The British Dam Society

Draycote Reservoir – Drawdown Enhancement

A WALKER, Mott MacDonald
J CAMPBELL, Mott MacDonald
I M HOPE, Severn Trent Water
D McKUNE, Severn Trent Water

SYNOPSIS Permanent siphons are increasingly being fitted to increase the discharge capacity at reservoirs to ensure that the precautionary drawdown provision to mitigate the risk posed by the reservoir satisfies recent guidance. Routine 'wet' testing of reservoir drawdown systems is fundamental to providing confidence that they can be relied upon in emergency situations.

This paper summarises the optioneering, design and construction of the three, 1200mm diameter vacuum-primed siphon system installed at Draycote Reservoir in 2023 to enhance the existing drawdown capacity and testing functionality. The paper will discuss the arrangement and functionality of the drawdown enhancement works, including for routine 'wet' testing; the risk of pollution, including of invasive, non-native species, and flooding during testing and emergency operation; and constraints imposed by the water resources and amenity functions of the reservoir and site.

INTRODUCTION

Severn Trent Water, the Client, has a proactive approach to reservoir safety, with an integral element of this being Portfolio Risk Assessment (PRA). Since 2010, the Client has undertaken three PRAs across their full stock of statutory reservoirs. These PRAs have enhanced the Client's knowledge and understanding of their structures, as each dam is in effect a prototype. Another strand of this proactive approach by the Client is Pre-S10 Inspections, which are commissioned two years ahead of the statutory inspection to provide an early indication of the studies and works likely to be required. In common with all the Client's statutory reservoirs, this proactive approach was applied to Draycote Reservoir.

Draycote Reservoir is a lowland reservoir built in the 1960s and is impounded by six embankment dams (Figure 1). It provides a bulk, raw water supply to an adjoining water treatment works (WTW), principally for distribution to Rugby and its surrounding area. The reservoir is fed by pumped flows from its downstream watercourse, the River Leam, and by pipeline from Stanford Reservoir and Brownsover Pond. Whilst classified as an impounding reservoir, the direct catchment is small relative to the reservoir's size and provides minimal contribution to water storage. Legally binding environmental restrictions on releases from the reservoir via the existing Valve Tower to the Draycote Brook, a minor tributary of the River

Leam, amount to a mere 2Ml/day, reflecting the reservoir's location at the top end of the catchment.

