ANNEX A2.1

Hydrology and Aquator Validation Report

This document has been written in line with the requirements of the RAPID gate two guidance and to comply with the regulatory process pursuant to Severn Trent Water's and Affinity Water's statutory duties. The information presented relates to material or data which is still in the course of completion. Should the solution presented in this document be taken forward, Severn Trent Water and Affinity Water will be subject to the statutory duties pursuant to the necessary consenting process, including environmental assessment and consultation as required. This document should be read with those duties in mind.

Grand Union Canal Transfer SRO

Affinity Water, Severn Trent Water, Canal & River Trust

Grand Union Canal Hydrological analysis and Aquator Model Validation and Impact Assessment

Report (Final)

September 2022

www.jbaconsulting.com

Author names redacted

JBA Project Manager

[redacted]

JBA Consulting, Pipe House, Lupton Road, WALLINGFORD, Oxfordshire, OX10 9BS

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Contract

This report describes work commissioned by Affinity Water, by purchase order AWP120016343 dated 18/05/2021. [redacted] of JBA Consulting carried out this work.

Prepared by .... [redacted]

Assistant Hydrologist

Prepared by .... [redacted]

Engineer

Reviewed by .... [redacted]

Principal Hydrologist

Purpose

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Executive summary

Water companies in England and Wales are currently investigating a wide range of potential ways to address the long-term challenge of providing resilient, sustainable sources of potable water in the face of the challenges of climate change, population growth and the need to reduce unsustainable abstractions. One of these Strategic Resource Options (SROs) under consideration is to use the Grand Union Canal to transfer treated effluent from Birmingham to the Affinity Water central supply area which forms a ring around the west and north of London. The project is being developed collaboratively by Affinity Water, Severn Trent Water (STWL) and the Canal & River Trust (the Trust). JBA Consulting have been commissioned, through the Affinity Water Professional and Technical Services framework, to undertake hydrological, hydraulic and water quality modelling of the transfer, along with hydrometric and topographic surveys of the canal and connected watercourses.

As part of the Grand Union Canal Strategic Resource Option (GUC SRO) Gate 2 Integrated Design Strategy, this report documents the updates and validation of the Grand Union Canal Aquator Water Resources Model.

The overall purpose of the water resources modelling is to assess the impact and feasibility of the proposed transfer of water from Minworth to the Grand Union Canal on the navigability of the canal along with any increase in potential flood risk resulting from the transfer.

The SRO proposal under consideration is that up to 115 Ml/d of treated water is transferred from STWL's Minworth sewage treatment works (STW) to Affinity Water's area via the Grand Union Canal. Affinity Water will abstract the water at Leighton Buzzard.

A comprehensive modelling approach was designed and executed to model both water movement through the canal and hydraulic control aspects of the entire canal system involved in the SRO. Both water resource behavioural modelling (using Aquator XV software) and hydraulic modelling has been undertaken. In addition, a separate hydrometric survey compiled observed data to assist with validating current water level and flow in the canal network and improve the models. The hydraulic model development and performance is not addressed in this report (see Annex A2.2).

Original Aquator XV models were supplied by The Trust and a revised model was developed. The inflows used in the Aquator XV model required updating. The original inflows in the model are principally based in a calibration from data between 1997-1998. Since then, several additional gauges have data recorded, both owned by the Environment Agency (EA) and The Trust. The gauged data in the area was reviewed and a suitable set of gauges was identified and used as donor gauges for the development of revised inflows. Rainfall-runoff models were calibrated using the Probability Distributed Moisture (PDM) rainfall-runoff model.

The revised inflows have been validated against spot flows and continuous gauge data (where available) and have been benchmarked against LowFlows estimates for each feeder catchment to ensure the flows were representative. Modelled flows were deemed a reasonable representation of the observed and are suitable for use in Aquator modelling. The flow duration curve comparisons and the flow signature pattern for annual and monthly flow estimates compare very well.

Updated inflows were imported into the baseline model and used to run the model for the period 1961-2022 for the purposes of validation of the baseline model. Aquator flows have been validated against the spot gauging undertaken during Phases 1 & 2 of this study as well as against observed long term flows at The Trust's gauges. These comparisons concluded that the model performance is reasonable, but there are still some limitations associated with modelling back-pump operation and by-weir flow movement. Most comparisons made are based on volume and flow estimates as level is not a primary variable that Aquator estimates with sufficient accuracy. The

validation of pound water levels was carried out using the hydraulic model (Annex 2.2).

To stress-test the Aquator model performance under very low flow conditions, a drought scenario analysis was undertaken. Historical inflow data were inserted into the Aquator model, and an exercise was undertaken comparing drought to baseline model runs for the 2017-2019 period. The effect of the drought scenario flows on Aquator model results is small. Generally, the changes to the abstractions from Tove, Ouse and Ledburn are small (less than 5% change compared to baseline scenario). This lends confidence to the calibrated flows used for the updated Aquator model and their ability to simulate drought conditions in the GUC canal system.

Following development and validation of the baseline model, the SRO transfer was input into the model, modelled as an input into the Atherstone Pound and as an abstraction (via a demand centre) at Leighton Buzzard. A series of changes were made in the model to facilitate the transfer including increases to back-pump capacities, increases to by-weir capacities and lowering control curves where necessary to allow storage.

The with-scheme model has been run and the results analysed with key conclusions being as follows:

- There are 12 years where failures have been observed which are summer failures when the maximum demand of 115 Ml/d is not met. Several of the years identified are in line with national hydrological droughts. The deficit is between 10-30 Ml/d depending on the drought incident and typically last between 1-3 weeks. These occur because during these periods, normal operating procedures in the canal are not occurring due to the canal levels dropping below normal operating levels. So, although the water is still supplied from Minworth, it is not possible to move through the canal due to lower-than-normal levels.
- Comparison of annual abstractions for the baseline and with-scheme scenarios suggest that generally the largest increases in annual abstracted amounts are related to changes in control curves made, increasing the amount of water abstracted from the feeders. These abstractions are all limited however to the existing licence, with is never allowed to be exceeded.
- An attempt was made to amend the control curves for the pounds along the SRO transfer route to operate more seamlessly and minimise spillage, however this aspect needs more work at Gate 3. The activation of back-pumps is reliant on these levels and as the system currently works, the with-scheme model abstracts more water from The Trust's reservoirs (Braunston Summit reservoirs and Tring Group reservoirs) as these are the sources that are used to fill the pounds to bring them back to a 'healthy' resource based on the current control curve rules. If this is addressed, there will not be as much water pulled from the reservoirs as the need for it is due to model limitations.
- The impact of the scheme on pound spills has also been assessed and there are instances where there is significant spill, especially in the Atherstone pound when water cannot be moved through the back-pump to the upstream pound. However, this is not necessarily observed in the same locations within the hydraulic modelling when velocities and slope of pound are introduced which cannot be hydraulically simulated in Aquator.

Generally, the modelling suggests that the SRO scheme can generally safely pass through the canal.

Further work will be required at Gate 3 to address:

- Location and magnitude of changes to the operations of the canal to activate back-pumps.
- Location and nature of engineering solutions to allow for increased flow to by-weirs needs to be added to the model.
- Operational rules to manage levels for the pounds along the SRO transfer route to operate more seamlessly and minimise spillage. Due to the way Aquator works, the activation of back-pumps is reliant on these levels and as the system currently works, it shows more of an impact on The Trust's reservoirs as these are the sources that are used to fill the pounds to bring them back to a 'healthy' resource based on the current control curve rules.

Contents

1 Introduction

1.1 The project

Water companies in England and Wales are currently investigating a wide range of potential ways to address the long-term challenge of providing resilient, sustainable sources of potable water in the face of the challenges of climate change, population growth and the need to reduce unsustainable abstractions. One of these Strategic Resource Options (SROs) under consideration is to use the Grand Union Canal to transfer treated effluent from Birmingham to the Affinity Water central supply area which forms a ring around the west and north of London. The project is being developed collaboratively by Affinity Water, Severn Trent Water, and the Canal & River Trust (the Trust). JBA Consulting are commissioned, through the Affinity Water Professional and Technical Services framework, to undertake hydrological, hydraulic and water quality modelling of the transfer, along with hydrometric and topographic surveys of the canal and connected watercourses.

As part of the Grand Union Canal Strategic Resource Option (GUC SRO) Gate 2 Integrated Design Strategy, this present report documents the updates and validation of the Grand Union Canal Aquator Water Resources Model.

The SRO proposal under consideration is that up to 115 Ml/d of treated water is transferred from STWL's Minworth STW to Affinity Water's area via the Grand Union Canal. Affinity Water will abstract the water at Leighton Buzzard.

1.2 Study context

The Gate 2 Integrated Design Strategy consists of several parallel investigations including an engineering study[1] and environmental and water quality monitoring to identifying areas of potential impact of the scheme. The Gate 2 modelling study has been commissioned to build and develop the hydraulic and Water resources models. The purpose of the water resources modelling is to assess the impact of the proposed transfer of water from Minworth to the Grand Union Canal on the navigability of the canal, along with any increase in potential flood risk resulting from the transfer, any changes to operations compared to the baseline and to provide inflows into the hydraulic model. The hydraulic model development and performance is not addressed in this report.

Under Phase 1 and 2 of this study (as recommended in Gate 1) the Trust's existing Aquator XV models of the Birmingham Canal Network (BCN), Oxford Grand Union (OxGU) and Grand Union Tring (GUT) have been combined into a single system model, hereafter referred to as the combined model. Model tools to run multiple simulations and transfer data between the water resources and hydraulic models have been developed to increase efficiency, capacity for scenario runs and reduce the potential for manual errors in the process. In parallel to this, hydrometric survey has been specified and collected for the period November 2021 – March 2022 for use in validation of the Aquator and hydraulic models (Section 2.5.2).

Phase 3 focuses on updating and improving the Aquator model, with updated hydrology of feeder catchments and validating the Aquator model performance a key focus of this process.

The modelled extent of the canal network is shown in Figure 1-1.

[1] Concept Design Report (WSP)

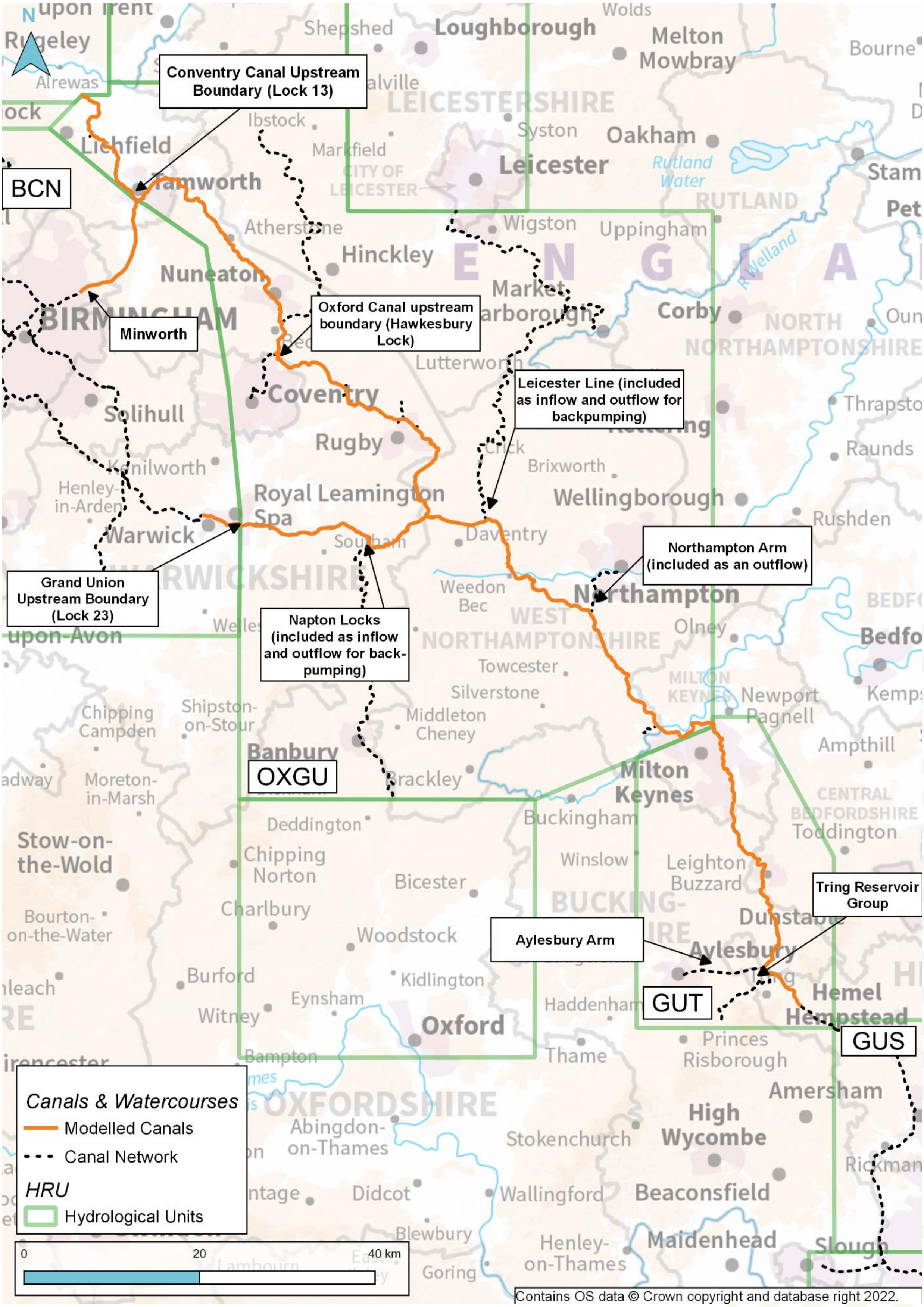

Figure 1-1 Overview of the key features along the transfer route and modelled extents

1.3 Approach

Water supply modelling projects typically involve simulating systems made up of many component parts that are interrelated and often not fully understood. For this project, a comprehensive modelling approach was designed and executed to model both water movement through the canal and hydraulic control aspects of the entire canal system involved in the SRO. A The modelling exercise is complemented by a hydrometric survey, This was a field-based data collection exercise which collected spot and continuous data over 130 locations across the canal network, compiled observed data to assist with validating current water level and flow in the canal network and to improve the models.

The whole modelling study has been done in close collaboration with The Trust who are owners and operators of the canal network, and their local knowledge and understanding is very important for the development of realistic models. The modelling was based on the Trust's existing Aquator models.

The approach used in the modelling of the SRO transfer through the canal network is outlined in Figure 1-2.

Key steps of the process are:

- Development of a baseline model to simulate the movement of water through the canal and subsequently the proposed SRO transfer.
- Two types of models were developed:
    - Water resource behavioural modelling: the Aquator XV model has been used for this with a specific canal pound and lock component developed for the purposes of simulating canal movement. This specific software was developed to simulate complex, conjunctive use water resource systems which have complex interrelationships between components and often competing objectives. Canal and reservoir operating rules are incorporated. The purpose of this model is to holistically represent the canal with the inclusion of the Minworth effluent, the canal feeders, and the reservoir system, as well as the demands and exports from the system and to assess if, where and when the introduction of the SRO could lead to imbalances to the demands of the system. A 60-year continuous model run is undertaken, and results are exported and analysed. Flows from this model will be used as boundary condition input to hydraulic modelling.
    - Hydraulic modelling: Canals have several hydraulic controls and levels at pounds trigger decision making. This cannot be simulated through the water resource modelling and a hydraulic model is developed. This is discussed in a separate report[2].
- The inflows used in the Aquator XV model required updating. The original inflows in the model are principally based in a calibration from data between 1997-1998. Since then, several additional gauges have data established, both owned by the EA and The Trust. The gauged data in the area was reviewed and a suitable set of gauges was identified and used as donor gauges for the development of revised inflows. Rainfall-runoff models were calibrated using the Probability Distributed Moisture (PDM) rainfall-runoff model[3].
- As mentioned previously, a simultaneous hydrometric survey has been collecting:
    - 3-month continuous level data at key pound spill locations; and
    - spot gauging data at key feeder flow locations, pound spills and by-weirs

  The purpose of the above data is to validate both the Aquator XV and the hydraulic model results and contribute to improvements with these models.

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[2] Hydraulic modelling Gate 2 (2022)

[3] Moore, R. J.: The PDM rainfall-runoff model, Hydrol. Earth Syst. Sci., 11, 483–499, https://doi.org/10.5194/hess-11-483-2007, 2007.

This report describes:

- The updates to the hydrology based on the revised data review and calibration of the PDM models.
- The validation of the revised inflow series based on the spot gauging data and observed data supplied by The Trust.
- The validation of the Aquator model using both spot gauging information and observed data supplied by The Trust.
- Stress testing of the Aquator model using historical flow data to simulate a drought period (2018-2019).
- Aquator modelling using the proposed scheme in place and the results of this process.

The hydraulic model is described and discussed in a separate report(Annex A2.2).

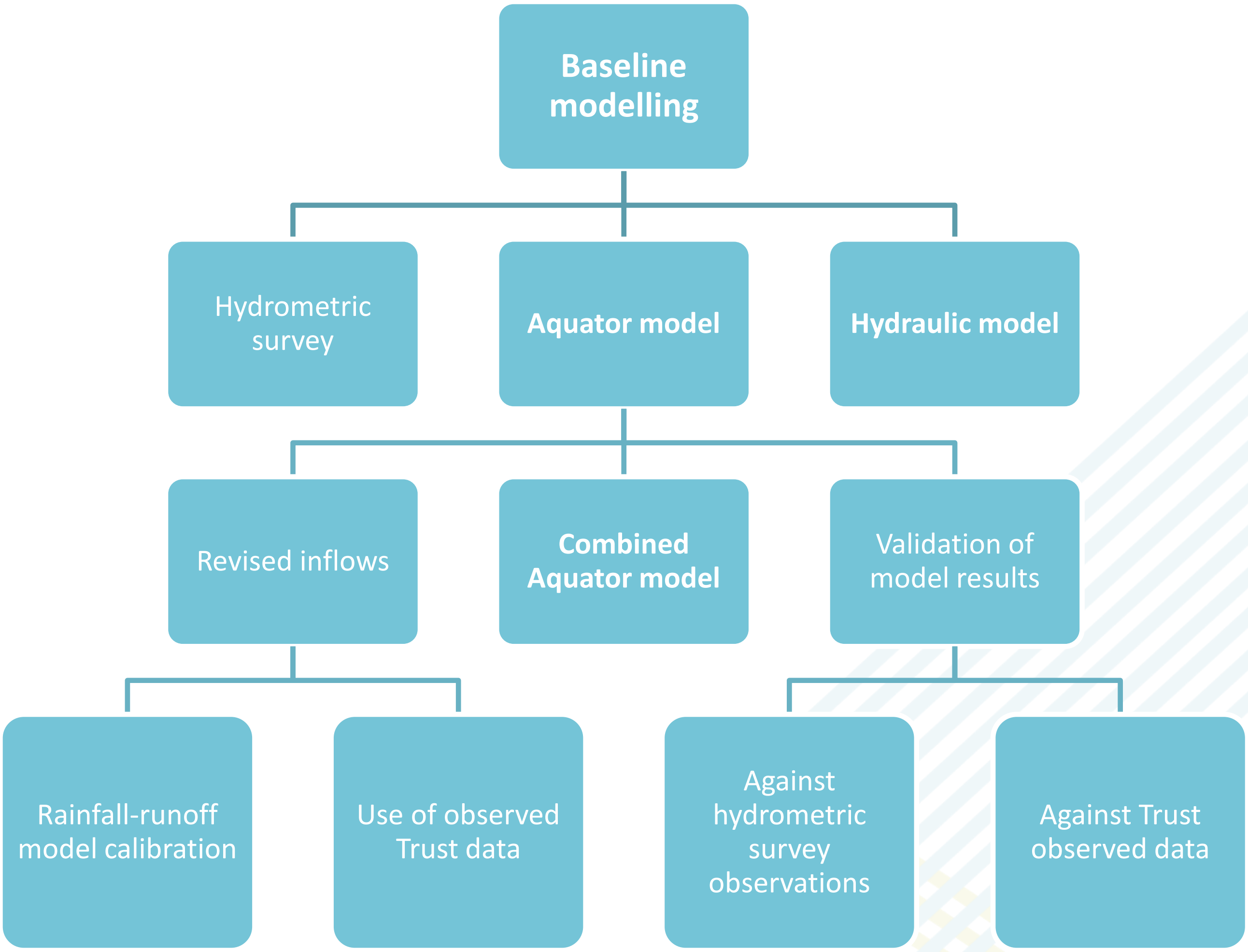

Figure 1-2; GATE 2 -Modelling approach

2 Available Data

2.1 Context

This study made use of several hydrological and meteorological datasets both available in the public domain and specifically sourced from The Trust and other government organisations. The hydrometric survey undertaken as part of this project also greatly assisted with validating the modelled outputs. Rainfall, potential evaporation, river flow and canal-specific level and flow data have all been used to update and validate the Aquator model.

2.2 Rainfall

For each feeder catchment continuous 60-year long rainfall records have been derived for the period 1961-2021 using HadUK[4] data and nearby EA permanent gauges.

For the period 1961-2020 HadUK daily rainfall data has been used. HadUK is a gridded dataset of meteorological variables based on observations at weather and climate stations. The data have been interpolated from the irregularly spaced stations to a regular grid at a 1kmx1km resolution. The gridded data has been aggregated to feeder catchment areas by calculating the fractional area contribution of each grid cell to a relevant catchment and calculating an average rainfall timeseries. This dataset has been used in preference to CEH data as it has been through extensive QA, requiring no infilling of suspect and missing data and as it is understood that it is frequently updated.

HadUK data is yet to be released for 2021 and 2022 (at the time of writing) therefore EA rain gauges have been used to derive weighted catchment rainfall records for the period 2021-2022 using Thiessen Polygons. Initial quality checks on the EA data from the rain gauges raised some instances of missing or suspect data that required infilling. The records for gauges were infilled using donor gauges which were geographically close and with comparable average annual rainfall.

Following QA, further checks were done comparing the EA and HadUK data for the common period 2018-2019/2020 (dependent on gauge data availability) to ensure the two data sources gave comparable rainfall and to give confidence to the suitability of the combined long-term rainfall record as representative of the local rainfall conditions in the catchment. Overall, for the catchments examined, there is a good agreement between the HadUK, and EA rain gauge data and the combined records are suitable for use in PDM rainfall runoff modelling.

A detailed table with information on gauge and weights is shown in Appendix A.

2.3 Potential Evaporation data

The newly released EA PET dataset[5] has been used for representing catchment potential evapotranspiration (PET). This dataset represents well-watered grass and is available either with an Interception element (PETI) or without one (PET). The dataset has been calculated from homogenised climate station data, gridded to a 1km resolution. The dataset starts in 1961, is available on a water day (09:00 to 09:00 on the following day) timestep and is updated regularly.

The PET gridded data (without an interception element) has been aggregated to feeder catchment areas by calculating the fractional area contribution of each grid cell to a relevant catchment and calculating an average PET timeseries.

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[4] Met Office, Hollis, D, McCarthy, M, Kendon, M, Legg, T and Simpson, I (2018) HadUK-Grid Gridded and Regional Average Climate Observations for the UK. Centre for Environmental Data Analysis, Didcot, UK.

[5] https://environment.data.gov.uk/dataset/f8836b22-ba9a-4bd1-8a42-d44b68ef837e

2.4 River Flow

The Environment Agency (EA) have several gauges on watercourses that serve as canal feeders or are deemed suitable as donor catchments for hydrological modelling. These are located along or adjacent to the study reach which have been used for purposes of model calibration. Daily inflow data for these gauges has been downloaded from the NRFA website[6] or the EA hydrology portal[7]. The Trust also gauge some of their feeder catchments, particularly around the Tring summit and have provided data up to February 2022. Where available, this data has been used for calibration and validation of the hydrology.

