GARD review of Resilience of the Abingdon reservoir in the event of droughts more severe than droughts of the 20th Century

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Group Against Reservoir Development

www.abingdonreservoir.org.uk

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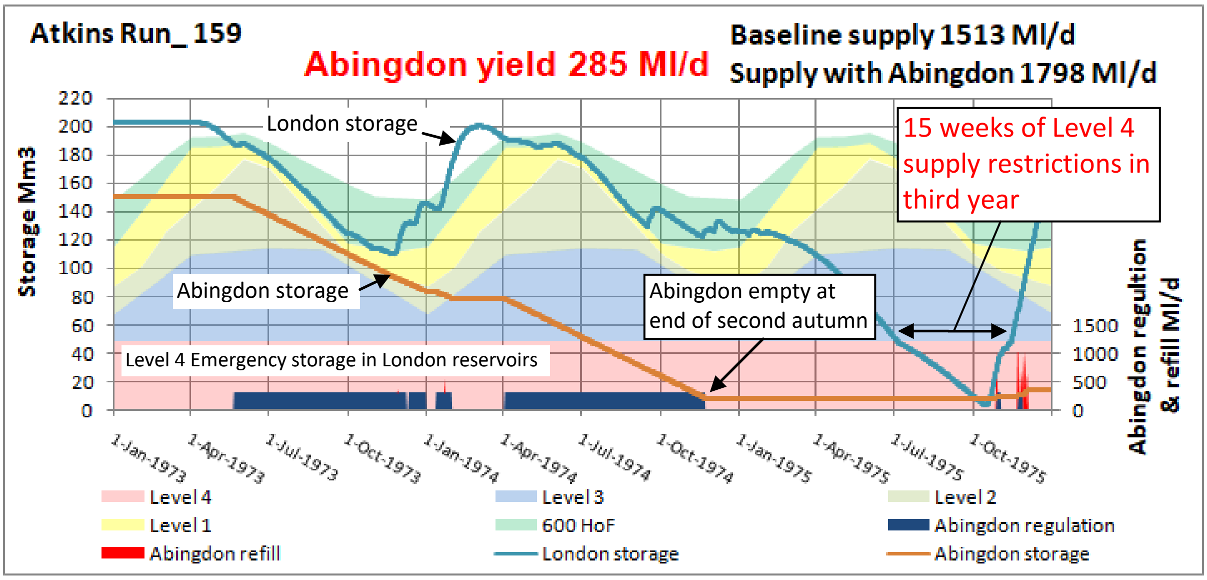
The fundamental weakness of London's existing water supplies is over-dependence on reservoirs filled by pumping from the River Thames. Already, there is insufficient water to refill the existing reservoirs over-winter in major 18-month droughts similar those of the 20th Century. With increasing future demands, it will become more difficult to refill the London reservoirs, unless there is "new water" in the system, as would be provided by schemes like the Severn-Thames transfer, desalination or effluent reuse.

Thames Water's proposed Abingdon reservoir would almost double the storage to be filled by pumping from the River Thames, but would provide no "new water" for filling the reservoirs**.** In consequence, the reservoirs would often be significantly depleted at the start of summer droughts, making the supply system vulnerable to droughts longer than those of the 20th Century and especially vulnerable to multi-year droughts.

We have reviewed Thames Water's assessment of the resilience of Abingdon reservoir and undertaken our own analysis, using the drought data generated stochastically by Atkins in a commissioned report for Thames Water. The conclusions that we have drawn are:

1. Although we agree with Thames Water's conclusion that the Abingdon reservoir yield of about 285 Ml/d, assessed for the droughts of the 20th Century, is resilient against more intense droughts (with even lower river flows), <u>this only applies if their duration is less than 18 months</u>.
2. Thames Water have identified that the yield of Abingdon reservoir is <u>not</u> resilient to droughts of longer duration than those of the 20th Century. However, they have dismissed the risks as being extremely small, without proper consideration of either their likelihood or their consequences.
3. Our analysis has confirmed Thames Water's finding that, in 30-month droughts, Abingdon yield can drop to about 100 Ml/d. We have also shown that, if the output from Abingdon reservoir is maintained at the planned 285 Ml/d in a 30-month drought, the reservoir would be empty at the end of the second autumn, with catastrophic failure of London's supplies in the third year:



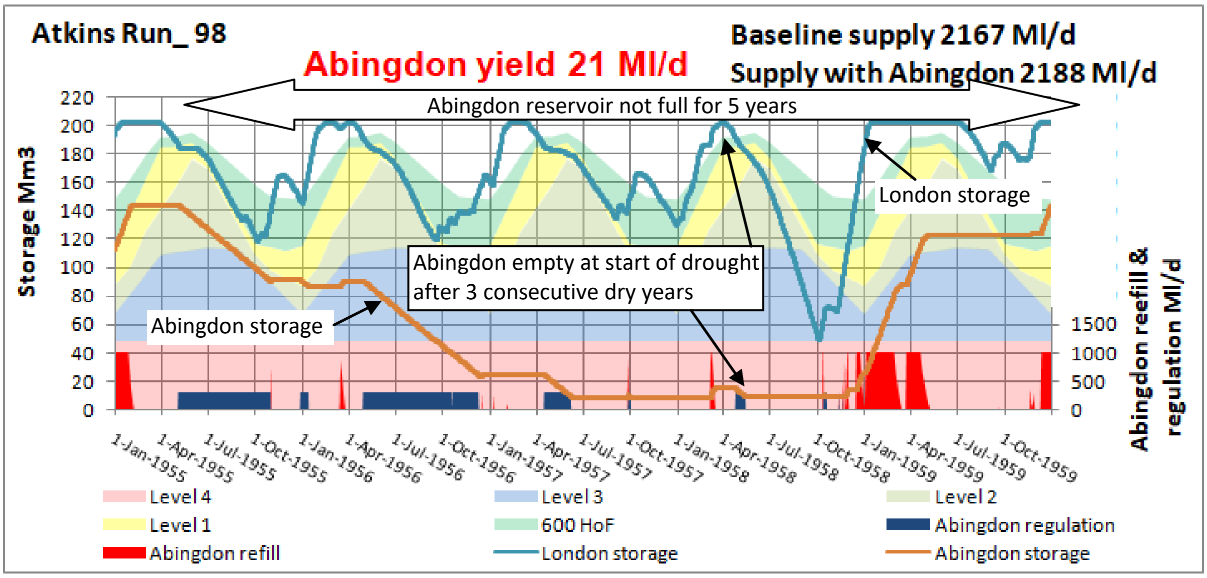
Note: dates on plots are nominal dates as per Atkins' stochastic data

Example of 30-month drought leading to catastrophic failure of London's supplies, if Abingdon reservoir yield is expected to be 285 Ml/d

4. The Environment Agency has identified the huge potential damage of Level 4 emergency supply restrictions in London, which would include rota cuts for households and businesses. They have suggested economic costs of £7-10 billion per month, break-down of social cohesion and serious impacts on public health. If a decision was taken not to enforce Level 4 supply restrictions, perhaps under pressure from politicians or customers, relying instead on emergency storage in the London reservoirs, the reservoirs would be totally empty within two months and would remain empty for another four months.

5. In our opinion, the consequences of a 30-month drought, whilst expecting an Abingdon reservoir yield of 285 Ml/d, are so severe that even the 1 in 1000 year probability crudely estimated by Thames Water is an unacceptable risk for London's supplies.

6. If there are several consecutive moderately dry years with low winter refill availability, Abingdon reservoir can be progressively drawn down, leaving it nearly empty at the start of a typical 18-month drought. In these circumstances, the yield from Abingdon reservoir could be reduced to almost zero. There would be catastrophic failure of London's supplies if the yield had been expected to be Thames Water's planned 285 Ml/d:



Example of 3 consecutive moderately dry years preceding a single-year drought – Abingdon reservoir yield reduced to just 21 Ml/d

7. If summer-winter-summer droughts similar to the major 20th Century droughts last longer than 18 months, say 21 months, the yield of Abingdon reservoir can drop to below 200 Ml/d. We expect such events to occur a lot more frequently than once in 1000 years, as suggested by Thames Water.

8. If summer-winter-summer droughts like the 20th Century droughts are followed by another dry winter, there would be supply restrictions lasting through the second winter and into the third summer. Even though a 285 Ml/d yield from Abingdon reservoir might be maintained, the extent of supply restrictions seems unlikely to be acceptable to householders, businesses and other water companies dependent on supplies from Thames Water. This can be expected to occur, perhaps, once a century.

9. Some droughts in Atkins' records would result in Abingdon reservoir being drawn down for several years before refilling – for 8 years in at least one case. In these circumstances, there could be prolonged supply restrictions and persistent poor water quality in the near-empty Abingdon reservoir. This risk has not been identified or addressed by Thames Water.

10. The majority of Thames Water's "random selection" of 30 droughts for their resilience analysis, said to be "at, or worse than, the severity of the of the critical 20th Century droughts", were actually <u>less</u> severe than the 20th Century droughts, in terms of probable yield from Abingdon reservoir. Consequently, Thames Water have not considered some of the different types of long duration droughts identified in this report, in which the yield of Abingdon reservoir would be much less than their expected value of 287 Ml/d.

Thames Water's assessment of the resilience of Abingdon reservoir in severe droughts has not adequately addressed the likelihood or consequences of droughts longer than those of the 20th Century. This now needs to be done as a matter of urgency in time for the draft WRMP due in December 2017. The work should include proper assessment of the various types of long duration droughts we have identified in this report. Thames Water's work should be undertaken transparently, informing customers and stakeholders about the risks of long duration droughts.

1. Introduction

1.1 Background

Recent Government guidelines are encouraging water companies to increase the resilience of their water supplies to severe droughts and climate change[1,2].The essence of Defra's guidance is that water companies should "understand the future risks of drought when setting their level of service" and should "have regard to the impacts of restrictions on businesses and households when deciding on their planned level of service".

In GARD's response to Thames Water's Fine Screening Report of October 2016[3], we presented some simple analysis of the resilience of Abingdon reservoir to droughts that were more severe than those that occurred in the 20th Century. We concluded that:

- Abingdon reservoir yield would be resilient to droughts that are more intense than the droughts of the 20th Century, ie lower rainfall and river flows
- Abingdon reservoir yield would not be resilient to droughts of longer duration than those that occurred in the 20th Century

In particular, we concluded:

> *If the 150 Mm^3 Upper Thames reservoir is designed only to cope with the historic two-season droughts, as assumed in Thames Water's estimate of its 291 Ml/d deployable output, by the end of the second summer it would be empty and the London reservoirs would have dropped to the brink of the emergency level. If another winter/summer drought then follows, the London reservoirs would empty completely in the next summer. There would be catastrophic failure of London's supplies.*

Thames Water's published response to our concerns[4], based on their analysis of stochastically generated droughts, concluded that *"the reservoir can be considered to be resilient in terms of water resources planning, down to an extremely low frequency of return period."* This conclusion was reached without any discussion with GARD to understand the basis of our concerns. It did not distinguish between long duration droughts and high intensity droughts.

This report reviews Thames Water's resilience assessment and presents some analysis to restate our conclusion that Abingdon reservoir is not resilient to droughts longer than the 20th Century droughts.

1.2 Thames Water's assessment of drought resilience

Thames Water's methodology

Thames Water have assessed the resilience of the Abingdon reservoir to stochastically generated droughts as described in Atkins' report for Thames Water[5].

[1] Department of Environment Food & Agriculture, Enabling Resilience in the Water Sector, March 2016
[2] Environment Agency, Water Supply and Resilience and Infrastructure, October 2015
[3] GARD response to Thames Water's Fine Screening Report on WRMP19 Options, October 2016, pages 31-36.
[4] https://corporate.thameswater.co.uk/-/media/Site-Content/Corporate/Media/Thames-Water-Reports-Page/Summary-of-stakeholder-comments-on-resource-options-January-2017.pdf
[5] WRMP19 Stochastic Water Resources: Stage 4 Options Appraisal, Appendix Document for the Upper Thames Reservoir Development, 25 January 2017.

Atkins used stochastic methods to generate 200 separate time series of river flows, each time series comprising 78 years of daily river flows. Atkins termed these time series Run_0, Run_1, etc,....Run_199. In total, this amounted to 15,600 years of daily river flow records, all intended to have the same hydrological characteristics as the 78-year records of historic river flows from 1920 to 1997. The methodology for generating the river flow time series was described in Atkins' initial report on their stochastic modelling in December 2016[6].