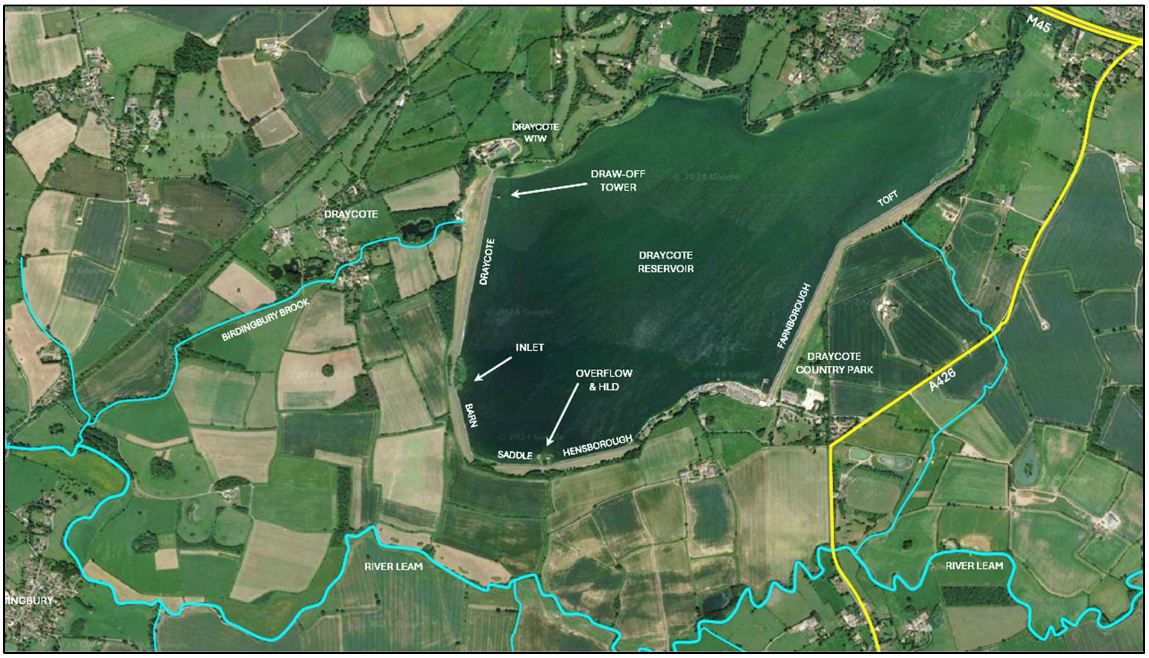

Figure 1. Site Layout of Draycote Reservoir

OPTIONEERING

Overview

Following receipt of the latest S10 Inspection Report in October 2019, the Client promoted a project to address the following measures to be taken in the interest of safety (MIOS):

- Undertake a study to identify options to improve the installed drawdown capacity to "meet latest UK industry guidance", including "a review of the vulnerability of the embankments to internal erosion and any risk mitigation provided by the embankment zoning".
- Upgrade the installed drawdown facilities in line with the agreed preferred solution, subject to a minimum installed drawdown rate of 0.7m per day over the upper 5m of the reservoir depth, equivalent to the top approximately 50% volume.
- Infill the Toft Culvert, including measures to secure the existing pressurised pipe.

For conciseness, only the elements of MIOS 1 and 2 relating to drawdown are discussed further in this paper. It should be noted, however, that MIOS required following a S10 do not necessarily reflect the safety of the reservoir or the lack thereof, as design standards and opinions change with time. Draycote Reservoir is a structure of its era, with the originally installed drawdown capacity considered inadequate against today's standards (EA, 2017).

Stantec, the Optioneering Consultant, was appointed to undertake a study to investigate options to enhance the installed reservoir drawdown capacity. Each option was assessed against its cost, buildability, impact on reservoir safety, operational requirements, and other key project constraints.

Existing Facilities and Drawdown Requirements

The existing drawdown capacity was provided by an 18" diameter scour from the Valve Tower discharging to Draycote Brook (approximate capacity of 1.85m^3/s), and the High-Level Draw-off system (HLD), comprising a 1600mm diameter culvert from the reservoir to the HLD Discharge Chamber at the end of the spillway channel and then a 42" diameter culvert – the HLD Scour – to an outlet structure at the River Leam (approximate capacity of 4.15m^3/s). Combined, the existing scour and HLD system provided an average drawdown rate over the top 5m of 0.13m/day.

The 'basic recommended standard' for drawdown capacity in accordance the drawdown guidance (EA, 2017) was confirmed by the Optioneering Consultant to be 0.99m/day (equivalent to 5%H/day). The existing drawdown capacity was therefore in significant deficit, requiring an additional capacity of approximately 21m^3/s to fully satisfy the 'basic recommended standard'.

The "minimum 0.7m/day" drawdown rate in the MIOS was originally set on the basis that granular drainage zones in the embankments from previous stability enhancements, including the construction of substantial berms on the upstream and downstream sides of all embankments, may provide filtering properties, and thus some protection against the threat of internal erosion, which had been identified as the principal threat at the reservoir from a previous quantitative risk assessment. Assessment of the drainage zones by the Optioneering Consultant concluded, however, that the drainage zones were too coarse to meet filter guidance, and hence, would not provide suitable mitigation against internal erosion.

The drawdown enhancement proposals and the past performance of the reservoir were reviewed by the Client's Independent Panel of All Reservoirs Panel Engineers, which concurred with the views of the Inspecting Engineer / Qualified Civil Engineer (QCE) for the works, that a revised minimum average drawdown rate over the top 5m depth of 0.8m/day should be applied. This drawdown capacity would be supplemented by temporary imported pumps to achieve the 'basic recommended standard'.