2.5 Canal flow and level data

2.5.1 Trust Data

The Trust have previously provided hydrometric data from over 159 monitoring points along the modelled length of the Grand Union canal for use in Gate 1 up to end 2019. An update to the data for relevant gauges has been requested, along with some new sites, to update the data to February 2022. Canal data provided includes:

- Canal levels
- Bypass flow around key locks represented in the Aquator model
- Canal pound flow
- Reservoir outflows
- Pump station flow and levels

It should be noted that generally much of the available data is canal level data and there is limited canal flow data available. Most of the flow sites shown on the below figure are flows recorded moving through a pumping station.

[6] https://nrfa.ceh.ac.uk/data/search
[7] https://environment.data.gov.uk/hydrology/explore

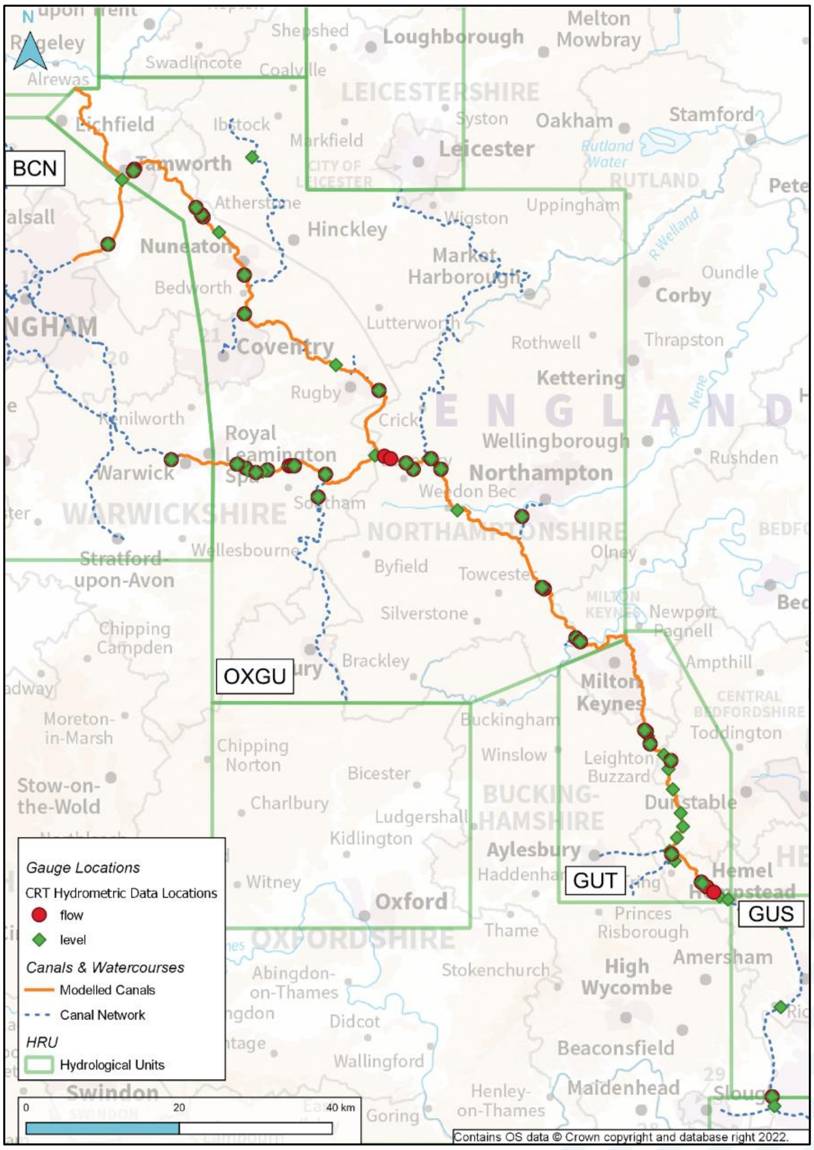

Figure 2-1; Trust Gauge locations along the transfer route

2.5.2 Hydrometric survey

Hydrometric Survey of the Grand Union Canal SRO transfer route was commissioned by Affinity Water to facilitate this project. The survey was undertaken by JBA Consulting and WHS over a period of 4 months, from November 2021 – March 2022. They key aims of this survey were to:

- Understand the relationship between canal level and spill over waste weirs in pounds which typically spill with current operation. This has been achieved by continuous level monitoring in pounds which spill in the baseline model runs, spot flows of spill over the control weir (lowest weir in the pound, feeders and the flow over the by-weir at the uphill and downhill locks in the pound.
- Understand the relationship between flow in the canal (measured at by-weirs where flow bypasses locks) in adjacent pounds and along a canal stretch between summit and trough pounds. This has been achieved by a canal spot level and flow survey along the length of the transfer route, measuring canal level at the lowest weir in each pound, spill (if there is any) and flow at the uphill and downhill by-weirs.
- Verify the feeder input to the canal for the largest feeders. Feeders contributing more than 1 Ml/d in the Gate 1 baseline model runs have been spot flow gauged during the monitoring period.

Hydrometric survey sites are shown in Figure 2-2.

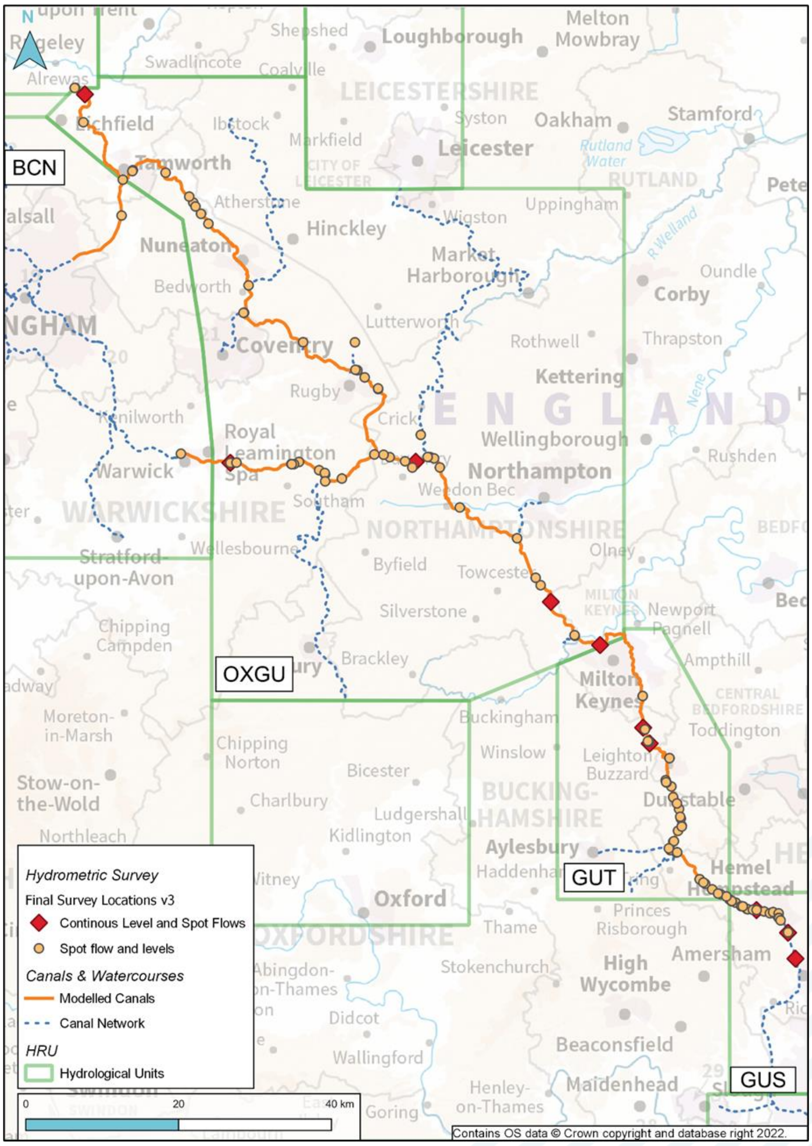

Figure 2-2; GUC Hydrometric Survey locations

Due to time pressures, hydrometric survey was collected during the Winter period, whereas the scheme is likely to be running at peak operation in summer. Canal operations are designed to conserve water in summer, so differences are expected in the system flow between these periods. However, spot gauging the canal in summer would have been a much more difficult task as boat movement is at its highest causing pound surging and disrupting measurements and velocities would have been lower making recording measurements more challenging. It also meant that the disruption to navigation was limited.

2.6 Trust Aquator Models

The Trust hold Aquator XV models of the canal systems required to be included in the combined model and these have been provided for use in this study. These were the starting point for the SRO Aquator model development. See Section 3.1 for more details.

JBA consulting

3 GUC SRO Aquator Model

3.1 Aquator XV software

The Aquator software enables the development and simulation of complex models of real-world water resource supply networks and systems. Users construct a representation of a water system by dragging and dropping components from a toolbox onto the schematic area. Users then enter values for the parameters required by each component to generate a fully working model. Each component encapsulates a set of operating rules; Hydro-Logic® Aquator seeks to satisfy daily demand by automatically enforcing these rules no matter how complex the system.

While obeying these rules Aquator executes a linear optimisation algorithm known as Aqua solver, which tries to find the best solution for daily water movement by supplying at lowest cost when water is plentiful or supplying according to the state of resources when water is scarce.

3.2 Canal Operations within Aquator

Some key concepts of how the canal system is modelled in Aquator are described to put in context the logic of the canal component and key changes required to be made to the baseline Aquator model so that the transfer is successfully moved through the system.

- Canal Pounds: A custom Canal Pound component is provided as part of The Trust Aquator extension which is based on the Reservoir component but with the crucial difference that water may be moved through each pound. The primary reason for including this behaviour is to allow for water to be moved through the canal network from a supply to a demand. This behaviour is not enabled by default in this component, but parameters are provided to override this by enabling bulk supply and refill in the canal pound component. This needs to be enabled for the transfer to take place.
- Canal Locks: Every lock along a canal has limits as to how much can flow through the lock each day. So even if it seems like water can be moved to meet demand the amount available may be limited. Water can be moved upstream to meet a demand if and only if every lock has the backpump option enabled. And then the amount is limited by the smallest backpump capacity in a flight of locks. The lock by-weir enables movement of water from upstream to downstream pound bypassing the lock.
- Control curves: A control curve needs to be set on each pound so that resource state is calculated in the way required. This is the level in the pound that transfer to a lower pound would normally cease.
- Bulk transfer is a transfer from a supply to a demand. By design a bulk transfer from a supply (reservoir, groundwater, river abstraction) to a demand (demand centre, reservoir refill) cannot affect the level of any pound. Conceptually the water is moved along the canal, into each pound and immediately out of each pound, through each lock, from supply to demand. Pound levels do not change unless the pound parameters "Pound.Can bulk supply" and "Pound.Can bulk refill" are set to true, which can add additional bulk water movements along a canal which will change the level for a pound.
- Advance order: This is the order in which supply network calculations are advanced

3.3 Phase 1 & 2: Combined Model Development

The water movements that take place in Aquator follow the sequence below:

i. Catchments add water to the river supply network and this water propagates down the river network until a Reservoir or Canal Pound is reached, or the end of the network is reached.
ii. Reservoirs and Canal Pounds lose water due to seepage and evaporation and gain water due to rainfall. If they sit in the river supply network, they will have gained in storage due to any catchment inflows.
iii. River regulation takes place to raise flows in rivers to the required level. The order in which this is done is called the *Regulation Order*, which is a parameter of each Canal Lock component.
iv. Aquator demand centre demands are met by drawing water from water sources. For example, if demand is met from a reservoir or pound this will decrease its storage, if drawn from a river abstraction this will decrease all downstream flows. This is done in Advance Order 1.
v. Reservoirs or Canal Pounds that have been drawn down by this process and are connected to an upstream Reservoir or Canal Pound by 'Supply' type components then refill to their fill control curve level from available sources which may include another upstream Reservoir or Canal Pound. This is called Advance Order 2.
vi. If there are more Canal Pounds in a canal system this process continues upstream, until the topmost Canal Pound is reached, using successively Advance Order 3, 4, …. The top pound may then be able to request extra water from one or more sources at the head of the system e.g., a supply reservoir or a river abstraction.
vii. At the end of the day any pounds or reservoirs that have a storage level above the 'spillway' or side weir crest, spill the excess water. The amount spilled each day can either be the entire amount (default) or specified by rating equation or rating table.

At each Advance Order, Aquator's optimisation is invoked whose objectives are to minimise cost and preserve resources that are being overused. From this, it can be seen that, in the context of a canal system there will be many of these optimisations during the day, one for each Advance Order. There will be no 'overall' optimisation. However, the single Advance Order optimisations help when a pound has more than one source that is able to restore its state to the preferred operating level.

3.4 Phase 1 & 2: Combined Model Development

Four Aquator XV models were provided by The Trust for use in this study and used to develop the combined model including:

- Oxford and Grand Union (OxGU) v2.4.4
- Grand Union Tring (GYT) v2.1.1
- Birmingham Canal Navigations (BCN) WTS
- South Oxford (SOX) v1.0

The SOX model has not been used at this stage as it was not needed to represent the area of interest as it was too far downstream. The other three models were combined into a single model. The starting point was the OxGU model into which were brought in a few components of the Birmingham Canal model (up to BF Pound 3-1) and the whole of the GUT model has been imported and linked through GU Pound 21-22. The figure in Appendix B shows the three models used and where they have been joined.

Several locks and reservoirs included VBA code which has been imported and updated to reflect the new component names where relevant for each component where code was present. General code was also present in the Grand Union Tring model and imported into the model section of the code.

Model checks were undertaken to ensure model components have been imported in a suitable way and that their behaviour is representative of the way they were built in the separate models. Model checks included:

- Check of all of references from old model to new
- Check of all locks and pumps dimensions
- Check on model components being represented
- Checks on time series and profiles used in sequences (including model boundaries and Control level refill and supply)
- Check VBA code transferred appropriately
- Checks to ensure the transfer from one model to the other is reasonable
- Introduction of custom variables where appropriate

3.5 Phase 3: Addition of the Trust Pound component

Following on from the combination of the models into a single Aquator XV model, JBA was supplied[8] with a new beta release of Aquator XV and additional VBA code including:

- Trust Macros
- Canal Connection
- Canal Connections

Revised Trust Macros, Canal Connection and Canal Connections code and Aquator XV release was later received[9] and replaced in the model.

The TrustMacros contained code to convert the model to use new components within canals: Canal Pounds and Canal Locks rather than Reservoirs and Locks previously used. This code converted all Locks to Canal Locks and Reservoirs linked to a Lock to Canal Pounds.

Following the conversion, sample checks were made to some of the Canal Lock and Canal Pounds to ensure data had been properly converted and that none was lost in the conversions process. This identified some discrepancies between lock components which were manually adjusted.

Additional adjustments undertaken was the conversion of two reservoirs (Startopsend and Wilstone) and back to reservoir components which were erroneously automatically converted to pounds and change of the Tove abstraction to a diversion to represent the flow more realistically. Both changes were agreed with The Trust.

3.6 Existing Hydrology and Model Inflows

In the existing Aquator Model (as provided by The Trust) daily inflows to feeder reservoirs have been generated by rainfall-runoff modelling using existing HYSIM models. The original model coverage was 1918 to 2003 (the first two years of which are set aside for model warm-up); and these model runs are extended as required with contemporary rainfall data and PET data to produce flow time series. Daily inflows from other feeders such as watercourses or effluent use scaled rainfall-runoff model outputs, gauged data if available, or annual profiles of flow.

There are 49 feeders in the along the transfer route which are split into the following types:

- Watercourse Inflows
  - The canal has inflow from a few rivers and smaller feeders. These can operate in two ways. Either the water flows into the canal without any control (i.e., inflow at all times) or the inflow is controlled, and water is

Author names redacted

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[8] Email from [redacted] received on 28/02/2022
[9] Email from [redacted] received on 28/02/2022

abstracted from the watercourse and transferred into the canal when canal levels are below their top water level.

- Reservoir Inflows
    - Canal flow is supported by a few reservoirs at the summit of the Oxford Grand Union and Grand Union Tring canal sections.
- Wastewater Treatment Works
    - There are two WwTWs that discharge into the canal in the OxGU and GUT canals, and Whilton WwTW's and Tring WwTW's. These are both continuous discharges of treated effluent.
- Lateral flows
    - Lateral inflows and losses are water entering the canal between the point inflow locations. This includes upslope natural drainage, inflow from the drainage network and inflow from groundwater. The net lateral inflow also includes losses to groundwater and evaporation. These components are uncertain and they cannot be measured individually and form the residual term in the water balance.

4 Hydrological analysis

4.1 Context

The existing inflows within Aquator are based on rainfall-runoff models developed in the early 2000s on behalf of The Trust by Water Resource Associates. The original inflow series were from 1918-2003 and length of time series was updated on a periodical basis.

These flows are principally based in a calibration from data between 1997-1998. Since then, several additional gauges both owned by the EA and The Trust have been installed in the region. The gauged data in the area was reviewed and a suitable set of gauges was identified and used as donor gauges for the development of revised inflows. The previous analysis used the HYSIM rainfall-runoff model. This software has not been updated for a few years and it was deemed that PDM modelling was a more appropriate tool, given contemporary widespread use across the UK hydrological community, and ease of use compared to HYSIM.

This section outlines the development of updated hydrology for use as input to the combined Aquator XV model.

4.2 Study Catchment Overview

The river catchments which feed water into the canal network are shown in Figure 4-1. The canal is fed by a diverse range of feeder catchments, with sizes ranging from over 1 km^2 to 500 km^2, though it should be noted that the majority of catchments are relatively small and have areas less than 20 km^2. Feeder locations were identified through examination of asset data provided by The Trust and discussions with The Trust hydrologists. Feeder catchments and catchment descriptors were subsequently downloaded from the FEH web service[10] for these locations. These catchments were checked against free mapping and the Detailed River Network (DRN) and manually updated where necessary.

Most feeder catchments are relatively flat and have surface water driven mechanisms for flow generation. There are a few catchments with special features:

- The Tring Summit Group- the Tring Summit Group feeders are a complex group of small chalk catchments, with spring-based flow regimes. All catchments in this group have a BFIHOST value of greater than 0.8 indicating significant influence of groundwater on flow.
- River Cherwell, Cropredy Mill- the feeder flow to this catchment is hydraulically constrained to a set value of 1.5 Ml/d.

A list of feeders with key catchment descriptors given for reference is given in Table 4-1; List of feeders with key catchment descriptors given for reference.

[10] CEH 2015. The Flood Estimation Handbook (FEH) Online Service, Centre for Ecology & Hydrology, Wallingford, Oxon, UK.

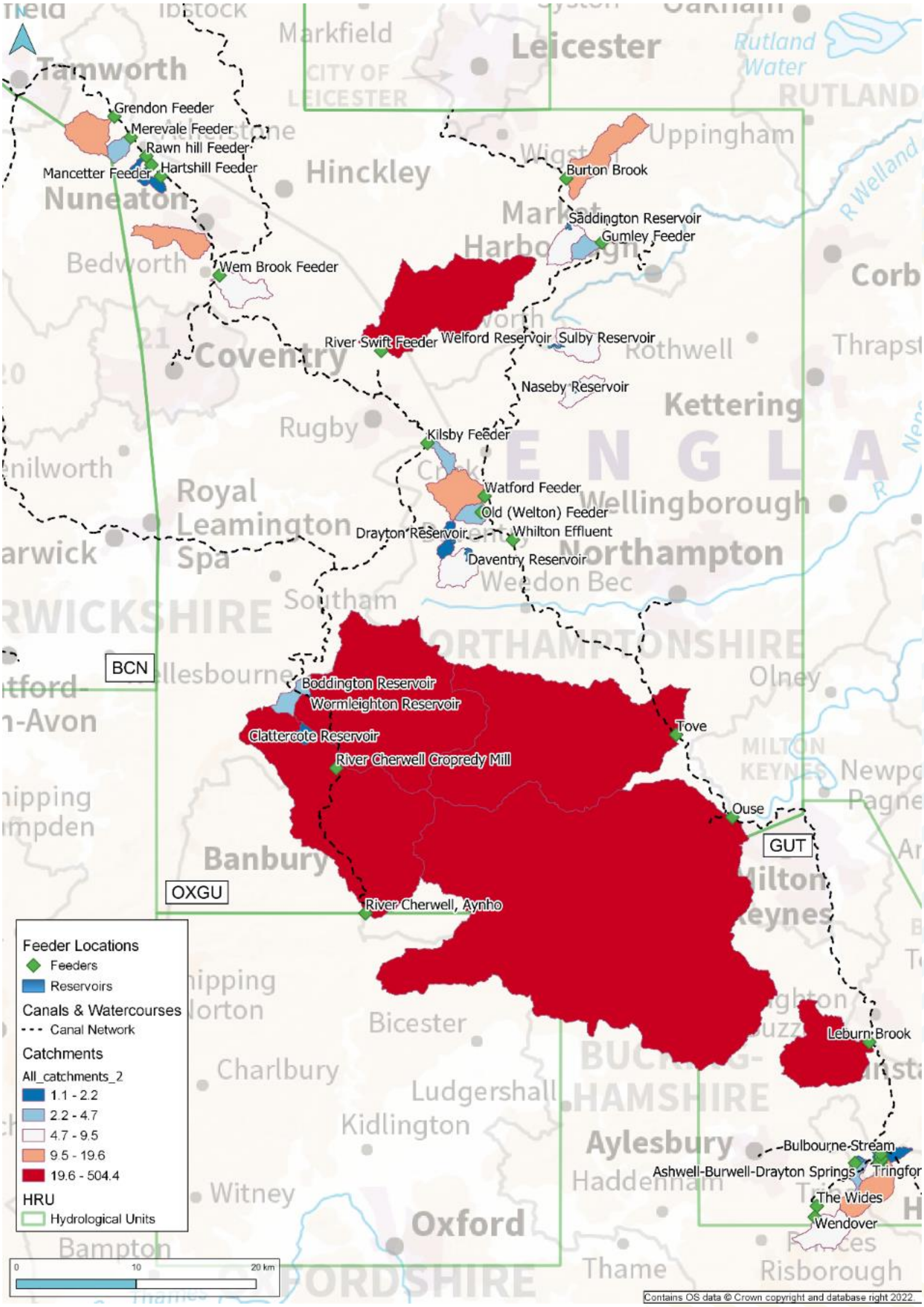


Figure 4-1; Feeder catchments colour coded by catchment area.

Table 4-1; List of feeders with key catchment descriptors given for reference. Catchment descriptors colour coded to add context and allow comparison between catchments. URBEXT: Red = more urbanised, White = less urbanised. BFI: Green= high groundwater component, White= small groundwater component. SAAR= White: higher annual average rainfall, Blue: lower average annual rainfall

Feeder	Area	BFI	SAAR	URBEXT
River Ouse	505.9	0.45	652	0.01
River Cherwell, Aynho	276.0	0.42	663	0.03
River Tove	171.9	0.38	655	0.01
River Cherwell Cropredy Mill	148.2	0.36	669	0.0113
River Swift Feeder	68.0	0.36	657	0.04
Ledburn Brook	34.5	0.34	651	0.01
Boddington Feeder	19.6	0.34	667	0.01
Burton Brook	15.4	0.35	648	0.00
Watford Feeder	11.2	0.36	665	0.00
Grendon Feeder	10.2	0.54	665	0.09
Griff Arm	9.3	0.37	675	0.06
Wem Brook Feeder	8.7	0.38	653	0.06
Sulby Feeder	8.4	0.35	681	0.00
Daventry Feeder	8.4	0.50	676	0.30
Tring Summit Feeder	7.6	0.87	726	0.12
Wendover	7.3	0.85	745	0.04
Tring Drainage	6.5			
Saddington Feeder	6.3	0.31	652	0.00
Naseby Feeder	4.7	0.40	684	0.03
Wormleighton Feeder	4.7	0.26	654	0.00
Old (Welton) Feeder	3.4	0.45	670	0.00
Gumley Feeder	3.2	0.25	650	0.00
Merevale Feeder	3.0	0.40	683	0.04
Kilsby	2.9	0.34	649	0.06
Wilstone Feeder	2.7	0.90	681	0.00
Bulbourne Stream	2.2	0.86	685	0.00
Clattercote Feeder	1.9	0.54	653	0.00
Drayton Feeder	1.8	0.36	674	0.33
Hartshill	1.5	0.44	689	0.06
Rawn hill Feeder	1.3	0.50	689	0.00
Mancetter Feeder	1.2	0.51	692	0.02
Tunnel Feeder	1.1	0.30	672	0.00
Welford	0.5	0.35	681	0.00

4.3 Donor Catchments

Most of the feeder catchments are small and ungauged, requiring the use of analogue or donor gauges. A review of the gauged catchments in the vicinity of the study area was undertaken, which identified several catchments that have useful data and hydro-climatological similarities with the feeder catchments and could be used as donors for the development of long-term flow sequences to be used in Aquator modelling.

