacts are likely to be small.

4.2 Recommendations

The results presented here provide a pragmatic assessment of the impacts of stochastic drought on groundwater potential yield. Using lumped aquifer models provides an excellent means of quickly processing large volumes of climate scenarios and converting into regional-scale effects. We consider the LPM storage results provide an accurate indication of the regional-scale impacts on groundwater available for abstraction. However, the difficulty lies in translating those regional-scale impacts into local effects at the scale of individual groundwater sources. Distributed regional groundwater models provide some extra resolution, but they cannot accurately determine impacts on groundwater levels or potential yield in considerably heterogeneous, dual permeability aquifers. We note the following limitations to the existing models in the Cambridge WRZ Region with regards potential yield.

- The horizontal and vertical resolution of regional groundwater models is designed for catchment-scale analyses, and are likely to be too coarse to accurately model groundwater level responses to drought in the vicinity of abstraction wells
- The structure of regional groundwater models is potentially too rigid (rectangular grid, with no ability to pinch out layers or represent detailed heterogeneity where this is known) to accurately represent flow patterns near abstraction wells (where radial flow is likely to occur), which could impact yield response
- Regional groundwater models may not have sufficiently detailed hydrogeological conceptual understanding represented in proximity to vulnerable abstraction wells to accurately model local groundwater response

- Model calibration is only valid for historical groundwater conditions and may not be accurate when the system is stressed under severe drought.

Several of the issues above could be addressed using updated modelling techniques involving unstructured grid models (USG). A MODFLOW6 USG model exists for the NEAC area, which incorporates the following benefits:

- Polygonal grid cells more closely model radial flow to a well and flow along rivers, streams, etc
- Ability to pinch out model layers completely near feather-edge of geological layers
- Easy to refine grid size as necessary close to point sources/abstractions
- The models can be based on open-source data, with simpler licensing – better ownership for AWS

The following approach is one option that could improve understanding of aquifer response to severe drought at a source level, reduce uncertainty in potential yields for droughts more severe than the historical record and improve the overall reliability of the assessment:

1. Review and refine the MODFLOW6 model for NEAC and check structure and properties using BGS geological models and Cambridge WRZ source assessments
2. Run the USG model with all PWS abstractions set to their current defined annual average potential yield (as per the latest SRO assessment).
3. Determine the minimum water level at each source cell under these conditions over the historic record.
4. Specify this water level as a “deepest advisable modelled water level” (DAMWL)
5. Re-run the model under each drought (and climate change) scenario with PWS abstractions set to annual licence (distributed by group licence where applicable)
6. Identify any sources where water level falls below the “DAMWL” in each scenario
7. Identify a sustainable modelled yield/abstraction rate under each scenario

The accuracy of source yield assessments could also be improved through using a radial flow source model linked (with Open MI) to the existing regional models (Upton, Butler, & Jackson, 2013).

5 References

Atkins for Anglian Water. (2017). *Water Resources East WRE Simulator QA Report.*

Mott MacDonald. (2017). *Water Resources East: Recharge Model.*

Mott MacDonald for Anglian Water Services. (2017). *Stochastic Drought Groundwater Yield Assessment for WRMP19.*

Mott MacDonald for Cambridge Water Company. (2016). *Climate Change and Source Vulnerability: Drought Plan Support.*

UKWIR and EA. (2002). *A Unified Methodology for the Determination of Deployable Output from Water Sources.*

Upton, K., Butler, A., & Jackson, C. (2013). Coupling a radial model of the Darcy-Forchheimer equation with a regional groundwater model to simulate drawdown at supply boreholes.