Key Project Constraints

As a large, impounding reservoir, Draycote Reservoir presented various constraints:

- Lack of hydraulic capacity within the Draycote Brook and River Leam to receive the emergency drawdown flows. This presents a potential risk of property flooding and damage. To avoid downstream flooding, operational discharge to the Draycote Brook is currently limited to 0.18m^3/s and is avoided to the River Leam via the HLD system.
- Requirement to undertake annual 'wet' testing of the installed drawdown facilities.
- Water resources: Draycote Reservoir serves an adjacent WTW. The reservoir can only be filled through the winter months by river abstraction, limiting the potential to drawdown the reservoir to facilitate the construction works.
- Water quality: invasive, non-native species (INNS), including zebra mussel and demon shrimp are present within the reservoir.
- The reservoir is the Client's most popular visitor site, having over 500,000 visitors per year, and hosts a visitor centre, sailing club, and fishery.
- The Client is investigating options to raise the TWL to provide additional water storage.

Managing Risks for Dams and Reservoirs

Drawdown Options

The Optioneering Consultant reviewed the following options:

- Option 1 – provide a washout-tee on the existing draw-off main.
  – **Rejected** due to insufficient increase in drawdown capacity and unacceptable increase in flood risk along the Draycote Brook during testing and emergency operation.
- Option 2 – increase capacity of the existing HLD system.
  – **Rejected** due to insufficient increase in drawdown capacity and unacceptable increase in flood risk along River Leam during testing and emergency operation.
- Option 3 – construct additional HLD system(s).
  – Several arrangements were considered. Sufficient additional drawdown capacity could have been provided, for example, by two, 2m square culverts. **Rejected** due to higher comparative costs; relatively more intrusive works, including into the dam core; and significantly higher initial discharge flows (up to approximately 50m^3/s), resulting in a significant and unacceptable comparative increase in flood and environmental risks, and severely limiting the options for 'wet' testing the system due to the discharge flows.
- Option 4 – construct new siphons.
  – **Preferred and selected**. Discussed within paper.

Preferred Drawdown Solution

A preliminary drawdown capacity assessment by the Optioneering Consultant confirmed that the installation of three or four 1200mm diameter siphons would satisfy the required drawdown rate (Table 1). These arrangements were therefore taken forward for further assessment.

Table 1. Siphons – Preliminary Average Drawdown Rate (m/day over top 5m)

Option	Existing TWL	Future TWL (+0.6m)
3 No. 1200mm siphons	0.82	0.89
4 No. 1200mm siphons	1.04	1.14

Siphon Location

The optioneering study considered each of the six embankments for siting the siphons:

- Draycote Main – **rejected** due to restricted capacity of downstream watercourse (<2m^3/s), and the higher risk of installation through the largest embankment.
- Barn and Saddle – **rejected** due to constricted landownership downstream of the embankment; the proximity of the reservoir intake structure; and the local topography / bathymetry being unsuitable for siphon hydraulics and drawdown.
- Toft and Farnborough – **rejected** due to constricted landownership downstream of the embankment, and because emergency flows would be conveyed by small tributaries to the River Leam, risking flooding of the A426 road (main site access) and other properties.
- Hensborough – **preferred and selected** due to proximity and access to the River Leam; preliminary flood modelling indicated no additional sensitive receptors would be

impacted during emergency operation; its proximity to the existing HLD system; the suitable local topography / bathymetry for siphon hydraulics and drawdown; and the existing available access for construction traffic, plant and laydown.

Drawdown Testing

Routine testing of drawdown facilities is a fundamental part of reservoir safety to ensure that there is full confidence that the system can be operated and relied upon in an emergency event. Where practicable, this is best simulated by full ‘wet’ test conditions. This is particularly true for large siphon systems as they (i) are more complex than typical gravity outlet systems, typically requiring the use of mechanical and electrical equipment, and (ii) have a complex operation sequence to allow priming and operate / terminate their discharge.

As the River Leam is located approximately 0.5km downstream via third-party land with no connecting watercourse, there is a need to provide a temporary flow storage structure upstream of, and / or a flow conveyance structure to, the river to enable routine ‘wet’ testing of the drawdown enhancement works without causing flooding and environmental issues. All other major reservoir siphon schemes allow for full “wet” testing to be undertaken.

A temporary flow storage structure – a Detention Pond – was selected as the preferred option to capture the discharged testing flows instead of discharging them to the River Leam.