Rainfall-runoff models have been calibrated for suitable donor gauges and the results scaled to feeder catchments. In the spring-based catchments of the Tring Summit group a mixed approach of both rainfall-runoff modelling and matching pairs analysis has been used based on available data and flow regime characteristics.

Donor gauges for ungauged catchments have been selected by considering spatial proximity, similarities in average annual rainfall, contributing catchment area and hydrological similarity as represented by base flow index and URBEXT2000. Due to the relative lack of gauged data on small catchments (compared to on larger watercourses) donor selection has focussed on hydrological similarity and spatial proximity rather than catchment area. Other considerations on donor selection were gauge record reliability and artificial influences on flow (reservoirs, WwTW's).

The donor gauges and their catchment descriptors are given in Table 4-2.

Table 4-2; Donor gauges and their hydrological characteristics

Gauge Name	Gauge Operator	Area (km^2)	BFIHOST19	SAAR	URBEXT	FARL
Wendover Springs at Wendover	Trust	7.3	0.85	745	0.04	1.000
Mease at Clifton Hall	EA	118	0.52	656	0.04	0.988
Bedford Ouse at Thornborough Mill	EA	389	0.47	655	0.01	0.980
Nene/Kislingbury at Dodford	EA	107	0.43	660	0.04	0.958
Swift at Churchover	EA	67	0.36	657	0.04	0.999
Tove at Cappenham Bridge	EA	138	0.36	661	0.02	0.986
Sence at South Wigston	EA	113	0.36	642	0.03	0.997
Clipstone Brook at Clipstone	EA	39	0.36	640	0.02	0.975
Tring Drainage	Trust	6.5	0.868	726	0.12	1.000

A map showing the donor gauges and the donor selected for each feeder catchment is shown in Figure 4-2. The full list of feeder catchments, donor selected, and catchment descriptors are given in Appendix D.

The resulting timeseries derived for each donor catchment has been scaled using either catchment area (scaled using the ratio of target and donor catchment areas) or mean flow scaling (scaled using the ratio of target and donor catchment mean flows as derived from the LowFlows 2 software). Where possible mean flow scaling has been used in place of catchment area scaling as this accounts for differences in catchment characteristics between the donor and target feeder catchment. Where catchments have similar characteristics and catchment areas catchment area scaling has been used. A summary of which method and donor has been used for each catchment is given in Table 4-6.

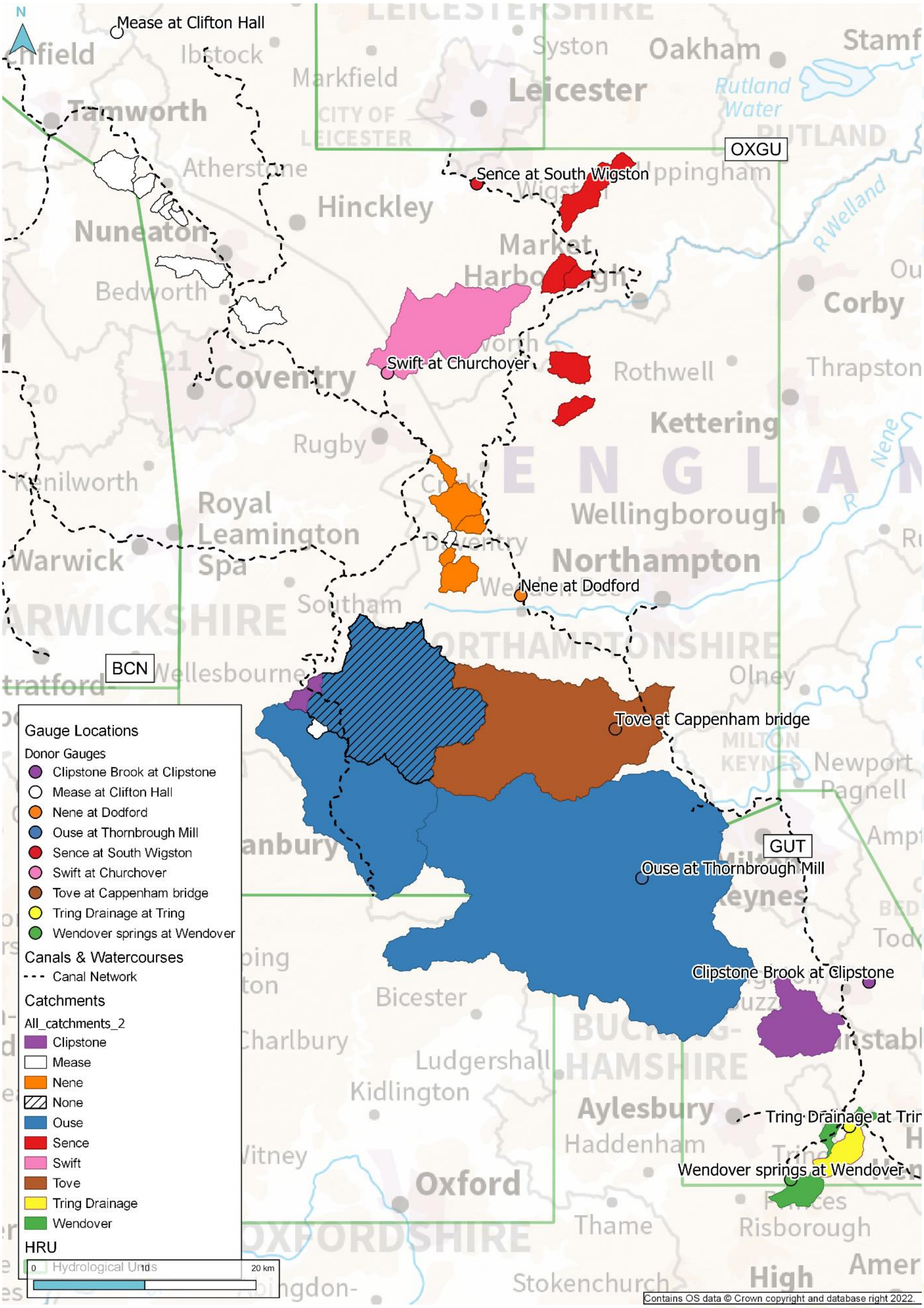


Figure 4-2; Location of donor gauges and the donor selected for each feeder catchment.

4.4 Rainfall-runoff modelling

The main purpose of the Probability Distributed Moisture (PDM) rainfall-runoff modelling is to produce flow datasets for use in an Aquator water resource model. The rainfall-runoff model is calibrated over a 10-year period using flow data from gauges on the feeder or an appropriate donor. The resulting model parameters from the calibrated 10-year model are then used to derive the 60-year flow series using the derived catchment rainfall and PET as an input.

4.4.1 Overview

The rainfall-runoff model used is the Probability Distributed Moisture model (PDM), a deterministic lumped conceptual rainfall-runoff model. The PDM concept, shared with other conceptual and transfer function models, includes the schematisation of the hydrological cycle as a series of stores, through which water travels as it falls as rain before finally emerging as river flow. The properties of these stores and how water is distributed amongst them are optimised during the model calibration, whilst the model parameters allow for physical properties of the soils and other catchment characteristics to be accounted for. This makes the PDM model a very suitable tool for this project. The version of the PDM used in this study specifies a surface store, through which direct runoff is routed, a soil store and a groundwater store. The generation of runoff is represented using a statistical distribution of soil moisture storage capacity. The proportion of the catchment where the storage capacity is filled up with water generates runoff, and it also generates drainage into a groundwater store. Over the rest of the catchment, rainfall goes into increasing the soil moisture (which can be depleted by evaporation, drainage, and runoff). Runoff and baseflow are routed through notional storage reservoirs (representing flow pathways via surface processes - such as river channels, soil, or overland flow - and aquifers respectively) before being combined to form the output of the model.

The default model structure has ten parameters, along with other optional parameters such as a time delay, addition of constant flow (e.g., known artificial inflow) and a rainfall scaling factor. The PDM model has been calibrated to observed flow data by adjusting parameters, informed by the lag response to rainfall, and the geology and soils of the catchment. The focus for calibration has been matching baseflows, while maintaining the recession on peak events.

4.4.2 Method and results

For each of the following donor catchments

- Mease at Clifton Hall
- Bedford Ouse at Thornborough Mill
- Nene/Kislingbury at Dodford
- Swift at Churchover
- Tove at Cappenham Bridge
- Sence at South Wigston
- Clipstone Brook at Clipstone
- Tring drainage

Initial parameters were imported in PDM based on catchment descriptors. Rainfall and PET derived as per sections 2.2 and 2.3 have been used for each catchment and the models were calibrated by amending key parameters. The PDM model has been calibrated to observed flow data by adjusting parameters related to catchment response and catchment store properties, informed by the lag response to rainfall, and the geology and soils of the catchment.

Final model parameters and detailed performance statistics are shown in Appendix A.

The main statistical measures used to assess performance of modelled versus observed data are:

NSE: Nash–Sutcliffe model efficiency coefficient

- PBIAS: Percent Bias
- R2: Coefficient of determination
- RSR: RMSE(Root mean square error) -observations standard deviation ratio

The majority of the model performance statistics suggests that performance is good to very good and this gives confidence to the performance of the model relative to the observed.

In addition to the above, key flow signatures have been investigated as these are continuous simulation models and flow signature patterns are important. The following were compared:

- Annual volume totals.
- Flow duration curves from observed, modelled, existing flows within model and Low Flows 2.
- Mean, median, and 5th-95th percentile of monthly flows, to establish differences between modelled and observed monthly variability to flows.
- Baseflow from observed vs modelled baseflow.

The performance of the models lends support to the calibration having been successful and the updated hydrology is considered an improvement to the previous one.

4.5 Tring Summit Group Hydrology

The Tring Summit Group feeders are a complex group of small chalk catchments, with spring-based flow regimes, feeding a large group of reservoirs. The feeders in this group are:

- Wendover Spring - gauged flow of the Wendover spring into the Wendover Arm.
- Wilstone Reservoir inflows - groundwater inflow into Wilstone Reservoir and flow from the Ashwell, Burwellhead and Drayton springs. The Wendover arm also feeds this reservoir as diverted by the Whitehouses sluice.
- Bulbourne Stream - groundwater inflow to Marsworth Reservoir.
- Tring Feeder – drainage channel draining the urban area of Tring. This feeder is gauged.
- Tring Drainage – thought to be combined flow from groundwater (including the Miswell-Dundale spring system) and a sewer/urban runoff component from the urban area of Tring. This feeder is gauged.

The exact sources of flow to the Tring Drainage and Tring Feeder catchments are uncertain, the above has been assumed based on discussions with Trust Hydrologists and examining the available flow data from both feeders.

The PDM model, while being suitable for modelling baseflow dominated systems, does not perform well when modelling entirely spring-based flows (with little to no surface runoff component) as they are not responsive to rainfall and due to the large variety of hydrogeological factors controlling flow which the model cannot replicate.

Therefore, in the Tring Summit group used a mixed approach of both rainfall-runoff modelling and transposing flows from other sites based on percentiles (matching pairs analysis) has been used based on available data and flow regime characteristics. The matching pairs approach has been used to infill and extend the long-term record at Wendover springs and this record has been area-scaled to represent the flow from the spring/groundwater systems. A rainfall-runoff model has been calibrated to the short gauge record at Tring Drainage and this has been extended. This has also been used based on mean scaling to represent the more urbanised Tring system.

4.5.1 Wendover Arm, Bulbourne Feeder & Wilstone Feeder

The Wendover Arm station record extends from 1963-present; the gauge record is relatively good though flows can be affected by weed growth on the weir and has been affected by drop out and missing data. The gauge record for Wendover has been infilled and extended to the start of the long-term model run period (1961) using matching pairs analysis. The record has then been area scaled to represent flows in the Bulbourne Stream and Wilstone Reservoir Feeder.

4.5.2 Transposing flow percentiles based on matching pairs analysis

Matching pairs is a technique used for linking the flow at the target gauge and an analogous longer term donor gauge to establish a relationship between the flows. In the Matching Pairs technique, the flow percentile from the analogue station is assigned to the daily mean flow recorded in the shorter record at the target station for coincident days. A relationship (commonly regression) is fitted to the data points to derive an FDC. The FDC is then converted back to a timeseries by assigning percentiles to each day based on the long-term record.

The analogue gauge chosen to infill the Wendover gauge is the Ver at Hansteads. This gauge has been chosen due to the length of record (1956-present) and hydrological similarities between the two gauges. The similarity of the two catchments is confirmed by a good Spearman’s rank correlation of 0.807, indicating this gauge is a suitable analogue. A comparison between the two gauges is given in Table 4-3.

Table 4-3; Comparison of the catchment characteristics between target and analogue gauges used in matching pairs analysis.

	Wendover Springs at Wendover	Ver at Hansteads
Catchment Area (km^2)	9.5	132
Record Length	1963-Present	1956-Present
BFI (from gauge record)	0.96	0.88

Matching pairs analysis was applied using the Ver at Hansteads as an analogue to the target site. Figure 4-3 shows a plot of the log flow values of the target gauge against the log flow values of the analogue station. The scatter of the observed target points about the fitted points is generally low, and there is a generally good fit to the regression line as demonstrated by the R^2 value of 0.66.

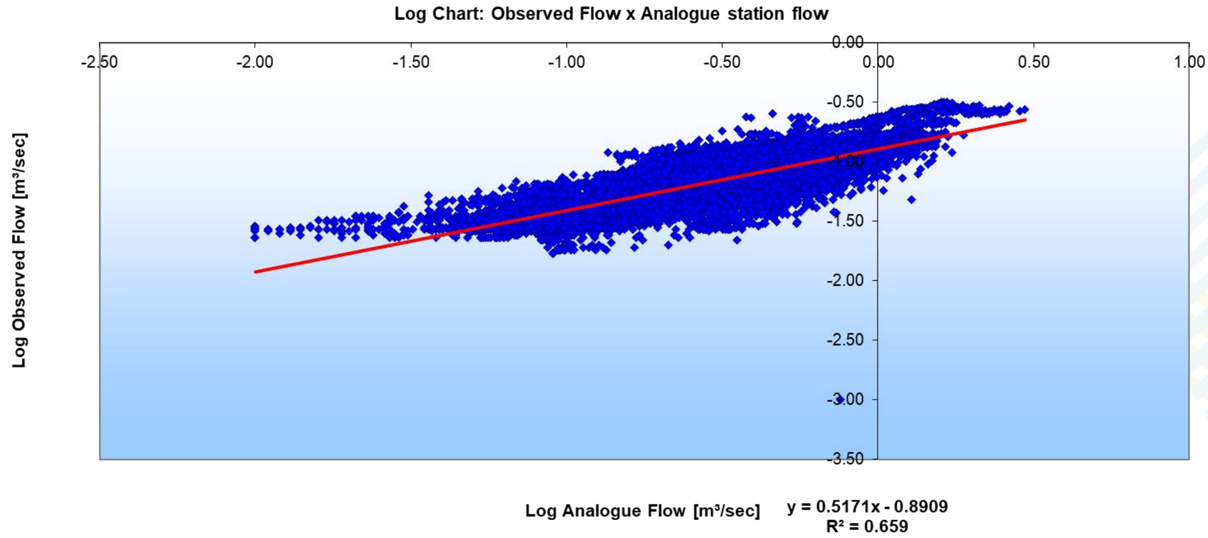


Figure 4-3; Wendover log flow plotted against Hansteads log flow for the common period

This analysis gives a relationship of $Q_{Target}=10^{Log(QAnalogue \times 0.517 - 0.8909)}$. This has been used to extend the Wendover Arm record back to 1961 and infill days of missing data. Overall, 9.1% of the record has been infilled for missing data. The extent of infilling is demonstrated in Figure 4-4 which shows the final infilled record for Wendover, with infilled sections highlighted for reference. Overall, the infilled sections compare well to the observed at Wendover. The infilled data shows more variability in flow than the flow at Wendover (Figure 4-5), it replicates longer-term flow patterns well.

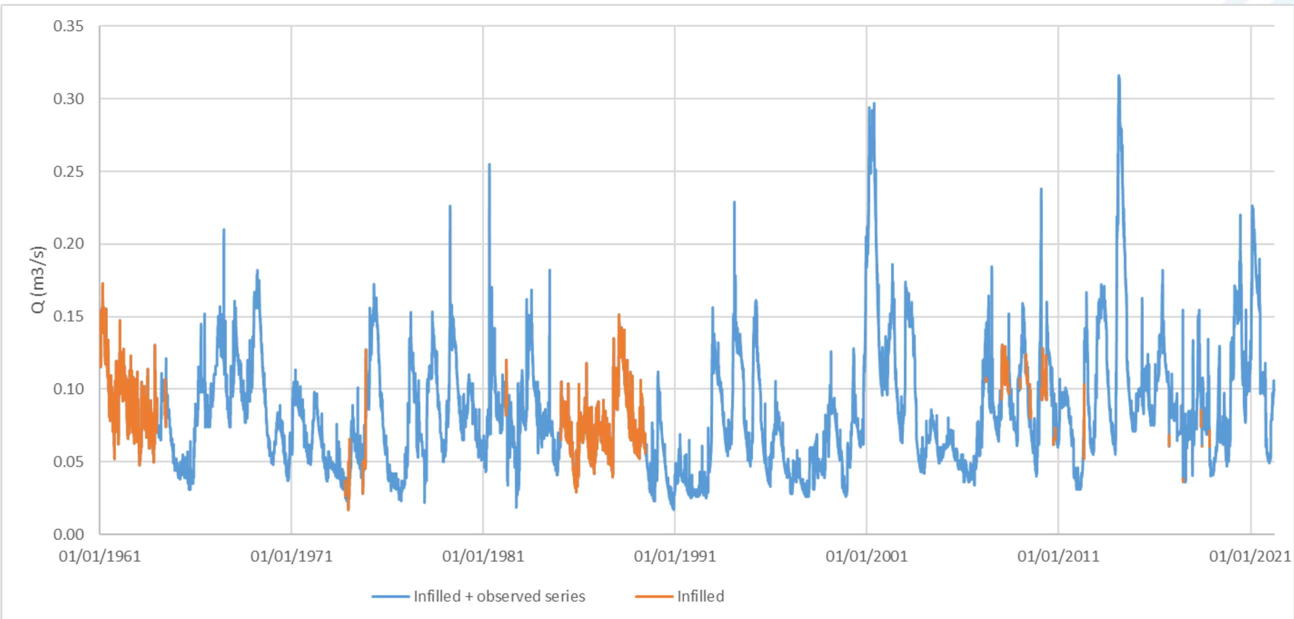


Figure 4-4; Final infilled record for the Wendover Springs, showing the extent of infilling with Ver at Hansteads.

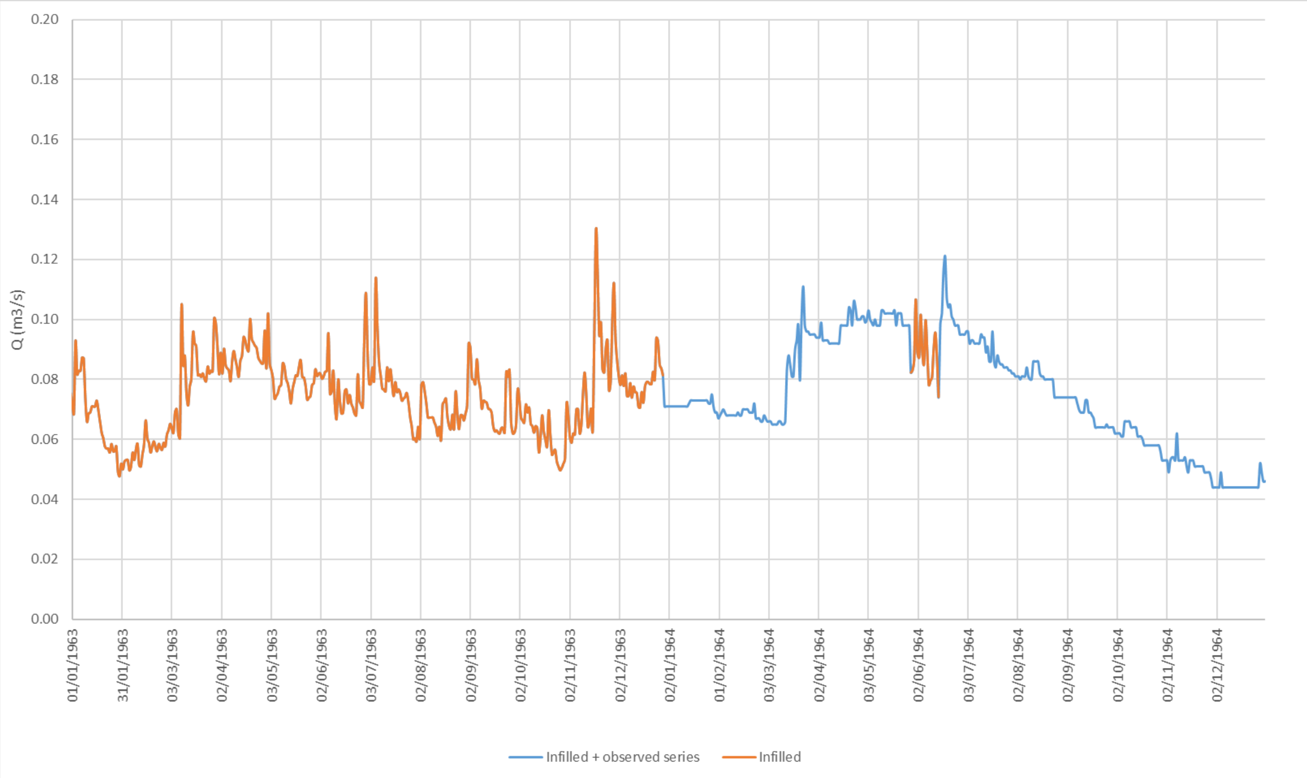


Figure 4-5; Final infilled record for the Wendover Springs, showing the transition between infilled and observed data in 1963.

4.5.3 Bulbourne Stream and Wilstone Feeder

Bulbourne Stream and Wilstone Feeder are ungauged feeders and therefore Wendover has been used as a donor to represent the flows from these feeders in the model. Table 4-4 shows a comparison of the catchment areas and descriptors of the Wendover Springs catchment, Bulbourne Stream, and Wilstone Feeder. This shows that all three catchments are very similar, with small urban components and high BFIHOST19 values of between 0.85 and 0.9.

Table 4-4; Comparison of the catchment areas and descriptors of the Wendover Springs catchment, Bulbourne Stream, and Wilstone Feeder.