Appendices

A. Storage v Level Scatter Plots

Figure A. 1: Abington Park

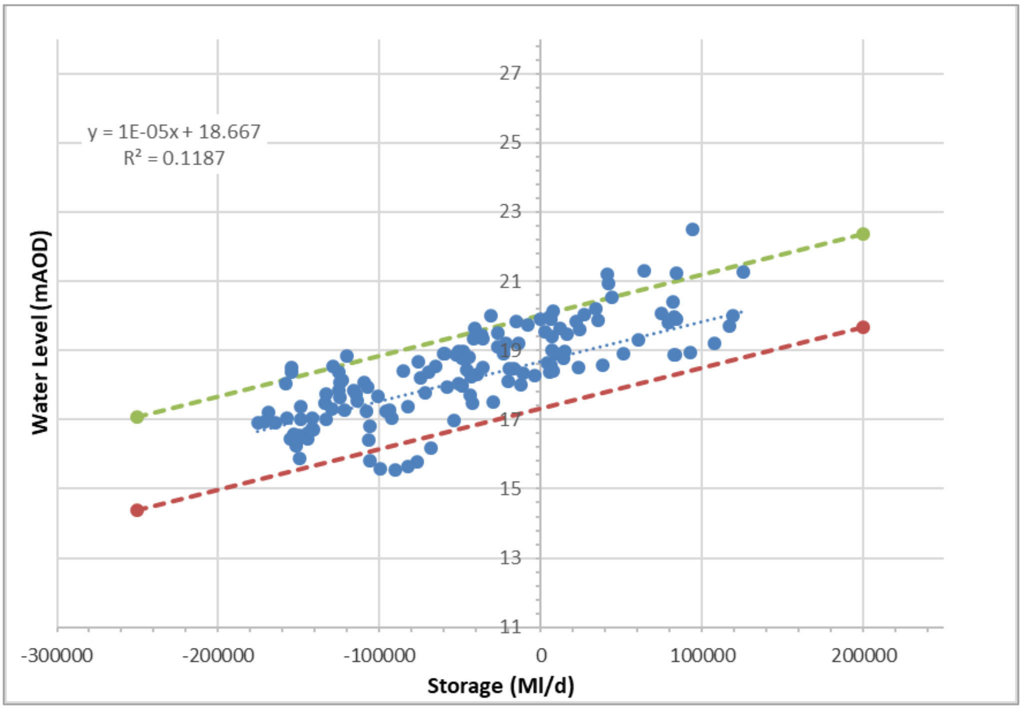


Figure A. 2: Babraham

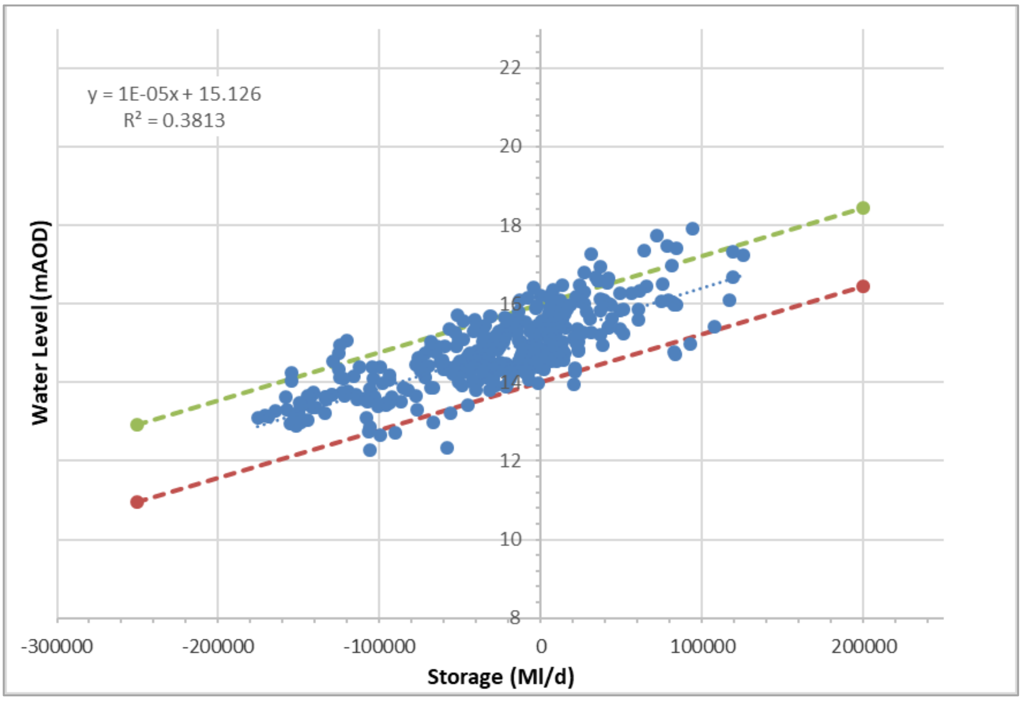


Figure A. 3: Brettenham

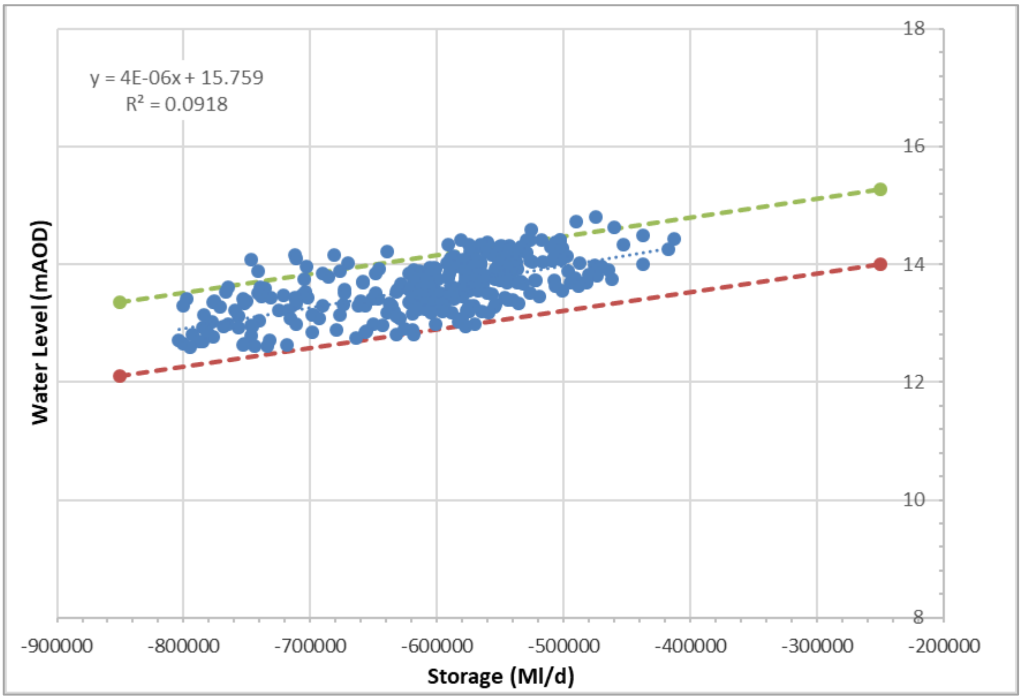


Figure A. 4: Croydon

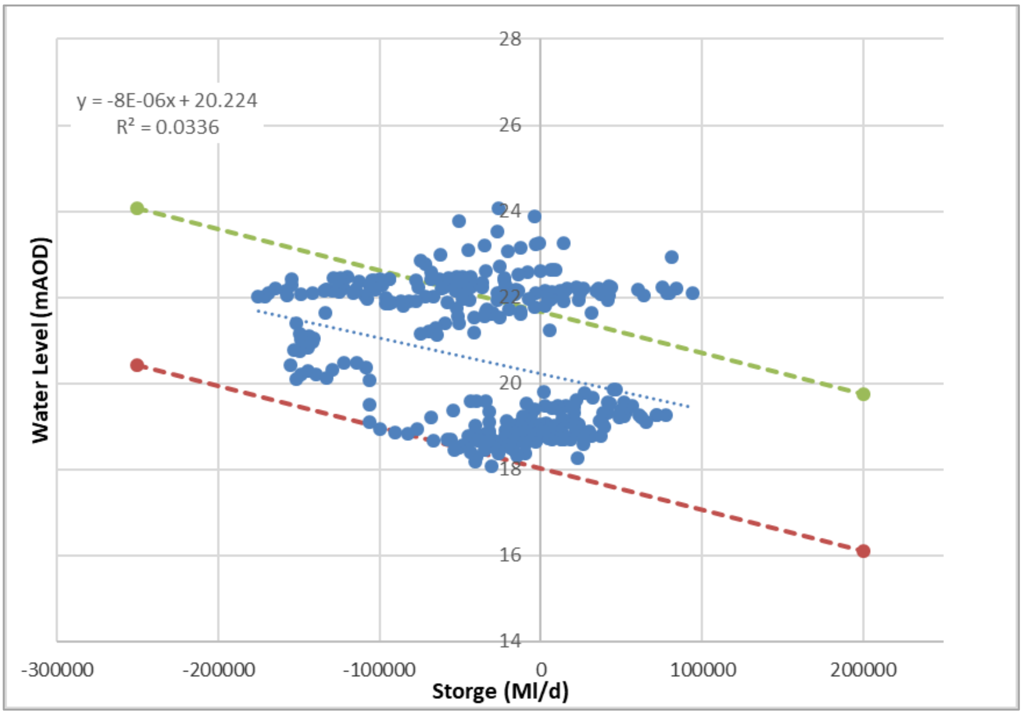


Figure A. 5: Dullingham

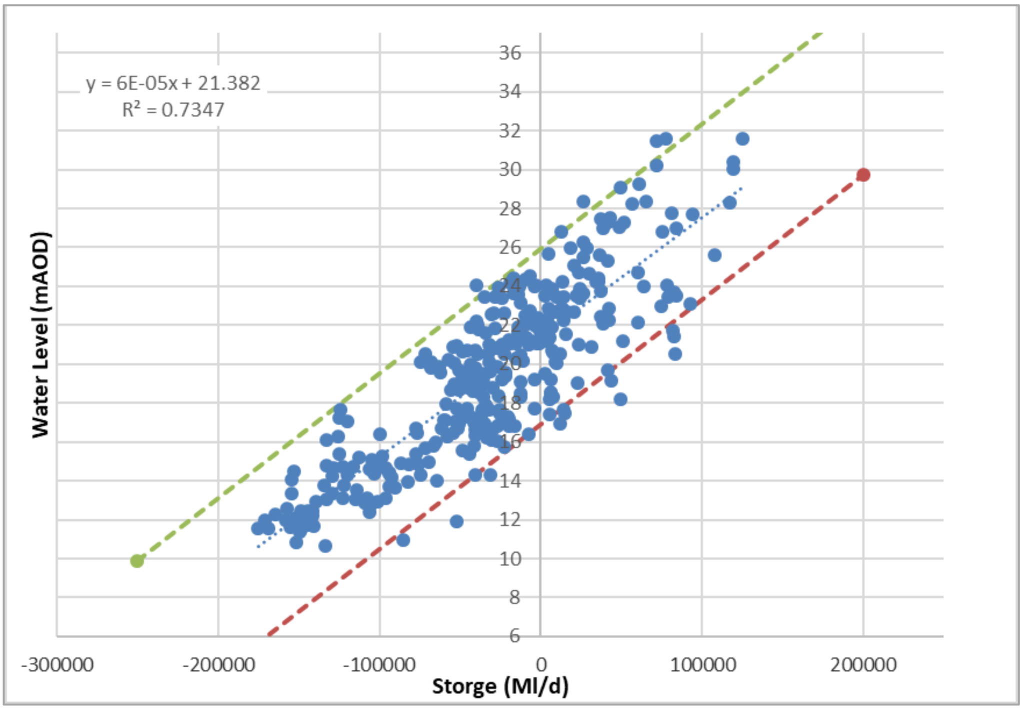


Figure A. 6: Duxford Airfield

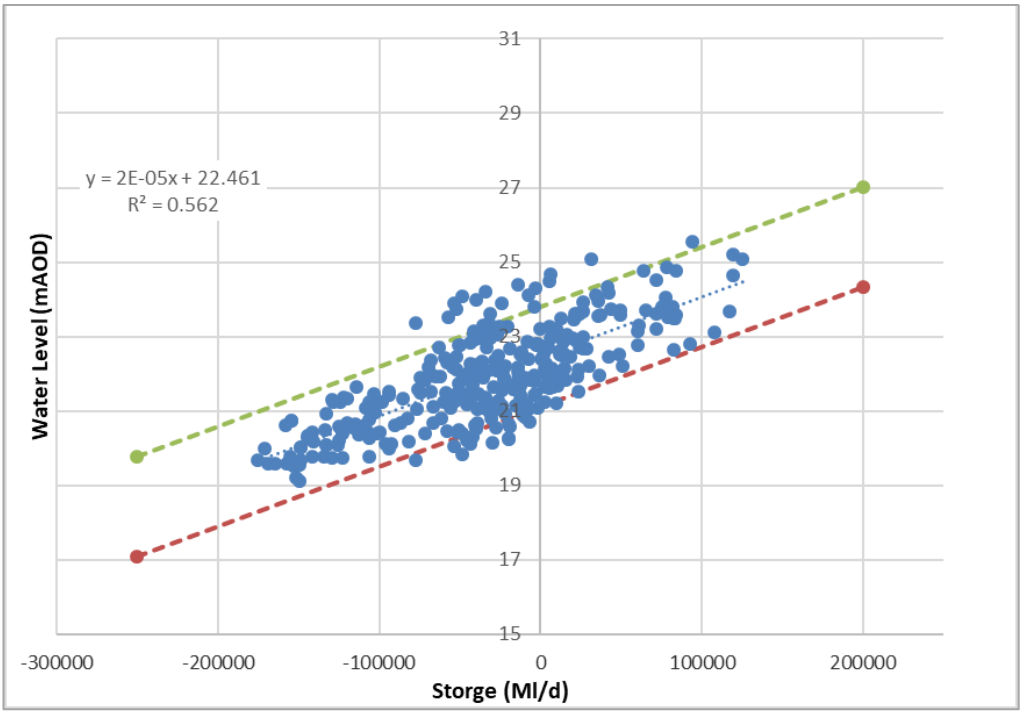


Figure A. 7: Duxford Grange

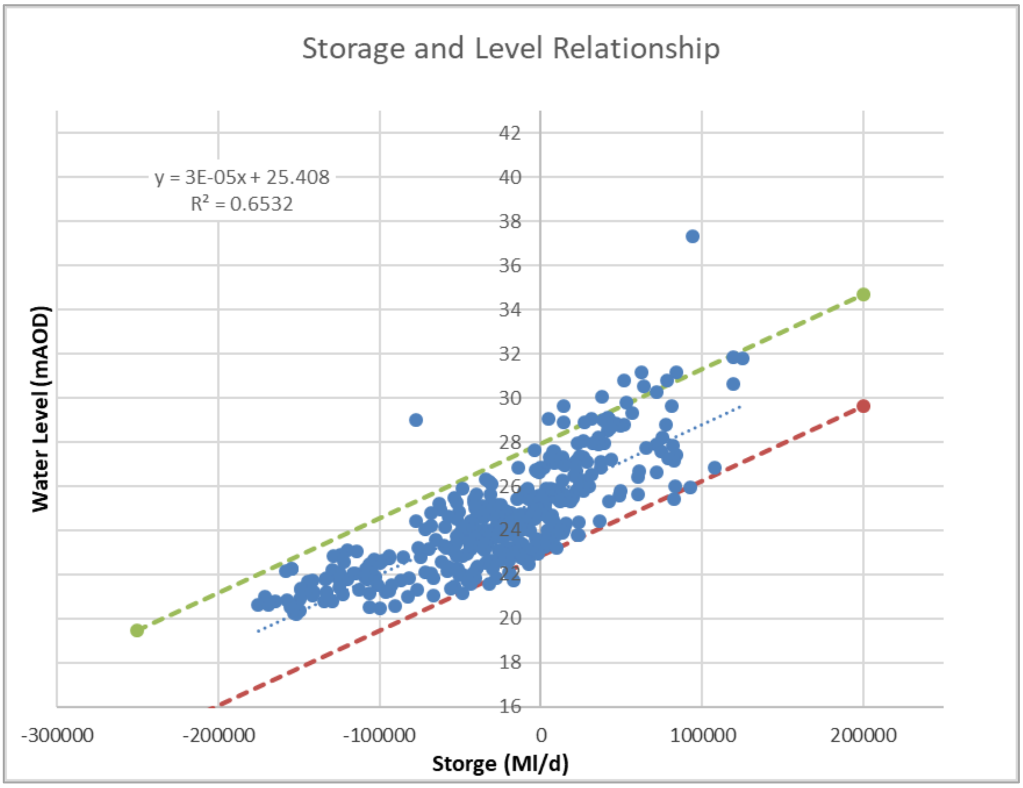


Figure A. 8: Euston

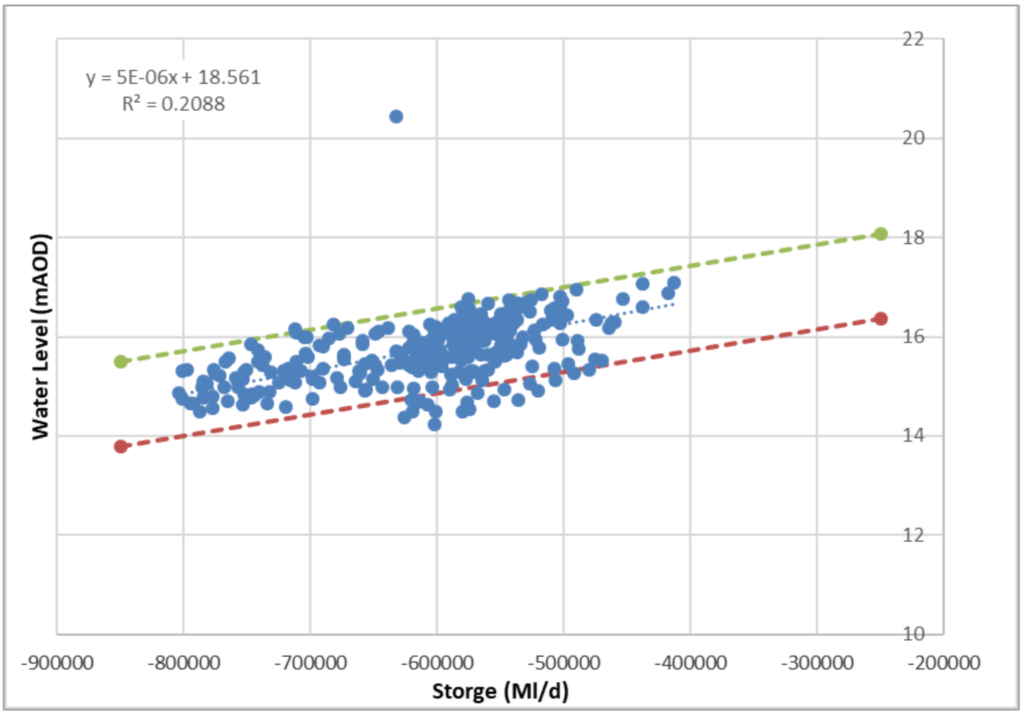


Figure A. 9: Fleam Dyke (12" and Main)