DESIGN DEVELOPMENT

Outline through Detailed Design

Mott MacDonald, the Designer, was appointed to undertake the outline and detailed designs. The outline design focused on developing the concept design from the Optioneering Consultant, with three key areas identified for more detailed consideration:

- the required drawdown depth to facilitate construction;
- the method of ‘wet’ testing the siphons, including the form of the Detention Pond; and
- the conveyance of emergency discharge flows to the River Leam.

The concept design set the siphon crest levels such that a 6m-deep excavation through the dam crest was required, necessitating a reservoir drawdown far beyond the reservoir’s typical annual cycle. The Client also stated a preference to avoid heightening the embankment crests. One way in which the temporary drawdown depth was reduced was by investigating various configurations of the siphon crest valves and resulting embankment crest levels. The excavation and temporary drawdown depth was decreased by approximately 1.6m by orientating the valves horizontally, rather than vertically. Whilst this widened the Crest Chamber by pushing the siphons further apart, staggering the valves minimised this impact whilst allowing access for operation and maintenance activities (Figure 2).

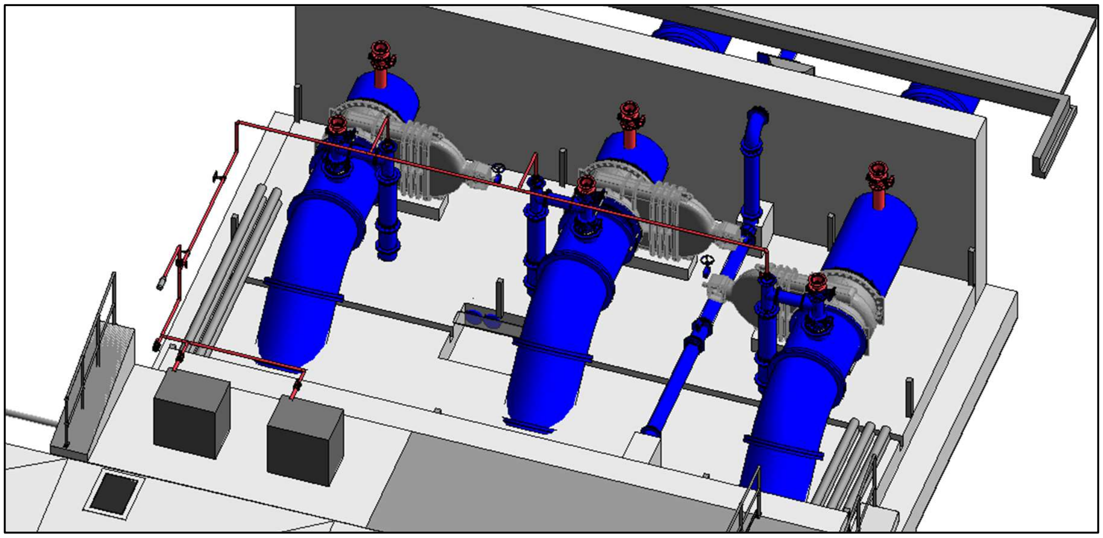

Figure 2. Crest Chamber valves and pipework (walls omitted for clarity)

A sheet pile cut-off was proposed within the embankment clay core to divorce the Crest Chamber and downstream construction works from the reservoir. This did not reduce the depth of the drawdown but did dramatically reduce the duration that the drawdown would be required for, minimising the impact to supply. Once the siphons had been installed through the sheet piles, the reservoir could return to TWL and follow its natural cycle, with the works to be sequenced to align the required drawdown with the lowest level during the natural cycle.

Due to the challenges around discharging directly to the River Leam and the resulting current inability to test the HLD system, the Client requested that the HLD Discharge Chamber at the end of the spillway channel be connected to the planned Detention Pond, via a new, valved conduit, to allow testing of the HLD system and the subsequent return of the testing flows back to the reservoir. The diameter of this HLD Testing pipe was set to maximise the discharge through the HLD system by minimising the throttling of flows through the existing HLD Scour.

The concept design proposed that the siphon downstream legs be laid within concrete culverts to provide double containment; however, double containment was deemed unnecessary by the Designer if the operational methodology was set to leave the siphons empty when not in use and the crest valves closed to avoid passing water from the reservoir. The rationale was that any failure would be immediately noticed during testing or emergency operation and the siphon discharge could then be terminated and the siphon drained. Thus, the residual threat within the siphon downstream legs would be from small-scale leakage only. The siphon bedding fill was therefore wrapped in sealed geomembrane, with an associated drainage outlet provided to allow any leakage to be readily identified.