Feeder name	Catchment Area (Km^2)	BFIHOST19	URBEXT 2000
Wendover Springs	7.3	0.85	0.04
Bulbourne Stream	2.22	0.86	0
Wilstone Feeder	2.69	0.90	0.04

This indicates that the catchments are generally hydrologically very similar, and area scaling the Wendover series is appropriate to represent flows in these catchments. The final derived long term flow series for the Wendover Springs, Wilstone Feeder and Bulbourne Stream are shown compared in Figure 4-6.

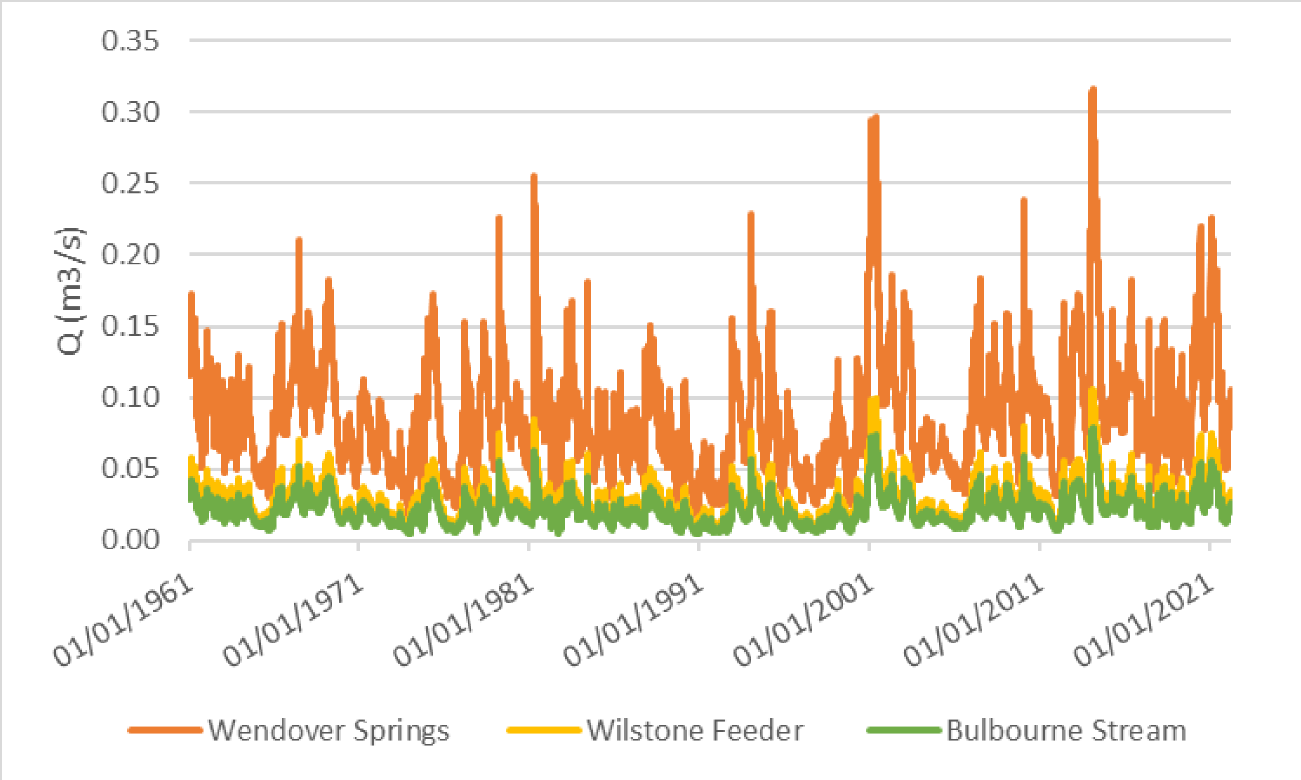


Figure 4-6; Comparison of the final derived long term flow series for the Wendover Springs, Wilstone Feeder and Bulbourne Stream.

4.5.4 Tring Feeder and Tring Drainage

4.5.4.1 Tring Drainage

The flows for this catchment have been derived using a rainfall-runoff model. This model has been set-up to calibrate to observed flow data at the Tring Drainage Gauge. The exact catchment area of this gauge is uncertain, as the exact sources of flow to this feeder are not known, and a significant proportion of the flow is from groundwater. The original HYSIM model of the Tring Drainage Feeder used a catchment area of 6.5 km^2 and this area has been maintained for use in this model. Rainfall and PET derived for the Wendover Catchment have been used as an input to the PDM.

Details of the PDM are found in Appendix C. The performance of the calibration has been good.

4.5.4.2 Comparison of Feeder flow regimes

Tring Feeder and Tring drainage are both gauged by the Trust, though both have relatively short gauge records. The gauge record for Tring Feeder begins in January 2021, Tring Drainage has been gauged since 2014 however the record is suspect until February 2020. Figure 4-7 shows a comparison of the gauged flows for Wendover Springs, Tring Feeder and Tring Drainage for the common period for which there is reliable data.

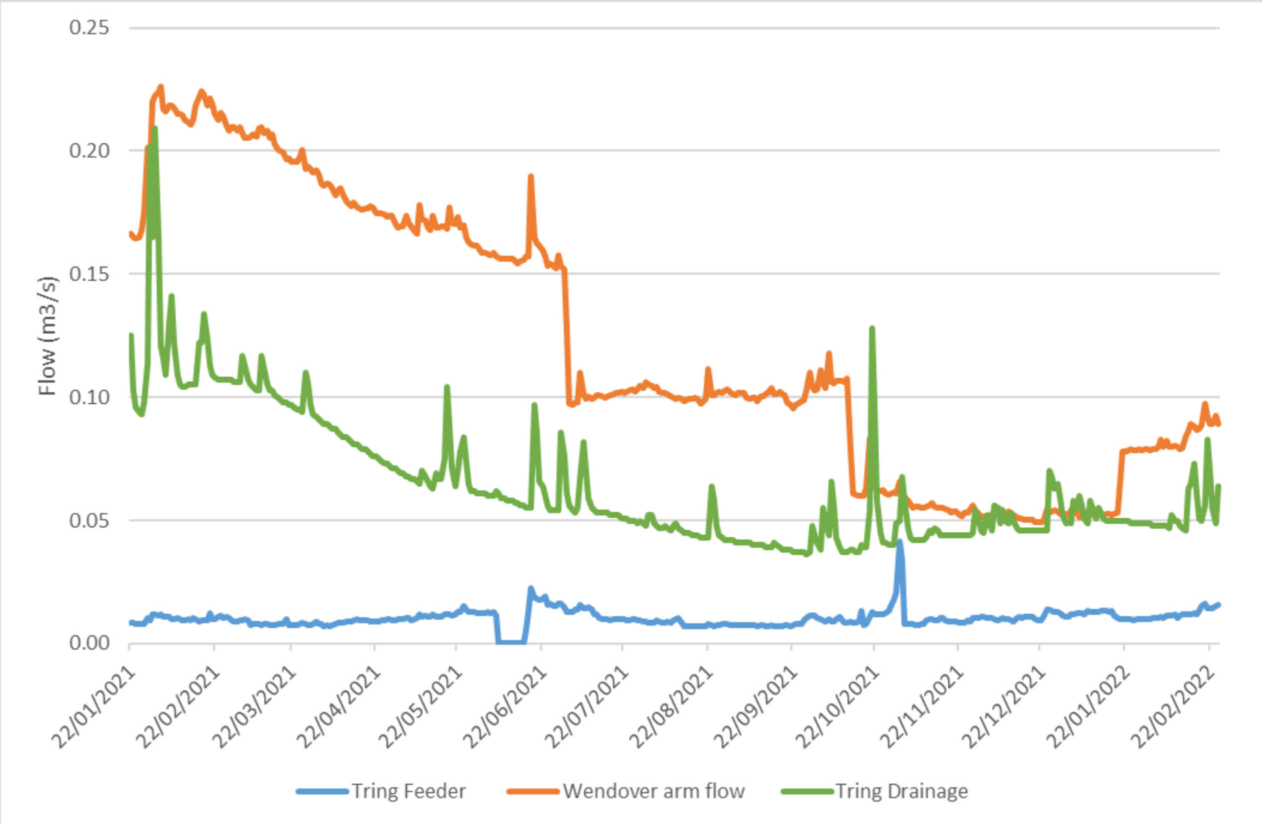


Figure 4-7; Comparison of the common period gauged flows for Wendover Springs, Tring Feeder and Tring Drainage

The Tring Drainage system shows a clearly different flow regime to the Wendover springs with a baseflow dominated regime with urban response runoff dominating peak flow behaviour. The Tring Feeder flows are typically very small with minimal baseflow contribution. Using Wendover as a donor for these catchments would therefore be inappropriate.

To represent the flow in this system a rainfall-runoff model has been calibrated to the Tring Drainage record. This has then been mean scaled to represent flows in the Tring Feeder.

4.5.4.1 Tring feeder

The rainfall-runoff model calibrated to the Tring Drainage flows has been mean scaled to represent flow in the Tring Feeder. Mean scaling has been used over catchment area scaling as the exact catchment areas of these feeders are uncertain. Mean flows were calculated for the Feeder and donor for the common period (Jan 2021-March 2022) and the scaling factor used to scale the Tring Feeder flows are given in Table 4-5.

Table 4-5; Mean flows for the Feeder and donor for the common period (Jan 2021-March 2022) and the scaling factor used to scale the Tring Feeder flows.

	Value
Average Feeder Flow (m^3/s)	0.01
Average Donor Flow (m^3/s)	0.06
Mean Scaling Factor	0.16

A comparison of the observed and model flows for the Tring Feeder are shown on Figure 4-8. Overall, the flows compare reasonably well for the common period, though the model flows have a higher baseflow component than the observed during Winter/Spring. The mean scaled rainfall-runoff series is considered suitable to represent the flows from the Tring Feeder for the purposes of Aquator modelling.

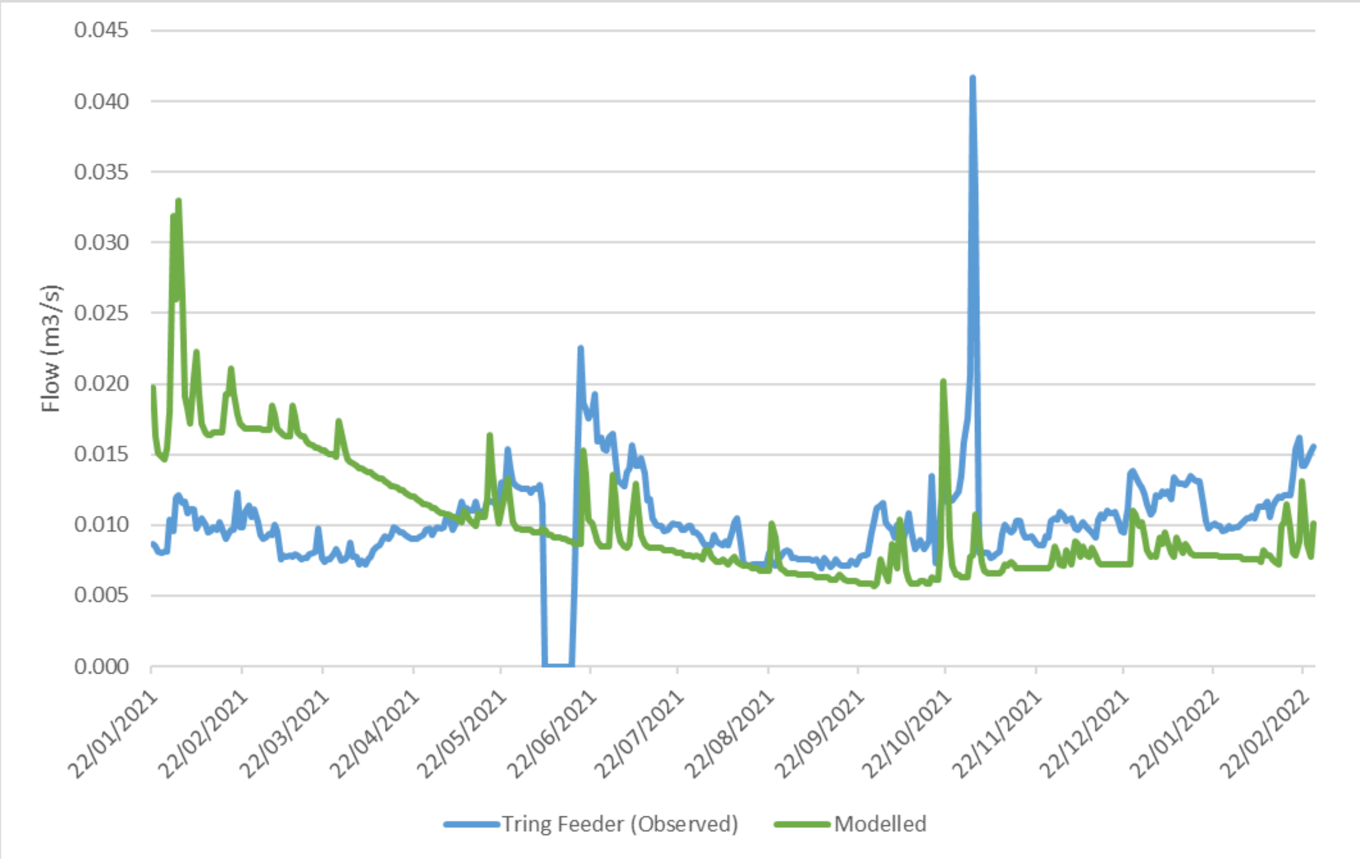


Figure 4-8; Comparison of the observed and modelled flows for the Tring Feeder

4.6 Method used to represent feeders – summary

The methodology for the derivation of the model inflows has been complex and based on analysis of several datasets, mainly post-2000 and review of donor suitability.

The table below summarises the feeders in the model, the donor used to represent the flow and the method used to represent the flows in the feeder catchment.

Table 4-6; Summary of method for inflow derivation

Feeder	Area	Donor	Method
River Ouse	505.9	Ouse	Area scaled model calibrated to the Ouse at Thornbrough Mill
River Cherwell, Aynho	276.0	Ouse	Mean scale Ouse rainfall-runoff timeseries
River Tove	171.9	Tove	Area scaled model calibrated to the Tove at Cappenham.
River Cherwell Cropredy Mill	148.2	NA	Feeder inflow hydraulically constrained, constant inflow of 1.5Ml/d in model maintained.
River Swift Feeder	68.0	Swift	Area scaled model calibrated to the Swift at Churchover.
Ledburn Brook	34.5	Clipstone	Area scaled model calibrated to Clipstone Brook at Clipstone
Boddington Feeder	19.6	Clipstone	Mean scale Clipstone rainfall-runoff timeseries
Burton Brook	15.4	Sence	Area scaled model calibrated to Sence at South Wigston
Watford Feeder	11.2	Nene	Mean scale Nene rainfall-runoff timeseries
Grendon Feeder	10.2	Mease	Mean scale Mease rainfall-runoff timeseries
Griff Arm	9.3	Mease	Mean scale Mease rainfall-runoff timeseries
Wem Brook Feeder	8.7	Mease	Mean scale Mease rainfall-runoff timeseries
Sulby Feeder	8.4	Sence	Mean scale Sence rainfall-runoff timeseries
Daventry Feeder	8.4	Nene	Mean scale Nene rainfall-runoff timeseries
Tring Summit Feeder	7.6	Tring Drainage	Model calibrated to Tring Drainage
Wendover	7.3	Wendover	Infilled flows from Wendover Springs
Tring Drainage	6.5	Tring Drainage	Mean scale Tring Drainage rainfall-runoff timeseries
Saddington Feeder	6.3	Sence	Mean scale Sence rainfall-runoff timeseries
Naseby Feeder	4.7	Sence	Mean scale Sence rainfall-runoff timeseries
Wormleighton Feeder	4.7	Clipstone	Mean scale Clipstone rainfall-runoff timeseries
Old (Welton) Feeder	3.4	Nene	Mean scale Nene rainfall-runoff timeseries
Gumley Feeder	3.2	Sence	Mean scale Sence rainfall-runoff timeseries
Merevale Feeder	3.0	Mease	Mean scale Mease rainfall-runoff timeseries
Kilsby	2.9	Nene	Mean scale Nene rainfall-runoff timeseries
Wilstone Feeder	2.7	Wendover	Mean scale Wendover timeseries
Bulbourne Stream	2.2	Wendover	Mean scale Wendover timeseries
Clattercote Feeder	1.9	Mease	Mean scale Mease rainfall-runoff timeseries
Drayton Feeder	1.8	Nene	Mean scale Nene rainfall-runoff timeseries
Hartshill	1.5	Mease	Mean scale Mease rainfall-runoff timeseries
Rawn hill Feeder	1.3	Mease	Mean scale Mease rainfall-runoff timeseries
Mancetter Feeder	1.2	Mease	Mean scale Mease rainfall-runoff timeseries
Tunnel Feeder	1.1	Mease	Mean scale Mease rainfall-runoff timeseries
Welford	0.5	Sence	Mean scale Sence rainfall-runoff timeseries

4.7 Hydrology validation against the hydrometric survey

One of the main aims of the hydrometric survey was to verify the feeder input to the canal for the largest feeders. Feeders contributing more than 1 Ml/d in the Gate 1 baseline model runs have been spot flow gauged during the monitoring period. The feeders have been gauged as part of the spot gauging and the number of visits is summarised in Table 4-7, along with if the feeder is gauged by the Trust or not.

Table 4-7; Summary of gauging of GUC Feeders

Feeder name	Continuous Gauging?	Number of spot gauging visits	To be used for hydrology validation?
River Swift: Outflow to Canal	No	3	No, actual feeder flow not gauged. Spot gauging to be used to validate the Aquator model.
Daventry Reservoir: Outflow to Canal	Yes	3	No, actual feeder flow not gauged. Spot gauging to be used to validate the Aquator model.
Drayton reservoir: Outflow to Canal	Yes	2	No, actual feeder flow not gauged. Spot gauging to be used to validate the Aquator model.
Watford Feeder	Yes	4	Yes
Ledburn Brook	No	4	Yes
Tring feeder	Yes	2	Yes
Wendover Springs	Yes	1	Yes
Tring Drainage	Yes	1	Yes
Wilstone Feeder	No	1	Yes

The following sections compare the derived model hydrology against spot gaugings and Trust gauge data where available.

4.7.1 Watford feeder

The long-term flow timeseries for the Watford Feeder catchment has been derived by mean scaling the Nene rainfall-runoff timeseries. Table 4-8 compares spot flows against the daily model flows on the Watford Feeder as well as a flow percentile for the day from the donor gauge for reference. It should be noted that the spot gauging represents the instantaneous feeder flow at the time at which the spot gauging was taken, whereas the model flows represent the average daily flow. These are shown plotted in Figure 4-9 and Figure 4-10

Table 4-8; Comparison of spot flows against the daily model flows on the Watford Feeder, flow percentile for the day from the donor gauge for reference.

Date	% Exceedance at donor	Spot gauging (m3/s)	Modelled daily flow (m3/s)
19/11/2021	77.0	0.005	0.023
09/12/2021	17.6	0.113	0.188
13/01/2022	29.7	0.044	0.047
12/02/2022	40.3	0.028	0.038

Figure 4-9 shows the predicted flows compared to observed spot and gauge flows and indicates that modelled flows compare reasonably well to observed flows on the feeder. This comparison does suggest that the model is overestimating low flows but does perform well at mid-range flows, which is supported by the spot flows (Figure 4-10). The model peak flow magnitudes compare quite well to the observed. This is adequate performance and should be kept in mind when validating the results of the Aquator model.

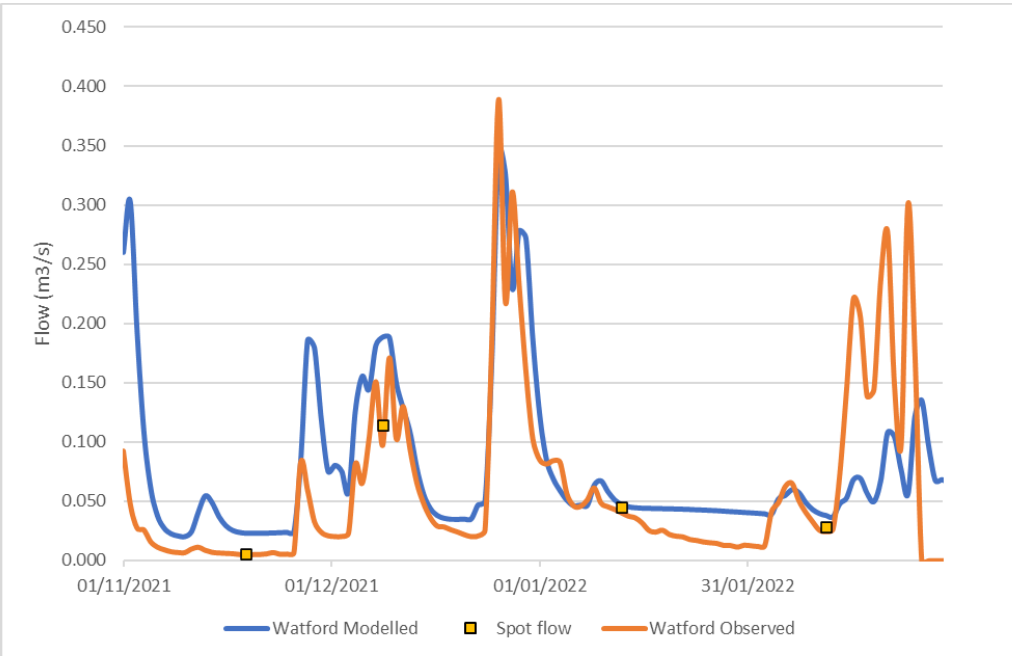


Figure 4-9; Comparison of spot flows against the daily model flows on the Watford Feeder with observed gauge flows shown for reference.

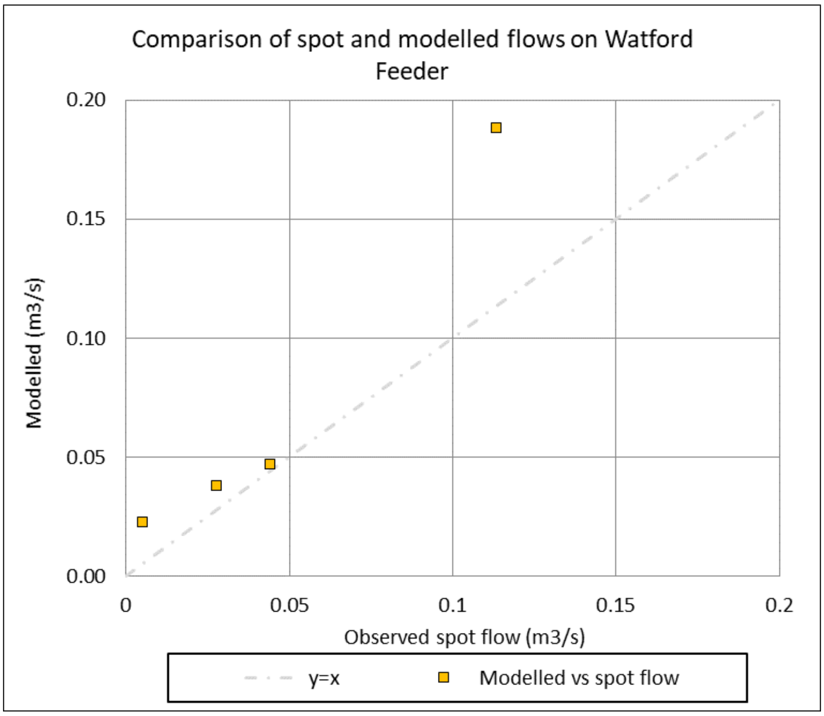


Figure 4-10; Modelled flows vs spot flows on the Watford Feeder

4.7.2 Ledburn Brook

The long-term flow timeseries for the Ledburn Brook catchment has been derived by area scaling the model calibrated to Clipstone Brook at Clipstone. Table 4-9 compares spot flows against the daily model flows on Ledburn Brook as well as a flow percentile for the day from the donor gauge for reference. It should be noted that the spot gauging represents the instantaneous feeder flow at the time at which the spot gauging was taken, whereas the model flows represent the average daily flow.