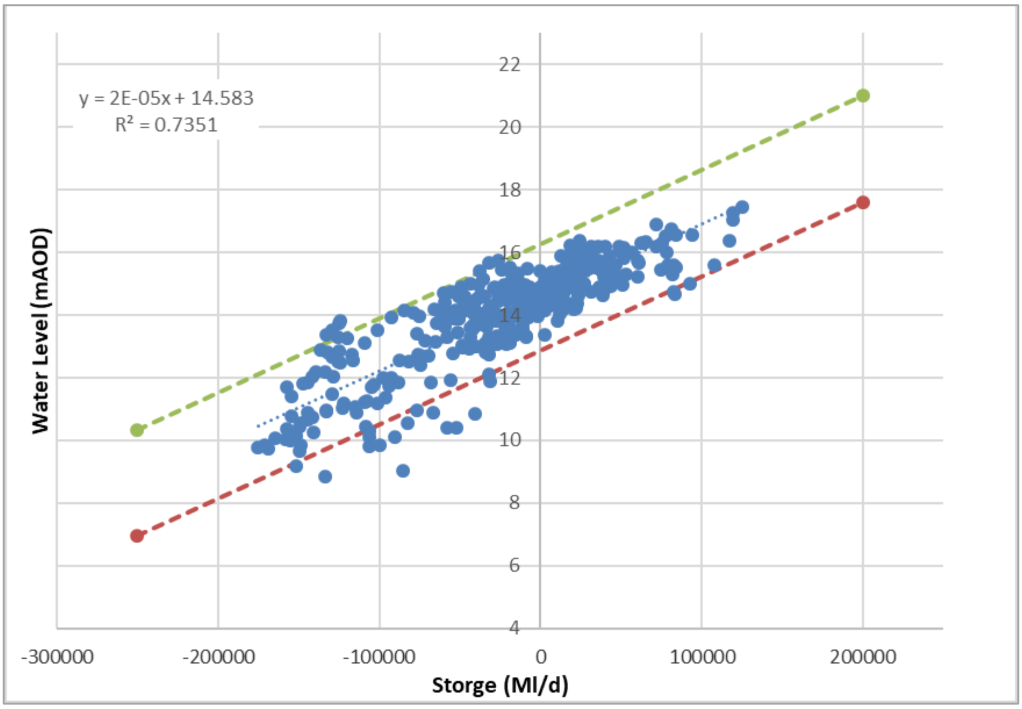


Figure A. 10: Fowlmere

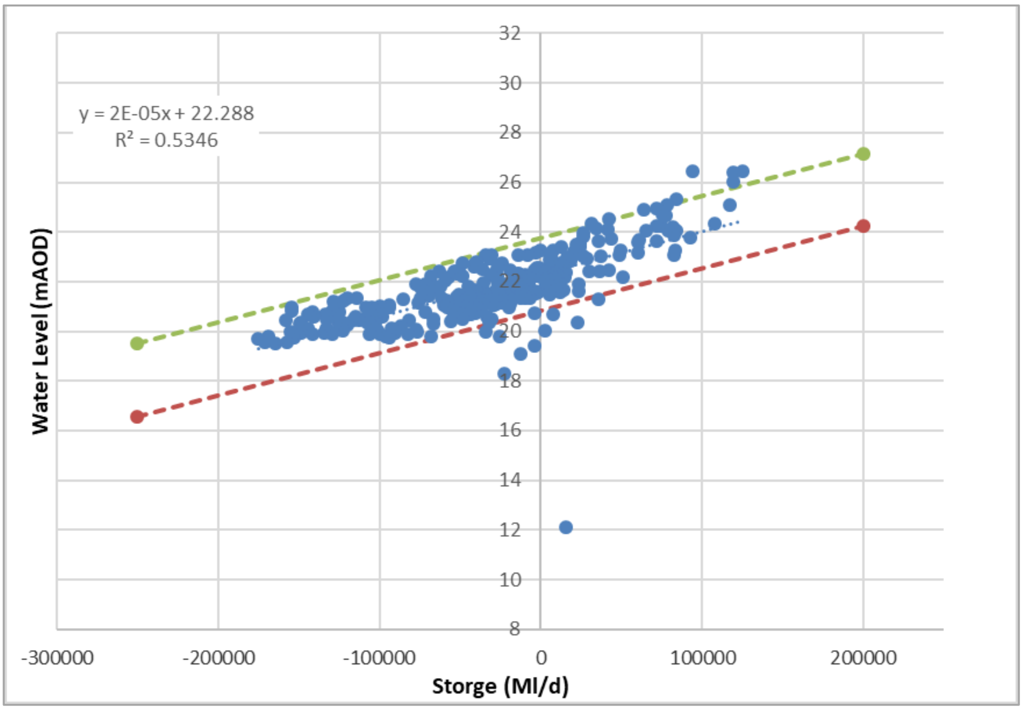


Figure A. 11: Fulbourn

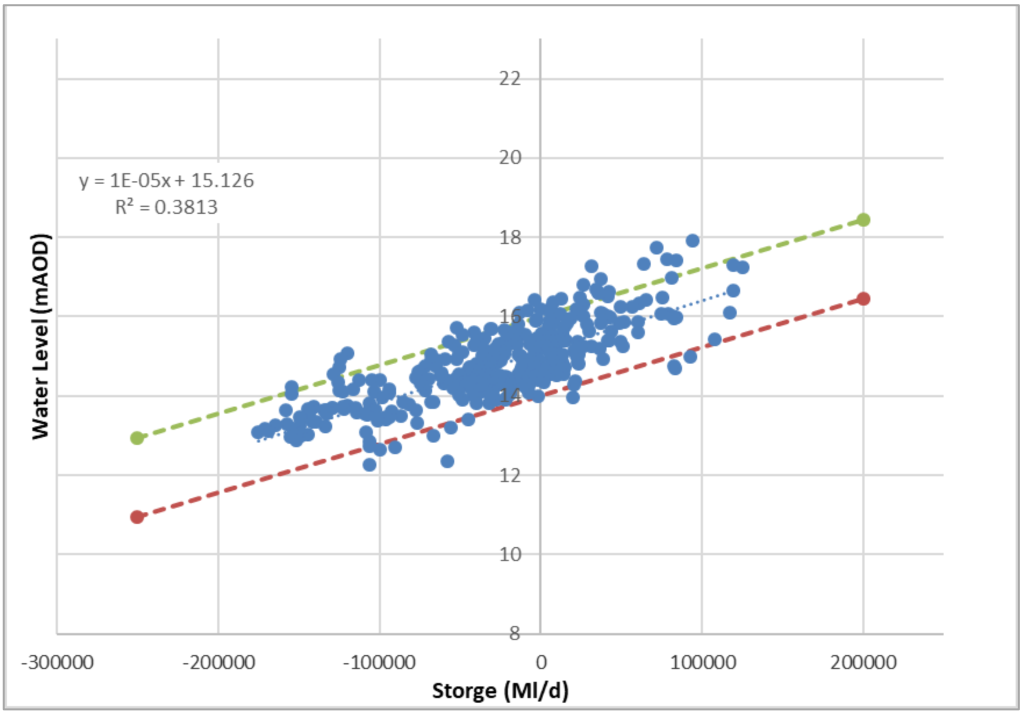


Figure A. 12: Great Chishill

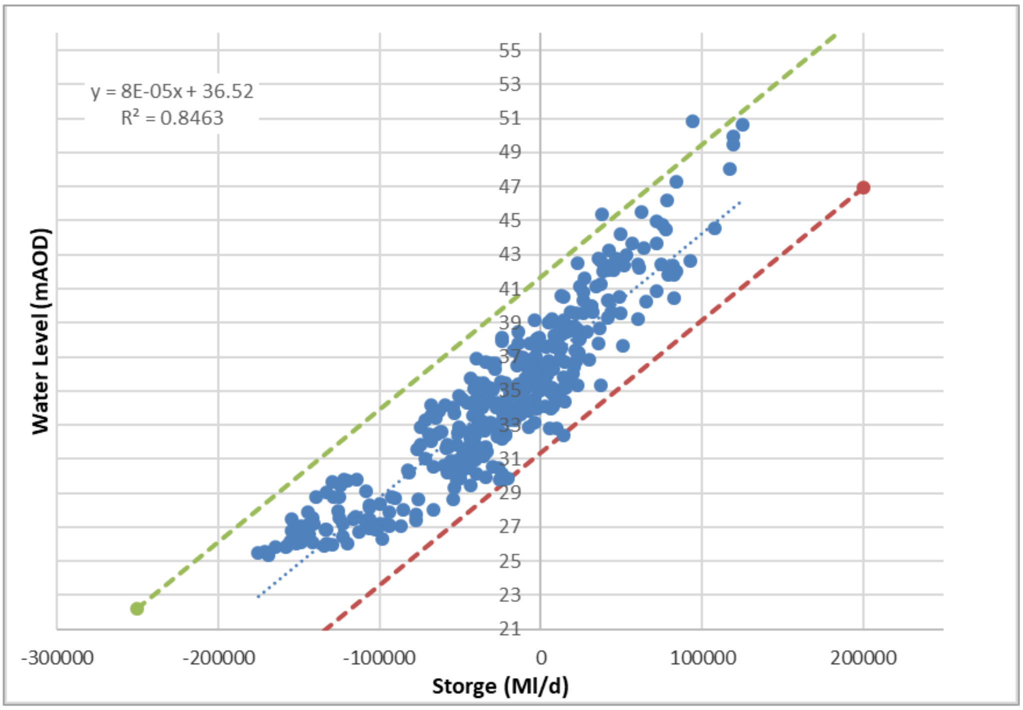


Figure A. 13: Great Wilbraham

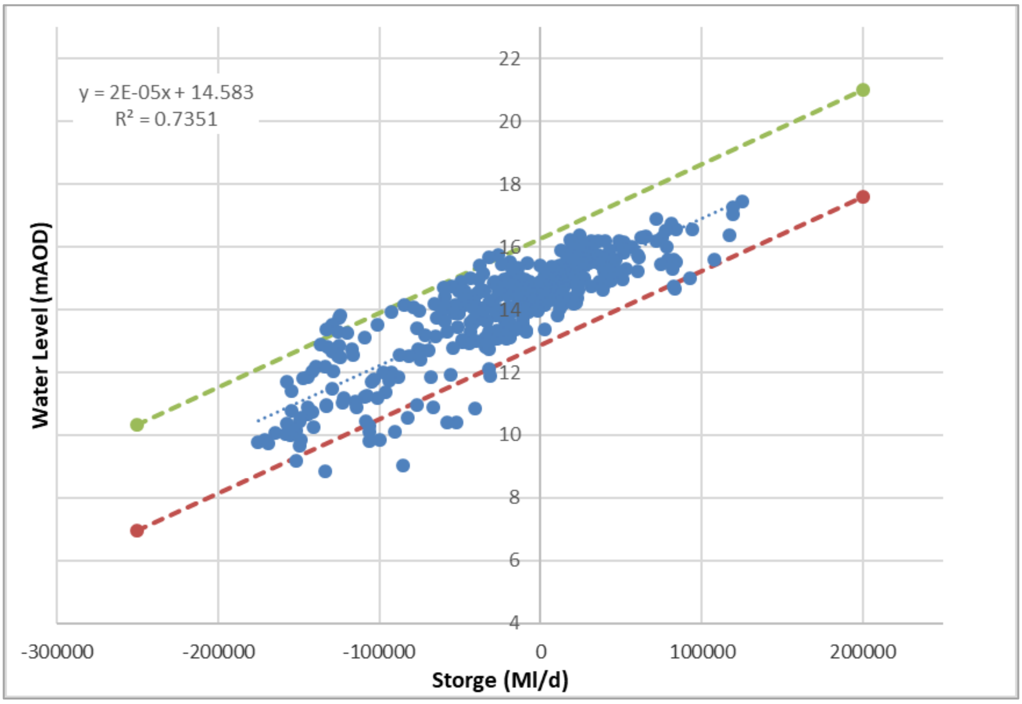


Figure A. 14: Heydon

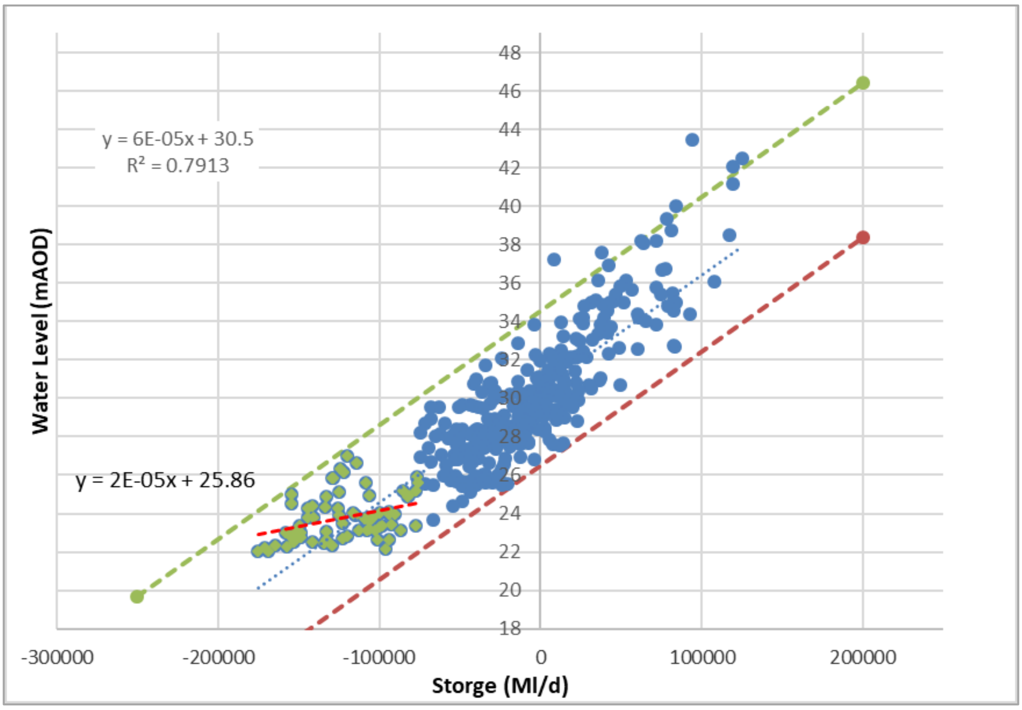


Figure A. 15: Hinxton Grange

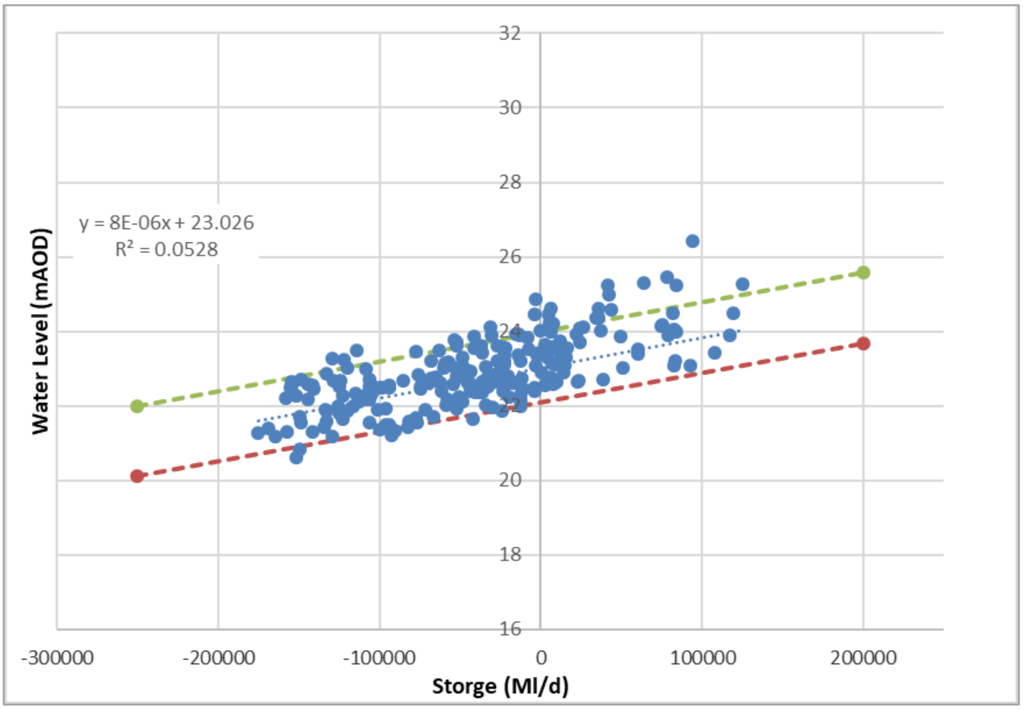


Figure A. 16: Horseheath

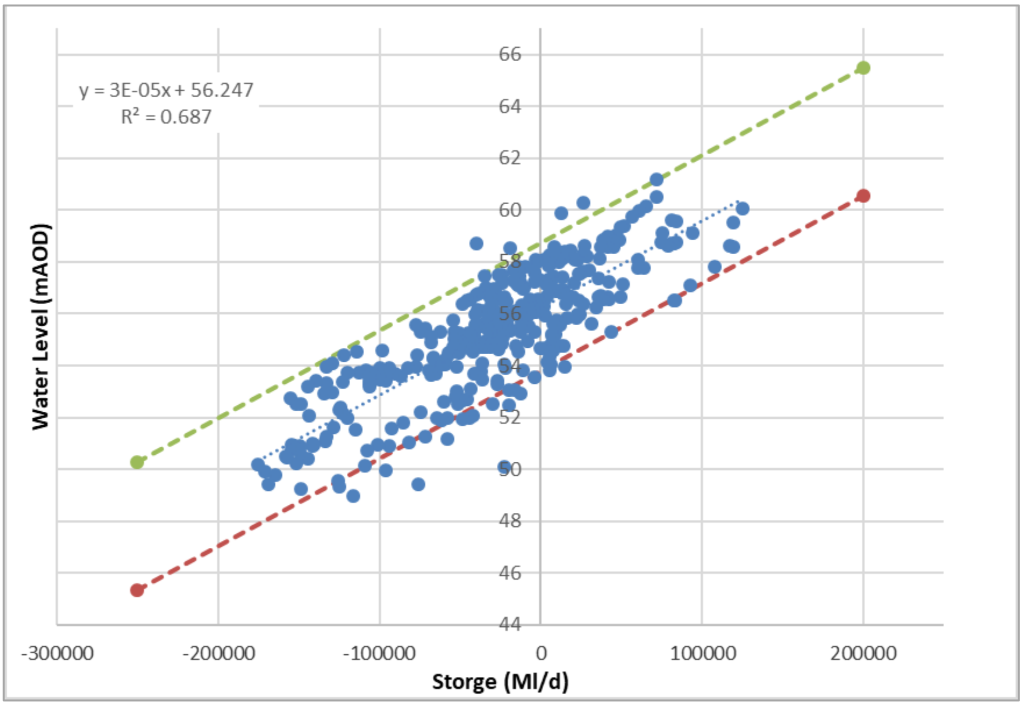


Figure A. 17: Kingston