The Optioneering Consultant proposed that the Outlet Chamber, located at the downstream toe of the embankment, be a vertical stilling basin with submerged discharge valves. However, early in the outline design other options were considered to 'design out' both the approximately 5m deep excavation and the expensive submerged discharge valves. The option selected by the Designer was to install an impact-style stilling basin, designed in accordance with US Bureau of Reclamation design guidance for "Type VI" outlet structures (USBR, 1987). This allowed gate valves to be used instead of submerged discharge valves, as the required energy dissipation would be provided by the outlet structure, and significantly reduced the excavation depth required, as the outlet structure is installed close to existing ground level on its downstream side.

Whilst the concept design did not address the risk of water freezing within the siphon upstream legs, it was identified during the outline design as part of a Hazards and Operability (HazOp) review with the Client. As the siphon priming method necessitates permanent compressors, the HazOp considered two options to utilise the compressed air to mitigate the risk: (1) agitation of the water surface within the siphons to disrupt ice formation; and (2) dewatering the pipes by pressurising the pipes to drive the water out. The Client, however, deemed the risk to be sufficiently low that such measures where not taken forward to construction. The pipes are buried to a set depth, however, to facilitate integration with the rip-rap protecting the embankment upstream face and to minimise the public safety risk of becoming trapped between the siphons where accessible.

The Client raised concerns over the potential for fouling of the siphon pipes from the growth of zebra mussels. Based on industry experience, however, this risk appeared to be low because the water within the siphon upstream legs will be relatively static, decreasing the likelihood of dissolved oxygen and food movement into the pipes. There remained a concern, however, that there would still be diffusion of oxygen and food into the initial leg of each siphon, which could facilitate zebra mussel growth. As a precaution, therefore, the first approximately 6m length of each siphon upstream leg was lined with a vinyl-ester resin to decrease the roughness of the pipe barrel to minimise the potential for zebra mussels to attach to the pipe and grow.

Priming

To enable operation of the siphons, they must first be filled with water, i.e. be fully primed. Three methods were considered:

- Suction priming – Suction pump connected to the crown of the siphon to draw water into pipe from the reservoir.
- Water priming – Pipe infilled via water pump or other piped conduit (pressure or gravity) connected to the crown of the siphon. (When the reservoir water level is above the crown of the siphon, the siphon may be considered 'self-priming' if it fully infills with water without intervention.)
- Vacuum priming – Compressed air is driven through a venturi air ejector at the crown of the siphon which creates a negative differential pressure (i.e., suction) across the venturi and thus the siphon. This draws out any air within the siphon which is then replaced by water drawn from the reservoir.

A vacuum priming arrangement was selected as the preferred method. Vacuum priming is increasingly being installed on siphon schemes as it minimises the scale of plant to be brought to site during testing and emergency events (e.g., high-capacity suction pumps, which are not always readily available). Vacuum priming of siphons has not previously been provided to a system as large as the three 1200mm diameter siphons provided at Draycote Reservoir. A venturi air ejector on each siphon is driven individually by a common compressor unit to prime each siphon sequentially. A target time of two hours to have all drawdown facilities fully operational, once on site and instructed to do so, was set by the QCE.

Managing Risks for Dams and Reservoirs

Due to the level of the crown of the siphons within the Crest Chamber and the typical natural reservoir cycle, the siphons are unlikely to ever be self-priming, despite this being theoretically possible at TWL. Whilst the siphons could be left in a primed state once initially primed this, as stated above, was avoided to negate the requirement for double containment of the siphon downstream legs. To minimise reliance on imported plant (e.g. high-capacity suction pumps or compressor units), the Client's preference was for the priming arrangement to be fixed. A fixed system also ensures that the Client's Operations staff will be familiar with the operation methodology for the system in the event of an emergency.

A cross-connection from the HLD testing pipe to the downstream leg of each of the siphons enables the siphon downstream legs to be infilled up to the reservoir level at the time of operation via the HLD system. This reduces the volume of air to be removed from the siphon via the vacuum priming system and thus the time to prime the siphons.