Table 4-9; Comparison of spot flows against the daily model flows on Ledburn Brook, flow percentile for the day from the donor gauge for reference.

Date	% Exceedance at donor	Spot gauging (m^3/s)	Modelled daily flow (m^3/s)
18/11/2021	64.93	0.06	0.09
14/12/2021	22.23	0.28	0.20
20/12/2021	33.31	0.13	0.10
22/02/2022	9.86	0.70	0.44

Figure 4-11 shows the predicted flows compared to observed spot flows and indicates that modelled flows compare reasonably well to observed flows on the feeder. This comparison does suggest that the model may be underestimating high flows but compares well at mid to low flows, this is supported by a plot the modelled vs spot flows (Figure 4-12). The model peak flow magnitudes compare quite well to the observed. This fit is good.

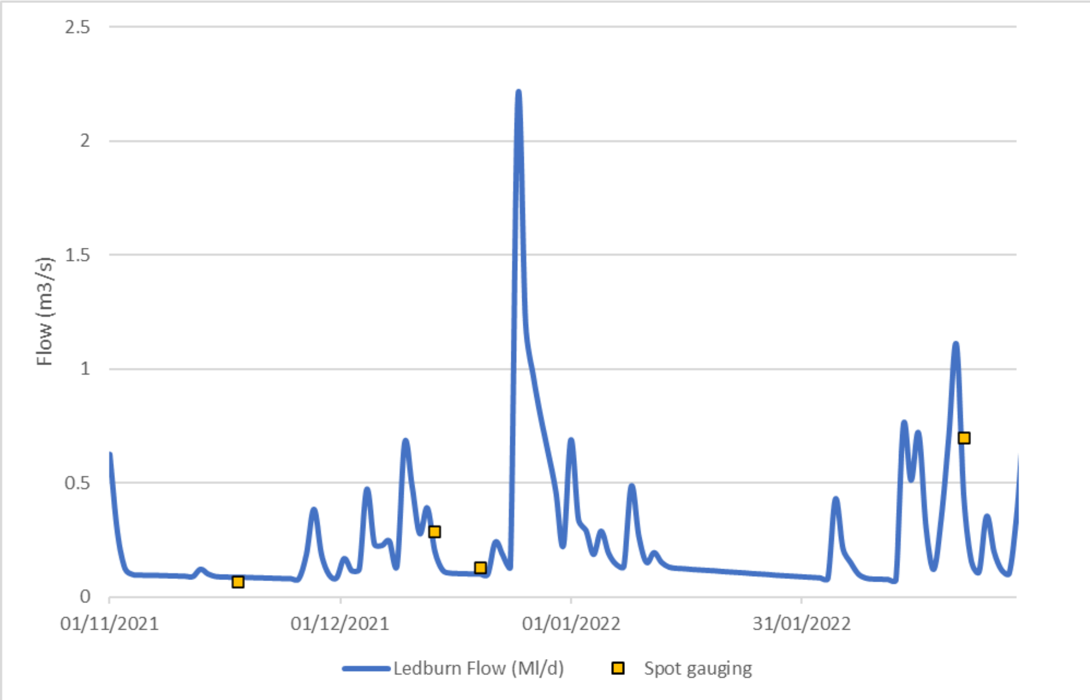


Figure 4-11; Comparison of spot flows against the daily model flows on Ledburn Brook observed gauge flows shown for reference.

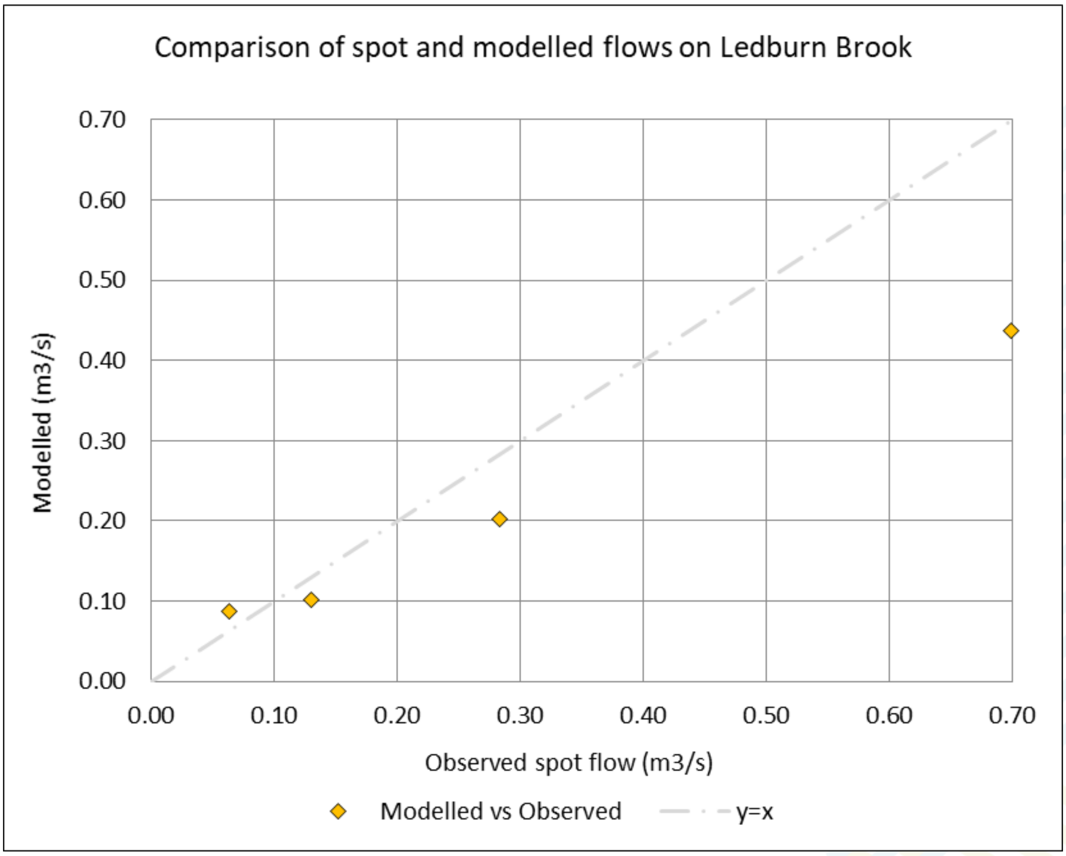


Figure 4-12; Modelled flows vs spot flows on the Ledburn Brook

4.7.3 Tring summit feeders

Table 4-10 compares spot flows against the predicted flow on selected feeders in the Tring Summit Group, Bulbourne stream was not gauged as this site was not accessible. It should be noted that the spot gauging represents the instantaneous feeder flow at the time at which the spot gauging was taken, whereas the model flows represent the average daily flow. These are shown plotted on Figure 4-13. While two spot gaugings were taken at Tring Feeder the flow on the first visit was 0m^3/s as the channel was blocked with vegetation and has not been included in this analysis.

Table 4-10; Comparison of spot flows against the daily model flows on the Watford Feeder.

Feeder name	Date	Spot gauging (m^3/s)	Modelled daily flow (m^3/s)
Wilstone Feeder	22/03/2022	0.02	0.033
Tring Feeder	22/03/2022	0.00	0.008
Tring Drainage	22/03/2022	0.06	0.051
Wendover Springs	22/03/2022	0.10	0.099

Figure 4-13 indicated that the predicted flows on the Tring feeders are a good match to the observed, with all points lying close to y=x.

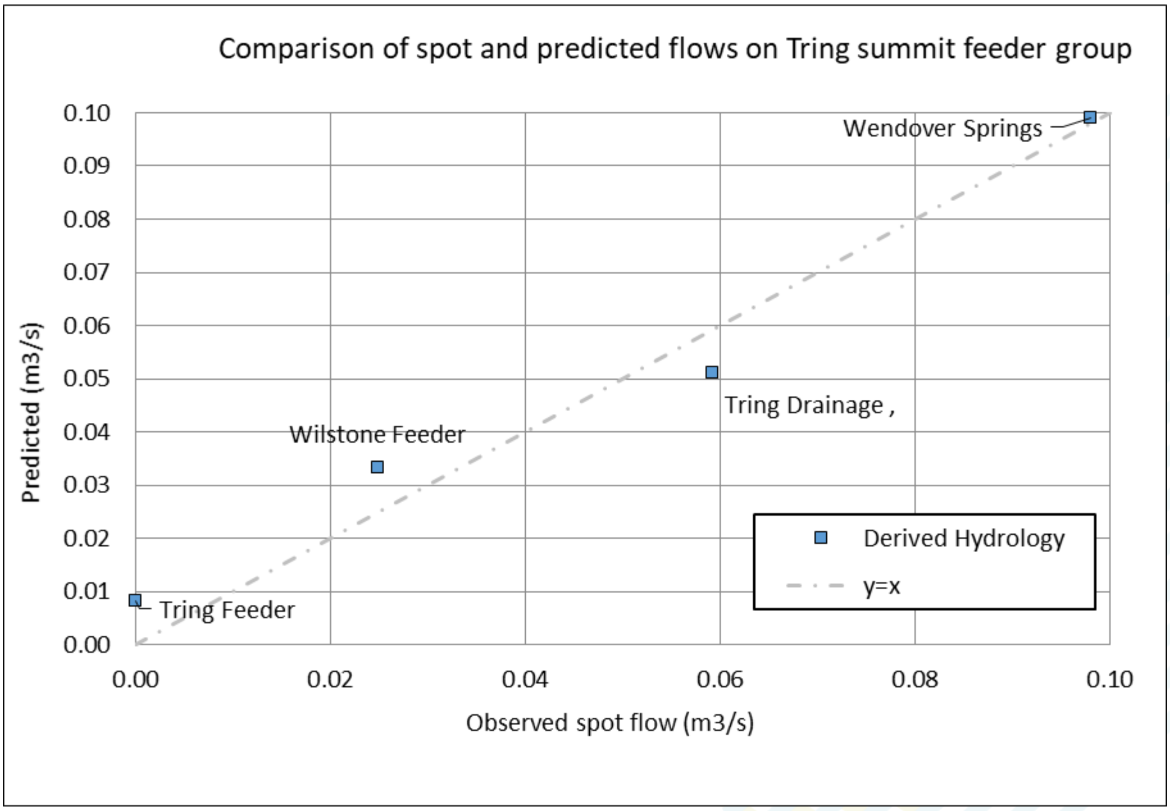


Figure 4-13; Predicted flow vs spot gaugings on selected feeders in the Tring summit group

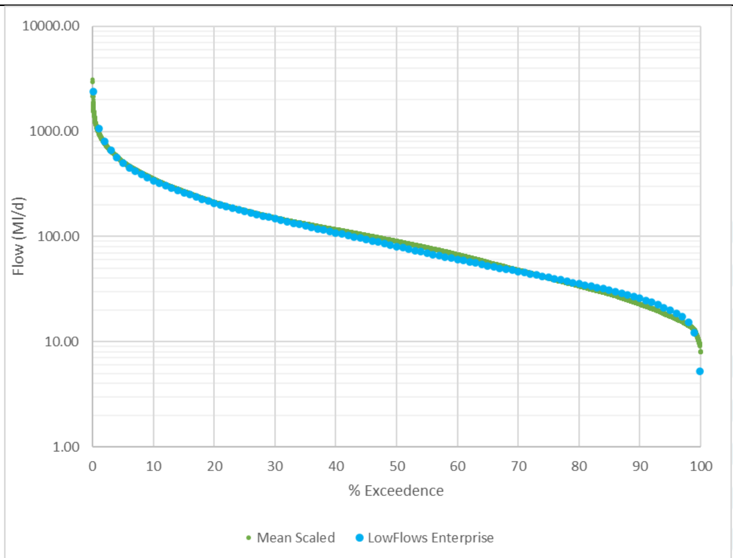
4.7.4 LowFlows 2 Comparison for Ungauged Catchments

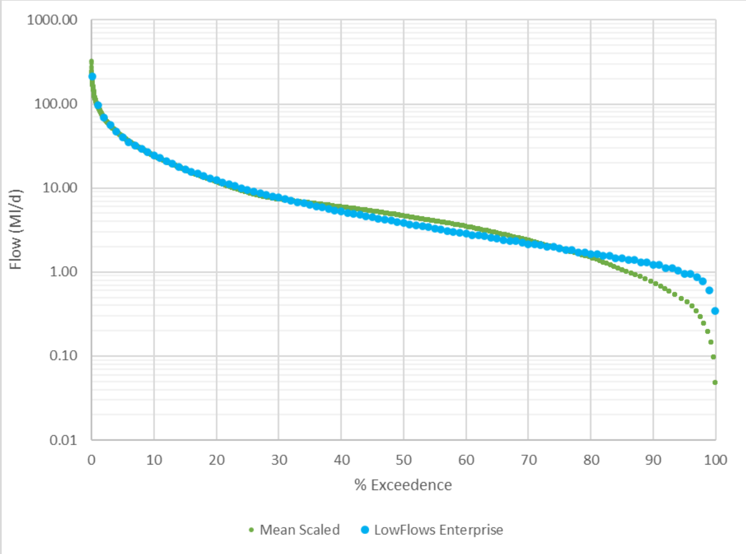
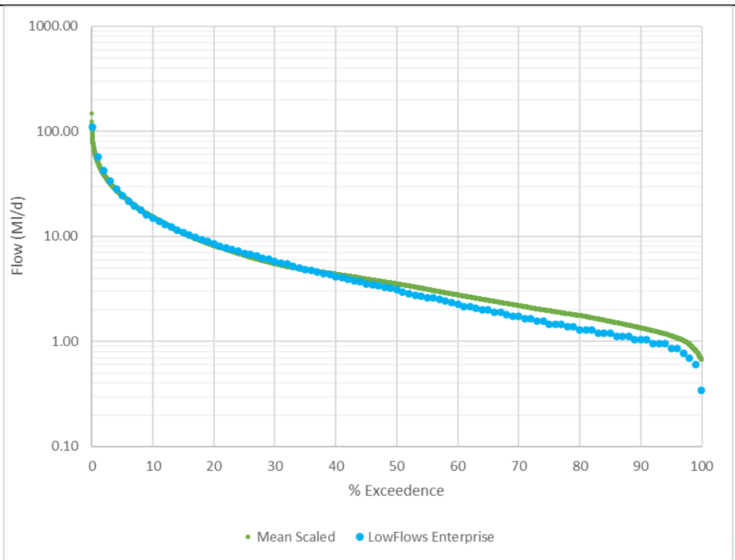
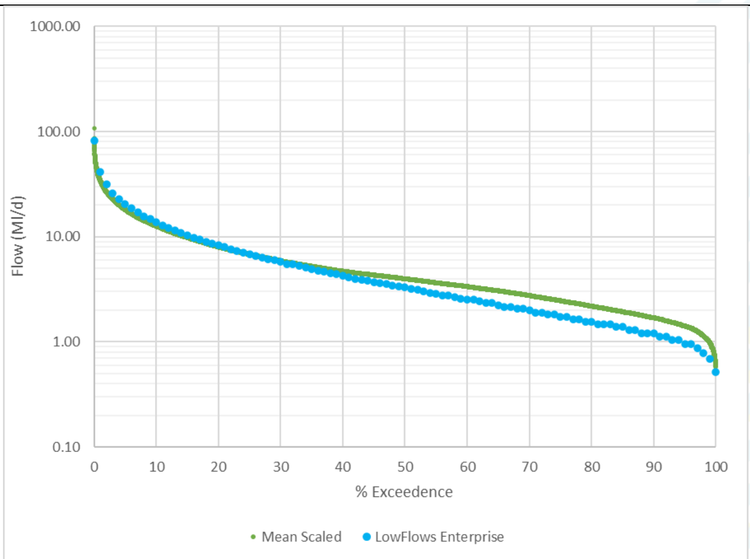
As a final check of the suitability of the selected methods for representing flows on ungauged canal feeders the flow duration curves of the derived long term timeseries has been compared against the LowFlows estimate for that catchment. This has been used as a benchmarking method to check the flows are within the correct order of magnitude and that the flows are broadly representative of catchment flow characteristics. The comparison to low flows has been rated good or satisfactory, based on the comparison at mid to low flows. These results are given in the Table 4-11. Criteria used to determine the rating included flow magnitudes and shape of the flow duration curve particularly in the low flow range.

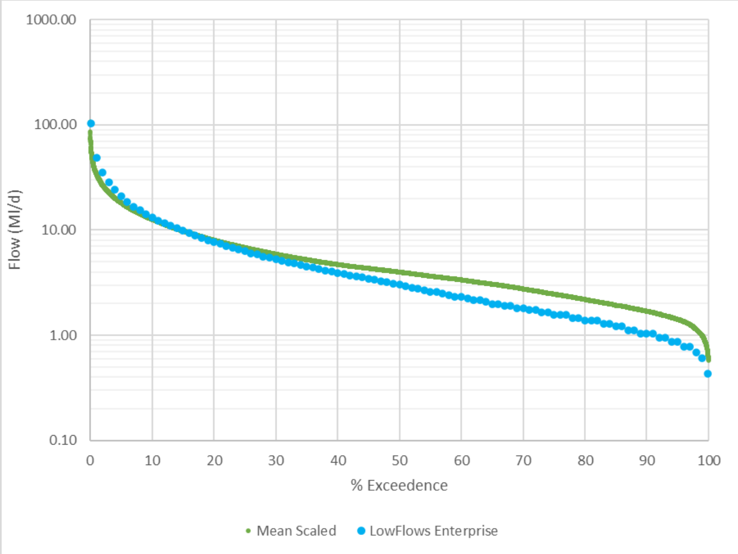
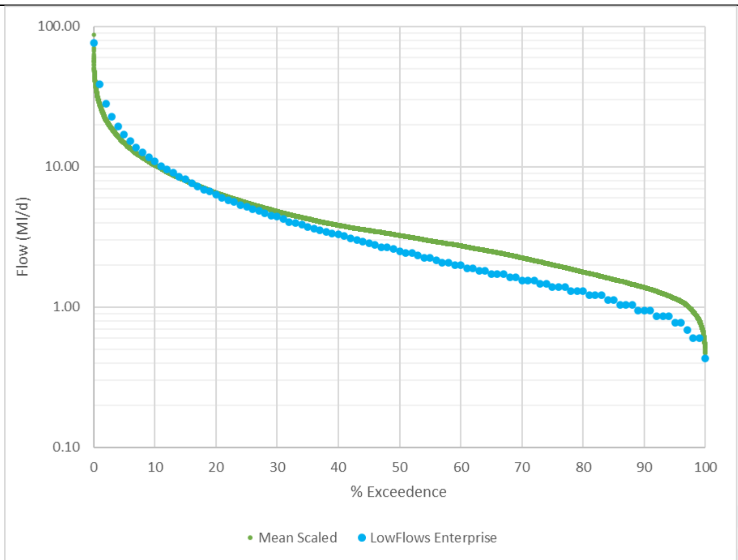
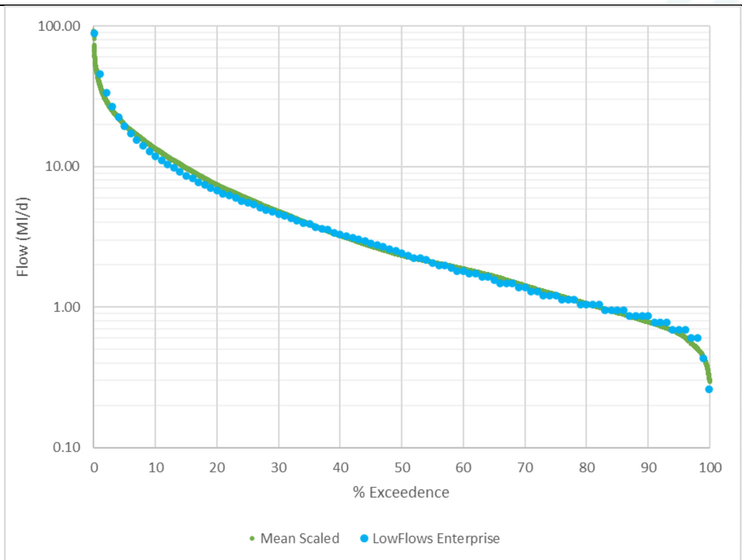
There is considerable uncertainty in LowFlows estimates for an ungauged catchment as a generalised flow package particularly for small catchments, and it should be noted that a satisfactory rating does not mean that this series is inappropriate for use in modelling.

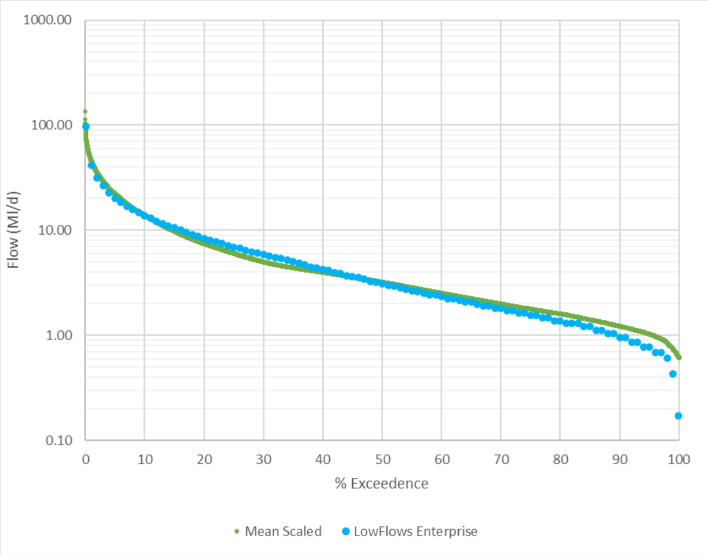
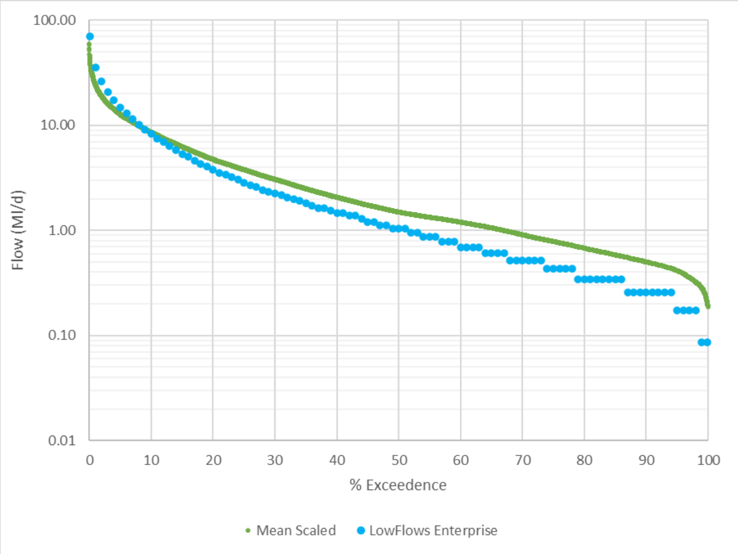
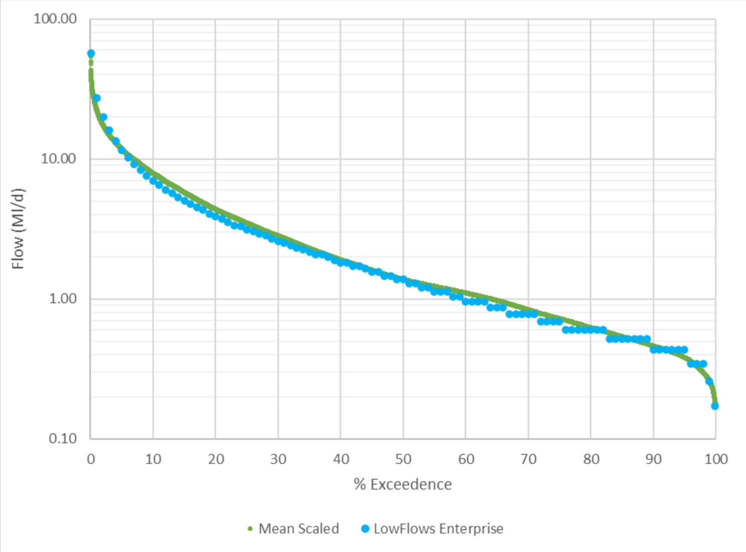
This analysis has been done in Ml/d, as when mean scaling the donors to the feeder catchments, flows were automatically converted to Ml/d for easy addition to the Aquator Model which required flows to be in Ml/d. This analysis has not been done for the Tring Summit group feeders as LowFlows 2 does not cope well in catchments where local hydrological behaviour may be influenced by discrete geological controls. Similarly, it may not perform well in smaller groundwater-fed catchments where part of the regional groundwater flow bypasses the surface water catchment.