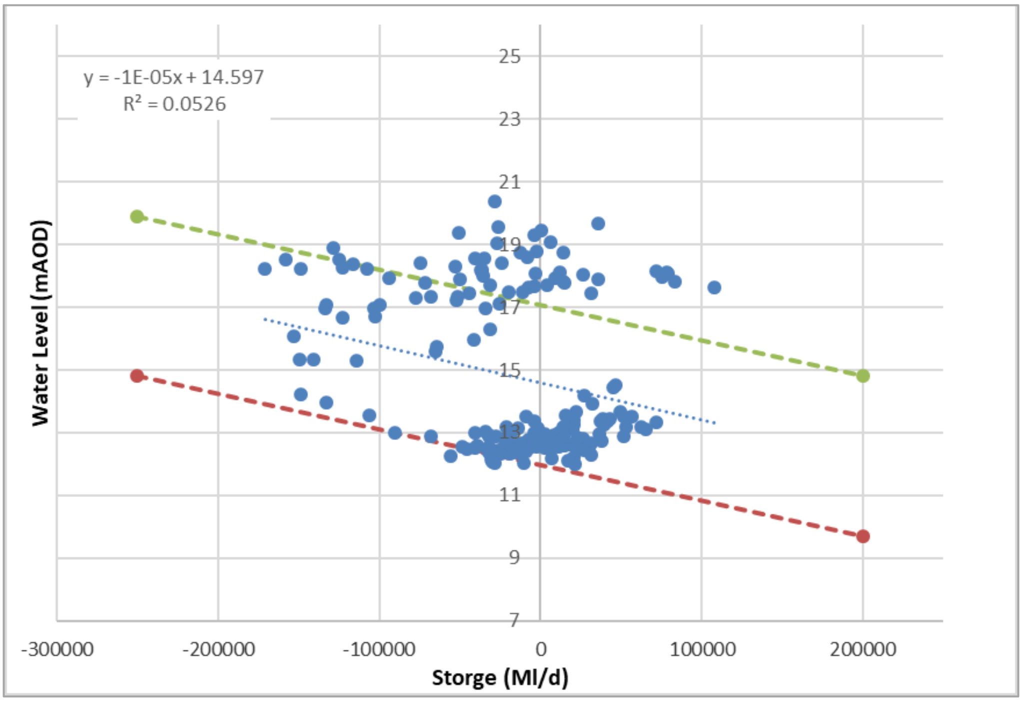


Figure A. 18: Linton

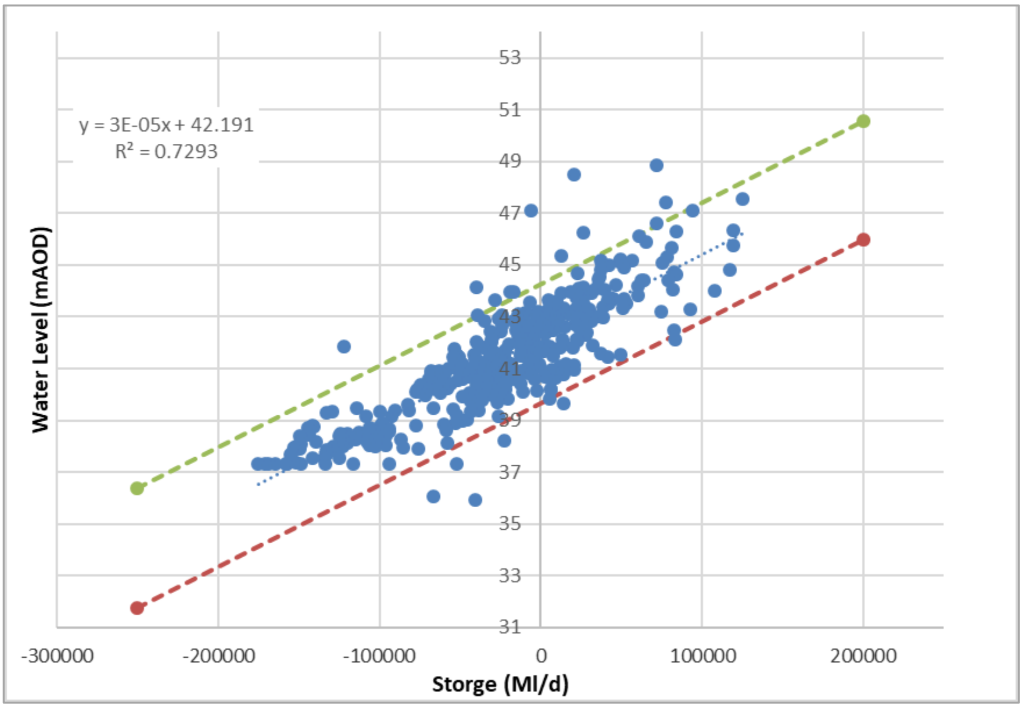


Figure A. 19: Lord's Bridge

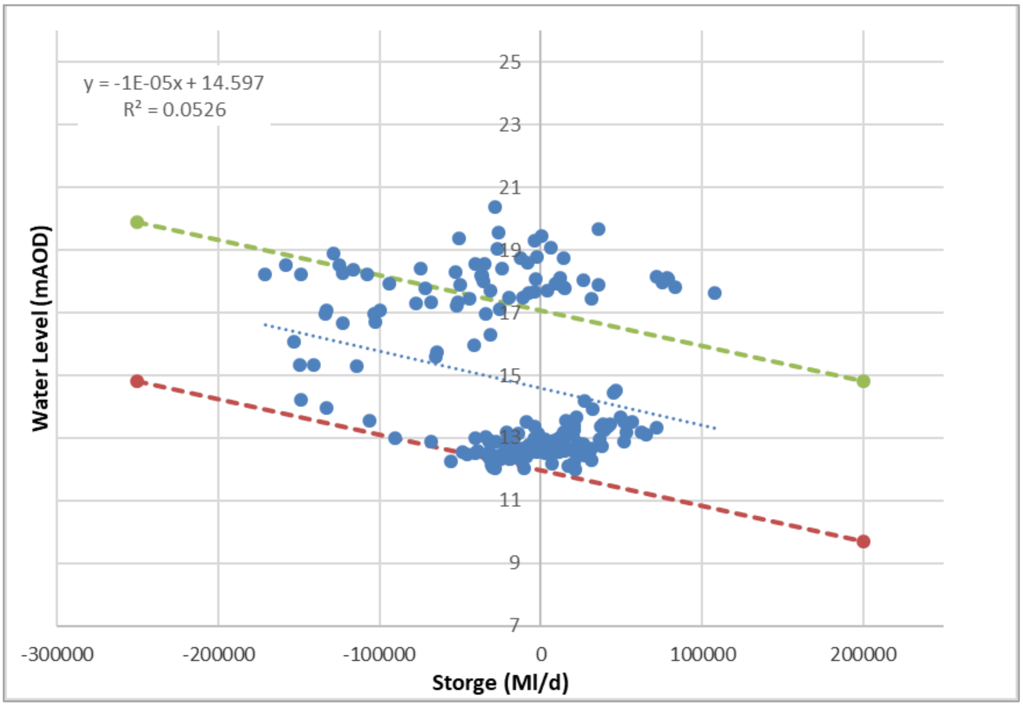


Figure A. 20: Lowerfield

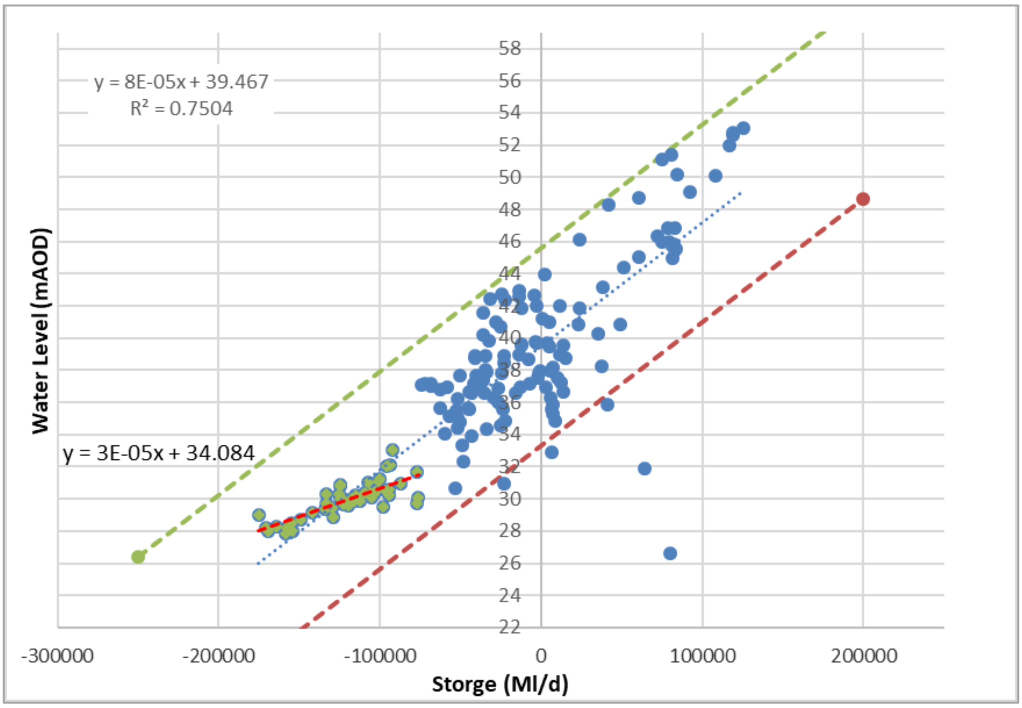


Figure A. 21: Melbourn

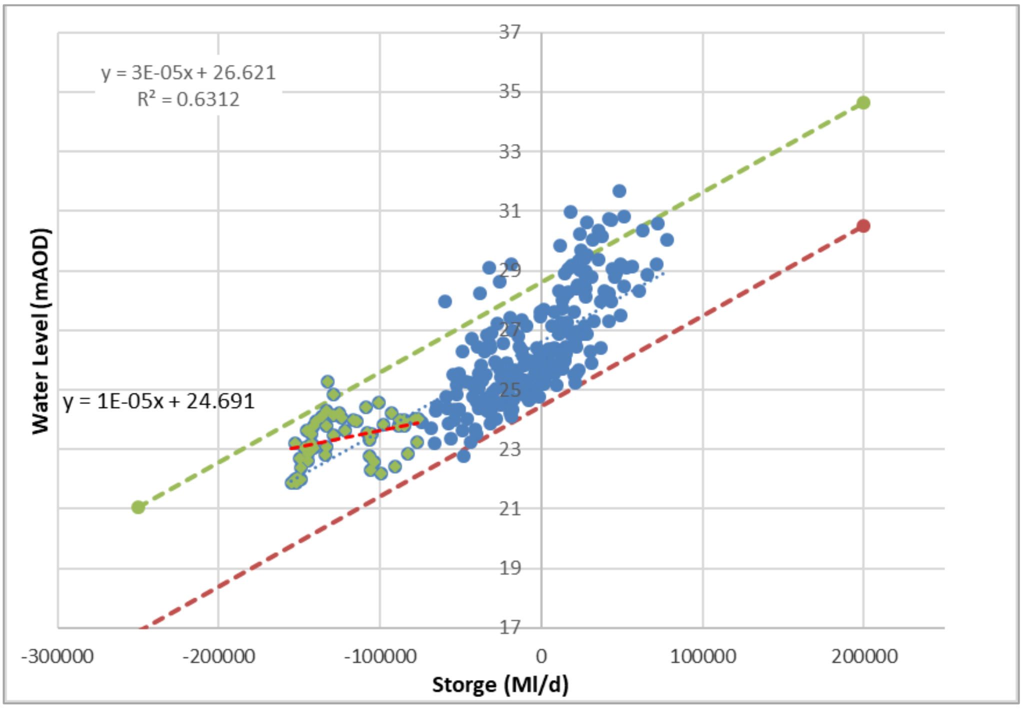


Figure A. 22: Morden Grange

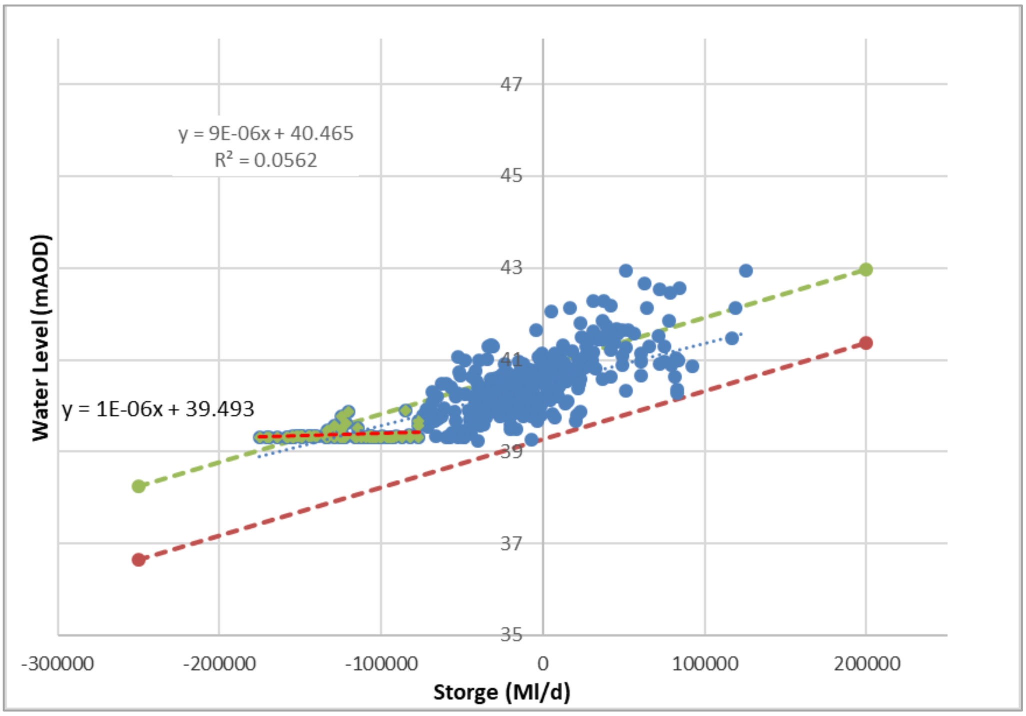


Figure A. 23: Rivey

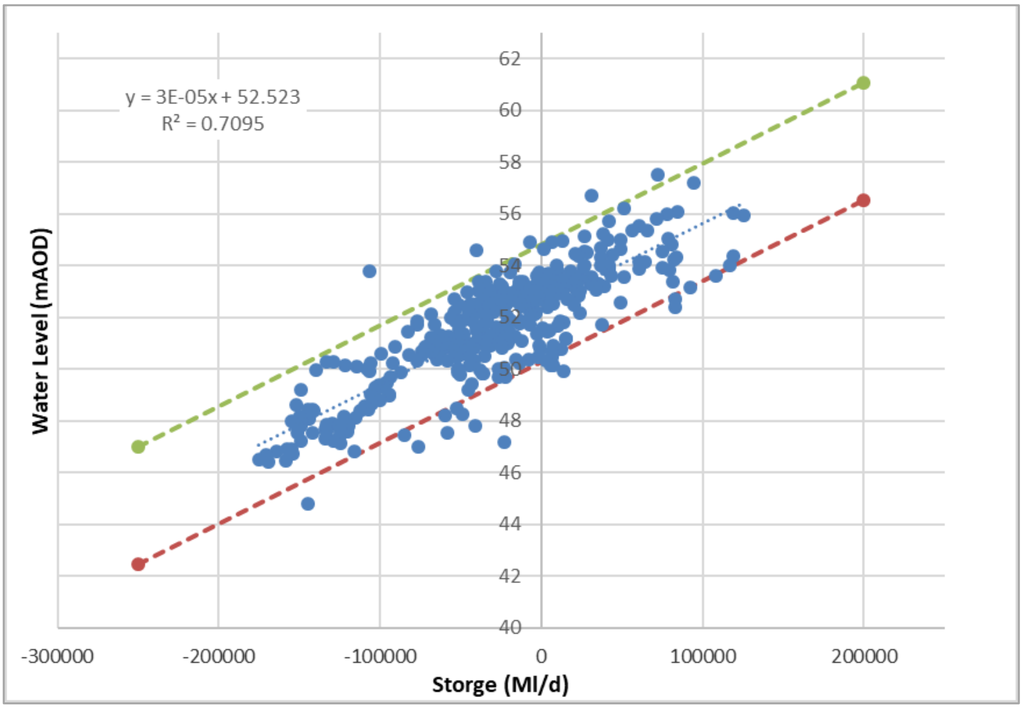


Figure A. 24: Westley

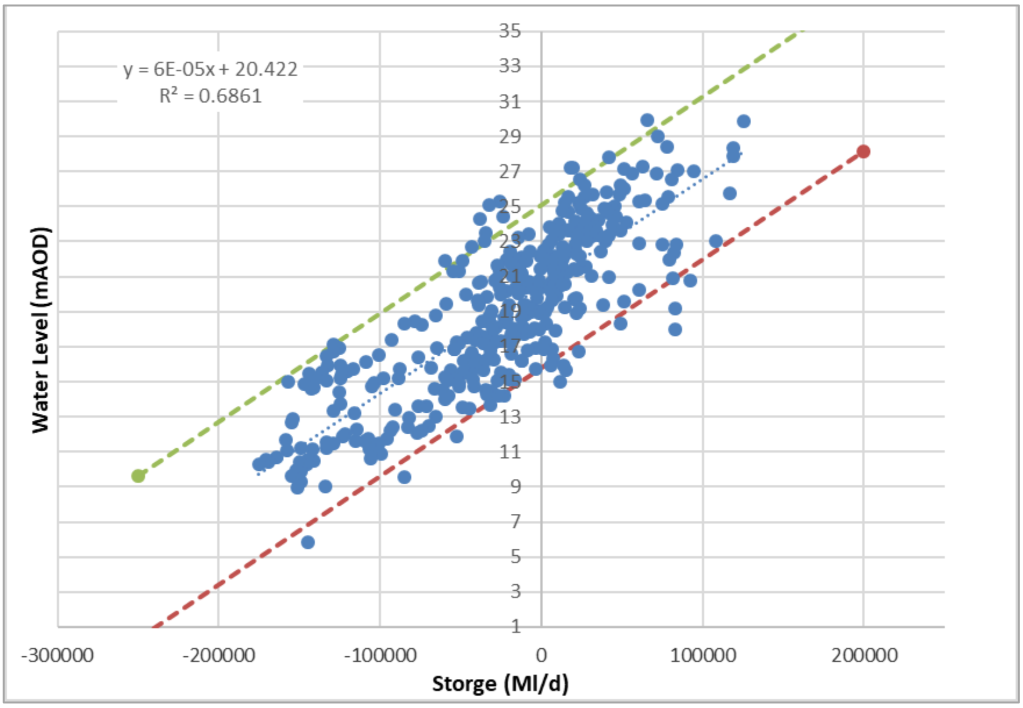
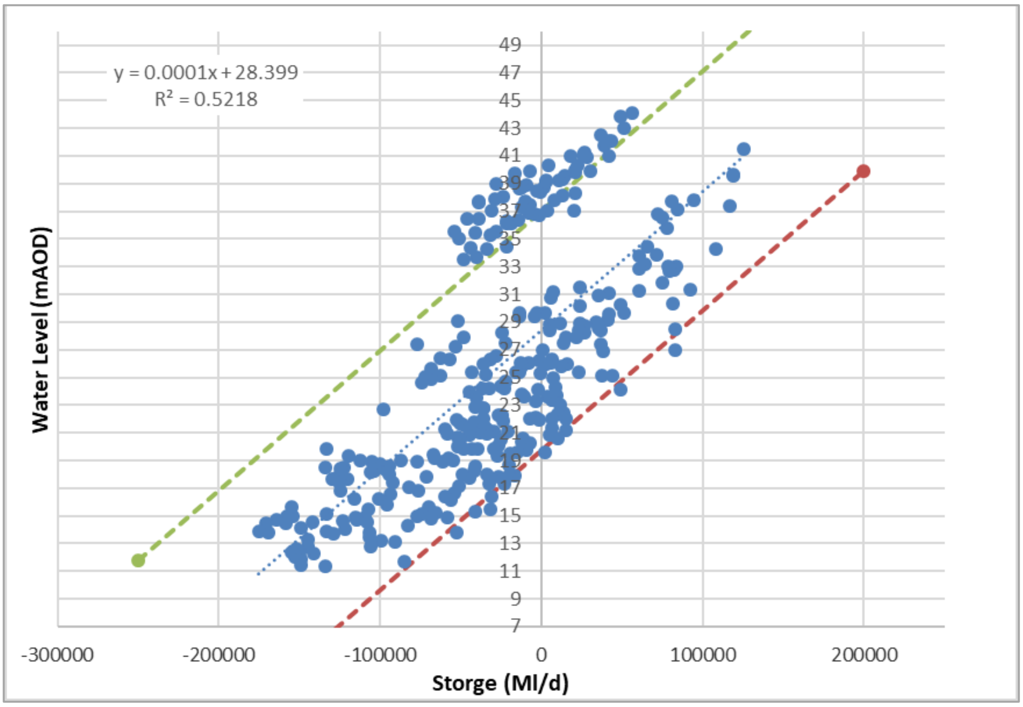