Thames Water's WARMS2 simulation model of the London supply system runs too slowly to be used to simulate the full 15,600 years of flow records. Instead, Thames Water randomly selected 30 droughts out of the full record, each comprising 8 years of daily flows. The selected droughts were said to be of return periods in the range 1 in 100 years to 1 in 1000 years. The 30 selected droughts were chosen to be "at, or worse than, the severity of the of the critical 20th Century droughts", ie the droughts of 1921/22, 1933/34, 1943/44 and 1975/76.The selected droughts covered 1/6th of the events within this probability range available from the full 15,600 year data set. There was no attempt to focus on the long duration droughts that GARD has identified as a major threat to the resilience of London's supplies.

The methodology for testing the resilience of the Abingdon reservoir to the 30 selected droughts was:

- Use Thames Water's "WARMS2" simulation model to determine the water supply yield that could be sustained by existing London supplies, giving a 'baseline' yield
- Use WARMS2 to determine the additional yield that could be maintained with support from the Abingdon reservoir
- Compare the additional yield available from the Abingdon reservoir in each of the 30 selected droughts with the 287 Ml/d yield gain that can be provided in the historic 20th Century flow record.

Even the restricted selection of 30 droughts contained too much data to be modelled properly by WARMS2, so Thames Water only simulated demands of 287, 242, 230, 220 and 95 Ml/d and determined the yield of Abingdon reservoir by interpolation.

<u>Thames Water's conclusions</u>

Thames Water concluded that:

1. For droughts of similar duration to the worst 20th Century droughts, ie up to the 17-month duration of the 1933/34 drought, the yield of the Abingdon reservoir is retained at about 287 Ml/d. In other words, the Abingdon reservoir is fully resilient for droughts of up to 17 months duration, even for 17-month droughts up to 1 in 1000 year return period in terms of intensity, ie much lower rainfall and river flows than the 20th Century droughts.

2. Three of the 30 droughts analysed were of longer duration than the 20th Century droughts which significantly reduced the yield of the Abingdon reservoir, in one case reducing the yield from 287 Ml/d to 95 Ml/d. However, the probability of longer duration droughts, which

[6] Thames Water Stochastic Resource Modelling Stage 2 & 3 Report. 16 December 2016.

would significantly reduce the yield of the Abingdon reservoir, was crudely assessed as less than once every 1000 years.

3. The average expected yield of the Abingdon reservoir, as measured from the 30 droughts that were tested, was 282 Ml/d, only slightly less than the 287 Ml/d yield assessed using the historic river flow records, 1920 to 2011.

From this Thames Water concluded that the Abingdon reservoir would be resilient against severe droughts down to an extremely low frequency return period. Using this conclusion, Thames Water upgraded the resilience of the Abingdon reservoir to having "material benefit" in their April 2017 Fine Screening Report, as compared to having "material disbenefit/risk" in the October 2016 FSR.

GARD's view of Thames Water's resilience assessment

We do not agree Thames Water's assessment that the resilience of the Abingdon reservoir against severe droughts provides a "material benefit". We think their analysis has six major flaws.

1. Having correctly identified that the yield of the Abingdon reservoir is drastically reduced in some long duration droughts, the analysis doesn't properly assess the likelihood of such events, describing them as "extremely unlikely" on the basis of a crude calculation using a small sample of droughts "randomly selected" through a flawed process (see paragraph 5 below).

2. It doesn't consider the consequences of longer duration droughts on the reliability of supplies or on the level of service to customers (for example the duration of supply restrictions to customers).

3. It doesn't consider what likelihood of supply failure is acceptable, taking account of the consequences of emergency supply restrictions and their duration.

4. It doesn't consider the operating rules that would be needed for the combined Abingdon reservoir and London supply system, for example the reservoir control curves and associated frequency of demand restrictions, taking account of the possibility of Abingdon reservoir being near-empty for extended periods.

5. 18 of the 30 droughts "randomly selected" by Thames Water for their analysis, with "return periods in the range 1 in 100 years to 1 in 1000 years" and said to be "at, or worse than, the severity of the of the critical 20th Century droughts", were actually less severe than the 20th Century droughts, in terms of probable yield from Abingdon reservoir. Tables 3-1 to 3-3 of Atkins' report[5] show 18 of the 30 droughts gave yields in excess of the 287 Ml/d yield assessed by Thames Water using the 20th Century flow records. The flaw lies in the "random selection" being based on the "yield severity response of the London reservoir system without the UTR" (Atkins report[5], unnumbered page 3). It is apparent from the modelling described in Section 2 of this report that droughts which are only moderately severe for the existing London reservoir system can become extremely severe for the yield of Abingdon reservoir, for example the long duration droughts shown on Figure 8.

6. Aside from the majority of the 30 selected droughts being less severe than the droughts of the 20th Century in terms of Abingdon reservoir yield, the averaging of the yield of the 30

modelled droughts at 282 Ml/d is meaningless and misleading. It is equivalent to telling householders that their homes are secure against "average floods". It is only the extreme events that matter.

Thames Water's conclusion that the c.280 Ml/d yield of the reservoir is resilient to droughts of similar duration to the droughts of the 20th Century, ie less than 18 months duration, did not require stochastic modelling. A simple calculation shows that a reservoir of net capacity 141,000 Ml will sustain a yield of 282 Ml/d over a 500 day drought, even with zero refill during the drought (141,000 Ml ÷ 500days = 282 Ml/d). This conclusion holds regardless of the intensity of the drought – the yield will always be at least 282 Ml/d**, but only if the drought lasts no more than about 500 days**.

Similarly, if a drought lasts more than 500 days, it is inevitable that the reservoir yield will be less than 282 Ml/d, unless significant refill of the reservoir is possible during the drought. Therefore, the focus of Thames Water's stochastic analysis should have been on the likelihood of droughts lasting longer than 500 days and the volume of water available to refill the reservoir during droughts, particularly in the winters between summer droughts. Unfortunately, having correctly identified poor resilience of the Abingdon reservoir in long duration droughts, Thames Water have not properly investigated either the likelihood or the consequences of such droughts.

It should be noted that the net storage capacity of the Abingdon reservoir is only as high as 141,000 Ml if one accepts Thames Water's unusually low value for its proposed emergency storage (6% or 9000 Ml). If the more usual emergency storage of 25% is used (as in Thames Water's other storage reservoirs), then the available capacity of the UTR would drop to 112,500 Ml, and the 282 Ml/d yield could only be maintained for droughts lasting 400 days or less. We shall return to this point below.

Overall, we are concerned that Thames Water have not emphasised in their reporting or statements to stakeholders that there is often insufficient winter river flow to allow the Abingdon reservoir to refill by the start of the following summer. The lack of resilience of the Abingdon reservoir to droughts <u>longer</u> than those that occurred in the 20th Century has not been made clear.

1.3 GARD's approach to reviewing Thames Water's assessment

GARD has used its model to simulate the operation of Thames Water's supplies, using Atkins' stochastically generated 15,600 years records of river flows, with the objectives of:

- Understanding how the Abingdon reservoir would behave in droughts that are longer than the droughts in the 20th Century record.
- Testing Thames Water's conclusion that the reservoir is resilient against all types and severity of drought that might reasonably be planned for.

Before simulating Atkins' river flow data in GARD's model, we have analysed summer and winter water availability in Atkins' 15,600 year river flow records to identify which of the 200 "Runs", each with 78 years of daily flows, are likely to contain droughts longer than those that occurred in the 20th Century. We have then modelled 27 of the 200 "Runs" containing the longer duration droughts for which we have determined:

- The baseline yield of existing London's supplies in the droughts
- The extra yield obtainable for London's supplies, if supported by the Abingdon reservoir
- The pattern of drawdown of the Abingdon and London reservoirs during the drought

For some of the longer duration droughts, we have also modelled the effect on London's water supplies if an additional 287 Ml/d of supply, ie Thames Water's estimate of yield from the Abingdon reservoir, continues through the drought. This has allowed a view of the consequences of the supply failures that are unavoidable with some droughts of longer duration than the 20th Century droughts, if the expected yield is Thames Water's assumed value of 287 Ml/d.

In addition to modelling the 27 selected longer-duration droughts, we have modelled 1560 years of randomly selected stochastic data (ie 1/10th of Atkins' data) to determine the probability of Abingdon reservoir being full at the start of each summer.

A description of the main features of GARD's model are given in Appendix A. Thames Water have not provided GARD with requested details of their proposed operating rules for Abingdon reservoir or samples of WARMS2 output including Abingdon reservoir. Therefore we have had to make some assumptions for operating rules for Abingdon reservoir:

- Regulation release triggered when Teddington flows have been less than 3000 Ml/d for 10 days and London reservoir storage has been in Teddington Target Flow band 2 for 10 days (the same as Thames Water's proposed rule for triggering the Severn-Thames transfer)
- Regulation release of 300 Ml/d
- 2% transmission loss between Culham and Teddington
- No change to the existing Lower Thames Control Diagram or to Service Levels
- Emergency Abingdon storage level of 9 Mm^3 (6% of gross storage), as compared to an industry norm of about 20-25% of gross storage. We have used Thames Water's figure, although we consider this too low on grounds of risk and water quality.

The resilience of the Abingdon reservoir to a range of stochastically generated droughts is described in Section 2, focusing on droughts of longer duration than those that occurred in the 20th Century.

2. Resilience to stochastic droughts of different durations

2.1 Vulnerability of London's supplies to long droughts

The fundamental weakness of London's water supplies is over-dependence on reservoirs filled by pumping from the River Thames. Already, there is about 150 Mm^3 of usable storage (200 Mm^3 gross storage) in the Lower Thames reservoirs and, in events like the major droughts of the 20th Century, there would be insufficient water to refill the existing reservoirs over-winter. With increasing future demands, it will become more difficult to refill the London reservoirs, unless there is "new water" in the system, as would be provided by schemes like the Severn-Thames transfer, desalination or effluent reuse.

Thames Water's proposed Abingdon reservoir would add another 141 Mm^3 of usable storage, almost doubling the storage to be filled by pumping from the River Thames. **The scheme would provide no "new water" for filling the reservoirs.** In consequence, the reservoirs would often be significantly depleted at the start of summer droughts, making the supply system vulnerable to droughts of more than one year duration and especially vulnerable to multi-year droughts.

In Section 2 of this report, we have considered various types of longer duration droughts that could threaten the ability of Abingdon reservoir to provide its planned yield or to maintain Thames Water's expected level of service.

2.2 Droughts of two summers and the intervening winter

Figure 1 shows an example of a very severe drought of about 16 months duration – slightly shorter duration than the worst droughts in the 20th Century, but much more intense:

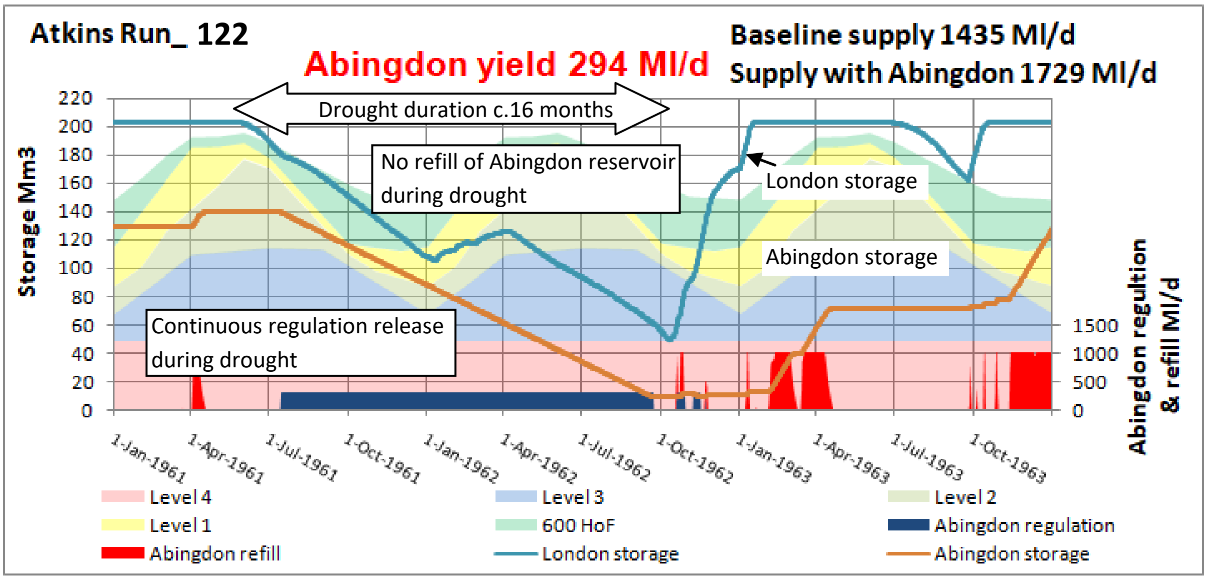


Figure 1 - Example of very severe drought of less than 18 months duration

> **Note:** for all the plots in this report, the calendar dates shown are the same as the dates in Atkins' stochastic data – each Atkins "Run" of 78 years has nominal dates of 1920-1997.