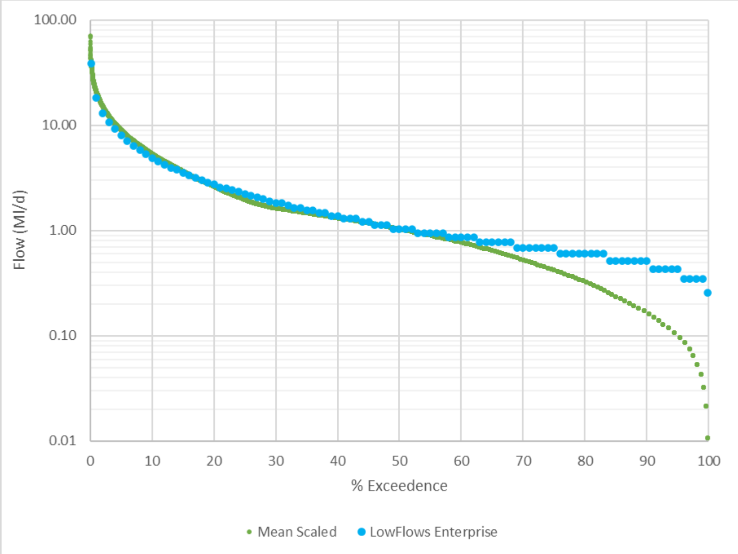
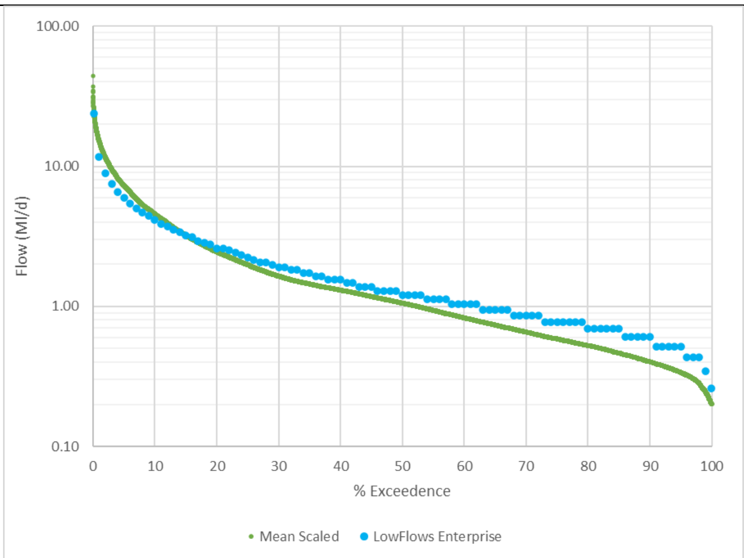
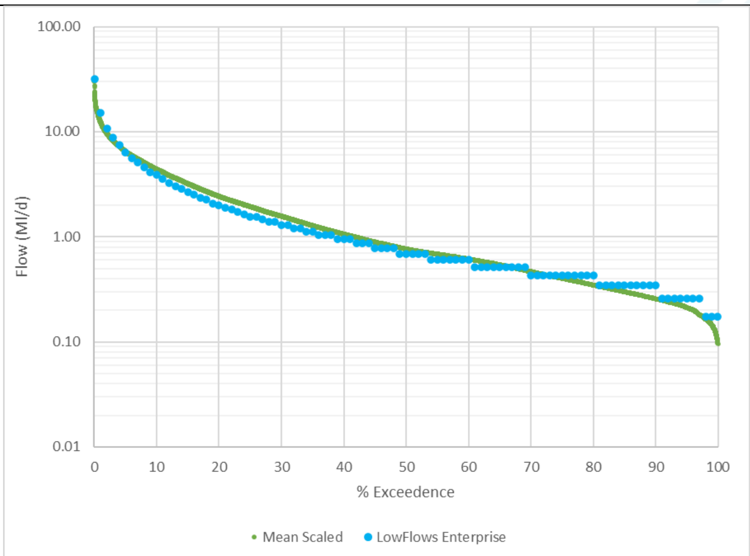
Table 4-11; Comparison of LowFlows2 Estimates and derived model hydrology for ungauged feeder catchments.

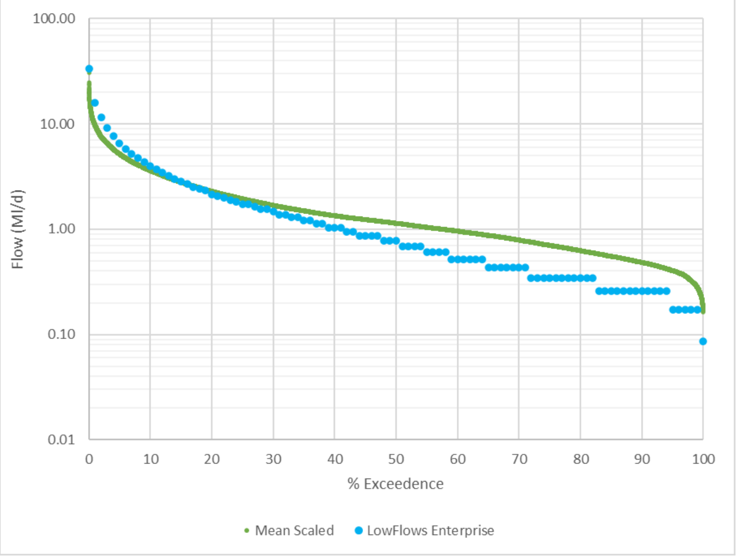
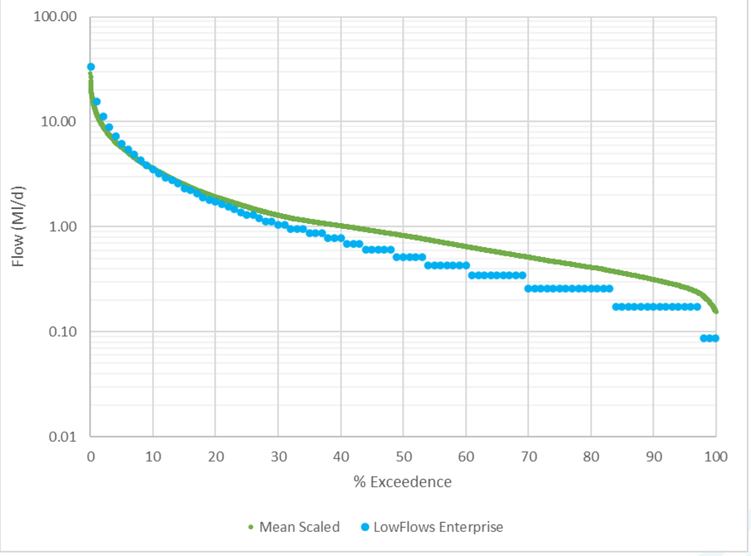
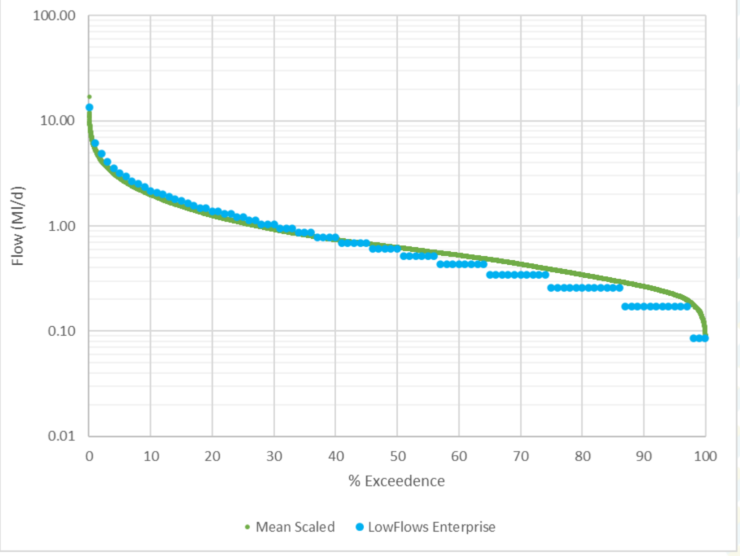
Feeder name	Flow duration curves	Assessment
River Cherwell, Aynho		Good

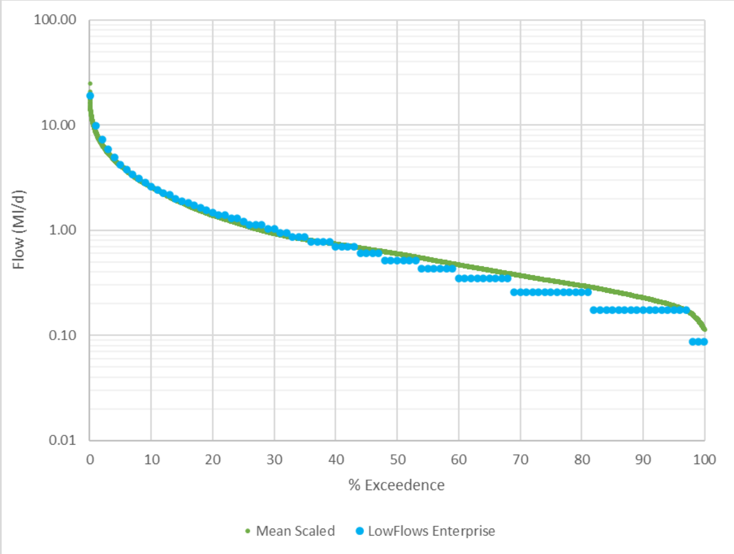
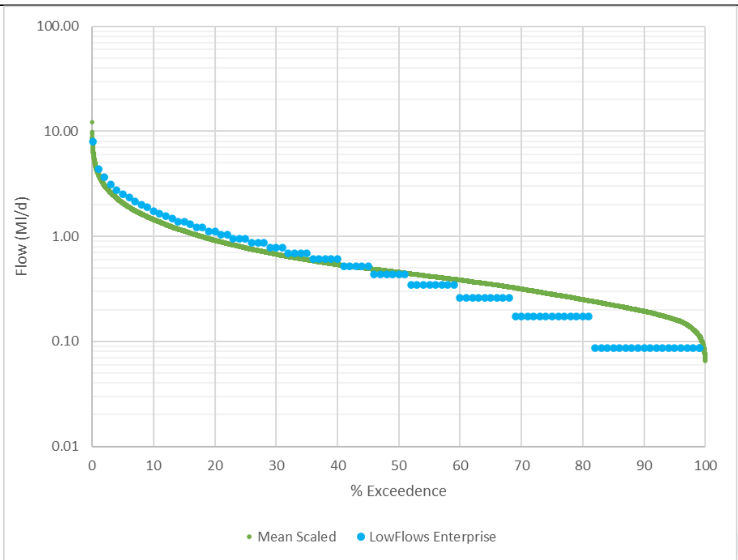
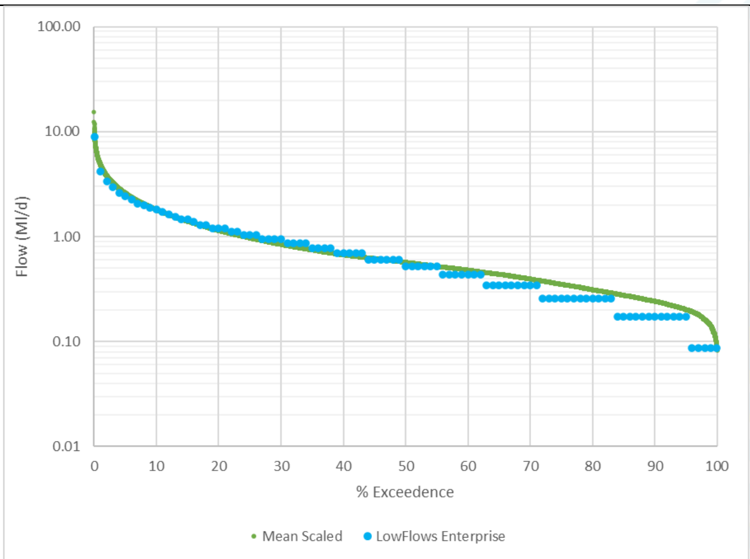
Feeder name	Flow duration curves	Assessment
Boddington Feeder		Good
Watford		Good
Grendon		Good

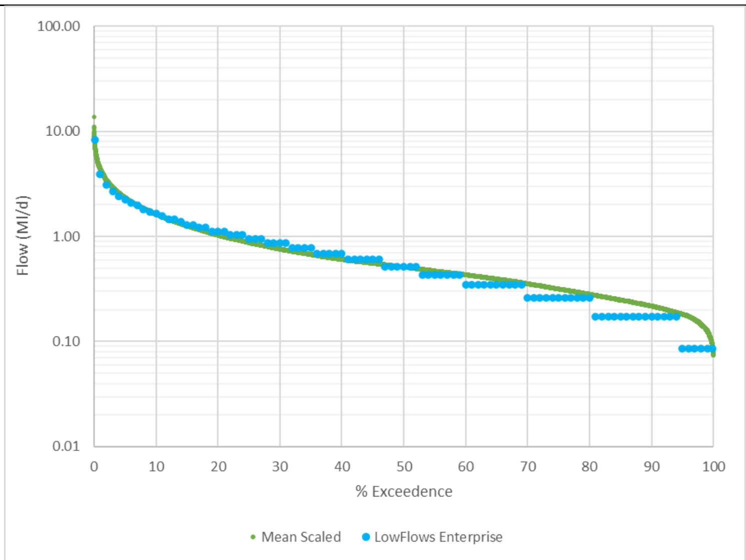
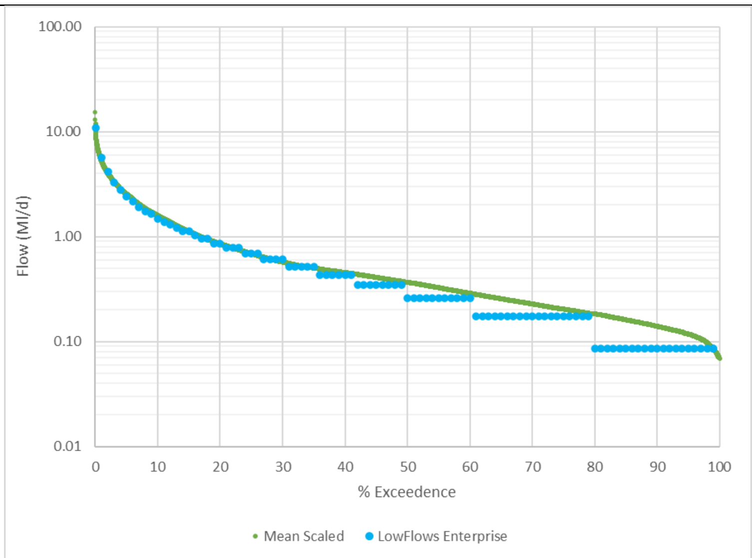
<table>
<tr><th>Feeder name</th><th>Flow duration curves</th><th>Assessment</th></tr>
<tr><td>Griff Arm</td><td>
</td><td>Satisfactory</td></tr>
<tr><td>Wem Brook</td><td>
</td><td>Satisfactory, best fit with donors available</td></tr>
<tr><td>Sulby</td><td>
</td><td>Good</td></tr>
</table>

Feeder name	Flow duration curves	Assessment
Daventry		Good
Saddington		Satisfactory, best with donors available
Naseby		Good

Feeder name	Flow duration curves	Assessment
Wormleighton		Satisfactory, conservative
Old Welton		Good
Gumley		Good

Feeder name	Flow duration curves	Assessment
Marevale		Satisfactory
Kilsby		Satisfactory
Clattercote		Good

Feeder name	Flow duration curves	Assessment
Drayton		Good
Hartshill		Good
Rawnhill		Good

Feeder name	Flow duration curves	Assessment
Mancetter		Good
Tunnel		Good

4.8 Comparison of existing Trust Aquator inflows with revised inflows for reservoir feeders

The following sections show comparisons of the original Aquator model hydrology, as provided by The Trust, and the JBA analysis. Comparisons are derived for select key feeders relevant to the transfer route.

4.8.1 Drayton

Figure 4-14; Comparison of Trust and JBA Aquator model inflows for the Drayton Feeder

Figure 4-14 shows JBA Aquator inflows give lower estimates for high lows over the common period and give a better comparison with the LowFlows estimate for the Drayton catchment than Trust inflows (Figure 4-15). The Trust flow duration curve has larger peak flows and smaller low flows as the slope of the flow duration curve is steeper.

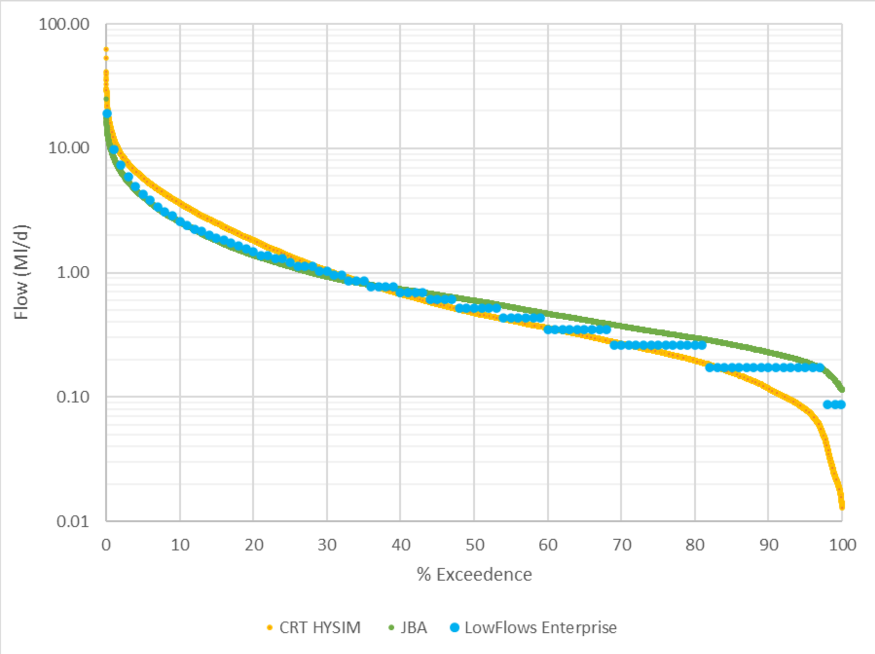


Figure 4-15; Comparison of Trust and JBA Aquator inflow flow duration curves for the Drayton Feeder with LowFlows shown for reference.

4.8.2 Daventry

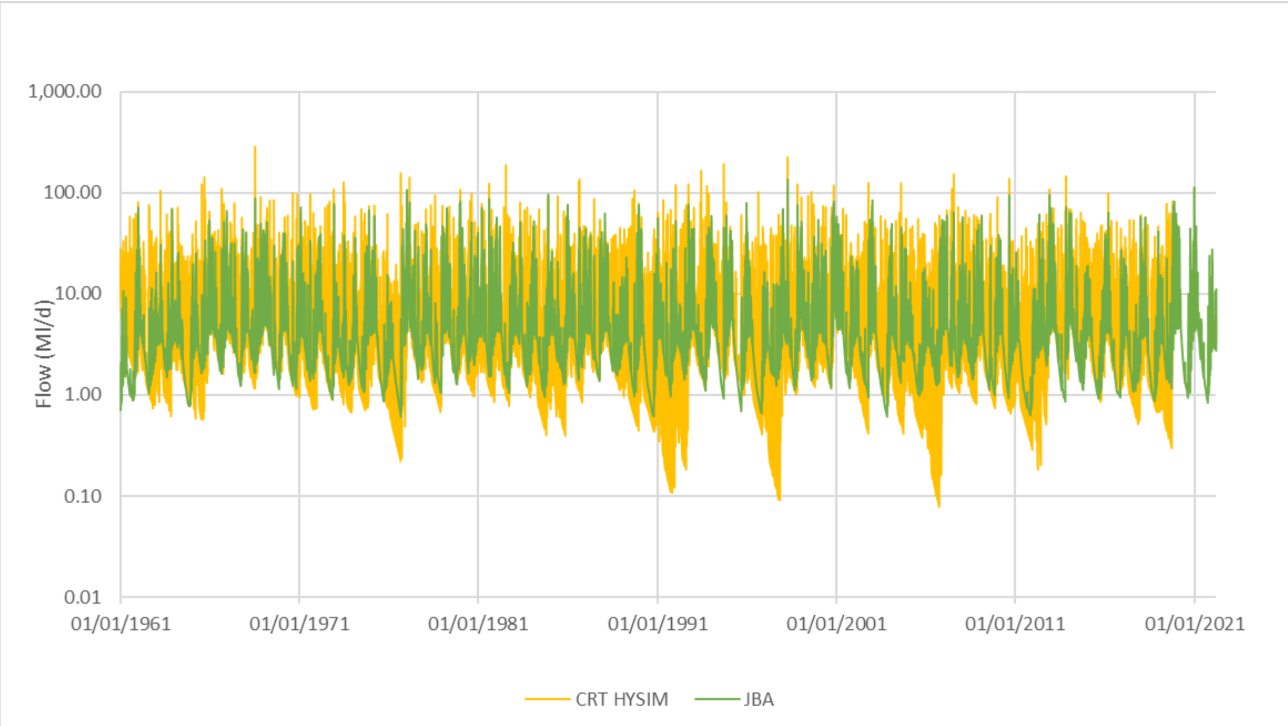


Figure 4-16; Comparison of Trust and JBA Aquator model inflows for the Daventry Feeder

Figure 4-16 shows JBA Aquator inflows give lower estimates for high lows over the common period and give a better comparison with the LowFlows estimate for the Daventry catchment than Trust inflows (Figure 4-17). Same as for Drayton, flow duration curve slope is steeper which is in line with the time series comparison. The peak flows are higher, and the low flows are lower.