Figure A. 25: Weston Colville



B. Summary Diagrams

Figure B. 1: Abington Park

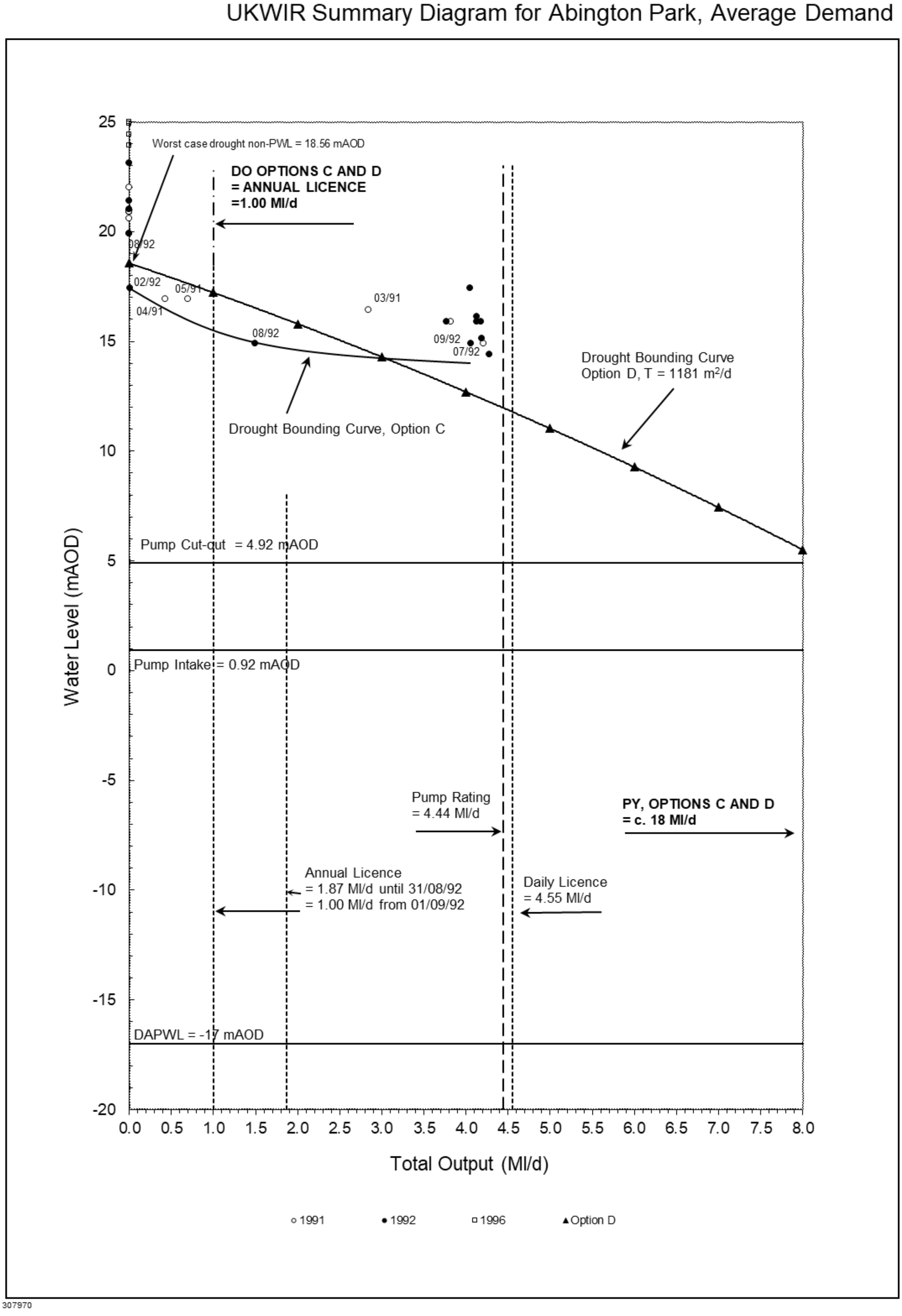


Figure B. 2: Babraham

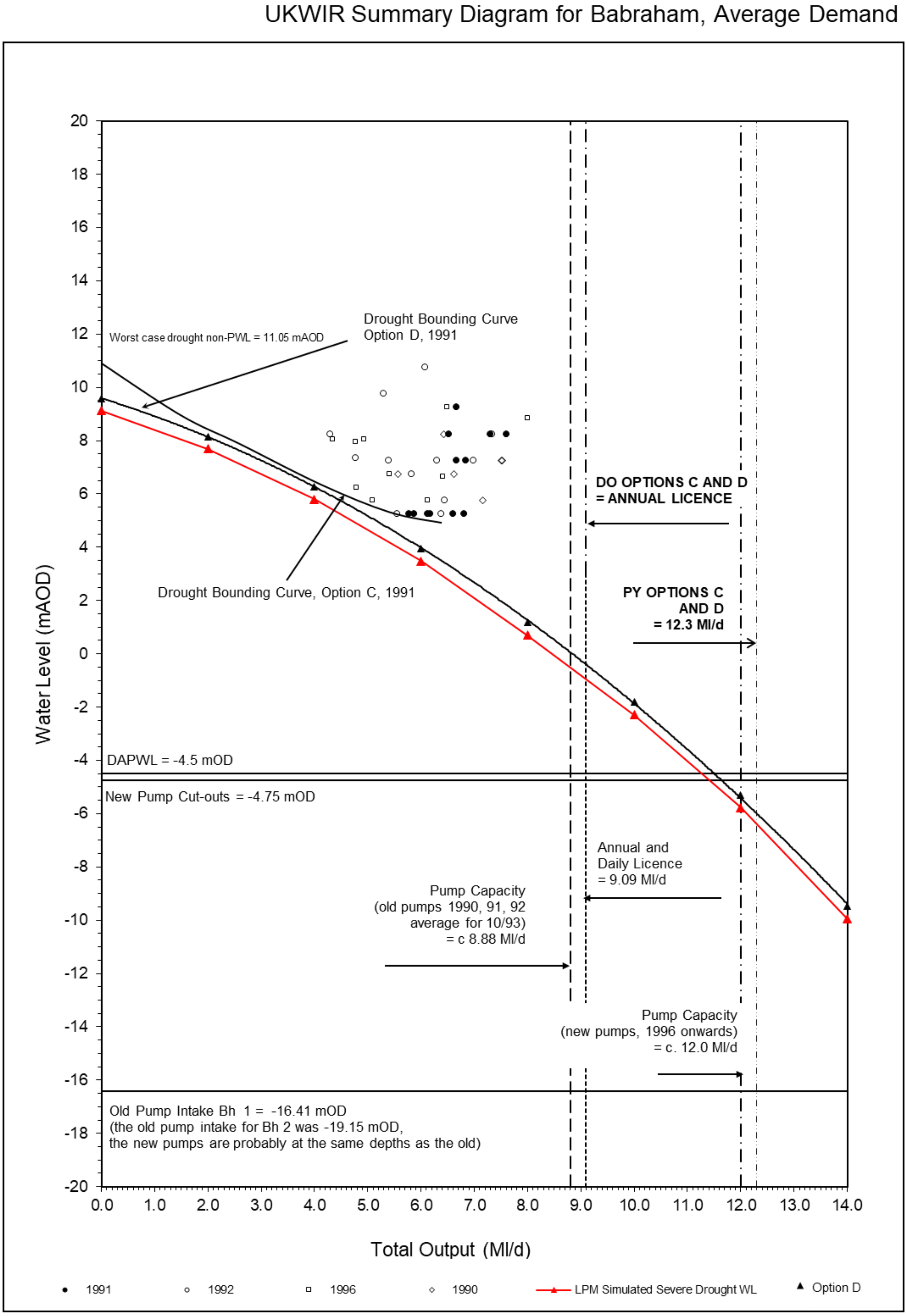


Figure B. 3: Brettenham

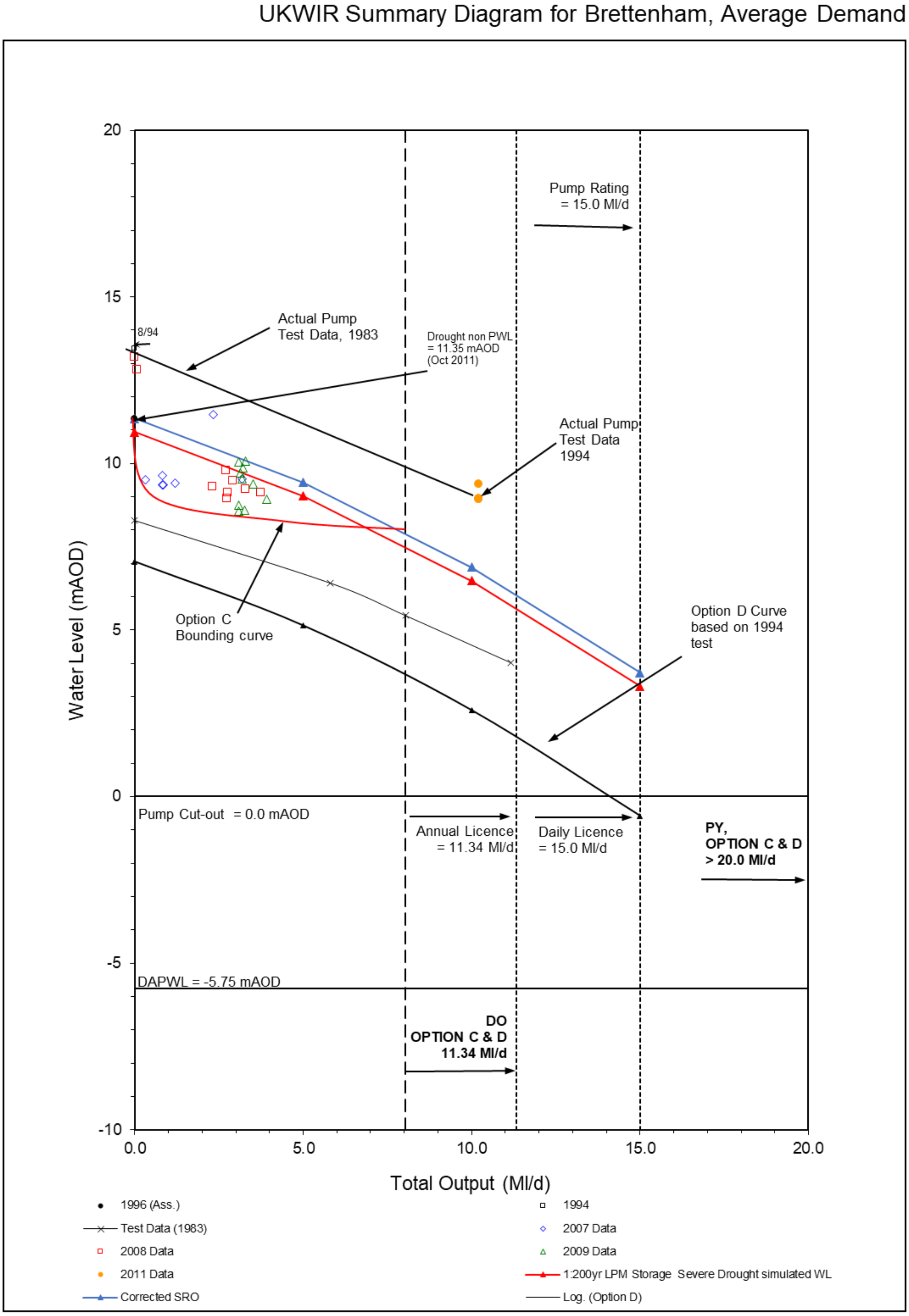


Figure B. 4: Croydon

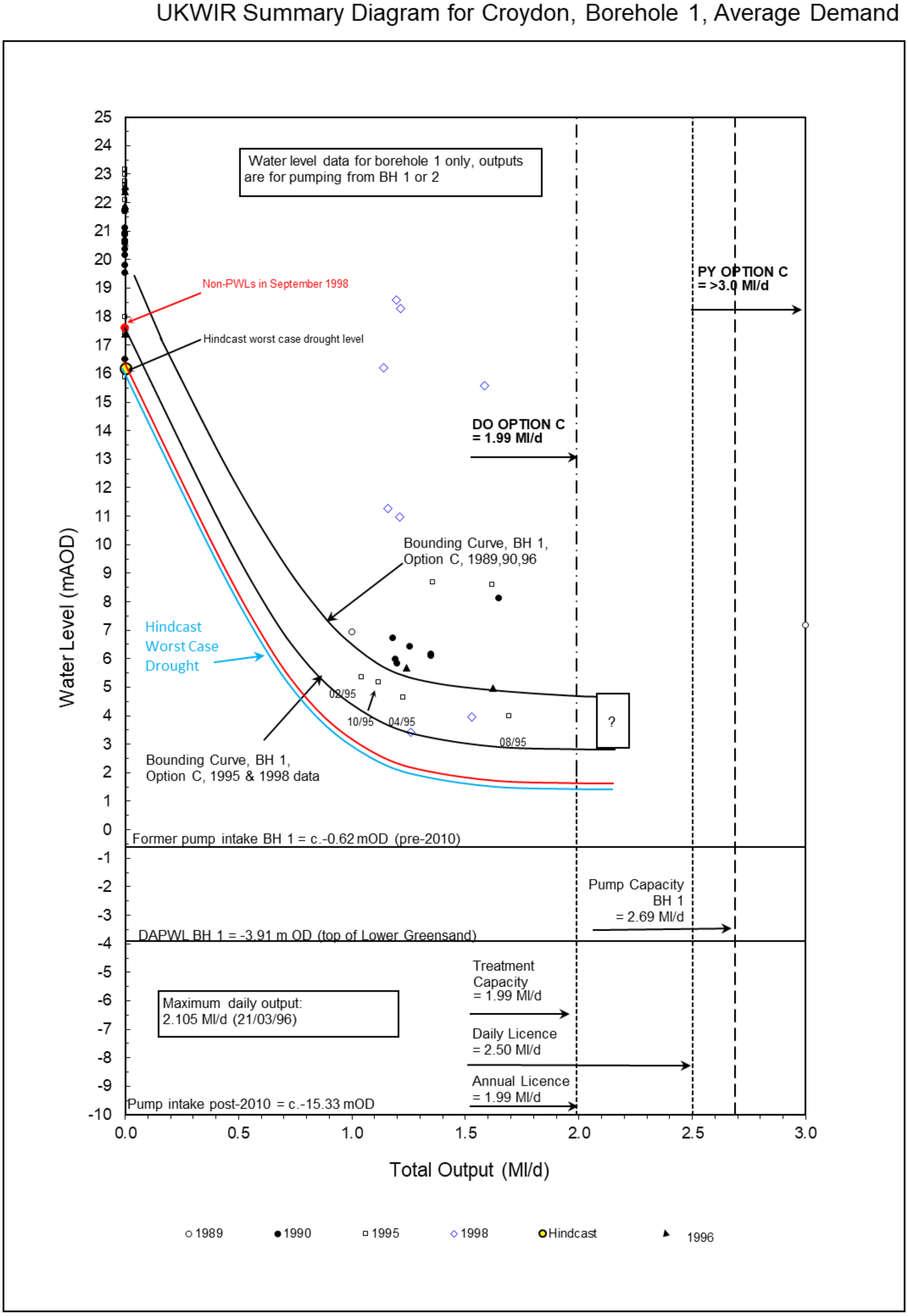


Figure B. 5: Dullingham

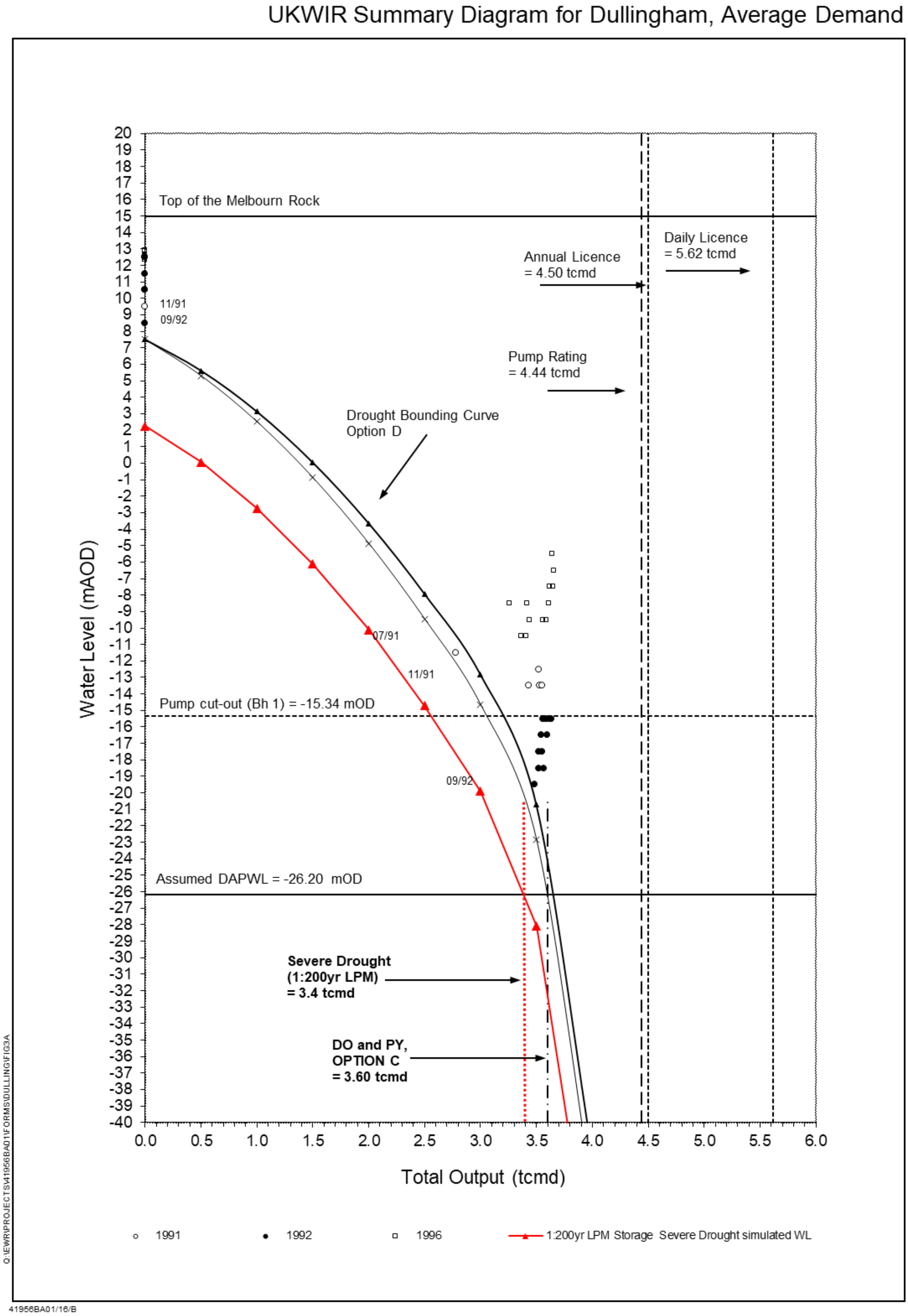


Figure B. 6: Duxford Airfield

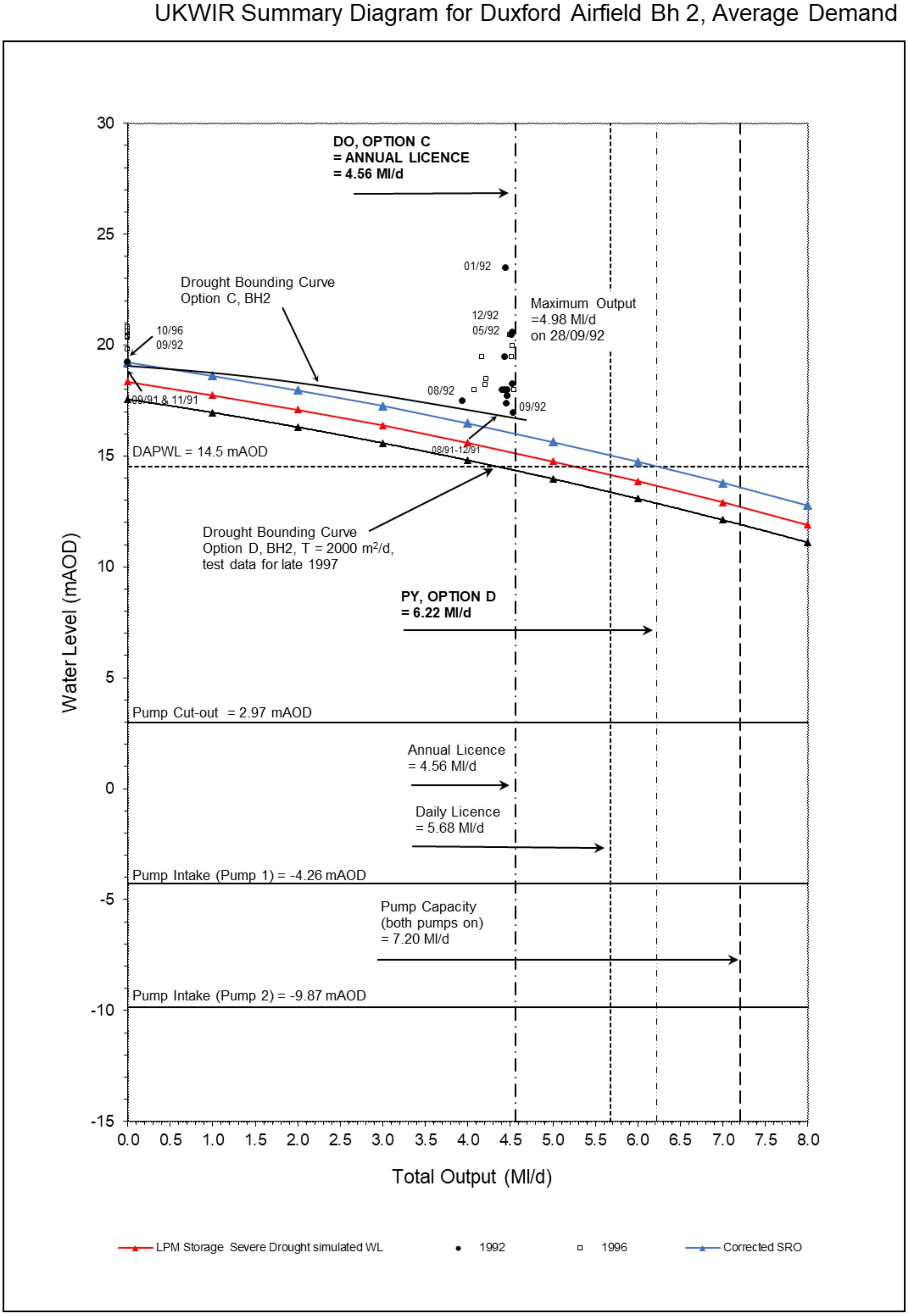


Figure B. 7: Duxford Grange

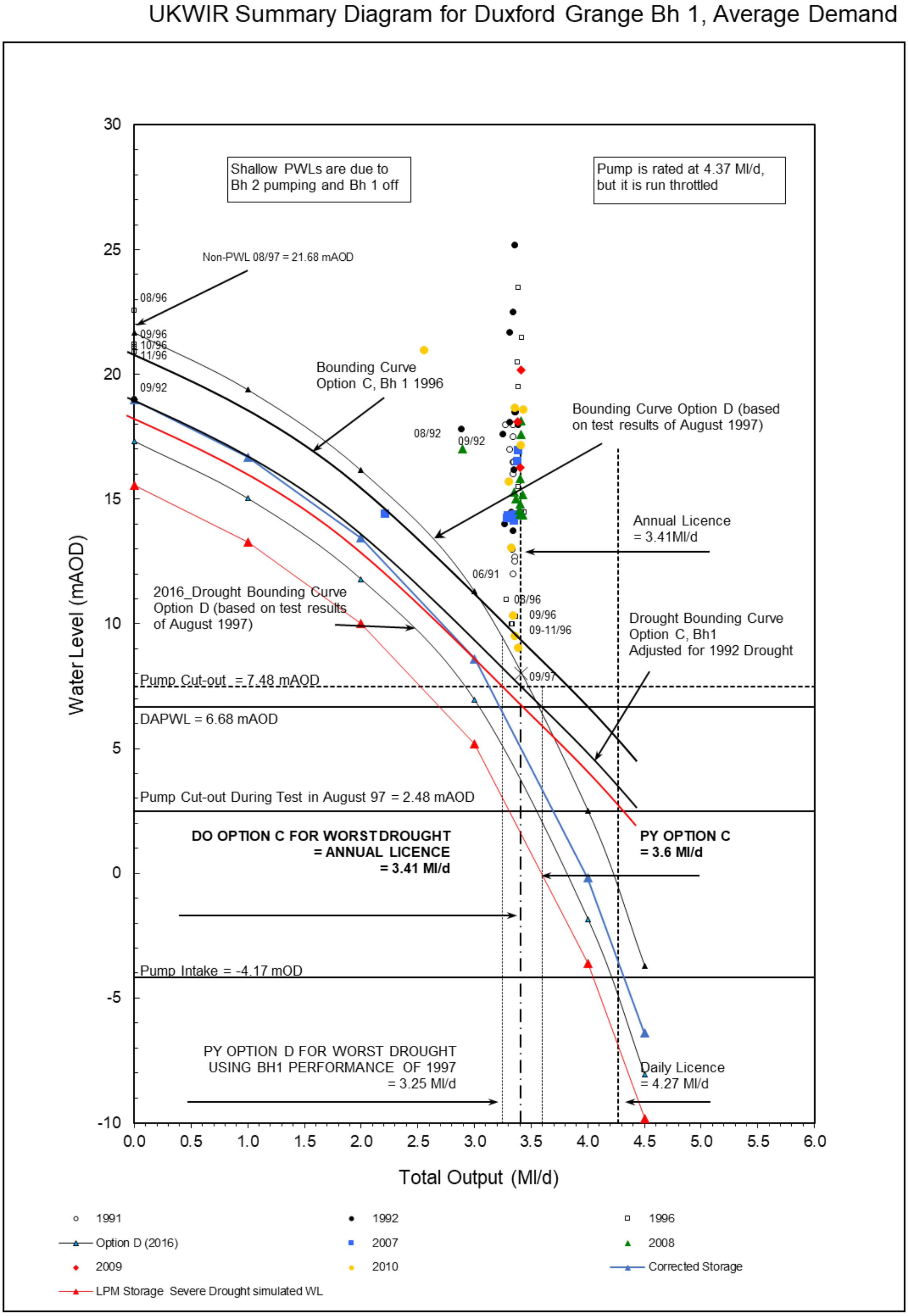


Figure B. 8: Euston

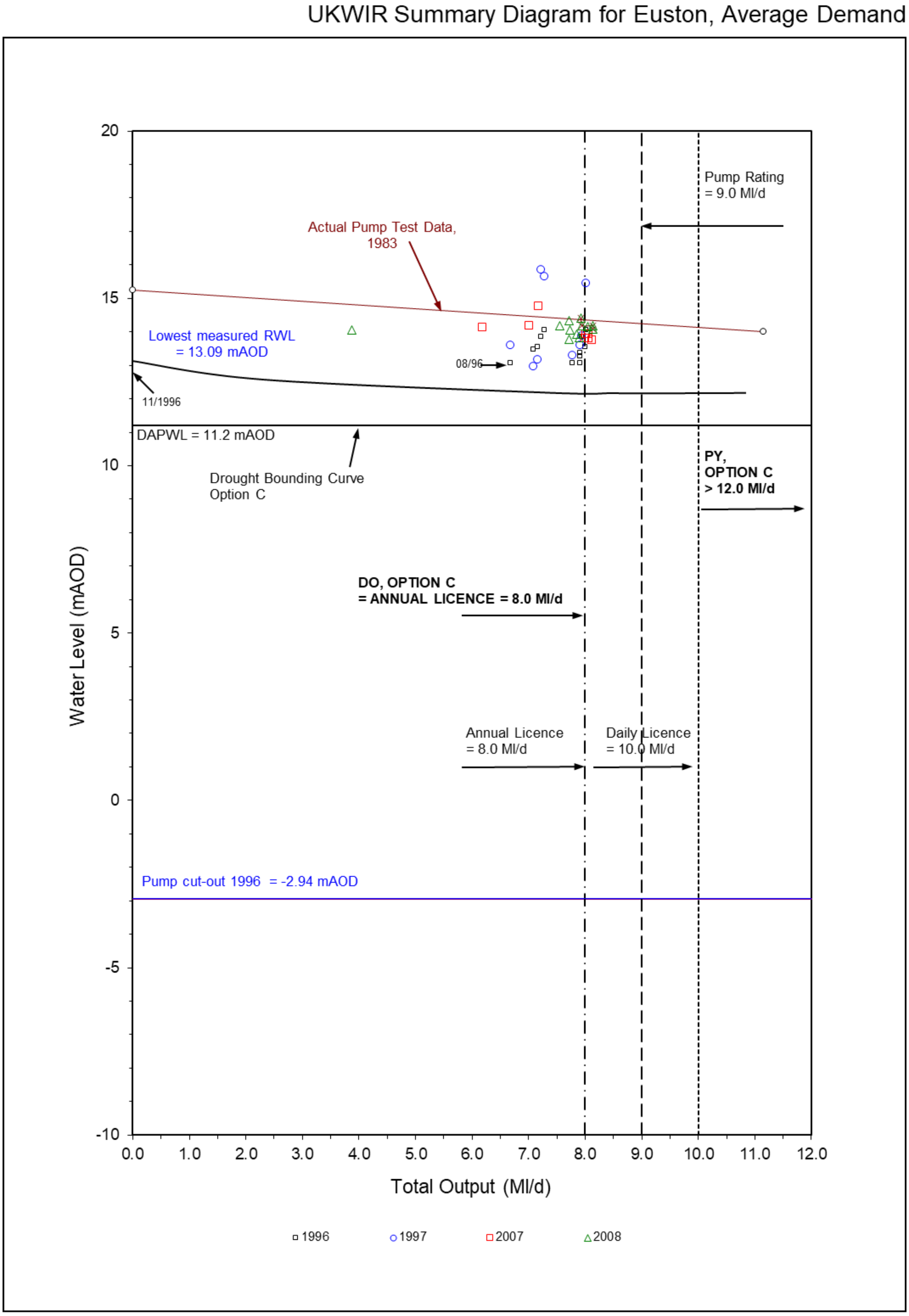


Figure B. 9: Fleam Dyke (12")