Without the Abingdon reservoir, the yield of existing London supplies is only 1460 Ml/d, a drop of about 850 Ml/d from the present deployable output of 2305 Ml/d, showing this drought is much more intense than the 20th Century droughts. However, because the drought only lasts for about 16 months, the Abingdon reservoir provides a yield increase of 294 Ml/d, even though there would be no refill of Abingdon reservoir during the drought and continuous regulation releases throughout.

The 16-month drought shown in Figure 1 provides a good illustration of the fact that the c.280 Ml/d yield of the Abingdon reservoir will always be fully resilient to droughts that last less than about 17 months, regardless of the drought intensity. We have found similar results for other droughts that are more intense than the 20th Century droughts, but not of longer duration. We conclude that the Abingdon reservoir would be fully resilient to summer-winter-summer droughts of extreme intensity but less than 18 months duration (but only if all the storage in the reservoir is fully usable down to the low value of 6% emergency storage proposed by Thames Water).

Figure 2 shows a drought of about 19 months duration, starting in late March of the first year and ending in late October of the second year.

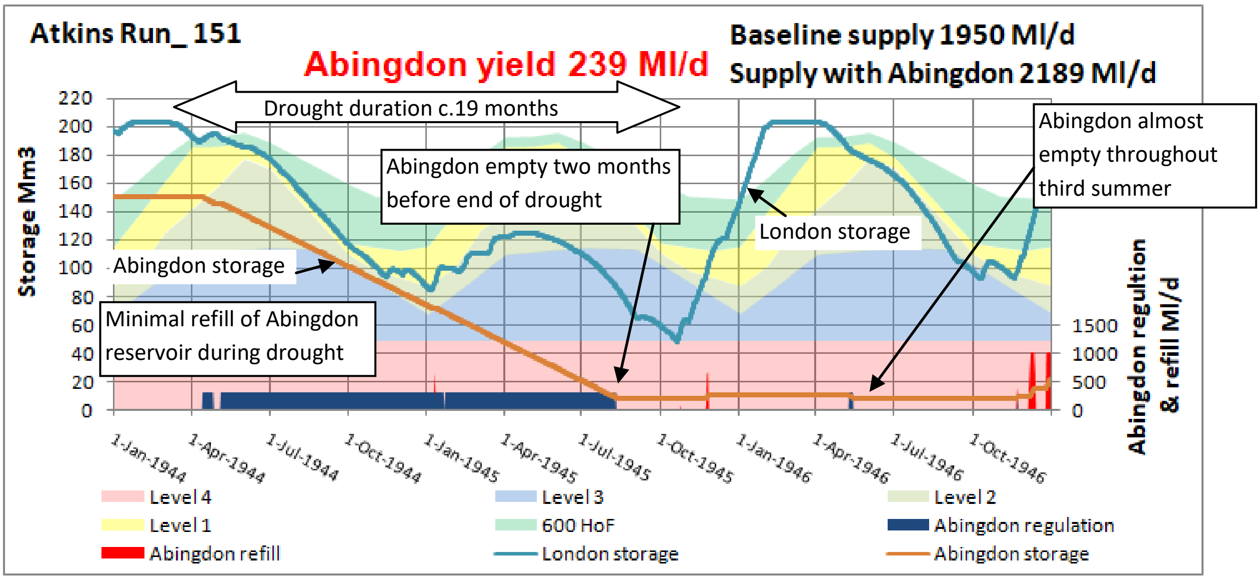


Figure 2 - Example of 19-month drought of moderate intensity

In this drought, the yield of existing London supplies is 1950 Ml/d, about 350 Ml/d less than the present deployable output of existing London supplies – a less intense drought than that shown in Figure 1, but more intense than the 20th Century droughts. The yield gain from Abingdon reservoir is only 239 Ml/d. Although this drought has a much smaller impact on existing London supplies than the drought shown in Figure 1 (baseline yield 1950 Ml/d v 1425 Ml/d), the yield gain from Abingdon reservoir is less because the drought duration is longer – Abingdon reservoir is empty and regulation stops in mid-August, two months before the drought ends. However, the next winter is also quite dry with poor groundwater recovery in the upper Thames catchment, so Abingdon remains almost empty throughout the third year, similar to the extended droughts discussed in Section 2.3.

Figure 3 shows a drought of about 21 months duration, starting in February of the first year and ending in late October of the second year. The intensity of the drought is similar to the droughts of the 20th Century, but the duration is about 4 months longer than the 1933/34 drought, starting in February of the first year (draw-down of the London reservoirs in a drought like 1933/34 drought would start in June 1933):

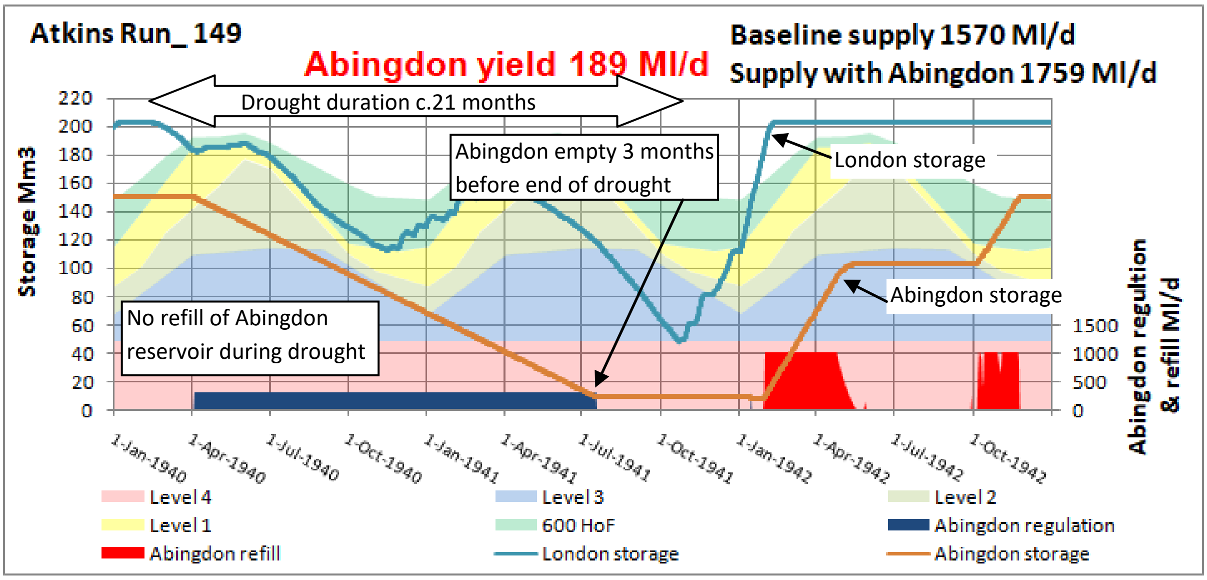


Figure 3 - Example of drought of 21 month duration

In this drought, the yield of from Abingdon reservoir is only 189 Ml/d, about 35% less than the yield in the 20th Century droughts because the drought lasts about 4 months longer. Abingdon reservoir is empty and regulation stops in late June of the second year, more than 3 months before the drought ends in October.

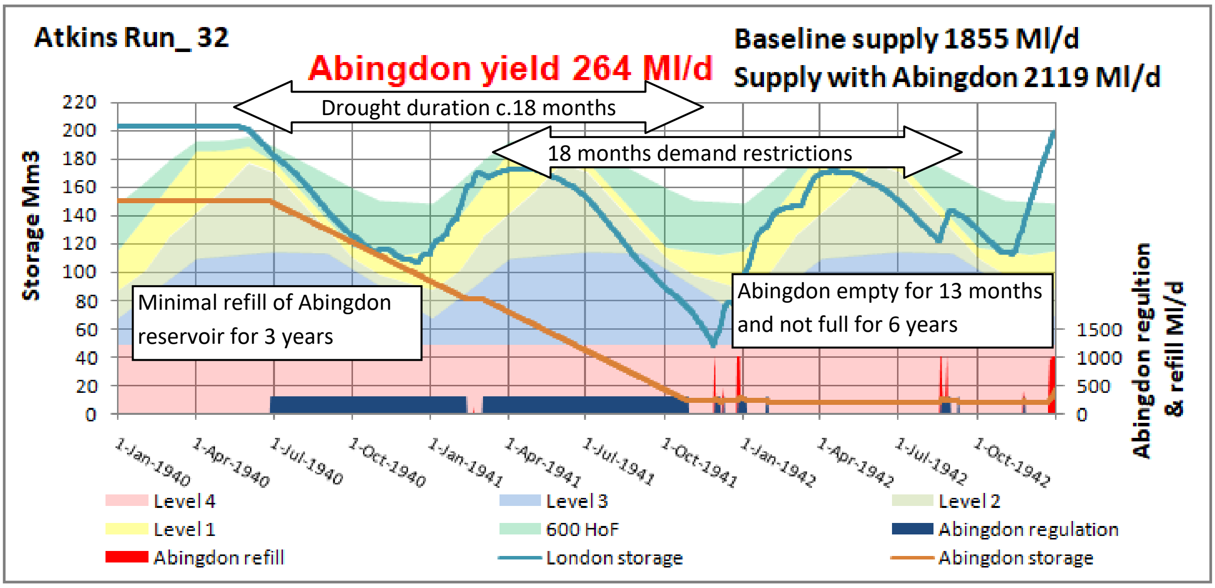
In the 20th Century, there were 4 significant droughts of less than 2 years duration, but all were of less than 18 months duration, and would thereby allow Abingdon reservoir to provide a yield of around 280 Ml/d. In Atkins' 15,600 years of stochastic records, there are numerous examples of summer-winter-summer droughts of less than 2 years duration, perhaps of the order of 300-400 such droughts, if there are about 2 or 3 per 100 years, as per the 20th Century. Our searches of the Atkins' record have shown that a significant proportion of these droughts last longer than 18 months and, therefore, would reduce the yield available from Abingdon reservoir.

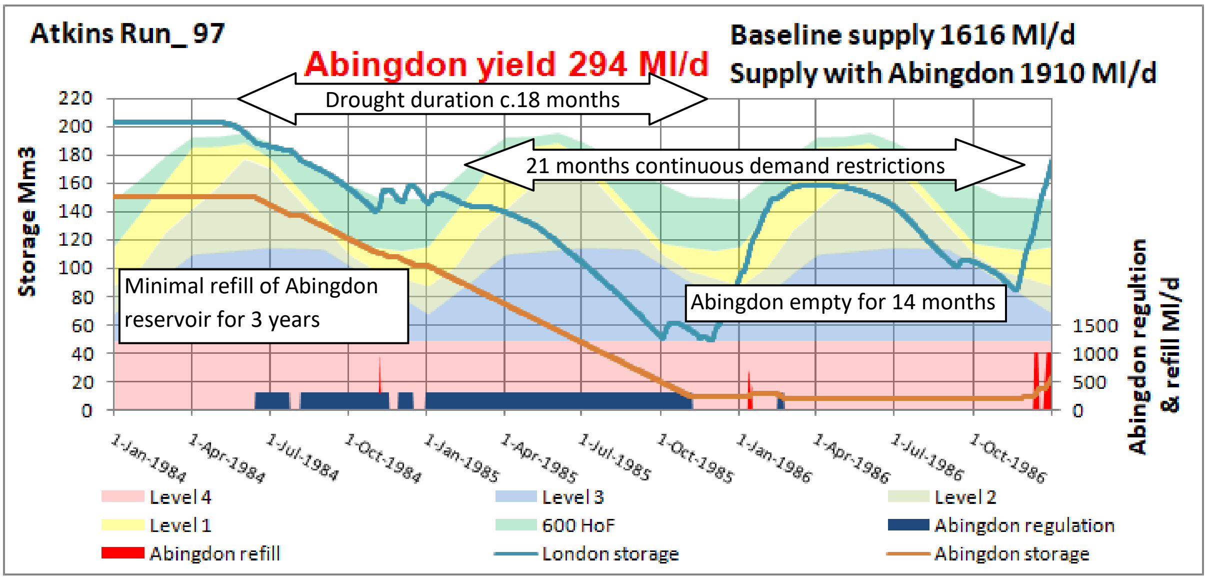
2.3 Two-summer droughts followed by a dry year

When summer-winter-summer droughts, typically of 18-months duration, are followed by a moderately dry winter, the Abingdon reservoir can remain largely empty throughout the next year. Therefore, without regulation releases from Abingdon, the London reservoir storage spends much of the next year in the demand restriction zones. Three examples are shown on Figure 4 overleaf.