Each siphon reaching prime is demonstrated to the operator by (i) the change in discharge via the venturi exhaust from a 'spray' / 'mist' to a flow of water to the common sump drain, and (ii) the head within the siphon, shown by the comparative readings on the pressure meter located immediately upstream of the outlet gate valve and the reservoir water level element and observed via the control panel within the Crest Chamber.

On either side of the siphon crest valves, a vent is provided to enable each leg of the siphons to be balanced to atmospheric pressure when not in operation. This prevents the build-up of gases from the breakdown of organics in the water and allows the water level in the upstream legs to balance with the reservoir to avoid the pipes floating, negating the requirement for significant quantities of ballast. These vents, along with the outlet and crest gate valves, allow multiple options for terminating the siphon discharge in case of valve failure. The options, in order of preference being: close outlet valve; close crest valve; then open all vent valves to break the siphon prime – if both the crest and outlet valves cannot be closed, breaking prime will only fully terminate the siphon flows when the reservoir is below approximately TWL-1.5m.

Detention Pond

A Detention Pond is proposed as the preferred method of allowing full simulated 'wet' testing to be freely undertaken by the Client. The Detention Pond captures the testing flows and allows the discharge to be returned to the reservoir via a return pumping station and rising main, thus avoiding: (i) the loss of water to be used for public supply; (ii) any increase in flood risk to or along the receiving watercourse; and (iii) environmental licensing / discharge consent restrictions due to water quality, (e.g., discharge of untreated water contaminated with INNS).

Flood modelling by the Designer confirmed that there are no new sensitive receptors (e.g. private property or public infrastructure) impacted for emergency discharge flows coincident with peak flows along the River Leam over a range of flood events, but that the impact to some existing sensitive receptors already affected by river flooding may be exacerbated.

Design Summary

The solution developed during the outline and detailed design can be summarised as follows:

- Install a triple 1200mm diameter vacuum-primed siphon system over and through Hensborough Embankment, discharging to a Detention Pond, with all valves and instrumentation operated and monitored via a control panel in the Crest Chamber which also links back to the Client's existing systems in the local WTW.

- Upgrade the existing HLD system to enable it to be 'wet' tested and enhance its capacity, with the new HLD Testing pipe facilitating a cross connection to each of the siphons, optimising the time required to prime the siphons.
- Construct a Detention Pond, with associated return pumping station and rising main, to enable full 'wet' testing of the siphons and HLD system whilst avoiding the release of raw reservoir water, overland or as otherwise conveyed, to the River Leam.
- The enhanced drawdown system will empty the upper 5m reservoir depth in approximately five days, with the discharge varying between approximately 30m^3/s and 13m^3/s. The resultant average drawdown rate satisfies the required minimum of 0.8m/day.
- The works caused negligible impact to the Client's water resource requirements for public water supply during construction, with the works able to be completed whilst the reservoir followed its natural cycle, i.e., no significant artificial reservoir drawdown was required to lower the reservoir below its natural levels.
- Operation of the existing HLD system control valves was previously via a 'wax' unit powered by a portable generator; therefore, this project provided an excellent opportunity to provide electrical actuation to these valves to increase the reliability of their operation. The electrical actuation is powered via the permanent connection to mains electricity supply to be provided to the Crest Chamber.

CONSTRUCTION AND OPERATION

Following the design, the construction phase was award to JN Bentley, the Contractor, on a build-only contract. A general arrangement plan for the scheme is shown on Figure 3.

Badger Sett Move and Site Set-up

An ecological study completed in 2020 identified a large and active badger sett at the right-hand abutment of Hensborough Embankment, immediately adjacent to the spillway channel and HLD Discharge Chamber – indicative area shown in Figure 3. The location of the badger sett clashed with the working area for the HLD Testing pipe and precluded access down the right-hand mitre of the embankment, restricting construction access opportunities.

To undertake the construction works, the badger sett had to be moved, which presented a significant programme risk. The alternative was to re-design that aspect of the works and leave the badgers in place. Whilst practical options were identified, the risks to the wider construction scheme and to the embankment itself were such that it was decided to re-locate the badger sett. This was completed in late 2021 following licencing from Natural England.