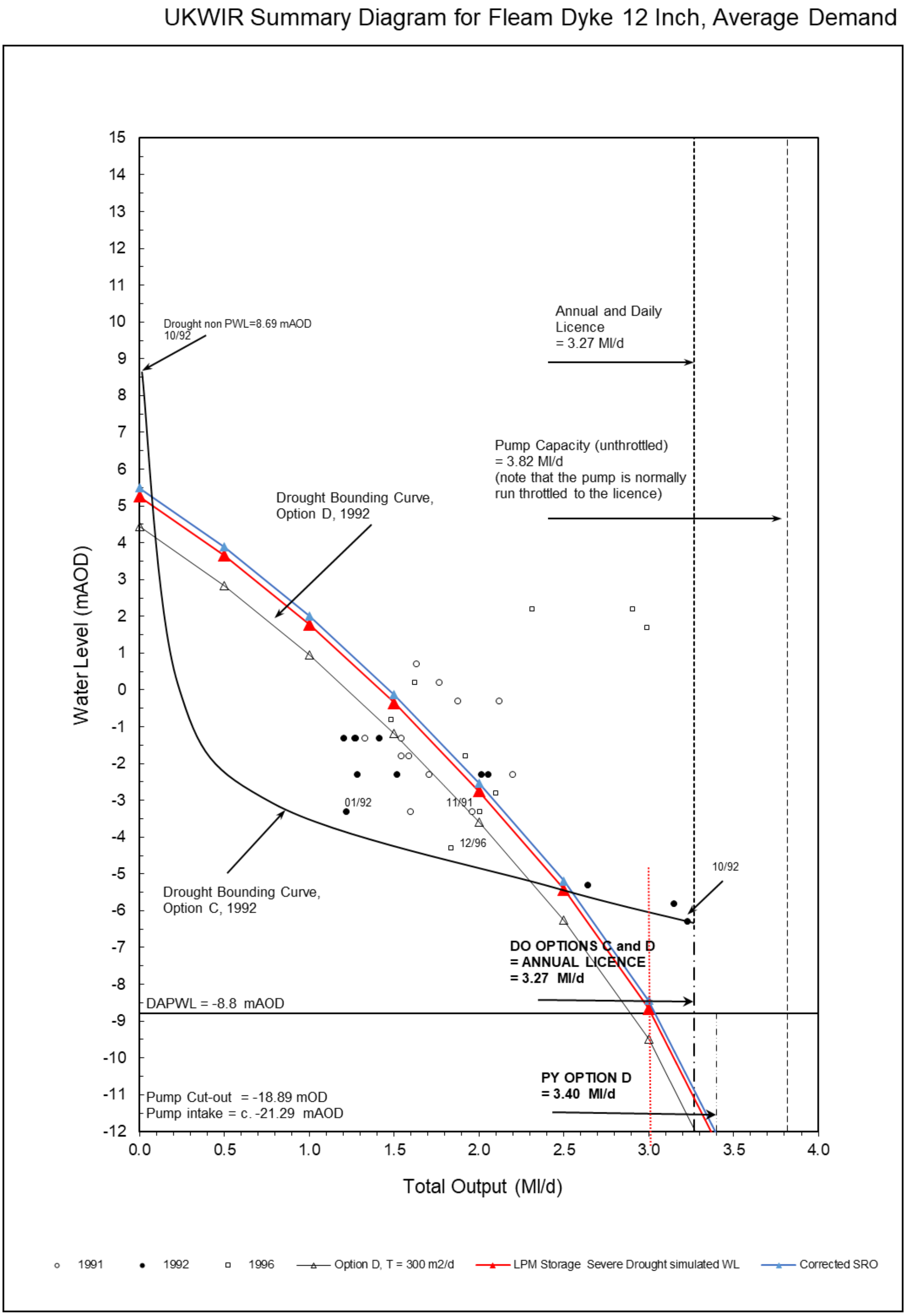


Figure B. 10: Fleam Dyke (Main)