Although for each drought the London storage starts to recover in the second autumn, Abingdon remains empty until late in the third year. For the two upper droughts on Figure 4, at the start of the third summer the London reservoirs would be in the Level 1 zone with Abingdon still empty. For the lower drought on Figure 4, the situation would be even worse with London storage still in the Level 3 restriction zone at the start of the third summer.

In our opinion, for all three cases London's supplies would need to be in a state of emergency throughout the third year, because Abingdon reservoir is empty, even though the Level 4 emergency supply zone in the London reservoirs is not reached.





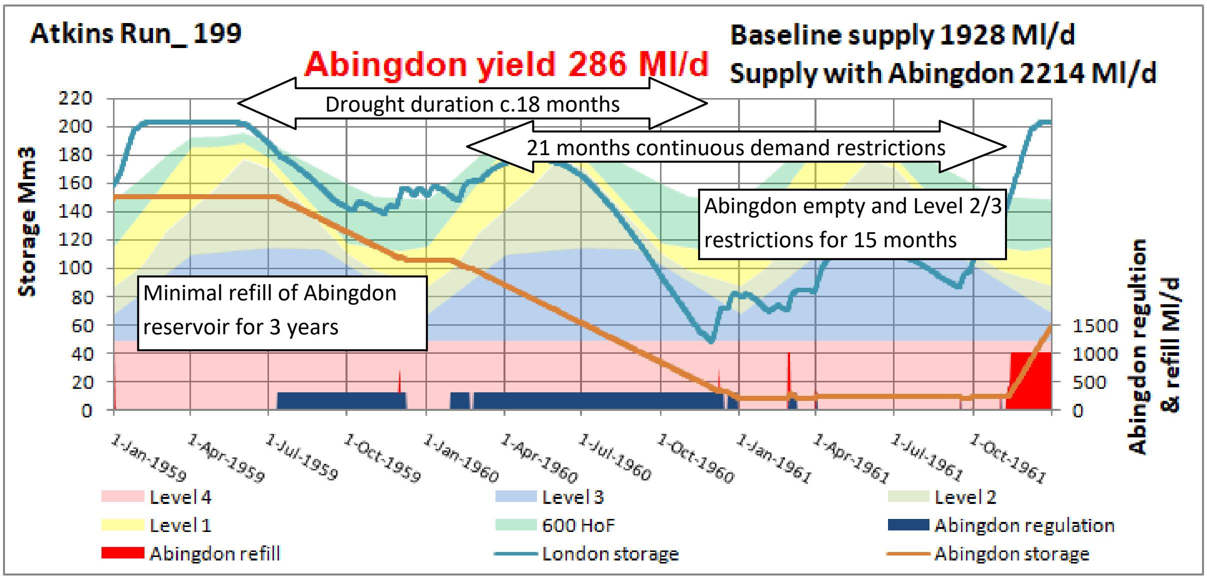


Figure 4 - Examples of 18-month droughts followed by moderately dry years

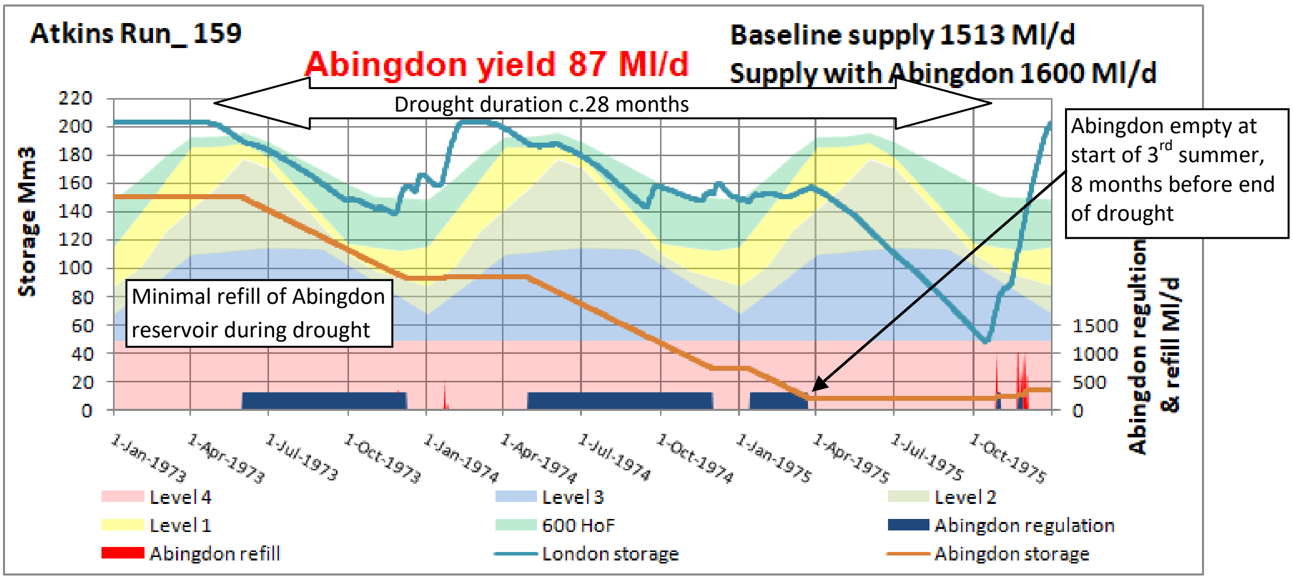
Section 2.4 below describes the disastrous consequences of a third dry year following an 18-month drought, with Abingdon reservoir being empty at the start of the third summer. Arguably, even the threat of the threat of the third year turning into another drought would be so great that drastic supply restrictions would be needed.

For all three of these droughts, Thames Water's simplistic analysis would have shown the yield of Abingdon reservoir to be around their planned figure of about 280 Ml/d, so the Abingdon reservoir would have been deemed "resilient". There has apparently been no consideration of the levels of service provided by the London supply system in the year following an 18-month drought. Droughts of the type shown in Figure 4 are a relatively common occurrence in Atkins' stochastic records. The year following the 18-month drought only needs to be moderately dry for this to happen. In particular, this type of situation will always occur if the winter following the drought is moderately dry. In Section 3.2 of this report we will show that winter refill of Abingdon reservoir would be restricted to less than 50% in about one year in five.

2.4 Droughts of three summers and two winters

If a typical 18-month drought is preceded by a fairly dry summer-winter, Abingdon reservoir may be half empty at the start of the 18-month drought. In that case, Abingdon reservoir will be totally empty throughout the third summer and the yield is drastically reduced. We have found two examples in the 27 Atkins "Runs" we have modelled (ie about 1/8th of Atkins' data), as shown in Figure 5 on the next page.

Although these three-summer-two winter droughts will be quite rare, we suspect that there are more in Atkins' stochastic records. For example, Drought 1 in Drought Library C of Thames Water's report gives a yield of only 95 Ml/d, and we think this is a different drought to those shown in Figure 5 (from inspection of plots, there seem to be different draw-down patterns).



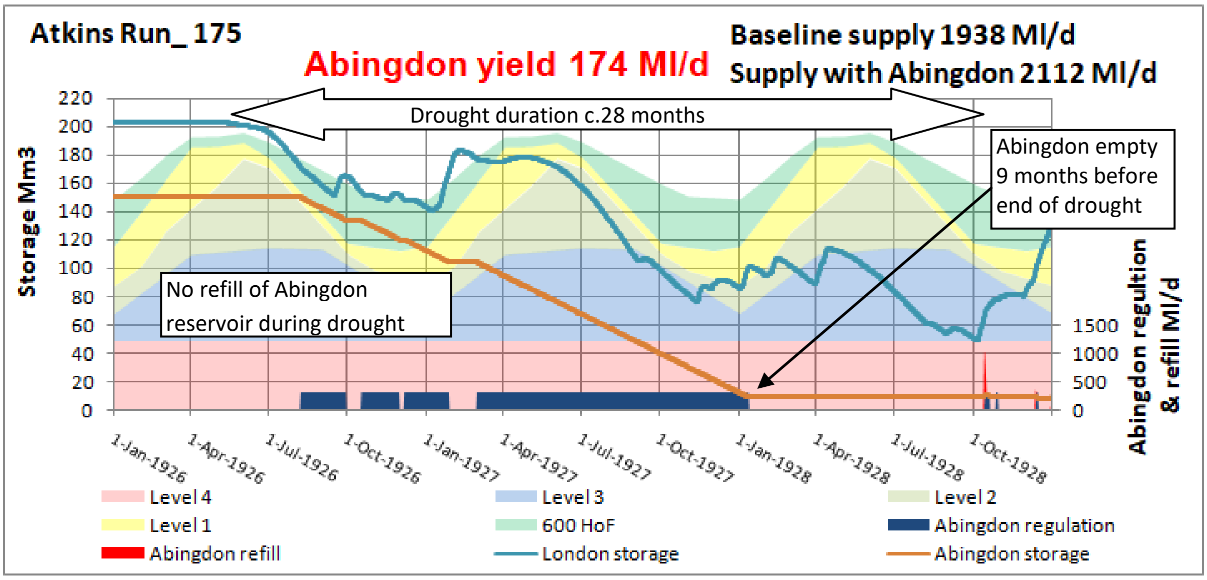


Figure 5 - Examples of c.30-month droughts with drastically reduced Abingdon yield

However rare these 30-month droughts may be, their acceptability as a risk needs to be viewed in the context of their impact on London's supplies if they occur without planning for them. We have explored this in the following section.