One of the key attractions for the more than 500,000 annual visitors to Draycote Reservoir is the approximately 8km complete circular walk around the reservoir. One of the original, key project drivers was to maintain this circular route. The Designer proposed for this to be maintained via an augmented footpath via third-party land during construction, which would also facilitate additional space for construction traffic and laydown; however, the land was not secured, so the circular route was severed for the duration of construction.

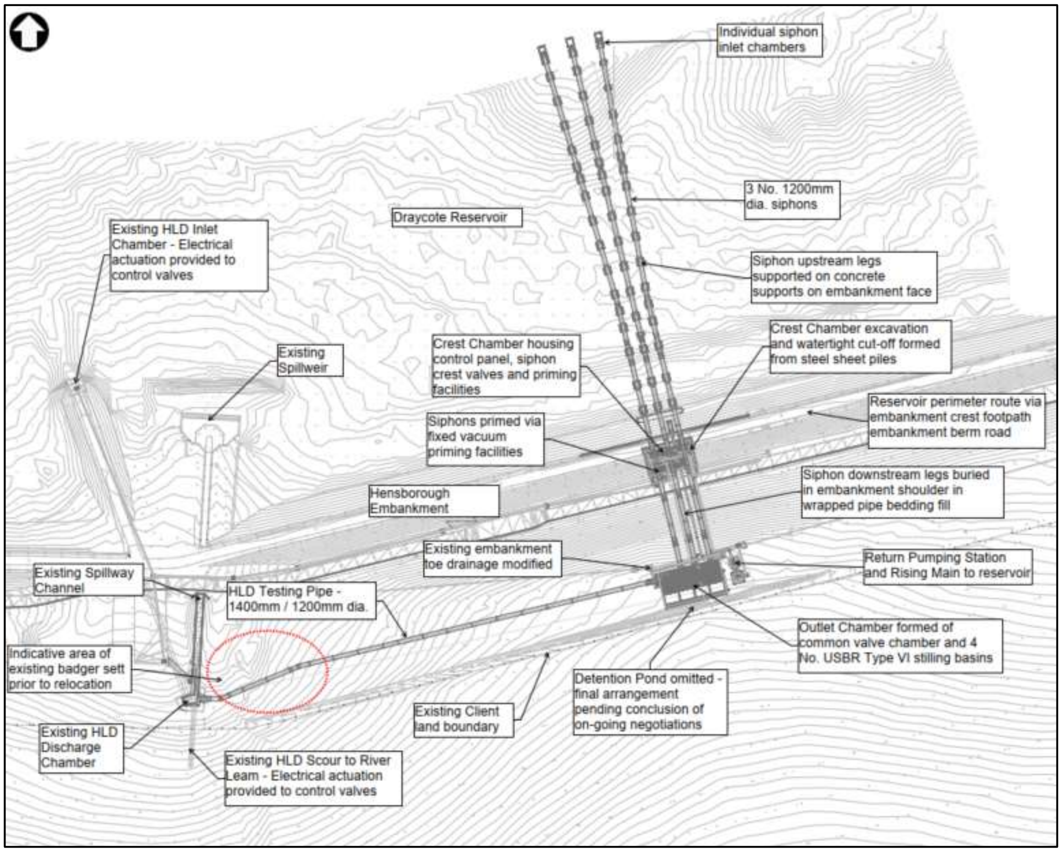

Figure 3. General Arrangement of the Drawdown Enhancements

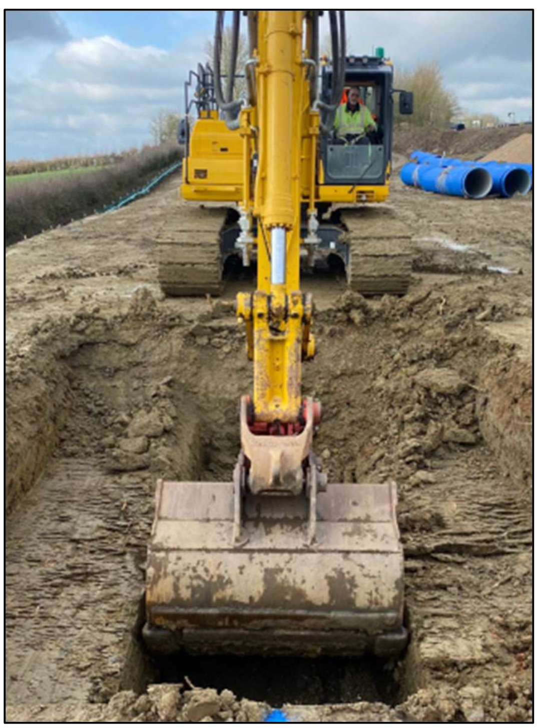

Figure 4. Installation of HLD Testing pipe

Figure 5. Installation of sheet piles using silent press (downstream)