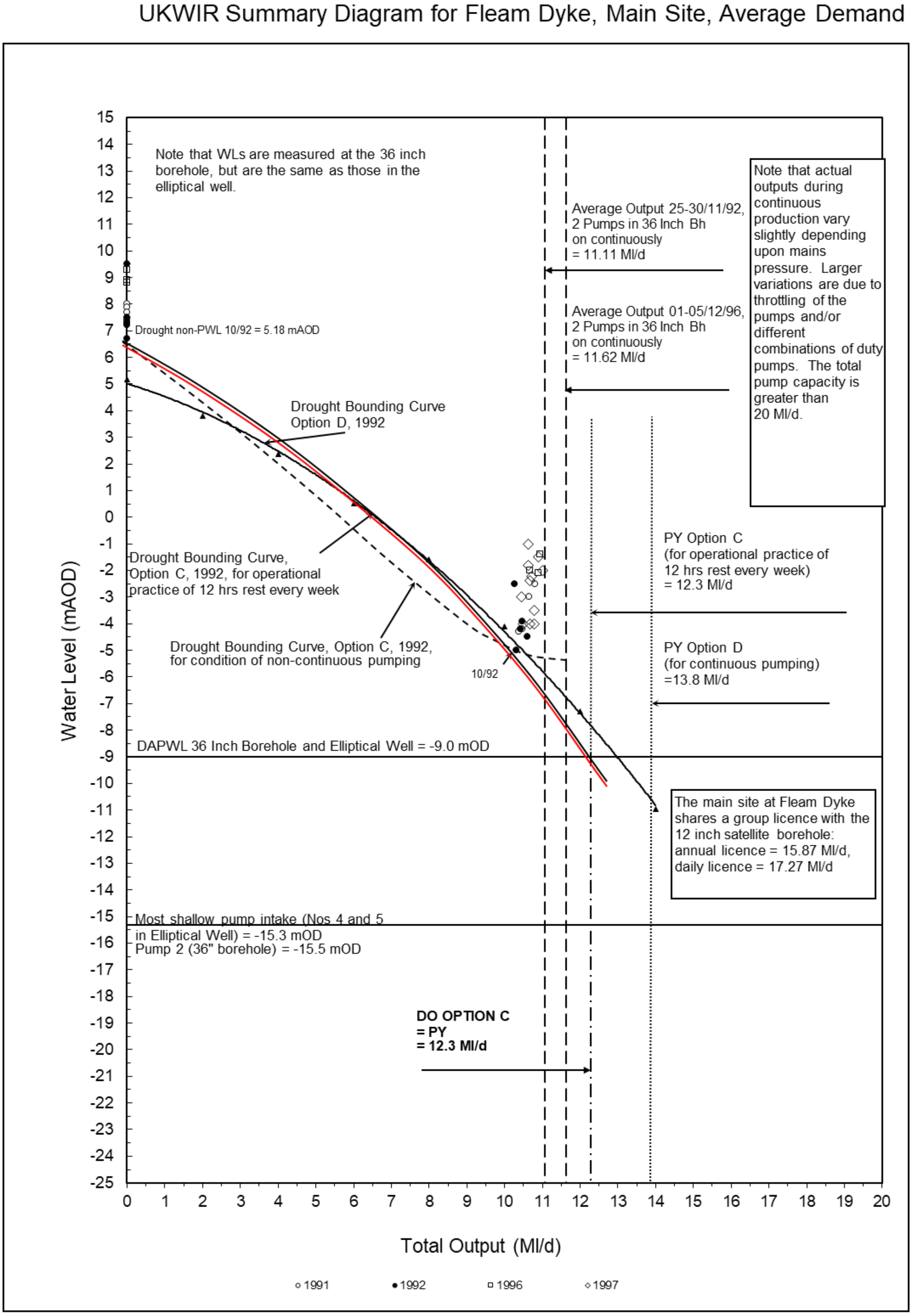


Figure B. 11: Fowlmere

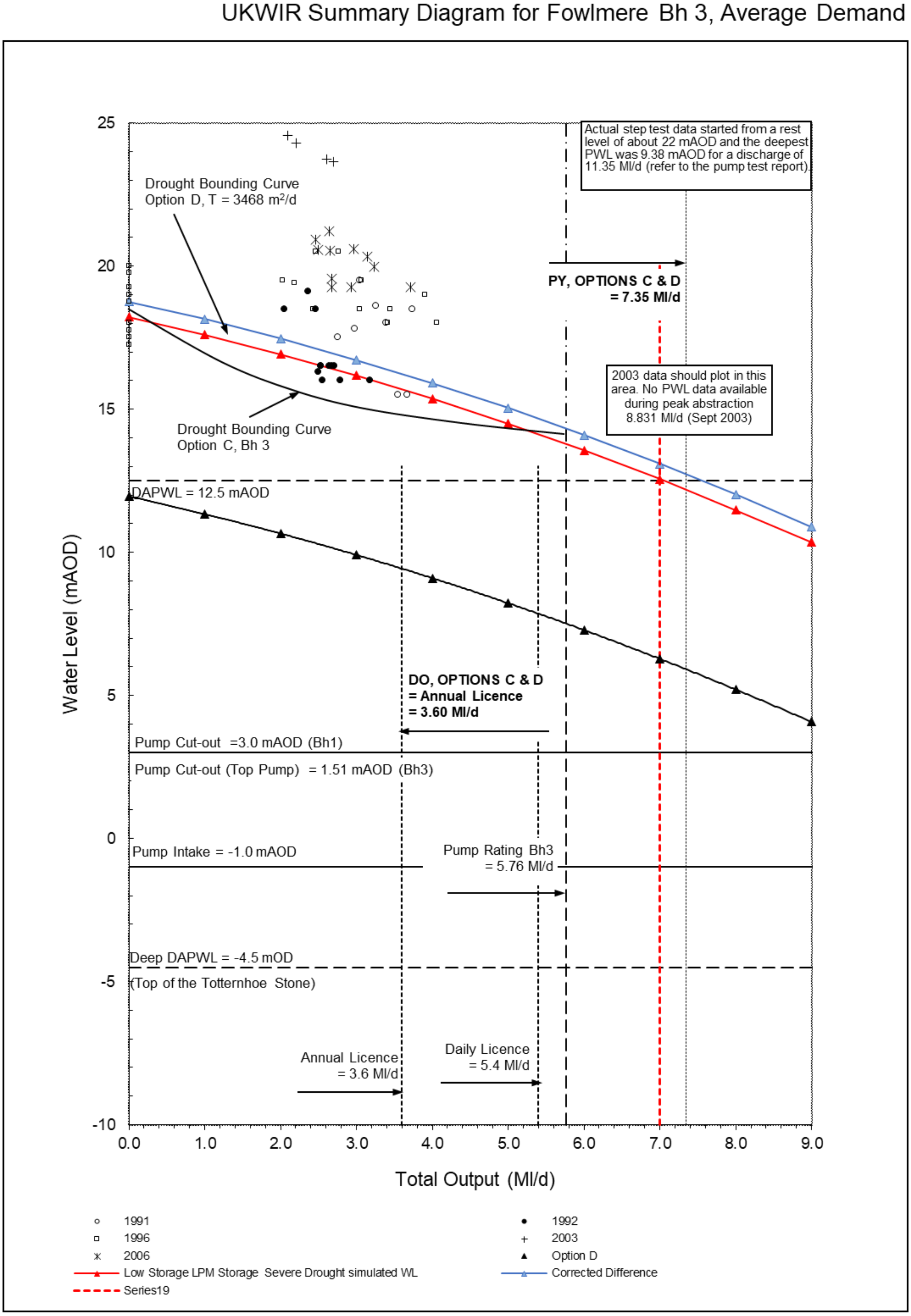


Figure B. 12: Fulbourn

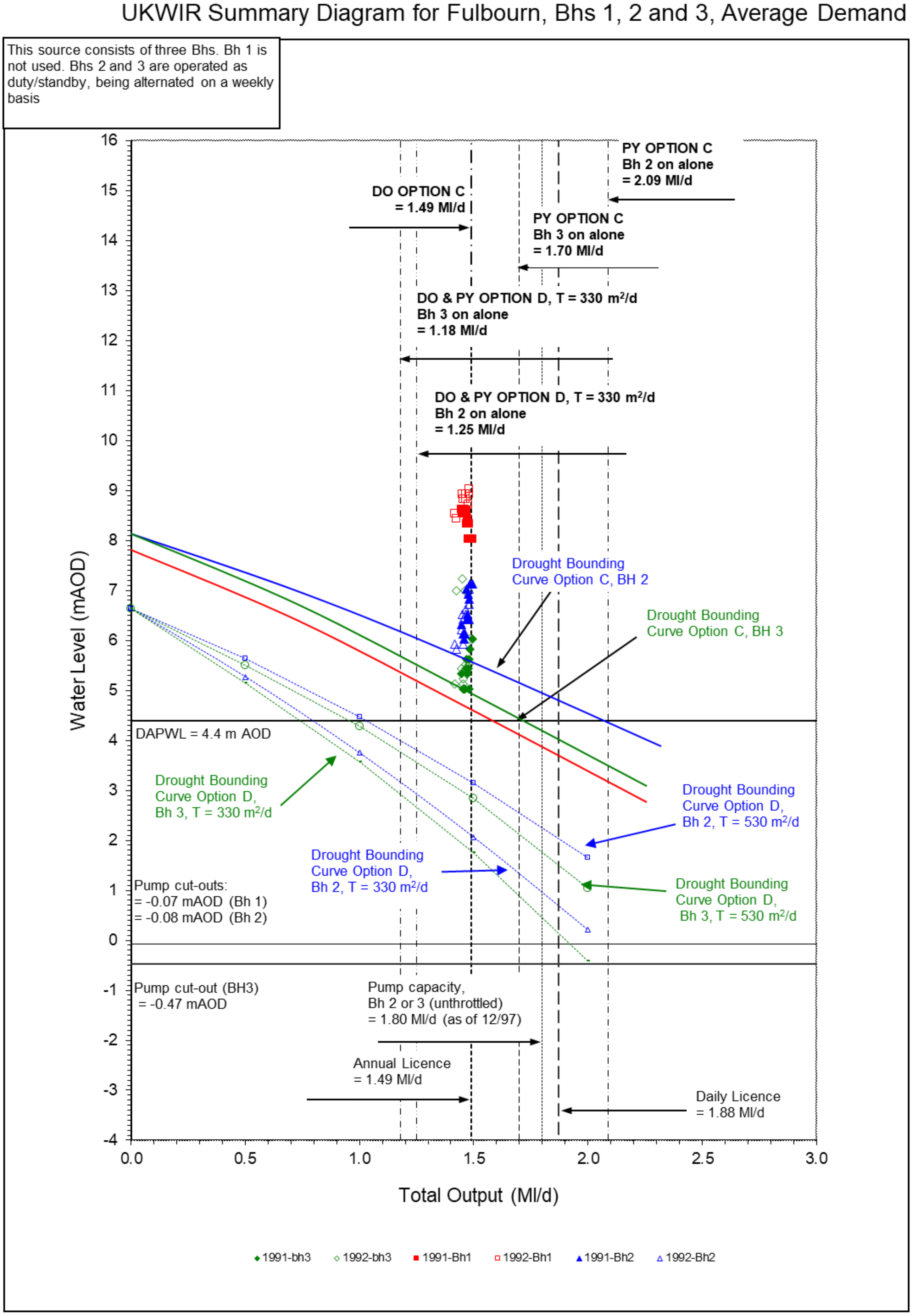


Figure B. 13: Gt Wilbraham

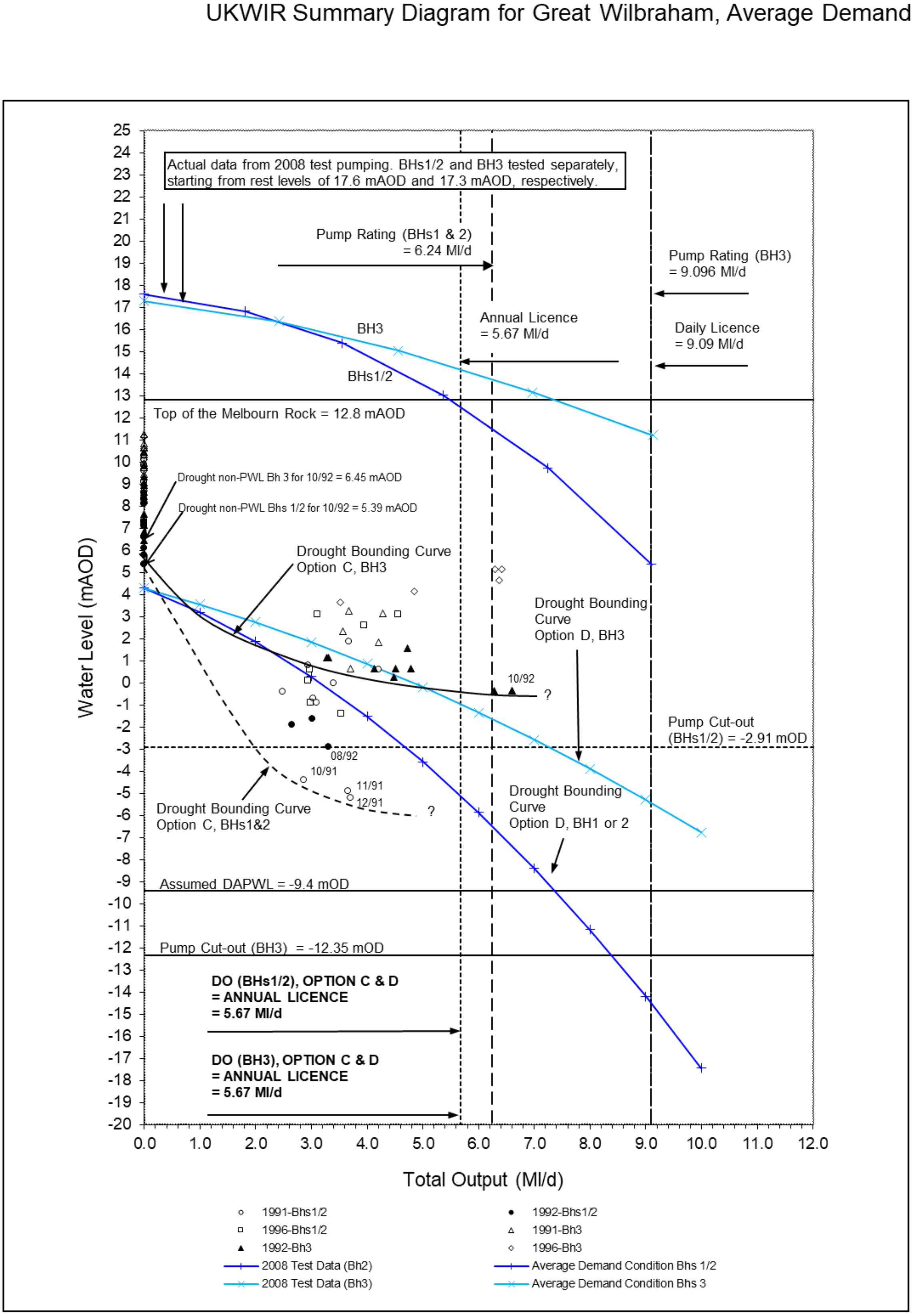


Figure B. 14: Heydon

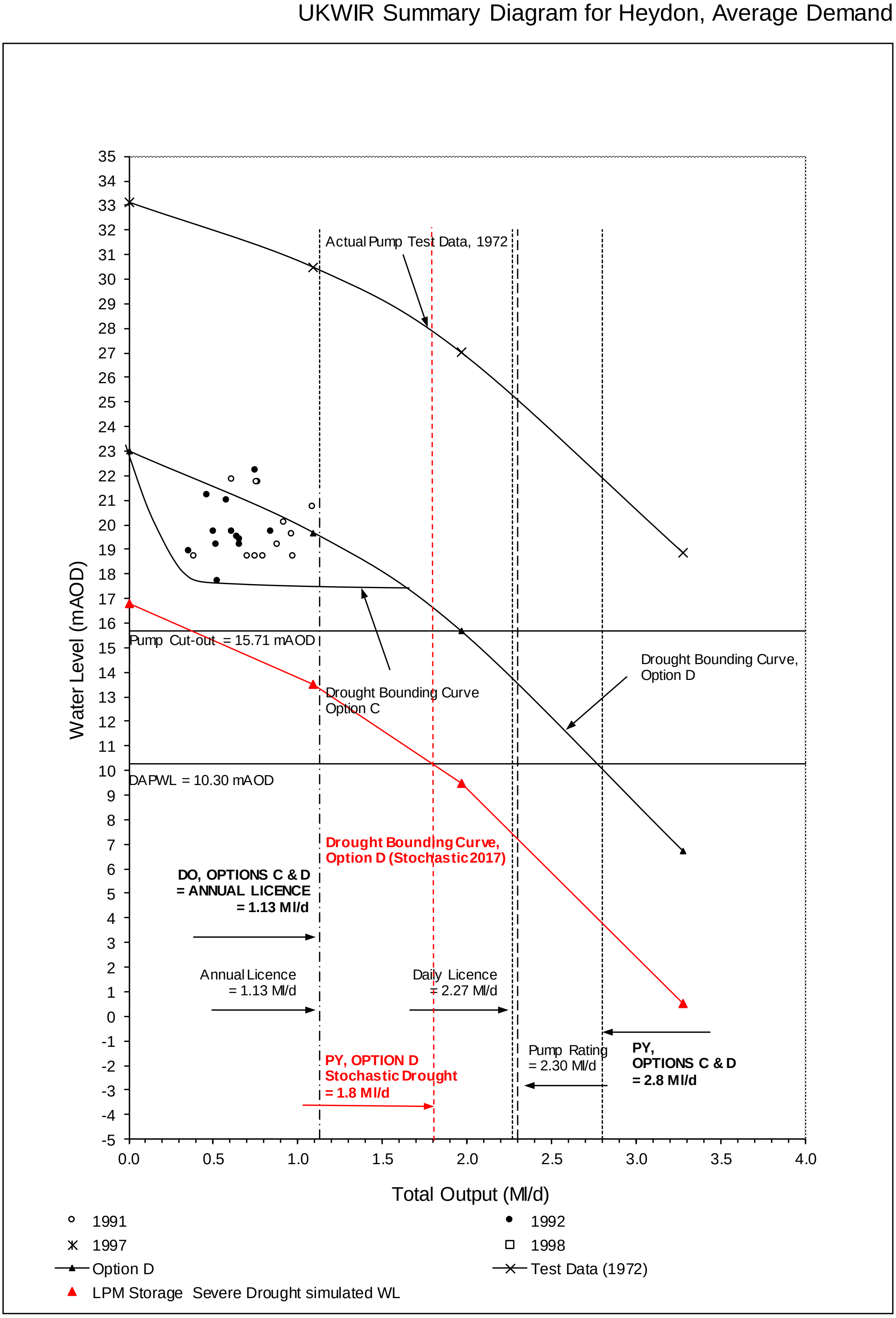


Figure B. 15: Hinxton

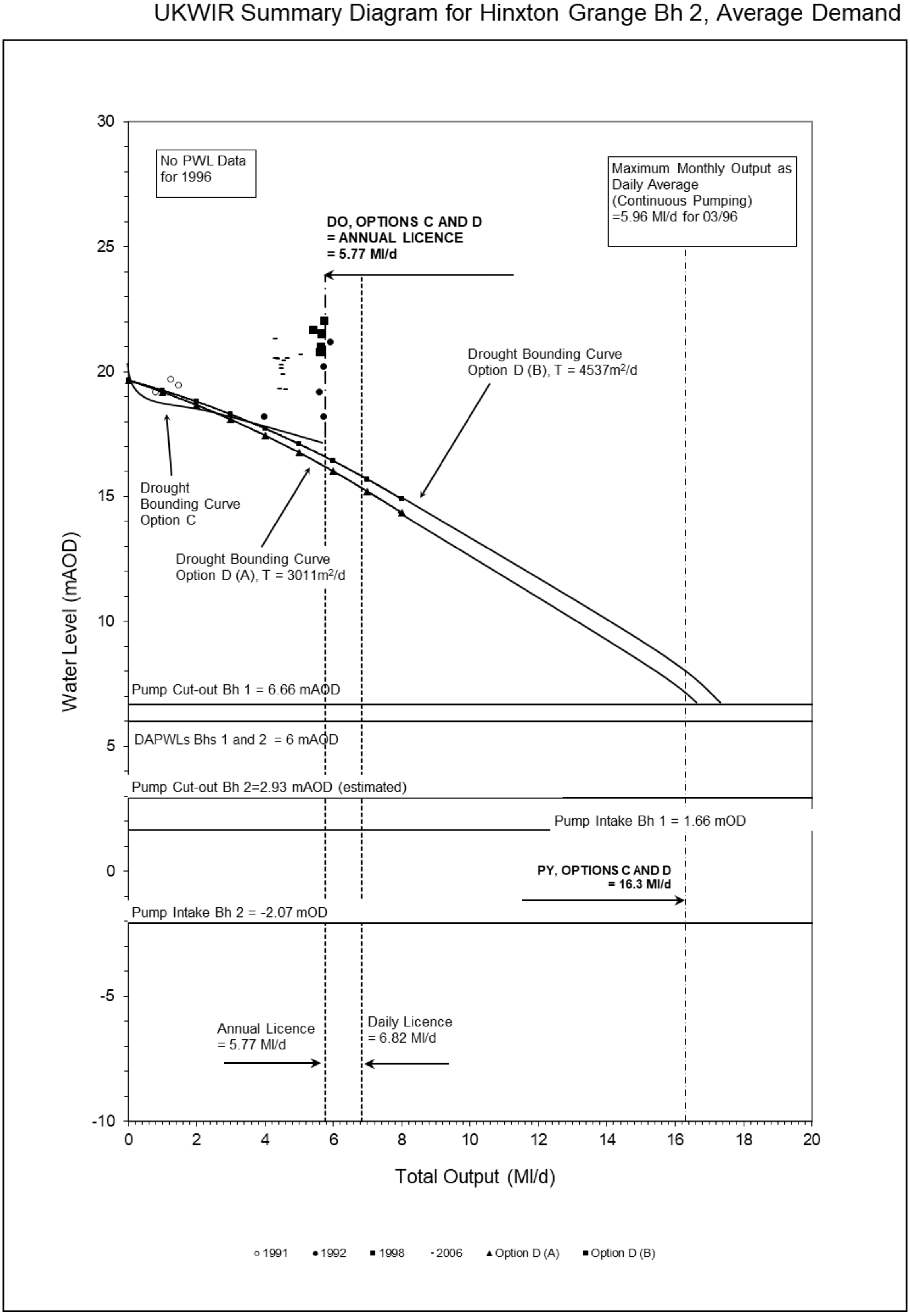


Figure B. 16: Kingston

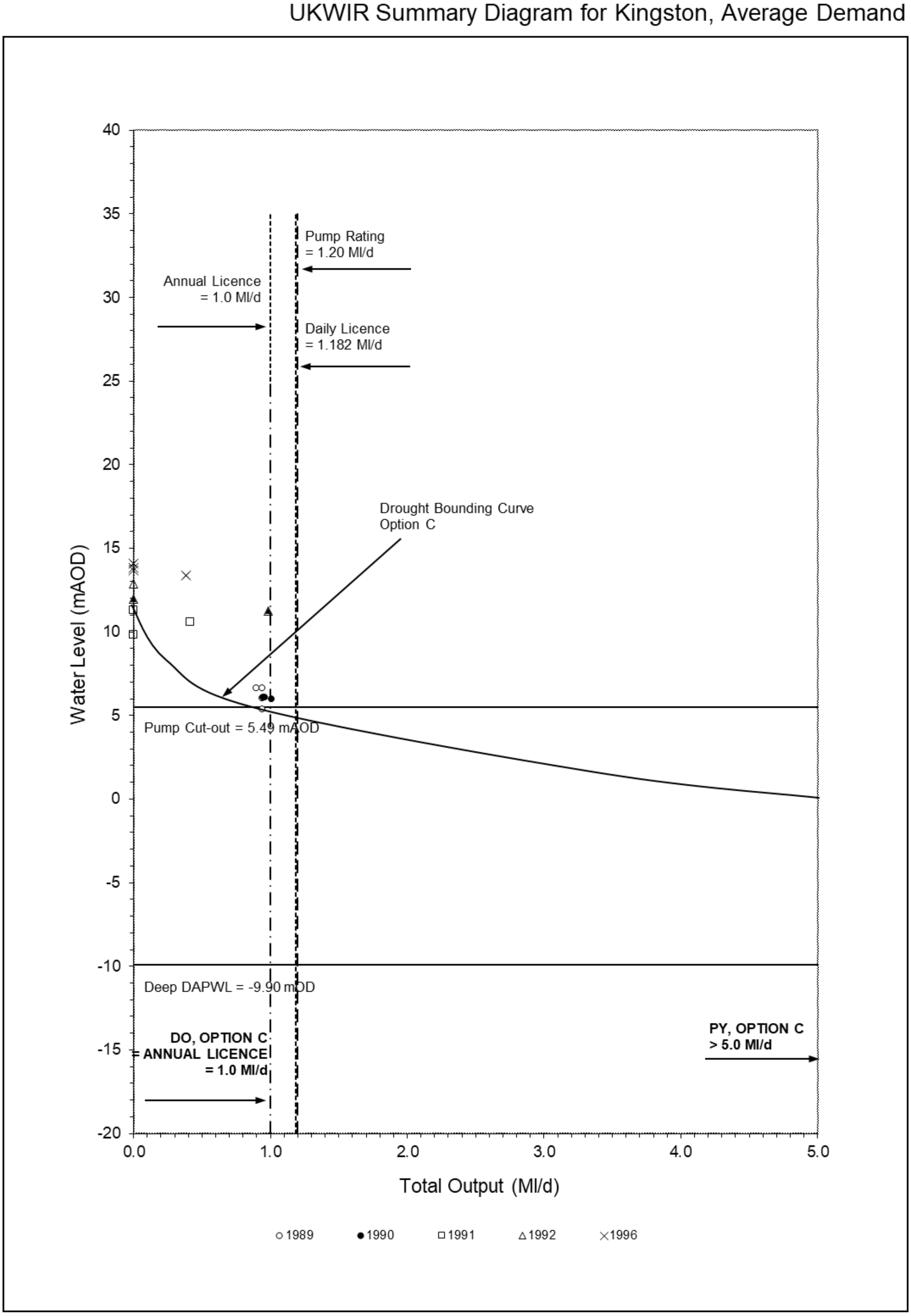


Figure B. 17: Linton