2.5 Consequences of not planning for 30-month droughts

If the c.30-month droughts shown in Figure 5 were to occur whilst still expecting the Abingdon reservoir to yield about 285 Ml/d, as proposed by Thames Water, the effect on supplies would be as shown on Figure 6:

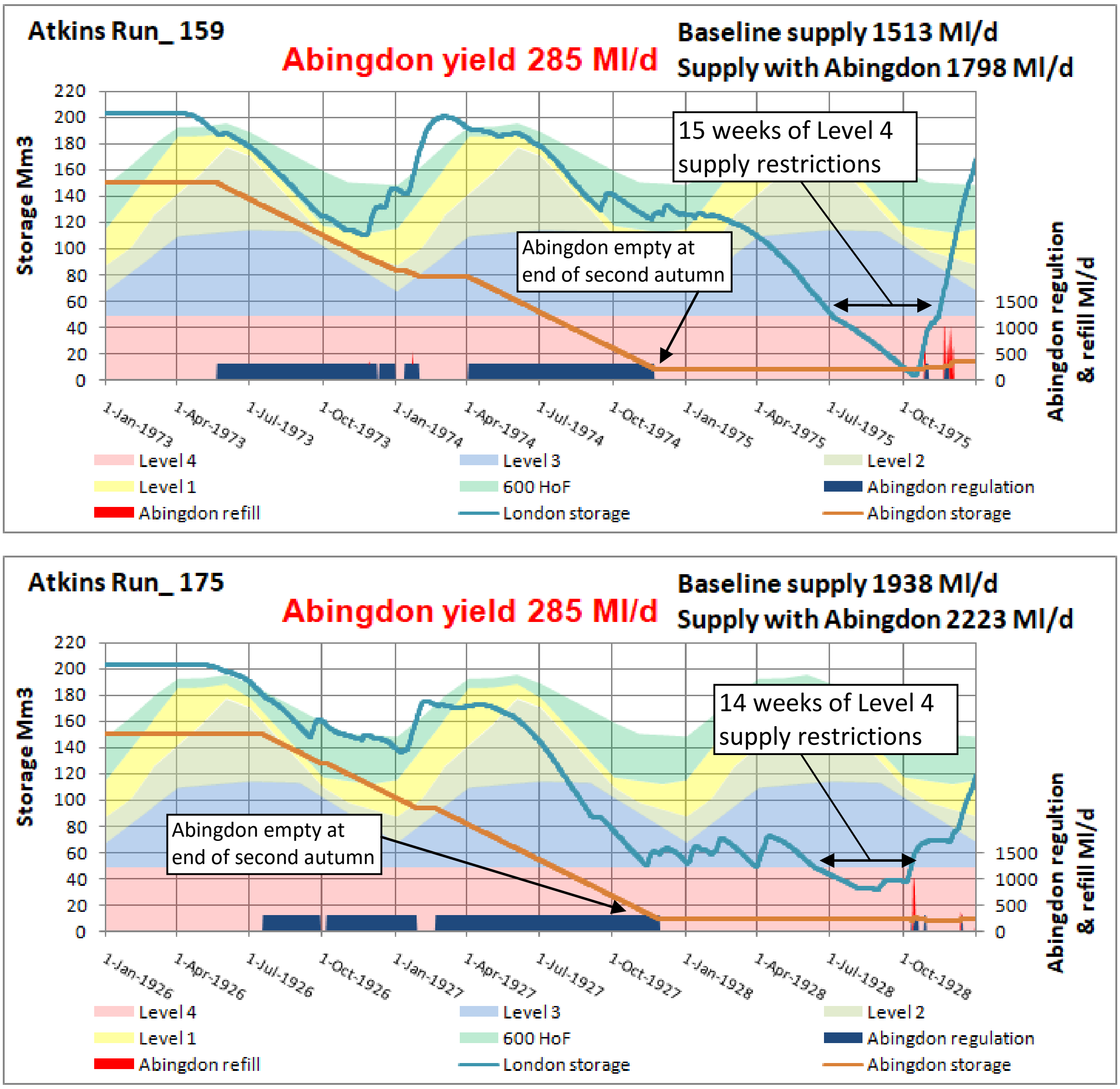
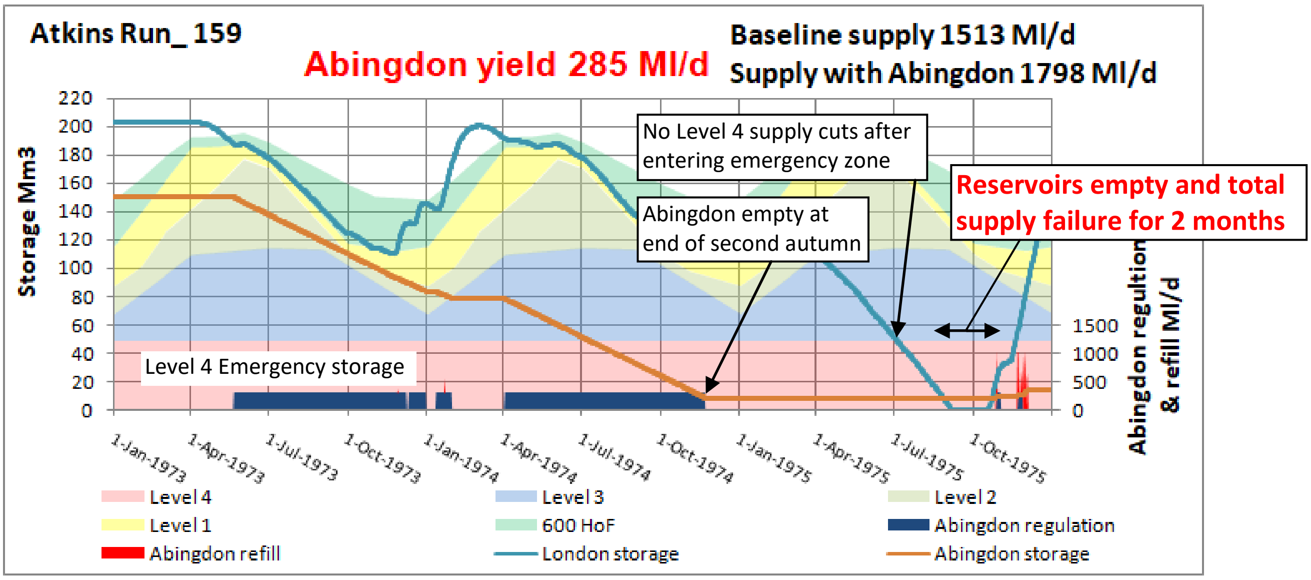


Figure 6 - Consequence of not planning for 30-month droughts with Abingdon yield 285 Ml/d

If the 285 Ml/d of yield from Abingdon reservoir is needed to meet demands, there would be about 3-4 months of Level 4 supply restrictions in London lasting through the peak tourism season and into the autumn. The Level 4 supply restrictions will include rota cuts to supplies. In our opinion, this would have a disastrous economic impact on tourism and City of London business confidence. The Environment Agency's 2015 report on water resilience describes the potential impact of Level 4 restrictions[2]:

> *The consequence of emergency water restrictions has the potential for severe economic, societal, reputational and environmental impacts – particularly in large conurbations. One study estimated the monthly cost for London alone at £7 – 10 billion. Although the evidence is not well developed it is possible that the societal impacts of such restrictions could include break-down of social cohesion and serious impacts on public health.*

Under these circumstances, if, with inevitable political and customer pressure, the decision was made <u>not</u> to enforce Level 4 supply restrictions, relying instead on the emergency storage, the London reservoirs would empty within about two months and there would then be total supply failure for several months as illustrated in the examples below:



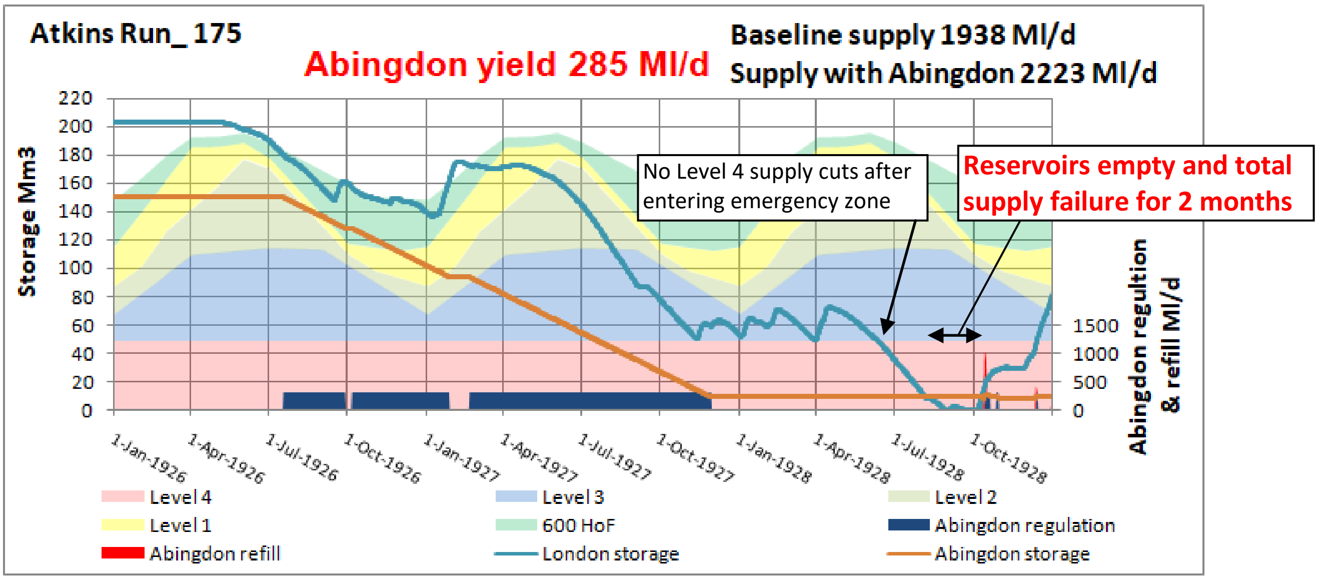


Figure 7 - Examples of total supply failure in 30-month drought if Abingdon yield is kept at 285 Ml/d without Level 4 supply restrictions

In our opinion, the consequences of occurrence of a 30-month drought while requiring a 285 Ml/d yield from Abingdon reservoir are so severe that the risk is unacceptable, whatever the theoretical probability. The approach to planning for such events should be equivalent to planning to avoid dam bursts through over-topping by floods – for this the concept of the "probable maximum flood" is used in the UK, roughly equivalent to a 1 in 10,000 year event. A similar approach should be adopted to avoid the type of supply failures illustrated in Figures 6 and 7.

2.6 Multi-year droughts

In modelling some of Atkins' stochastic drought "Runs", we have found a number of drought sequences that cause multiple years of draw-down of Abingdon reservoir. Some examples are shown on Figure 8:

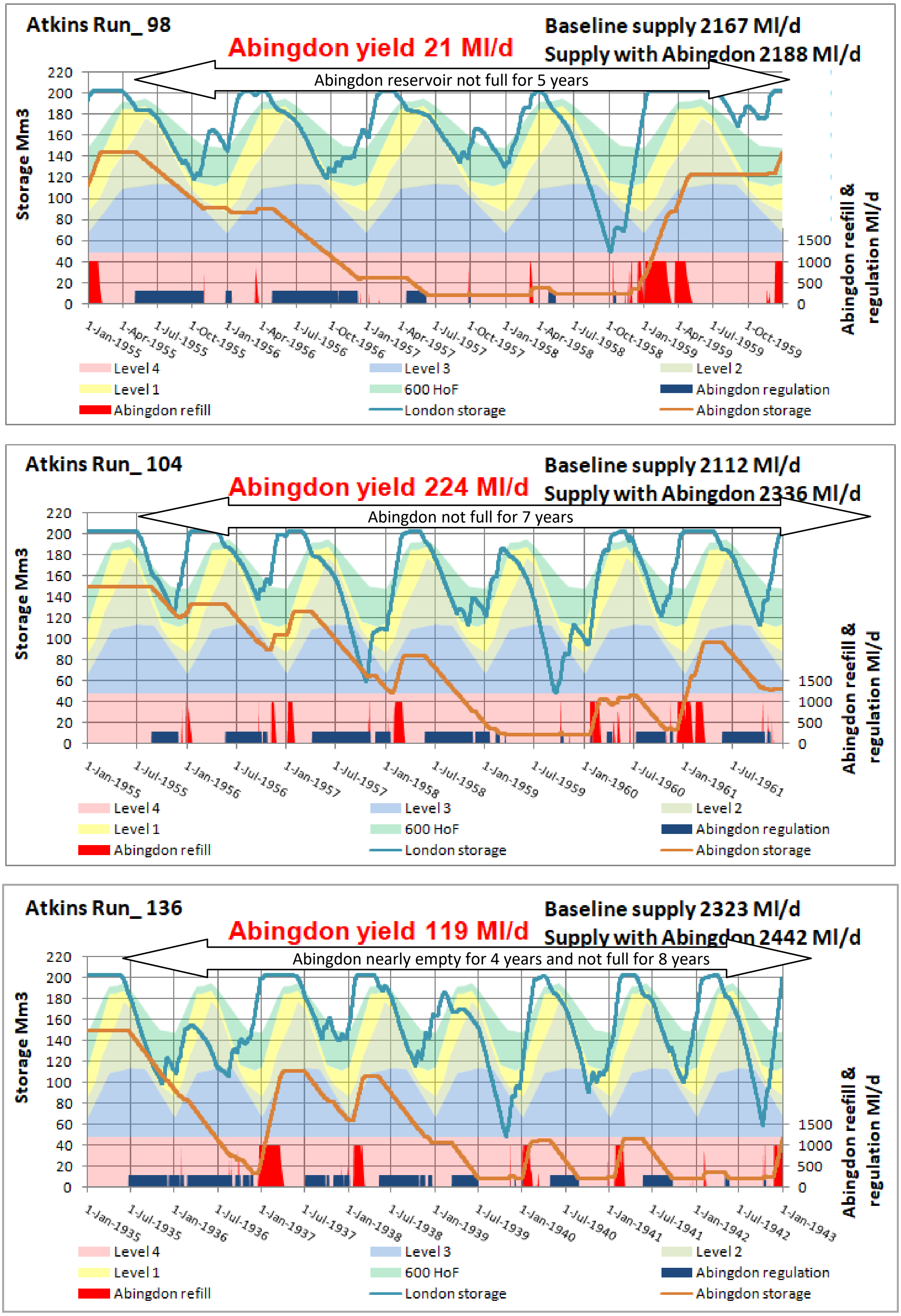


Figure 8 - Examples of multiple dry years causing continuous Abingdon draw-down

Thames Water do not have appear to have considered the effect of sequences of moderately dry years in their resilience analysis, or the extended supply restrictions that would be needed.