Siphon Construction

Construction of the siphons commenced in early 2023 with the installation of the steel sheet pile cut-off into the embankment clay core to allow the upstream and downstream works to progress independently. Sheet pile wing walls were also installed in both upstream and downstream directions to facilitate construction of the Crest Chamber and minimise the excavation extent required. The sheet pile cut-off within the clay core extended to a depth of approximately 13.5m and the piles, in conjunction with a temporary stiff frame of props and walers, allowed for an excavation to 5m below crest level – see Figures 4-12 for construction photos.

Figure 6. Installation of sheet piles using silent press (upstream)

Figure 7. Installation of siphon upstream legs

Diving operations to install the upstream siphon pipework and individual inlet cages began in earnest in 2023. It soon became apparent, however, that there was significantly more silt than anticipated from the previous bathymetric information. The design allowed for a depth of silt along the line of the siphons based on the previous information, but a detailed dive survey undertaken immediately prior to pipe laying confirmed that there was an additional depth of silt of up to~700mm and a discrepancy with the local bathymetry.

Combined, this meant that the siphon upstream leg would be greater than 2m above the embankment face at points. By this time, however, the pipework had already been procured; therefore, there was minimal scope to amend the alignment of the pipework. The Designer worked within the limits of the procured pipework to re-profile the upstream siphon legs to follow the embankment face as closely as possible and re-designed the upstream pipe supports to minimise their maximum height and ensure their stability. These two changes successfully ensured that the design remained valid, construction was able to continue without delay, and that there was minimal resultant impact to the pipework procurement.

Figure 8. Backfilling siphon pipes downstream of Crest Chamber

Figure 9. Blinding of Crest Chamber

Figure 10. Crest valves showing horizontal and staggered orientation

Figure 12. Construction of Outlet Chamber with outlet valves

Commissioning

At the time of commissioning, the Detention Pond had not been constructed. Whilst no water could be discharged from the siphons, each was fully primed as part of the final commissioning exercise. The accepted commissioning methodology set by the QCE consisted of priming each siphon without use of the cross connection from the HLD – the worst-case condition – in less than two hours and holding the siphons at prime for a minimum time of 30 minutes.

Priming of all three siphons was successfully demonstrated, with each primed from empty in approximately 35 minutes – the typical time to prime each siphon using the cross connection from the HLD is estimated to be approximately 15 minutes. The siphons were shown, via the installed instrumentation, to hold their prime for far longer than the 30-minute target set by the QCE.

The project fully achieved its objective to satisfy all MIOS by enhancing the reservoir drawdown capacity to provide an average drawdown rate over the top 5m depth of at least 0.8m/day. The Section 10(6) certification was issued by the QCE ahead of the MIOS deadline.

Flood Plans

The Client has Flood Plans in place for each of their statutory reservoirs and conducts a test of their emergency (on-site) plans at a selected site each year. The most recent exercise at Draycote Reservoir was in 2015 and accrued several “lessons learnt”.

The previous emergency drawdown at Draycote Reservoir was principally by temporary pumps established along each embankment. The 2015 exercise provided an appreciation of the logistics, establishment, and servicing (e.g., fuel, personnel, etc.) for the pumping installations required during an emergency event. The production of the inundation mapping, which showed impacts extending into several counties towards the west of the reservoir and beyond the M5, informed and captivated the attention of Local Resilience Forum responders.

The Client's Flood Plans, and the exercise undertaken at Draycote Reservoir in particular, provide confidence that the Client can enact the emergency (on-site) plan, including the operation of the significant capacity of temporary pumps when and where required.

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USBR (1987). *Design of Small Dams.* Bureau of Reclamation, US Department of the Interior, Washington DC, USA