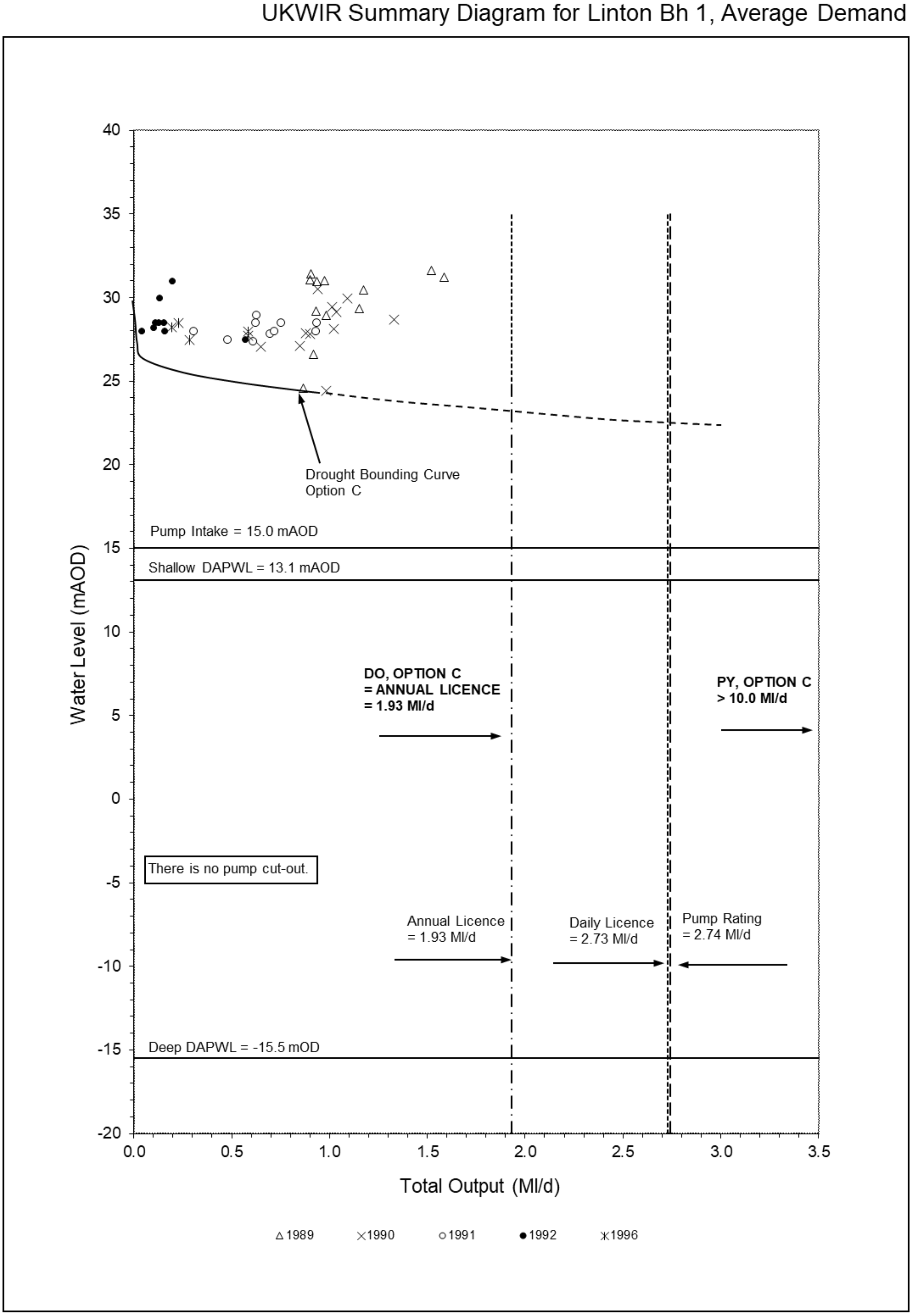


Figure B. 18: Lowerfield

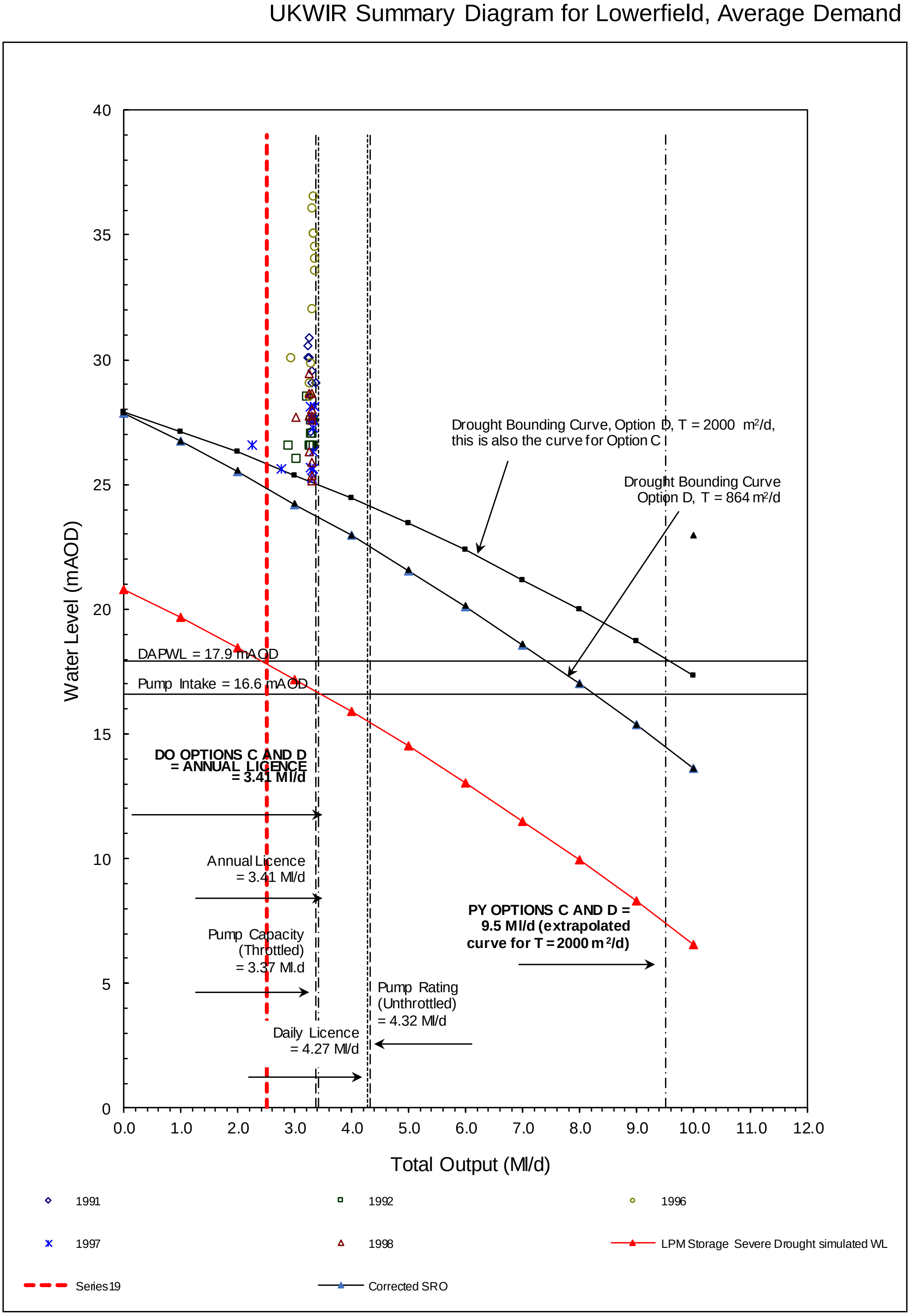


Figure B. 19: Melbourn

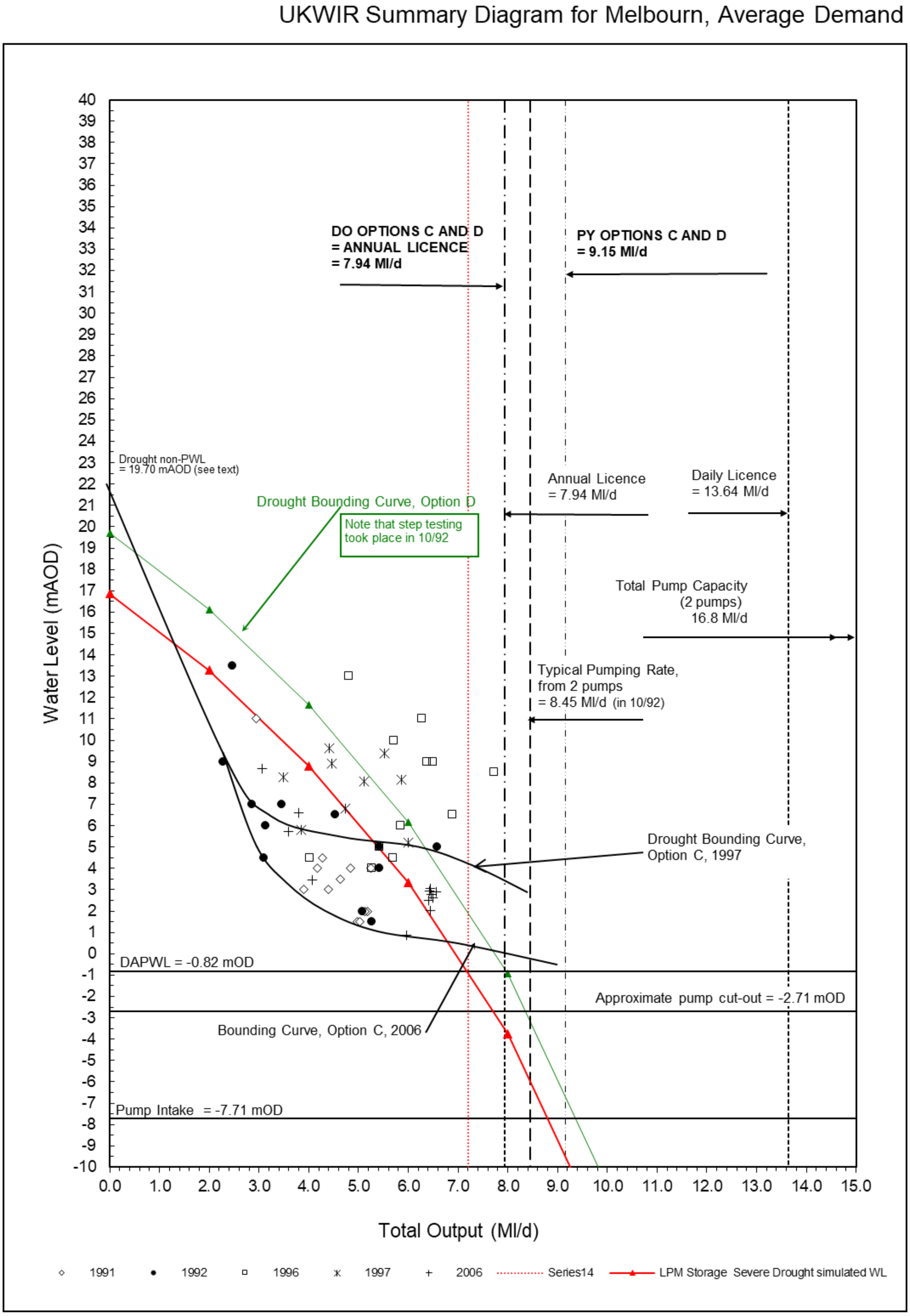


Figure B. 20: Morden Grange

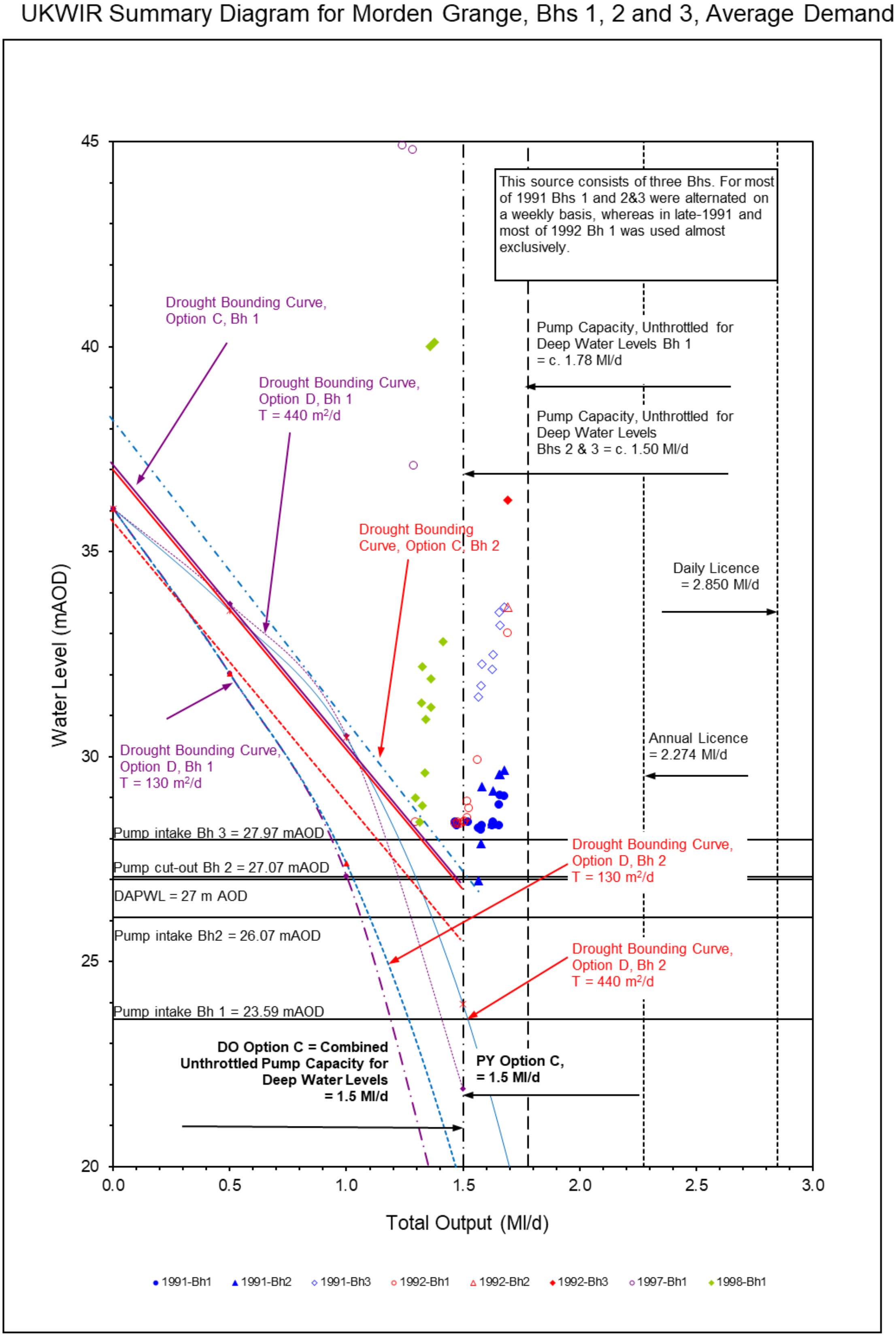


Figure B. 21: Rivey

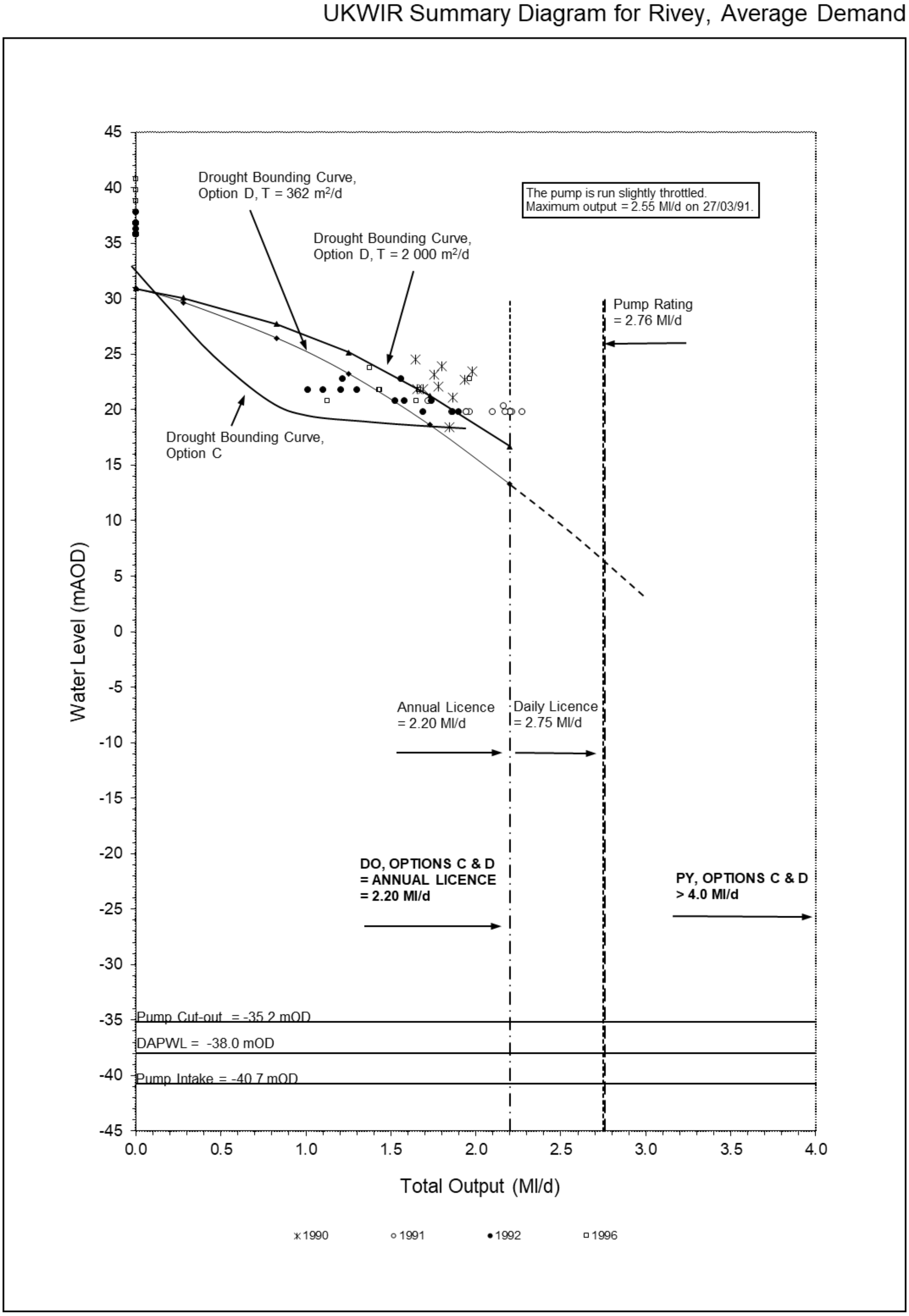


Figure B. 22: Westley

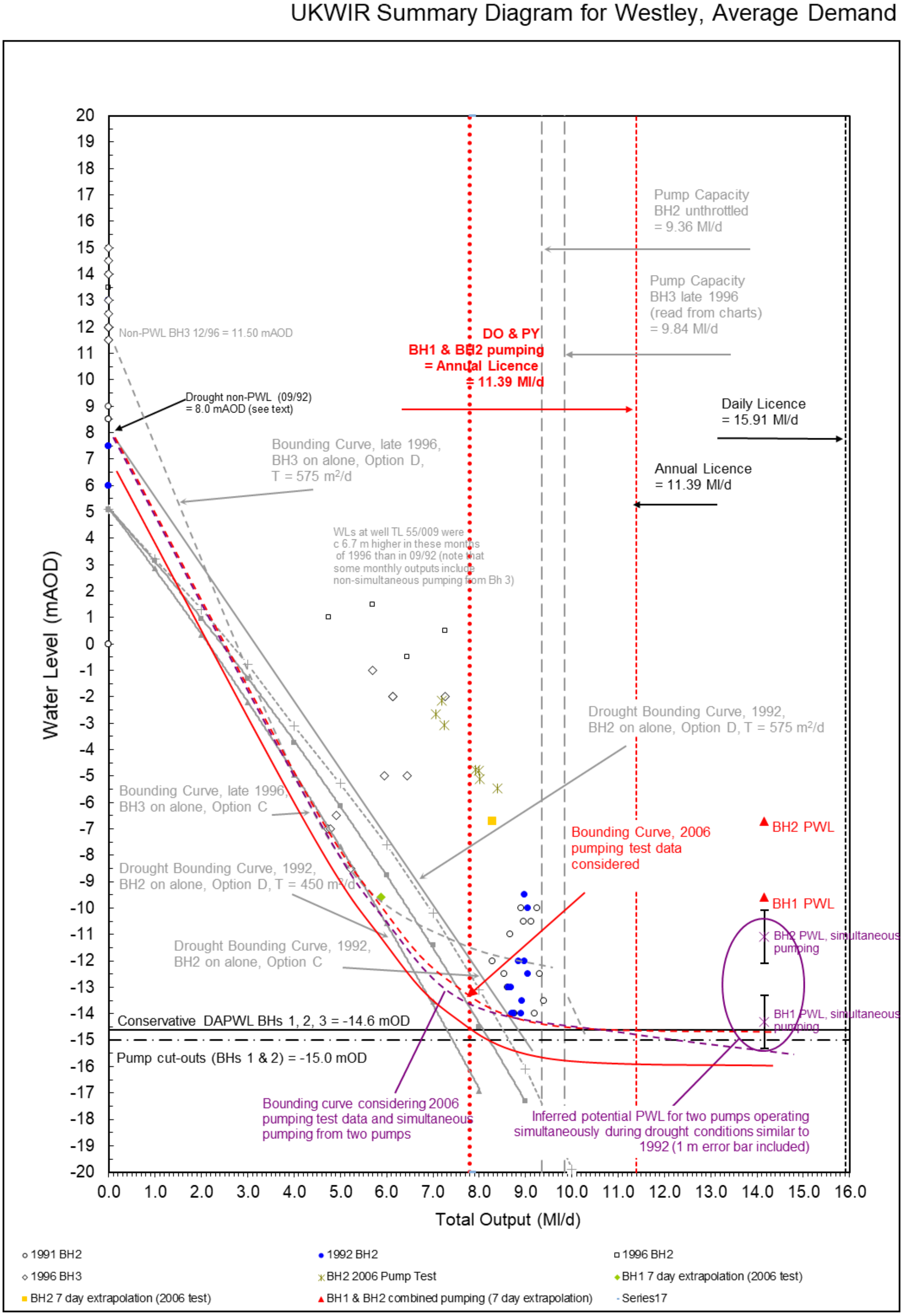
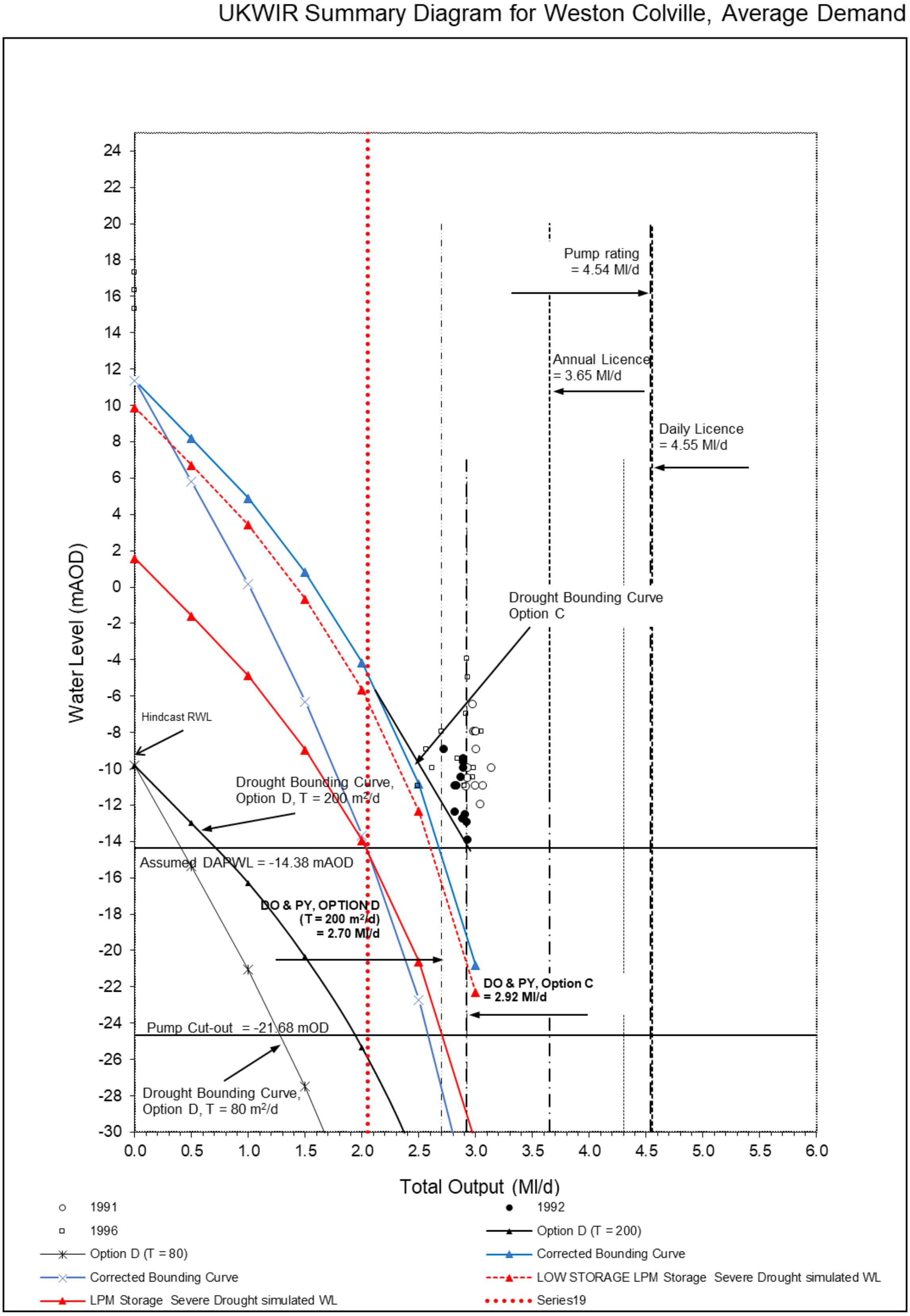


Figure B. 23: Weston Colville



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