In the upper example in Figure 8, the intense single year drought in 1958 follows 4 moderately dry years in which Abingdon reservoir is progressively depleted, leaving it almost empty at the start of the severe drought, sustaining a yield of only 21 Ml/d. If Abingdon reservoir is expected to yield 285 Ml/d, there would be catastrophic failure of London's supplies, similar to the failures described in Section 2.4 above. Abingdon reservoir would not be full for 5 continuous years.

In the middle example in Figure 8, the sequence of dry years precedes an 18-month drought, causing Abingdon reservoir to be substantially drawn down at the start of the drought. Consequently, the yield from Abingdon reservoir is reduced to 224 Ml/d. This is then followed by two more dry years, with Abingdon reservoir near-empty, leaving London's supplies vulnerable to the threat of another drought and probably necessitating several continuous years of supply restrictions. Abingdon reservoir would not be full for 7 continuous years.

In the lower plot on Figure 8, the sequence of three moderately dry years leaves Abingdon reservoir half empty at the start of a typical 18 month drought, reducing the Abingdon reservoir yield to only 119 Ml/d. If the yield is expected to be 285 Ml/d, there would be catastrophic failure of London's supplies. Even if the yield is only expected to be 119 Ml/d, in the following three years, Abingdon storage would never get above 40%, leaving London's supplies at severe risk to the occurrence of another drought. Abingdon reservoir would not be full for 8 continuous years.

For this type of event – several moderately dry years preceding a major drought – it may be possible to conserve water in Abingdon reservoir by prioritising use of the storage in the London reservoirs and delaying regulation releases from Abingdon, thereby making more Abingdon storage available at the start of a major drought. Possibly, this could be achieved by triggering the regulation releases only when London storage drops below a reservoir control line. However, this would also carry a danger of the Abingdon reservoir not being fully used if a "moderately dry" year turns out to be the first year of an 18-month drought. As far as we are aware, this type of operating rule has not been explored by Thames Water.

2.7 Droughts with climate change

All the analysis in this report has used Atkins' stochastic flow data without climate change. We have not considered the risk of climate change resulting in drier winters which would cause more severe conditions for the London supply system supported by Abingdon reservoir.

It is generally expected that climate change will cause wetter winters, as evidenced by an apparent increase in flooding in recent years. However, consideration should also be given to the possibility of more variable winters, with wet winters becoming wetter and dry winters becoming drier.

3 The risk of long duration droughts

3.1 The need for risk assessment for long duration droughts

In Section 2, we have shown that Atkins' stochastically generated flow data contain many droughts of longer duration than 18 months in which the yield provided by Abingdon reservoir would be a lot less than Thames Water's assumed "resilient" yield c.280 Ml/d. We have also shown that many 18-month droughts in which Abingdon reservoir can sustain a yield of c.280 Ml/d are followed by dry years necessitating long periods of supply restrictions which would give an unacceptable level of service to customers.

Thames Water have dismissed the risk of such droughts as extremely unlikely without undertaking any proper analysis of either the probability or the consequences of these long duration droughts. The "random selection" of 30 droughts for Thames Water's report[5] was made from droughts that were thought to have a probability of between 1 in 100 years and 1 in 1000 years for existing London supplies. When the amount of storage in the system is doubled by the addition of Abingdon reservoir, the probability of supply failure is much changed, with increased influence of dry winters and multiple moderately dry years.

This explains the apparent anomaly in Thames Water's analysis that shows the Abingdon reservoir yield in 18 of the 30 randomly selected droughts as being higher than the 287 Ml/d yield for 20th Century droughts, despite the randomly selected droughts being supposedly more severe than 20th Century droughts, having a probability of between 1 in 100 years and 1 in 1000 years for existing London supplies.

In our opinion, a full risk assessment is needed looking at both the probability and consequences of events that are severe with Abingdon reservoir in place. The assessment should examine the full 15,600 year record, not just the "randomly selected" droughts chosen by Thames Water – this misses longer duration droughts that are formed by combinations of consecutive single year droughts of relatively low intensity.

We have looked in detail at about 1/8th of the 15,600 years using the limited time and computing capability available to us. In our opinion, Thames Water and their consultants (and preferably also some truly independent experts) should model the full 15,600 year record, both for the existing London supplies and with the addition of Abingdon reservoir. If the WARMS2 model is too slow and cumbersome for this purpose, an alternative should be found.

3.2 The probability of dry winters

Our analysis of longer duration droughts in Section 2 has shown that dry winters are the main cause of lack of resilience of Abingdon reservoir because:

- Dry winters are usually followed by low summer river flows – River Thames flows are heavily dependent on groundwater-fed rivers (the chalkstreams and Cotswold limestone rivers) which rely on winter rainfall. The summer droughts that cause critical draw-down of the London reservoirs are always preceded by dry winters with low groundwater recharge.

- In dry winters, there is virtually no water available to refill the Abingdon reservoir, on account of the hands-off flow set at the high level of 1450 Ml/d (Q50) to protect downstream abstractors (including pumping to fill Thames Water's London reservoirs).
- In dry winters, there is a near continuous need to release regulation water from Abingdon, further reducing storage available at the start of the next summer (see Figures in Section 2).

In Figure 9 below, we have assessed the winter availability of water for filling Abingdon reservoir in the full 15,600 year stochastic record for Days Weir and compared it to winter water availability in the historic record. Our analysis looks at refill availability each winter, November to April, with a Culham hands-off flow of 1450 Ml/d and a refill pump capacity of 1000 Ml/d:

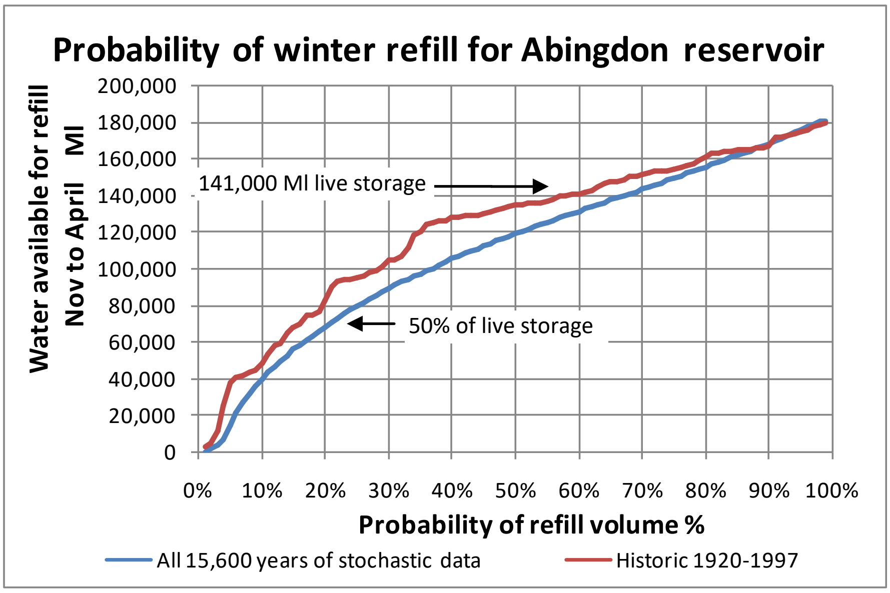


Figure 9 - Probability of winter refill of Abingdon reservoir

Figure 9 shows that, following a typical 18-month drought emptying Abingdon reservoir by the autumn, there is a 68% probability of the reservoir not being full by the start of the following summer. There is a 20% probability of the reservoir being less than half full by the start of the following summer.

Therefore, there is a fairly high likelihood of supply restrictions extending continuously through the winter and into a second summer – the type of event illustrated in the earlier Figures 4 and 8. This would not have happened with the three 18-month droughts of the 20th Century – 1933/34, 1943/44 and 1975/76 – all of which were followed by average or wet winters. However, if three 18-month droughts occur in a century, the likelihood is that at least one would be followed by a dry winter and a prolonged period of supply restrictions lasting into the next summer.

3.3 The probability of multi-year droughts

In Figure 10 below, we have shown the highest levels that Abingdon reservoir would reach in Spring in a random sample of 1,560 years of stochastic records (Atkins Run_0, Run_10, ... etc, to Run_190).

Atkins Run No	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	Historic
1920																					
1921												67%									
1922												**30%**	71%			83%					98%
1923		97%										55%									
1924		51%										66%		93%	68%						
1925		71%										56%			67%						
1926															93%						
1927				74%				60%	72%						56%						
1928				88%					52%						53%		71%				
1929																	**31%**				
1930				87%									91%				62%				
1931									74%												
1932									**42%**						86%						
1933									**7%**						66%						
1934				81%					53%						60%						67%
1935				**30%**					**17%**		96%										74%
1936									72%							86%					
1937																74%					
1938											73%										
1939																					
1940				72%		98%	82%		68%	85%											
1941								95%	82%						89%	79%					
1942	78%	95%	63%	67%					91%							**25%**					
1943	**28%**		66%										91%		95%	**44%**				96%	
1944	**27%**		66%			61%							87%								63%
1945	91%		93%			85%															
1946				92%	83%											89%					
1947				92%	95%																
1948																					
1949			51%	74%																	
1950				**21%**			98%														
1951									96%						88%				91%		
1952																		79%		81%	
1953											62%	99%						86%			
1954																		81%			
1955															72%			**42%**			
1956																		96%			
1957								69%													
1958				86%														98%			
1959				66%														65%			
1960	92%			65%									78%	61%	92%	81%		98%			
1961												65%				**31%**					
1962							76%					72%				55%					
1963							65%									90%					
1964														95%	73%						
1965															72%						
1966								90%													
1967										75%							95%				
1968				97%										53%							
1969													93%	60%							
1970					83%		69%							94%				79%		68%	
1971							**21%**											52%		74%	
1972	62%						57%										78%				
1973	72%			84%			69%			98%											
1974				93%			84%							85%							
1975		85%												78%							
1976																					92%
1977		64%												87%		69%	96%	92%			
1978		**10%**																			
1979		62%						76%				98%	84%								
1980		76%					89%														
1981		**40%**					**49%**		90%												
1982		52%			93%				79%										70%		
1983		73%								89%											
1984													83%				71%				
1985									92%		75%						74%				
1986									50%	67%	60%										
1987						79%				53%											
1988						**15%**		97%													
1989					91%	87%															
1990																					
1991		69%										58%	97%					72%			
1992		82%										91%		83%	91%			**40%**		82%	
1993														**29%**						**14%**	
1994														81%						61%	
1995																				91%	
1996															74%					69%	
1997															**7%**						78%

Notes:

1. Modelled London supply 2590 Ml/d giving Abingdon yield of 285 Ml/d over base case supply of 2305 Ml/d.
2. Storages shown are highest from January to April.
3. Only storages less than 100% are shown.
4. Less than **50%** shown red

Figure 10 - Frequency of Abingdon reservoir not filling in Spring (January to April)

As we have shown in the examples described in Section 2, the resilience of the yield of Abingdon reservoir is critically dependent on whether the reservoir is full at the start of the summer. Figure 10 shows that this is often not the case:

- 1 year in 10, Abingdon reservoir fails to reach 90% full at any time before the end of April
- 1 year in 70 , Abingdon reservoir is never more than 50% full before the end of April
- Years when the reservoir fails to fill in spring often come in clusters of several years
- When the reservoir fails to reach 50% full in spring, it has always failed to fill in the previous spring

The last two points are the consequence of the strong influence of groundwater levels on flows in the Thames at both Culham and Teddington. Groundwater levels depend almost entirely on winter rainfall – summer rain is mostly absorbed by vegetation. Therefore, dry winters affect both the winter refill of Abingdon reservoir <u>and</u> the need for regulation releases from Abingdon the following summer.