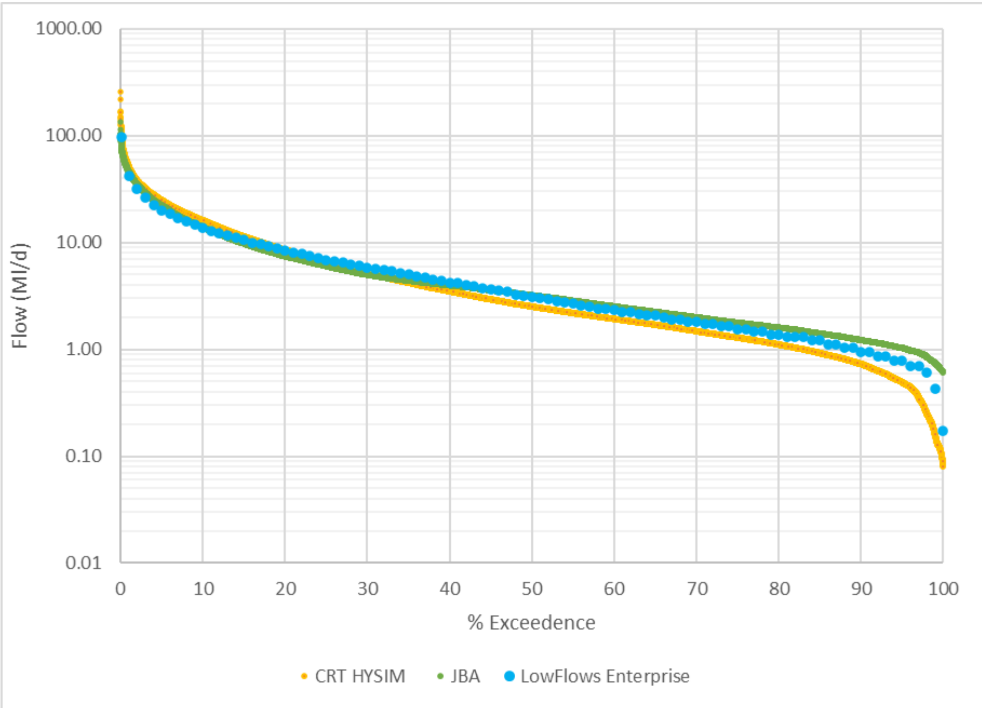


Figure 4-17; Comparison of Trust and JBA Aquator inflow flow duration curves for the Daventry Feeder with LowFlows shown for reference.

4.8.3 Tring feeder

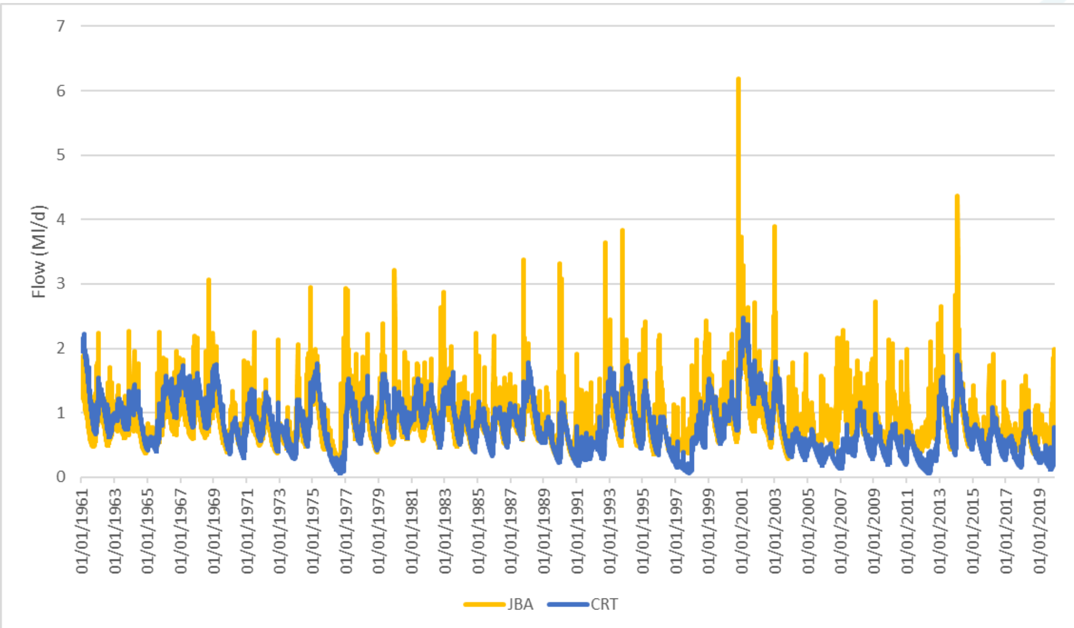


Figure 4-18; Comparison of Trust and JBA Aquator model inflows for the Tring Feeder

Figure 4-18 and Figure 4-19 show JBA Aquator inflows give higher estimates for both high and low flows than Trust. As JBA inflows reflect observed data over the gauged period on the feeder this is acceptable.

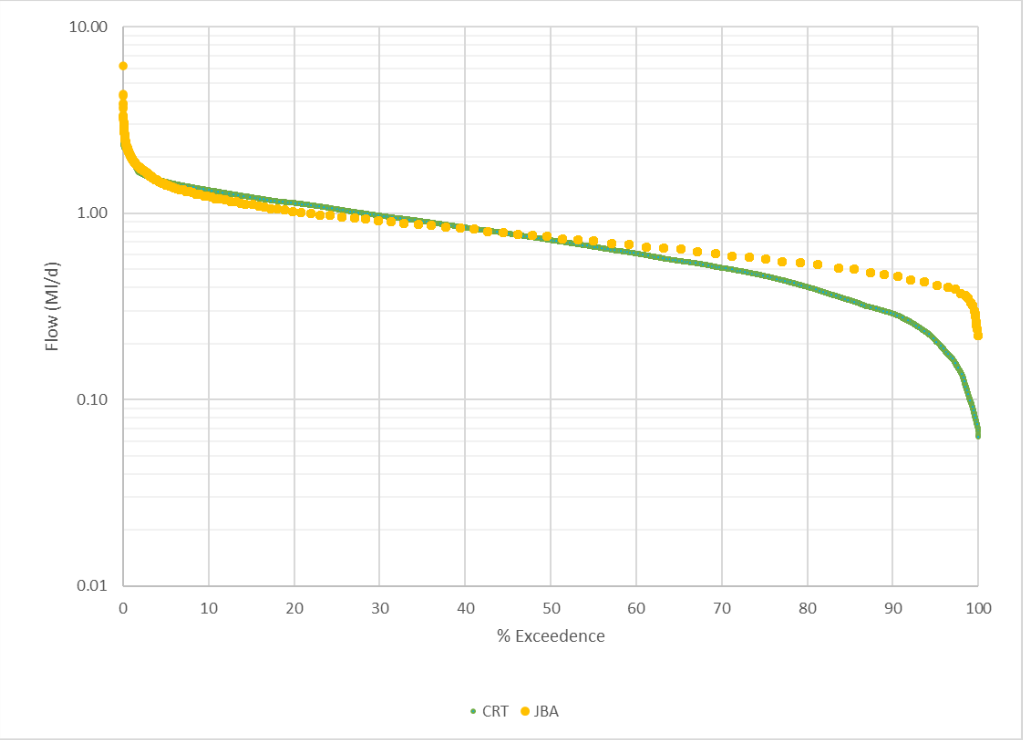


Figure 4-19; Comparison of Trust and JBA Aquator inflow flow duration curves for the Tring Feeder

4.8.4 Tring Drainage

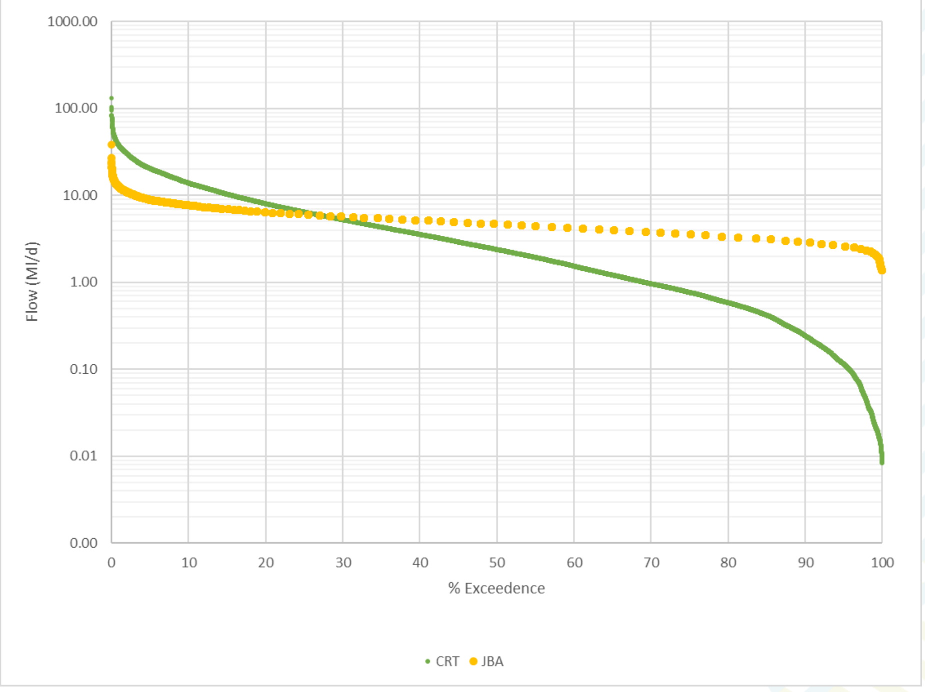


Figure 4-20; Comparison of Trust and JBA Aquator model inflows for Tring Drainage

Figure 4-20 and Figure 4-21 show JBA Aquator inflows give much lower estimates for the Tring feeder. JBA inflows better reflect observed data and are more realistic considering catchment areas.

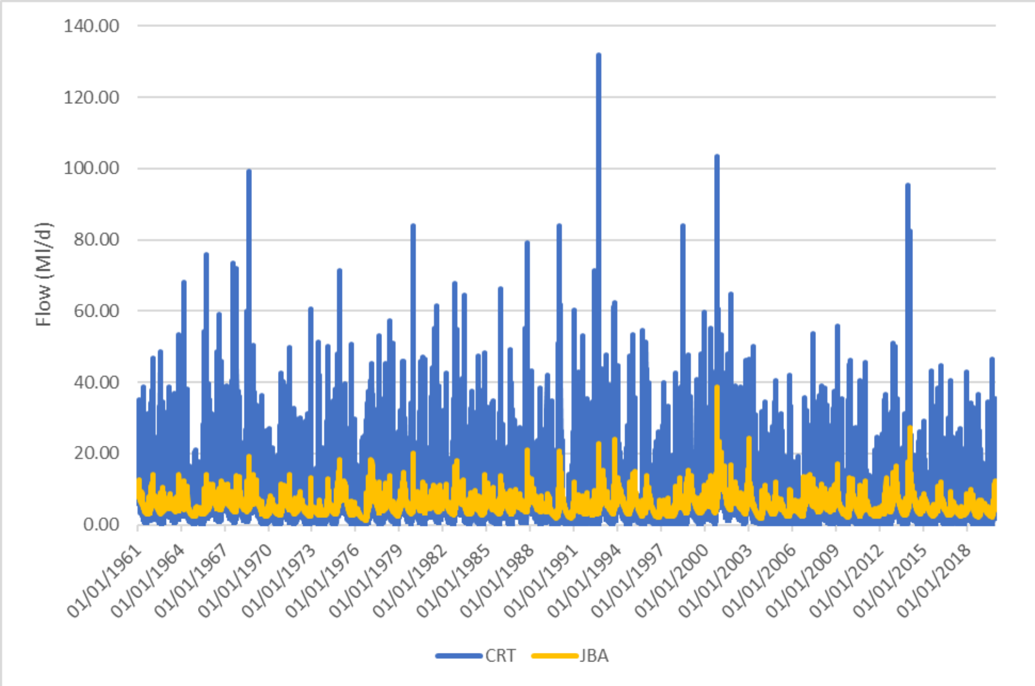


Figure 4-21; Comparison of Trust and JBA Aquator inflow flow duration curves for the Tring Drainage.

4.8.5 Wendover

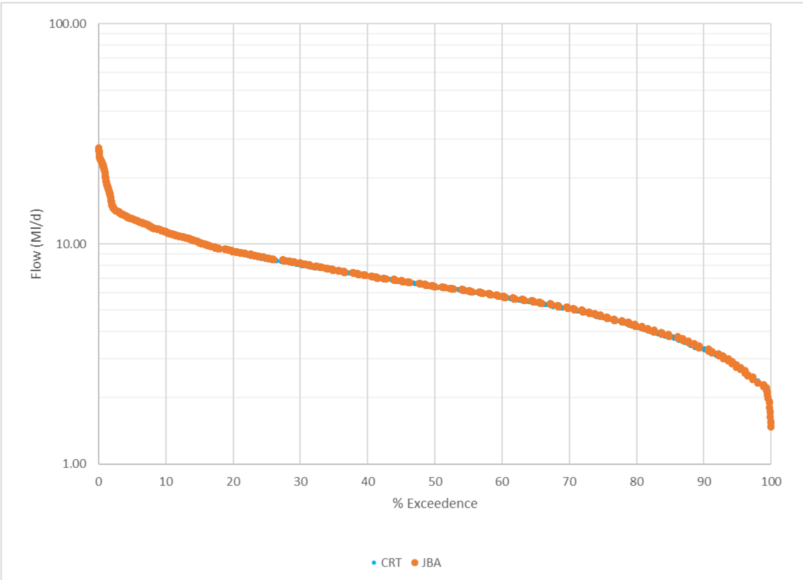


Figure 4-22; Comparison of Trust and JBA Aquator model inflows for the Wendover springs

Figure 4-22 and Figure 4-23 shows JBA Aquator inflows are comparable to previous Trust inflows for the Wendover springs.

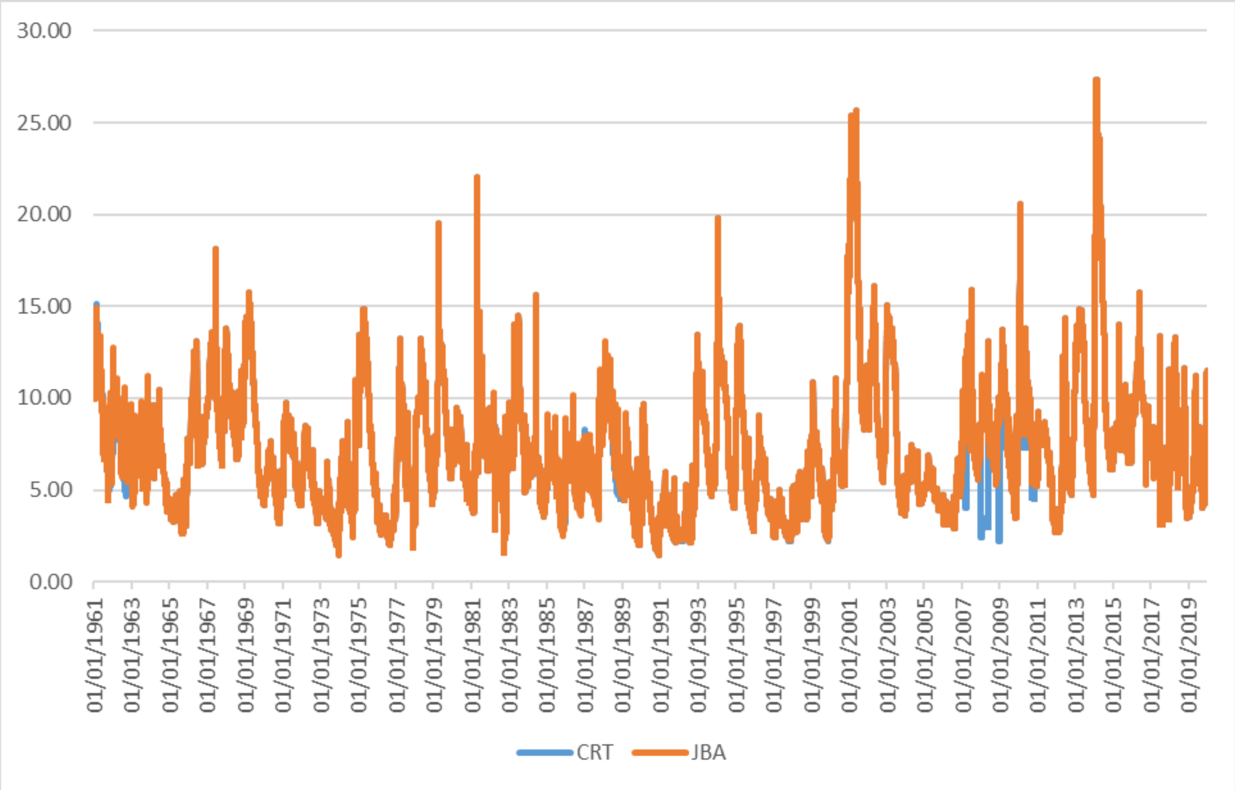


Figure 4-23; Comparison of Trust and JBA Aquator inflow flow duration curves for the Wendover springs

4.9 Flows unchanged in the model

Several model inflow sequences remain unchanged in the model, these include:

- Pound gains and losses: Pound gains and losses within the model are calculated using the Trust loss model, which is the best estimate available and have not been subsequently amended for the new model. Losses are only estimated for two pounds along the transfer route and account for relatively small volumes of flow. It is not expected that the model will be sensitive to changes in these volumes.
- Flows from WwTW's: These flows have been left as is within the model as it is not anticipated that these flows could be improved.
- Feeder inflow from the River Cherwell at Cropredy Mill. The inflow from this feeder is hydraulically constrained to ~1.5 Ml/d.

4.10 Conclusions and summary

To derive suitable long-term flow timeseries for each of the feeder flows in the combined Aquator Model rainfall runoff models have been calibrated for suitable donor gauges and the results scaled to feeder catchments. In the spring-fed catchments of the Tring Summit group a mixed approach of both rainfall-runoff modelling and matching pairs analysis has been used based on available data and flow regime characteristics. The resulting timeseries have been validated against spot flows and continuous gauge data (where available) and benchmarked against LowFlows estimates for each feeder catchment to ensure the flows were representative. Overall, all derived feeder flows are considered to representative, and appropriate for use in Aquator modelling. Limitations of the rainfall-runoff model calibrations should be considered when validating the Aquator model results.

5 Aquator Model Validation

Updated inflows have been imported in the model and used to run the model for the long-term series for the purposes of validation of the baseline model. Minworth flow has been added. The model does not allow use of emergency storage of the canal pounds, which means that there is always some volume of water within the pound even if demand is not met. Aquator flows have been validated against the spot gauging undertaken during Phases 1 & 2 of this study as well as against observed flows at Trust gauges. As mentioned previously due to the difficulty of gauging canal flows the Trust only have a few gauges monitoring flows on the canal.

Aquator pound levels have also been compared to the observed levels from the spot gauge survey as well as against observed flows at Trust gauges. Aquator level results for canal pounds should be treated with caution due to the daily timestep it uses and the very responsive water level regime in a pound given that it is sensitive to boat movements (that can influence downstream pounds at a great distance) and rainfall conditions. The level comparison has therefore only been used to assess if Aquator levels are broadly representative and follow the same seasonal and yearly patterns as the observed. These results have not been used to calibrate the model.

It should be noted that the spot gauging represents the instantaneous flow or level at the time at which the spot gauging was taken, whereas the model results are given at a daily timestep, and this should be kept in mind when interpreting the results. The results of the spot gauge validation exercise have been reported in reaches from Summit to Trough in the modelled system. The reaches of interest to this study and the modelled pounds within those reaches are given in Table 5-1, and are shown in Figure 5-1.

Table 5-1; Key reaches of interest to this study and the modelled pounds within those reaches

Reach	Modelled Pounds within reach
Oxford Summit – Coventry Trough	OX Pound 8-7 OX Pound 2-1 CC Pound 1-1 CC Pound 11-12 CC Pound 13-17
Braunston Summit – Fenny Stratford Trough	GU Pound 6-7 GU Pound 7-8 GU Pound 13-14 GU Pound 20-21 GU Pound 21-22
Fenny Stratford Trough – Tring Summit	GU Pound 45-46 GU Pound 38-39 GU Pound 36-37 GU Pound 33-34 GU Pound 31-32 GU Pound 29-30 GU Pound 27-28 GU Pound 26-27 GU Pound 23-24 GU Pound 22-23 GU Pound 21-22

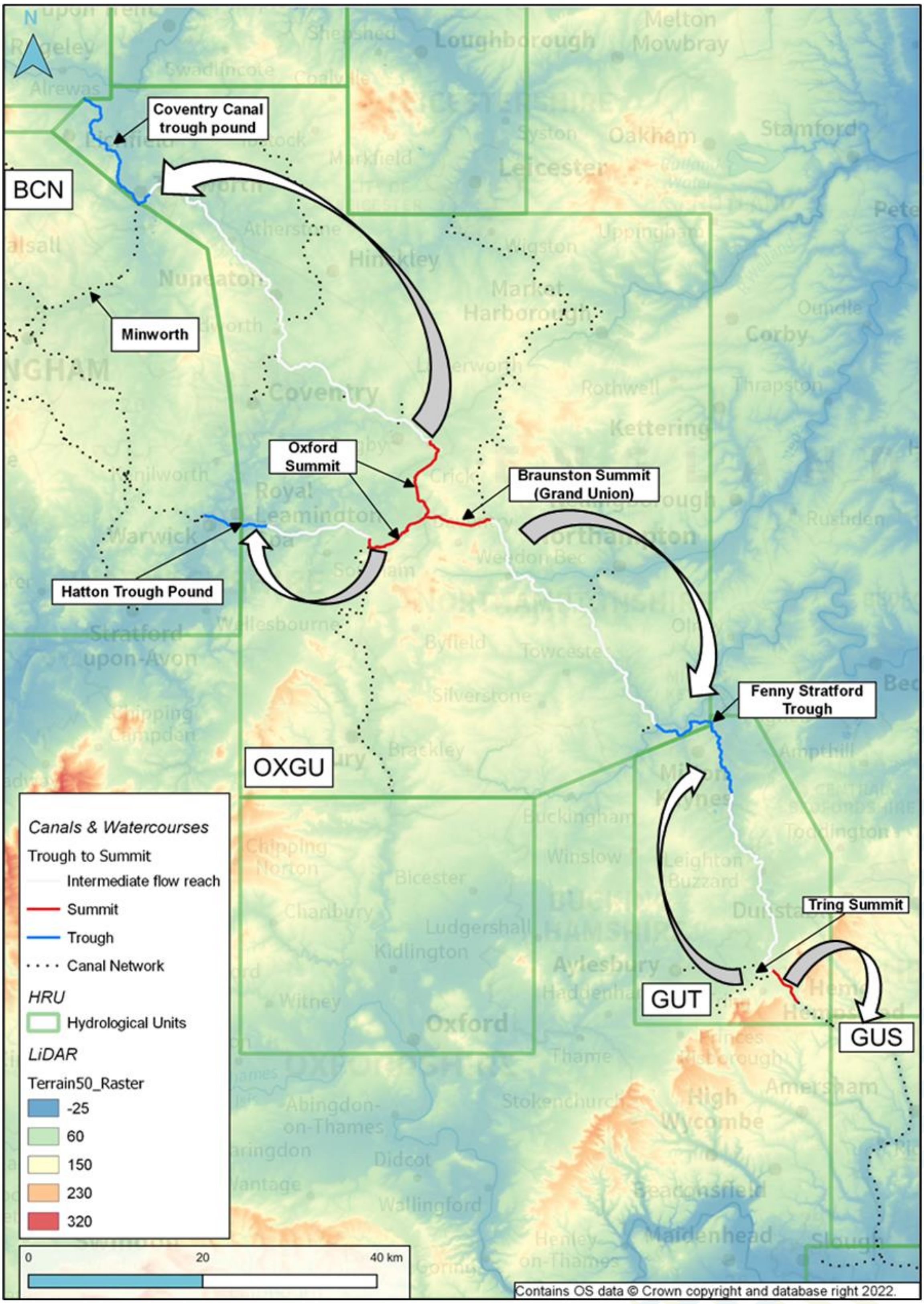


Figure 5-1; Locations of summit and trough pounds within the combined model with flow directions given for reference (pre-transfer).