This all shows that there are complex links between winter rainfall and summer /winter river flows. There are also complex relationships between the storages in London reservoirs, river flows and the various abstraction licence conditions, linked with the Lower Thames Control Diagram. From our modelling of the behaviour of Abingdon reservoir used conjunctively with the London reservoirs, we consider it is dangerous to make simplistic calculations about the probabilities of failure of London's supplies in multi-season droughts – there is too much interdependence between the flows in each season, linked to the behaviour of storage in groundwater aquifers and Thames Water's reservoirs.

In our opinion, the conclusion in Section 4 of Thames Water's resilience report is a gross over-simplification, using a flawed "random selection" of droughts:

> *Three out of the 30 droughts that were analysed contained longer critical durations with low enough winter recharge to significantly reduce the yield of the scheme. In other words, around 10% of the sampled droughts had a critical period that was long enough to present a resilience risk to the UTR. This means that the chance of encountering a drought that is both severe enough to test the existing London system and cause a failure of resilience in the UTR is extremely small. To put this in context Thames might expect to encounter such an event less than once every thousand years (maximum probability per annum calculated as 0.1*0.01 = 0.001). This reflects the observed nature of the climate and existing water resource system in the Thames basin. Whilst there is a reasonable chance of experiencing multiple dry winters in the catchment, the chances of experiencing 2 or more very dry winters (i.e. where there is no recharge available to the UTR) back to back, without high rainfall in any of the intermediate spring, summer or autumn periods, is very small.*

In our judgment, the type of 3-year drought that would drastically reduce the yield of Abingdon reservoir to around 100 Ml/d (as earlier Figure 5) would be a rare event, perhaps as rare as once in 1000 years as suggested by Thames Water. However, as we have shown in Section 2.5, the consequences of such an event are so severe that even a 1 in 1000 year probability is a major risk for London's supplies.

We have also shown in Section 2.6 that sequences of moderately dry years can progressively lower the storage in Abingdon reservoir, leaving it near-empty at the start of a typical 18-month drought, reducing the Abingdon reservoir yield almost to zero. Without modelling the full 15,600 years of stochastic data, we have not been able to estimate the probability of such extended sequences of dry years. However, the tendency of dry years to cluster, as shown by the random sample in Figure 10, suggests that this type of event could be a lot more frequent than once in 1000 years.

In Section 2.1, we have shown that for typical summer-winter-summer droughts (like the 20th Century droughts) Abingdon reservoir's c.280 Ml/d yield can be reduced to as low as about 200 Ml/d if the drought lasts longer than 18 months (see examples in Figures 2 and 3). The drought can last longer than 18 months if it starts early in the first spring or extends deep into the second autumn. The records of the 20th Century show that about three "typical" 18-month droughts can be expected every 100 years. Without doing a full analysis of Atkins stochastic records, we are loath to speculate on the likelihood of, say, a 21-month drought like that in Figure 3, reducing the yield of Abingdon reservoir to less than 200 Ml/d. However we would expect it to be a lot more frequent than 1 in 1000 years.

In Sections 2.2 and 2.6, we have shown that if a typical 18-month drought is followed by one or more dry winters, supply restrictions could be needed for extended periods, possibly several years. This seems likely to be an unacceptable level of service for Thames Water's customers, constituting a supply failure. In Section 3.2, we have shown that, after an 18-month drought, there is a 20% probability of Abingdon reservoir still being less than half full by the start of the third summer. Therefore, this type of event can be expected much more often than once in 1000 years, perhaps once a century.

3.4 Work needed to understand the resilience and yield of Abingdon reservoir

In our opinion, Thames Water have not properly investigated the resilience of Abingdon reservoir to droughts longer than those of the 20th Century. We consider that the following work is needed as a matter of urgency:

1. Simulation of the full 15,600 years of Atkins' stochastic record and a proper assessment of the probability of the various types of longer duration drought described in this report.
2. Consideration of the possibility that climate change causes more variable winter flows, ie dry winters becoming drier, as well as wet winters becoming wetter, thereby increasing the likelihood of long duration droughts.
3. Development of the likely operating rules for Abingdon reservoir, including:
    - revision of the Lower Thames Control Diagram and development of Abingdon reservoir control rules to allow for the volume of storage remaining in Abingdon reservoir, as well as the London reservoirs
    - refinement of Service Levels for supply restrictions, taking account of the duration of supply restrictions in longer duration droughts
    - refinement of the rules for making regulation releases from Abingdon reservoir
4. Assessment of the consequences of longer duration droughts in terms of the level of service that can be provided to customers.

5. Assessment of the consequences of prolonged duration of near-empty conditions and poor water quality in Abingdon reservoir, with up to 8 years between reservoir refills.

6. Assessment of the need for more than the currently proposed 6% of emergency storage in Abingdon reservoir, to mitigate the risks of service level failure and poor water quality in long duration droughts.

7. Engagement with customer groups and stakeholders to discuss the acceptability of service levels and supply restrictions in long duration droughts.

As a first step, Thames Water should acknowledge in their reporting and communication with the public that the Abingdon reservoir is not resilient to droughts of longer duration than the droughts of the 20th Century.

4. Conclusions

We have reviewed Thames Water's assessment of the resilience of Abingdon reservoir and undertaken our own analysis using Atkins' stochastic drought data, reaching these conclusions:

1. Although we agree with Thames Water's conclusion that the Abingdon reservoir yield of about 285 Ml/d, as assessed for the droughts of the 20th Century, is resilient against more intense droughts, <u>this only applies if their duration is less than 18 months</u>.
2. Thames Water have identified that the yield of Abingdon reservoir is not resilient to droughts of longer duration than those of the 20th Century. However, they have dismissed the risk as being extremely small, without proper consideration of either its likelihood or its consequences.
3. For example, Thames Water have shown Abingdon yield can drop to only 95 Ml/d in a 30-month drought. Our analysis of other 30-month droughts confirms a yield drop to around 100 Ml/d.
4. We have also shown that, if the output from Abingdon reservoir is maintained at the planned 285 Ml/d in a 30-month drought, the reservoir would be empty at the end of the second summer and there would be catastrophic failure of London's supplies in the third year. The consequences of such an event are so severe that even a 1 in 1000 year probability is a major risk for London's supplies.
5. If there are several consecutive moderately dry years with low winter refill availability, Abingdon reservoir can be progressively drawn down, leaving it nearly empty at the start of a typical 18-month drought. In these circumstances, the yield from Abingdon reservoir could be reduced to close to zero. There would be catastrophic failure of London's supplies if the yield had been expected to be Thames Water's planned 285 Ml/d
6. If summer-winter-summer droughts similar to the major 20th Century droughts last longer than 18 months, say 21 months, the yield of Abingdon reservoir can drop to below 200 Ml/d. We expect such events to occur a lot more frequently than once in 1000 years as suggested by Thames Water.
7. If summer-winter-summer droughts like the 20th Century droughts are followed by another dry winter, there would be supply restrictions lasting through the second winter and into the third summer. Even though a 285 Ml/d yield from Abingdon reservoir might be maintained, the extent of supply restrictions seems unlikely to be acceptable to customers. This can be expected to occur, perhaps, once a century.
8. Some droughts in Atkins' records would result in Abingdon reservoir being drawn down for several years before refilling – for 8 years in one case. In these circumstances, there could be prolonged supply restrictions and persistent poor water quality in the near-empty Abingdon reservoir. This risk has not been identified or addressed by Thames Water.
9. The majority of Thames Water's "random selection" of 30 droughts for their resilience analysis, said to be "at, or worse than, the severity of the of the critical 20th Century droughts", were actually <u>less</u> severe than the 20th Century droughts, in terms of probable yield from Abingdon reservoir. Consequently, Thames Water have not considered some of the different types of long duration droughts identified in this report, in which the yield of Abingdon reservoir would be much less than their expected value of 287 Ml/d.

10. Thames Water's assessment of the resilience of Abingdon reservoir in severe droughts has not adequately addressed the likelihood or consequences of droughts longer than those of the 20th Century. This now needs to be done as a matter of urgency in time for the draft WRMP due in December 2017. The work should include proper assessment of the various types of long duration droughts we have identified in this report. Thames Water's work should be undertaken transparently, informing customers and stakeholders about the risks of long duration droughts.

References

1. Department of Environment Food & Agriculture, Enabling Resilience in the Water Sector, March 2016
2. Environment Agency, Water Supply and Resilience and Infrastructure, October 2015
3. GARD response to Thames Water's Fine Screening Report on WRMP19 Options, October 2016, pages 31-36.
4. https://corporate.thameswater.co.uk/-/media/Site-Content/Corporate/Media/Thames-Water-Reports-Page/Summary-of-stakeholder-comments-on-resource-options-January-2017.pdf
5. WRMP19 Stochastic Water Resources: Stage 4 Options Appraisal, Appendix Document for the Upper Thames Reservoir Development, 25 January 2017
6. Thames Water Stochastic Resource Modelling Stage 2 & 3 Report. 16 December 2016.

Appendix A – GARD’s simulation model

1. Description of GARD’s model

GARD’s model is an almost exact replica of the component of Thames Water’s WARMS2 model that simulates London’s supplies. Unlike WARMS2, GARD’s model does not use rainfall/run-off modelling to generate river flows. Instead it uses the river flows supplied by Thames water:

- Either river flows generated by the rainfall/run-off component of WARMS2
- Or flows generated stochastically by Atkins

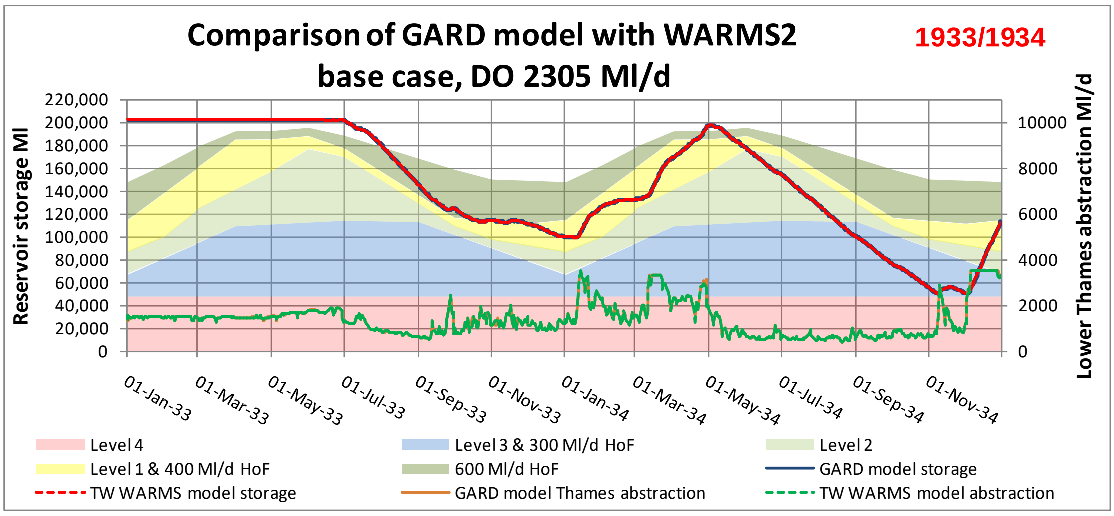
GARD’s model provides a daily simulation of the operation of the London and SWOX supply systems for the period of available flow records, eg for the Atkins stochastic data for the 78 years of daily flows in each of Atkins’ “Runs”. The model includes the detailed water supply operating rules modelled in WARMS2:

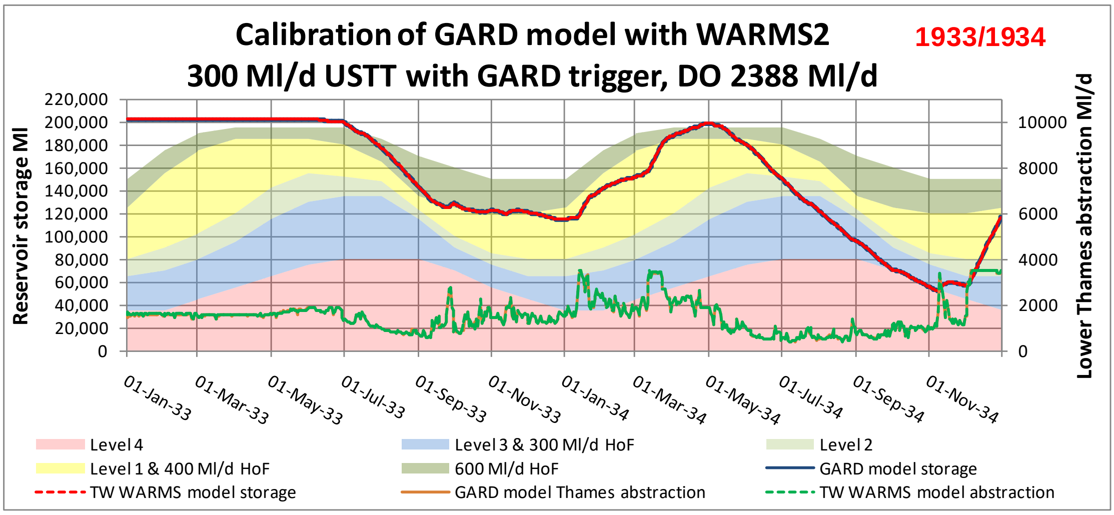
1. The operation of the latest Lower Thames Control Diagram as reported in Thames Water’s Annual Review 2016.
2. Levels of Service and Teddington Target Flows, triggered by the LTCD, including demand reductions at the various Levels of Service, as per Annual Review 2016.
3. Abstraction from the Thames, using the same pump ceilings as WARMS2, the same rules concerning flows in the Mole and Hogsmill and upper reservoir refill constraints.
4. Abstraction from the Lee, storage in the Lee reservoirs, balancing flows in the Thames-Lee tunnel, are all simulated, as WARMS2.
5. Operation of the Gateway desalination scheme, all ARS schemes, ELDRED, Hoddesdon, Stratford Box and the West Berkshire Ground Water Scheme, all as WARMS2. In validating GARD’s model, there is a perfect match of output from these strategic schemes to the output from WARMS2. However, as there are no droughts longer than two years in the historic records used in WARMS2, we are not able to know whether our assumptions are still valid for longer duration droughts.
6. Deployable output of London’s supplies is determined as the demand that can be sustained throughout daily simulation of through the period of river flow records, without storage dropping in LTCD Level 4.
7. Daily operation of Abingdon reservoir is simulated using the Days Weir flow record, with a 1000 Ml/d refill pump capacity, using the EA’s 1450 Ml/d hands-off flow and allowing for net upstream abstraction. The rules assumed for regulation releases are:
    - Regulation release of 300 Ml/d
    - 2% transmission loss between Culham and Teddington
    - Regulation release triggered when Teddington flows have been less than 3000 Ml/d for 10 days and London reservoir storage has been in TTF band 2 for 10 days.

The model operates as an Excel 2010 spreadsheet. It is a large, 150 Mb file. It takes about 90-120 seconds to run a 80-year simulation of the operation of the London supply system, including the Abingdon reservoir. This short run time compares with about 1 hour for running WARMS2.

2. Validation with WARMS2

GARD's model has been validated by comparing output with various scenarios of WARMS2 output that have been provided by Thames Water as shown in Figures A1 and A2.





Note: the plot above was generated with WARMS2 2015 river flow data and LTCD for which the London base case DO was 2246 Ml/d. Therefore, the DO gain from the Unsupported Severn-Thames transfer is 142 Ml/d

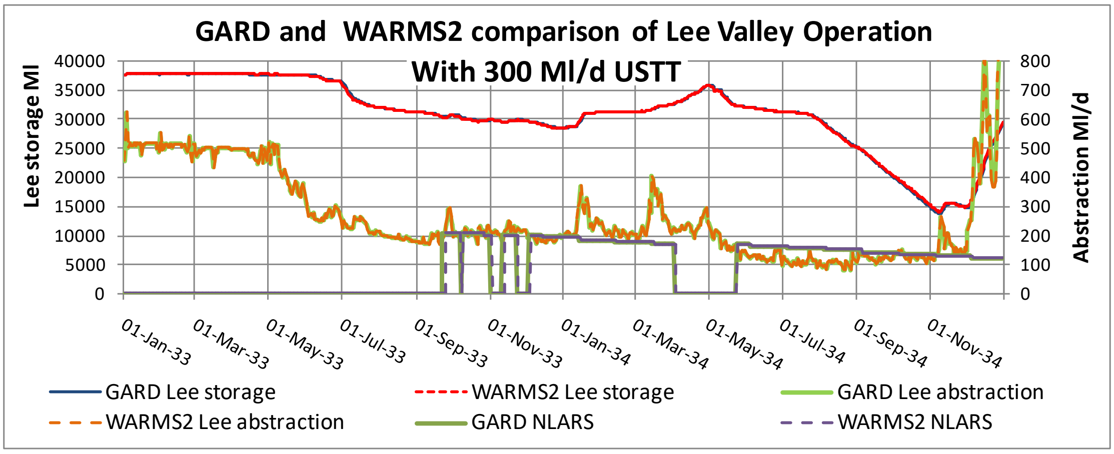


Figure A 1 - Validation plots comparing GARD London model output with WARMS2 output

In each plot, the lines generated by the GARD and WARMS2 models are almost indistinguishable, showing that the model outputs are virtually identical.

GARD's modelling of the SWOX supply system, which affects water availability for filling Abingdon reservoir, has been validated with WARMS2 modelling as shown in Figure A2:

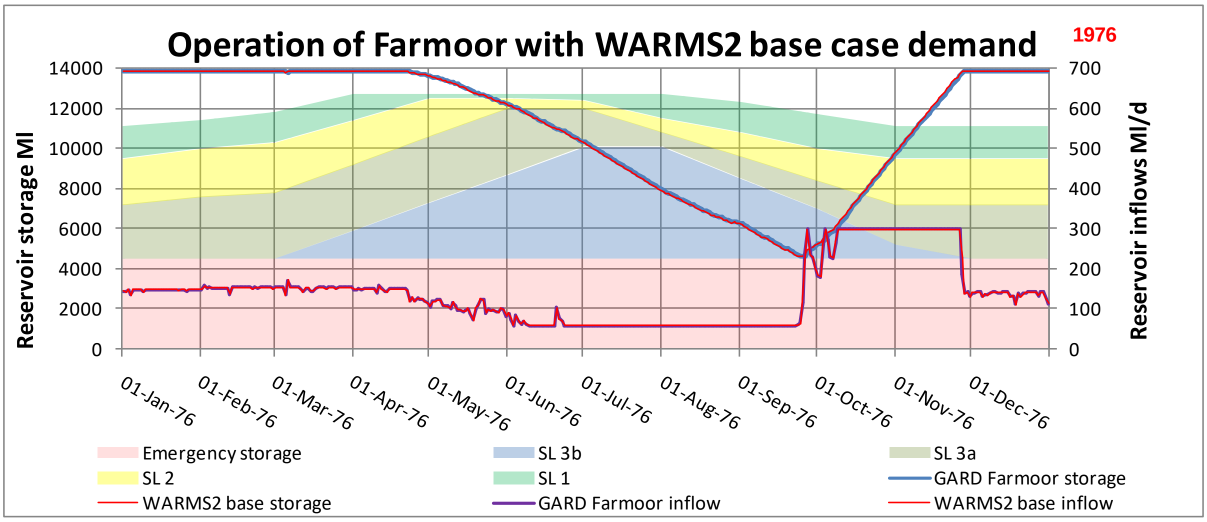


Figure A2 – Validation plots comparing GARD and WARMS2 model outputs for SWOX

Again, the abstractions and storages generated by the GARD and WARMS2 models are almost indistinguishable, showing that the model outputs are virtually identical.

Thames Water have not provided GARD with any WARMS2 output for the modelling of the Abingdon reservoir, nor details of their proposed operating rules for the Abingdon reservoir. Therefore, we have not been able to validate GARD's modelling of the Abingdon reservoir against equivalent WARMS2 modelling. However, GARD's modelling of the operation of London's supplies supported by regulation from a 150 Mm^3 Abingdon reservoir using the historic flow records, 1920-2008, gives a deployable output gain of 293 Ml/d, as shown in Figure A2:

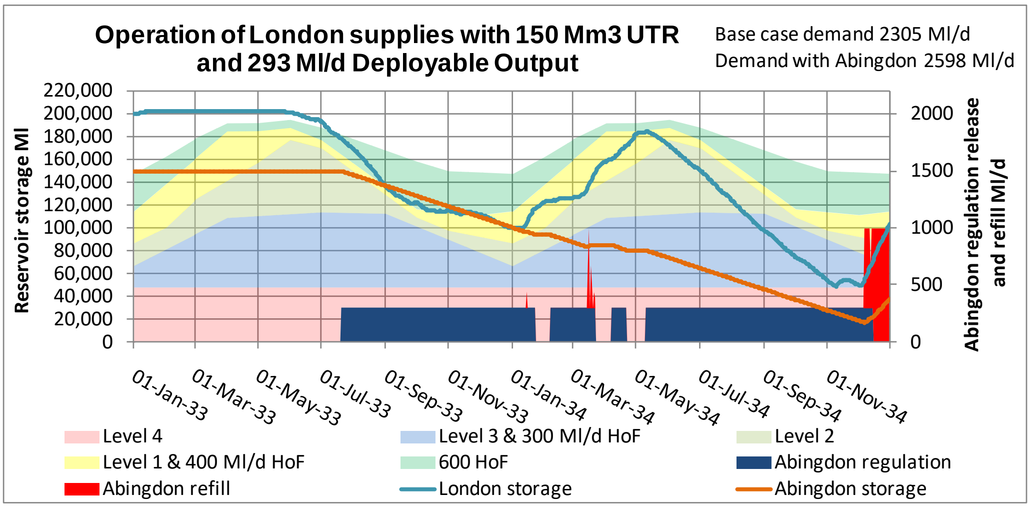


Figure A3 – GARD model simulation of operation of London supplies supported by Abingdon reservoir using historic flow records.

The deployable output of 293 Ml/d is a reasonably close match to Thames Water's quoted deployable output of 287 Ml/d for Abingdon reservoir, providing some validation of GARD's modelling of the operation of Abingdon reservoir.

3. Flow data used

For modelling the stochastically generated flows, GARD's model uses the daily flows without climate change provided by Atkins for Teddington, Feildes Weir and Days Weir.

Atkins' stochastic flows were not supplied to GARD for the River Mole or the River Hogsmill Therefore, the missing flows were generated by correlation with Feildes Weir data for Mole and Hogsmill flows.

Following a meeting with Atkins on 6th January 2017, the assumptions in the GARD model for using Atkins' stochastic data to assess flow availability at Teddington are:

1. The available flow for abstraction above Teddington by Thames Water and Affinity is:
    - Atkins' "semi-natural" Teddington flow, as supplied to GARD
    - less abstraction to fill Farmoor (from GARD's SWOX model)
    - plus Farmoor process water return (approx 6.7 Ml/d from GARD's SWOX model)
    - plus a nominal 130 Ml/d for Farmoor effluent return (95% of Farmoor DO of 136 Ml/d)
    - plus WBGWS output (from GARD's SWOX model)
2. This assumes that Atkins' semi-natural flows, as supplied to GARD, already allow for:
    - effluent returns from TW's Thames Valley supplies (other than Farmoor) and all water-only company supply effluent returns
    - effluent returns from the 1.93% of TW's London supplies that return above Teddington
    - all surface water abstractions for TW's Thames Valley zones
    - all water-only companies abstractions in the Thames Valley above Kingston (but not the c. 400 Ml/d of Affinity abstractions in the Lower Thames)
    - the Didcot power station abstraction
    - the impact of all groundwater abstractions on river flows

For modelling inflows to the Abingdon reservoir, it has been assumed that Atkins' stochastic data for Days Weir are true natural flows, ie do not include any allowance for operation of Farmoor reservoir or SWOX sewage effluents. In modelling Farmoor reservoir and its influence on downstream flows, the natural flows at Farmoor have been based on correlation of gauged flows at Days weir and Eynsford.