5.1 Validation of Aquator modelled flows and levels against hydrometric survey

The modelled flows were compared against the spot level and flow measurements with the following in mind:

- This is the first part of the model validation against the results from the hydrometric survey. The second use of the hydrometric survey data is during hydraulic modelling validation. Results will be reported separately for this.
- Canals are level mainly level controlled systems and therefore flows in by-weirs and spills over pounds may be due to hydraulic controls imposed in specific sections (e.g., boarded up spills to maintain levels).
- The focus of the comparison is to get long sectional consistency from Summit to trough for flows (primary parameter in Aquator) and levels (secondary parameter, often not able to model well).
- Exact flow magnitudes are very difficult to replicate between spot and modelled Aquator flows in the canal system and this is due to several factors:
    - Limitations in the model representation of structures such as by weirs and spills.
    - Local controls on flow within the canal affecting flows which cannot be replicated within the model.
    - Spot flows are instantaneous measurements of flow, whereas the model results represent average daily flow.

Model results should therefore be assessed within this context. Spot flows will be reviewed at a later stage more holistically along with the hydraulic model results.

5.1.1 Oxford Summit to Coventry Trough

5.1.1.1 Levels

Figure 5-2 shows a comparison of the Modelled Aquator Pound levels to the spot gaugings taken at key sites along this reach on four visits over the period November 2021 to February 2022. OX labelled pounds are on the Oxford Canal and CC pounds are on the Coventry canal.

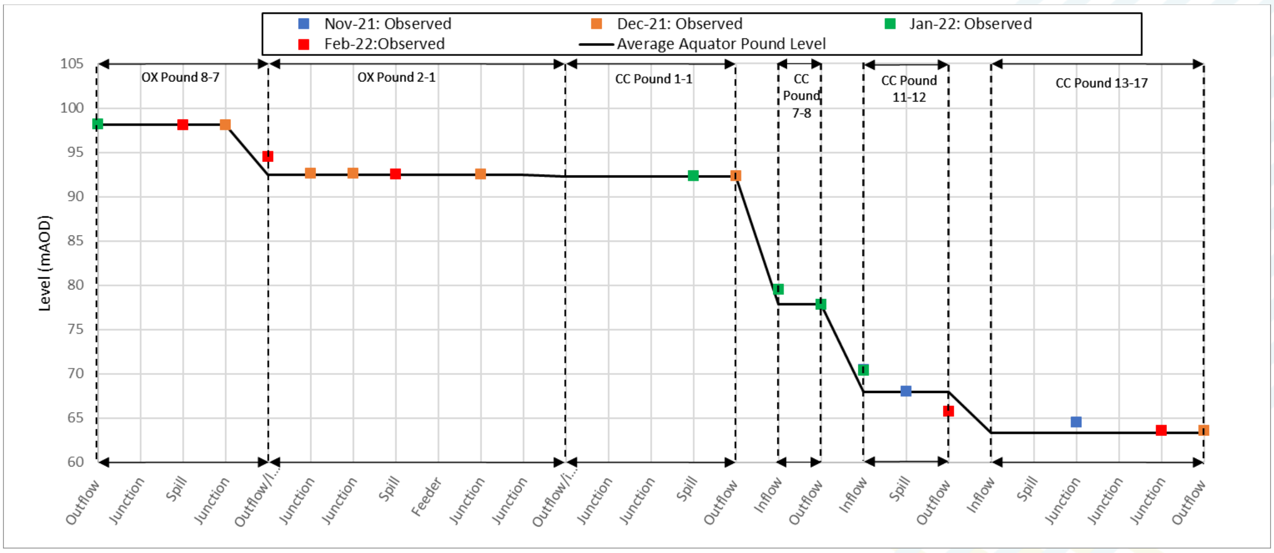


Figure 5-2; Comparison of the average Aquator pound levels to the spot gaugings taken at key sites during the survey period for the Oxford Summit to Coventry Trough reach.

Overall, considering the sub-daily variance of canal pound levels due to boat movements and rainfall response, the spot gauge levels compare well to the Aquator model levels over the survey period. This indicates the average level reported by the Aquator model along this reach is representative of observed levels.

5.1.1.2 Flows

Figure 5-3 shows a long section plot of the observed and modelled flows along this reach at key locations. Aquator flows are taken for comparison as a 7-day average. Model flows generally tend to be higher than observed, though there is a high degree of scatter in the results. This plot suggests a realistic pattern in line with the spot flow measurements from summit to trough. Response to wetter and drier periods is replicated between both the observed and modelled. When the model is spilling the model appears to spill higher volume than the observed. It should be noted that the model spill is often from a combination of weirs along the pound whereas the observed spill measurements are taken on the lowest weir in the pound.

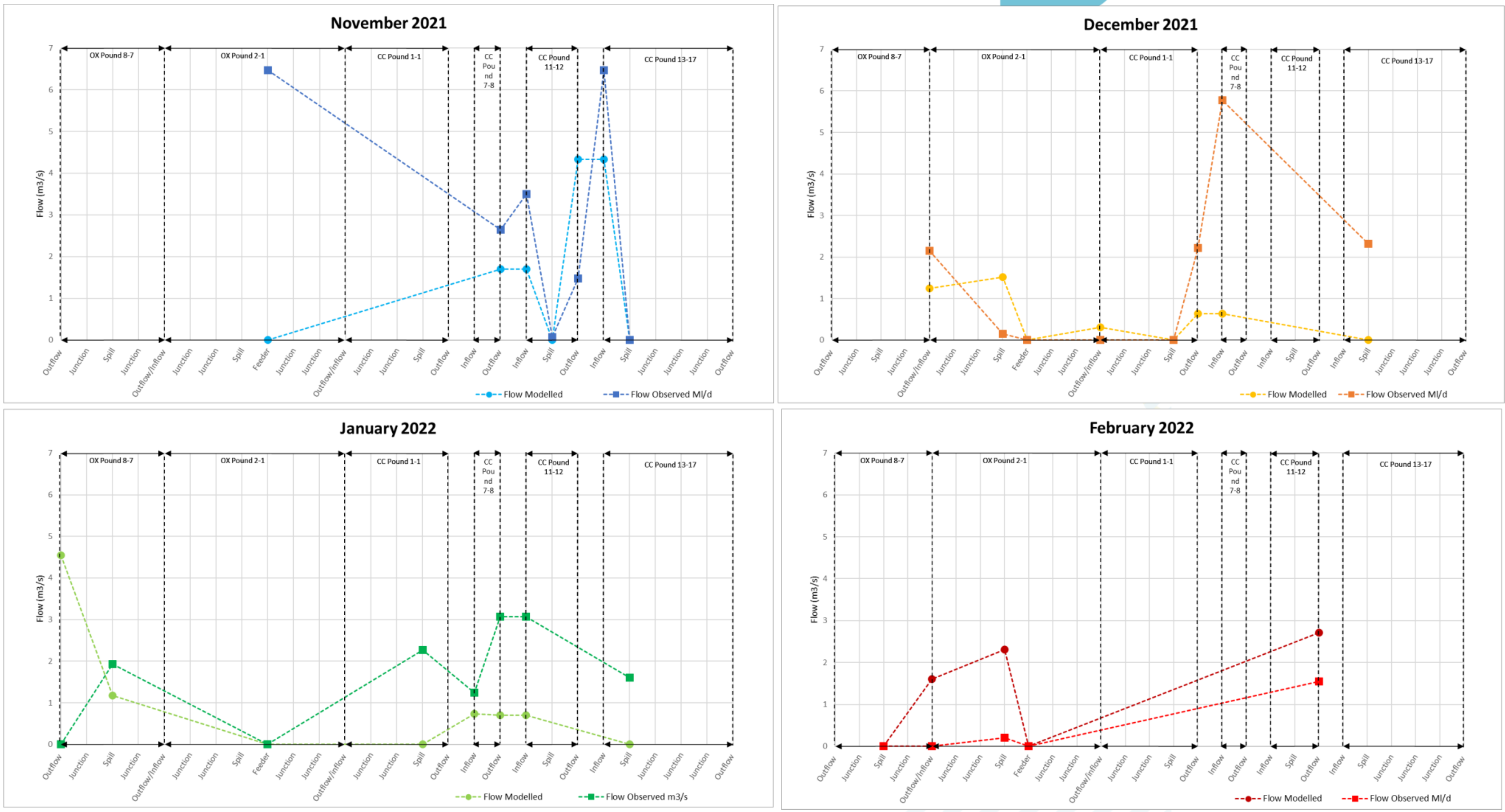


Figure 5-3; Long section of observed and modelled flows along the Oxford Summit to Coventry Trough Reach

5.1.2 Braunston Summit to Fenny Stratford Trough

5.1.2.1 Levels

Figure 5-4 shows a comparison of the Modelled Aquator Pound levels to the spot gaugings taken at key sites along this reach on four visits over the period November 2021 to February 2022.

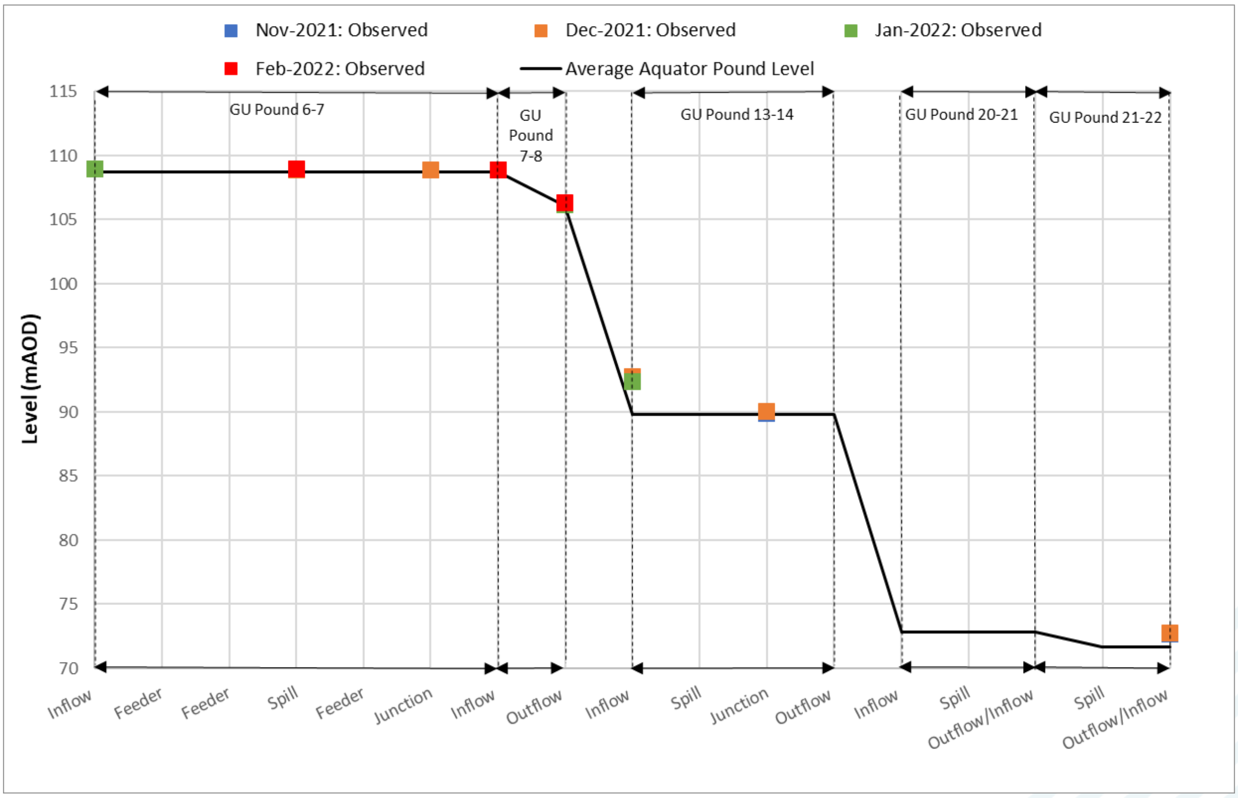


Figure 5-4; Comparison of the average Aquator pound levels to the spot gaugings taken at key sites during the survey period for the Braunston Summit to Fenny Stratford Trough reach.

Overall, considering the sub-daily variance of canal pound levels due to boat movements and rainfall response, the spot gauge levels compare well to the Aquator model levels over the survey period. This indicates the average level reported by the Aquator model along this reach is representative of observed levels.

5.1.2.2 Flows

Figure 5-5 shows a long section plot of the observed and modelled flows along this reach at key locations. Aquator flows are taken for comparison as a 7-day average. Model flows generally tend to be higher than observed, though there is a high degree of scatter in the results. This plot suggests a realistic pattern in line with the spot flow measurements from summit to trough. Response to wetter and drier periods is replicated between both the observed and modelled, aside from in November 2021 where the model is not replicating the very low observed flows. When the model is spilling the model appears to spill higher volume than the observed. It should be noted that the model spill is often from a combination of weirs along the pound whereas the observed spill measurements are taken on the lowest weir in the pound.

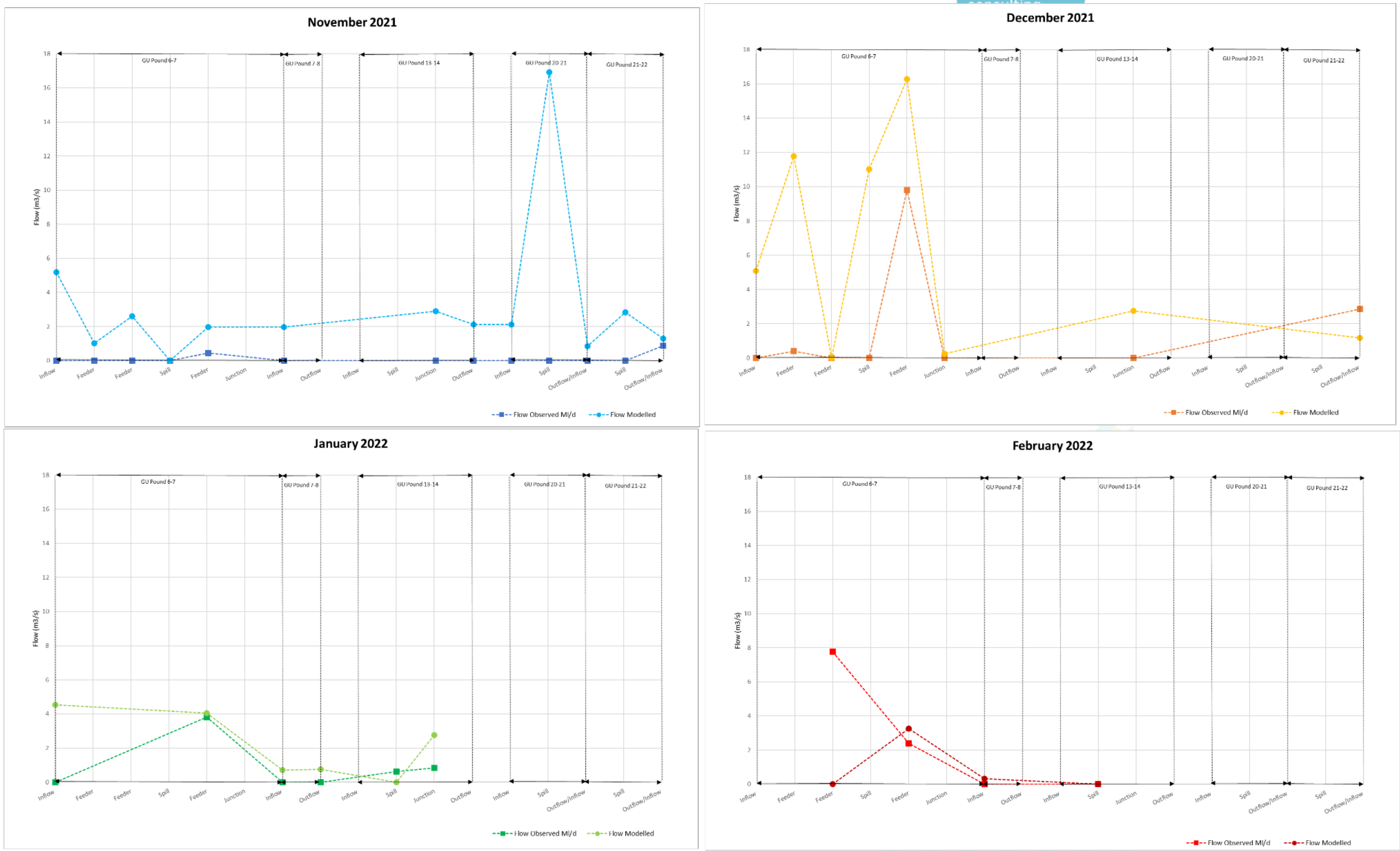


Figure 5-5; Long section of observed and modelled flows along the Braunston Summit to Fenny Stratford Trough Reach

5.1.3 Tring Summit to Fenny Stratford Trough

5.1.3.1 Levels

Figure 5-6 shows a comparison of the Modelled Aquator Pound levels to the spot gaugings taken at key sites along this reach on four visits over the period November 2021 to February 2022.

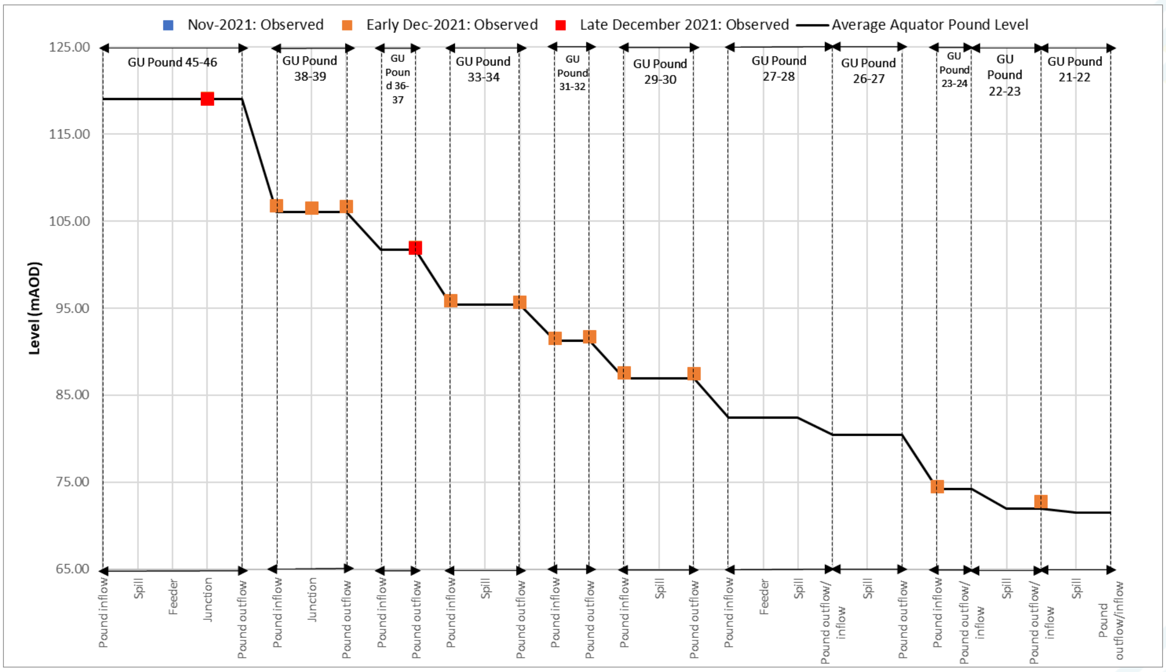
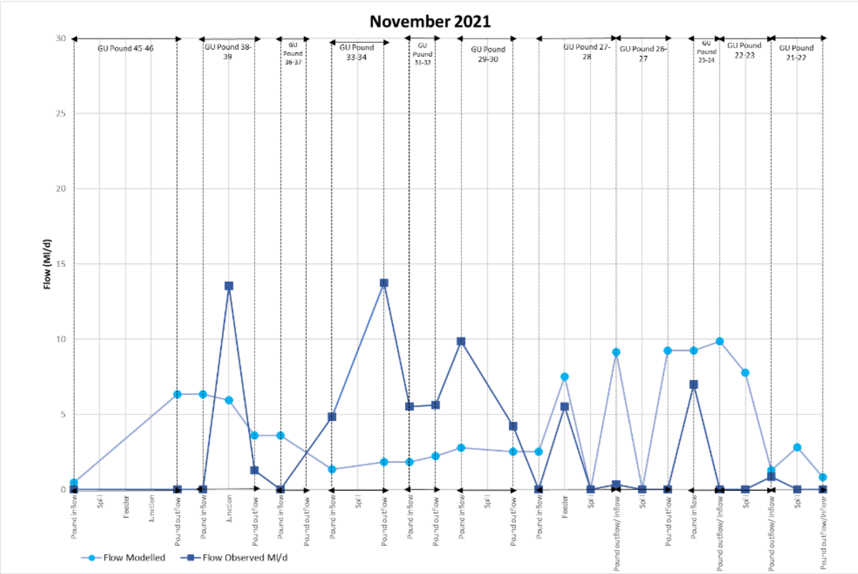


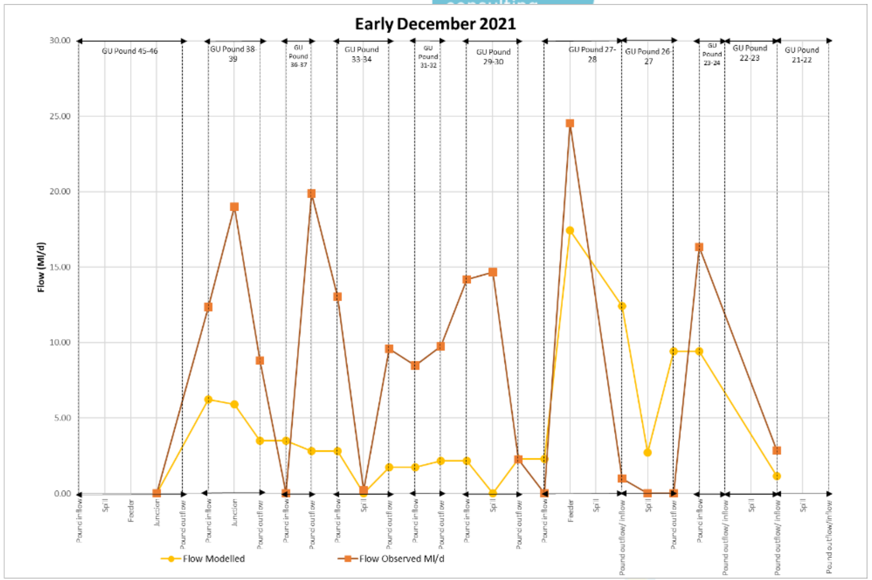
Figure 5-6; Comparison of the average Aquator pound levels to the spot gaugings taken at key sites during the survey period for the Tring Summit to Fenny Stratford Trough reach.

Overall, considering the sub-daily variance of canal pound levels due to boat movements and rainfall response, the spot gauge levels compare well to the Aquator model levels over the survey period. This indicates the average level reported by the Aquator model along this reach is representative of observed levels.

5.1.3.2 Flows

Figure 5-7 shows a long section plot of the observed and modelled flows along this reach at key locations. Aquator flows are taken for comparison as a 7-day average. Model flows generally tend to be higher than observed, though it is worth noting that in the reach between GU Pound 45-46 to GU Pound 29-30 where the observed has picked up flow these are much greater than the modelled. In the reach between GU Pound 27-28 and GU Pound 20-21 modelled flows are higher than observed. Response to wetter and drier periods is replicated between both the observed and modelled. When the model is spilling the model appears to spill higher volume than the observed. It should be noted that the model spill is often from a combination of weirs along the pound whereas the observed spill measurements are taken on the lowest weir in the pound.





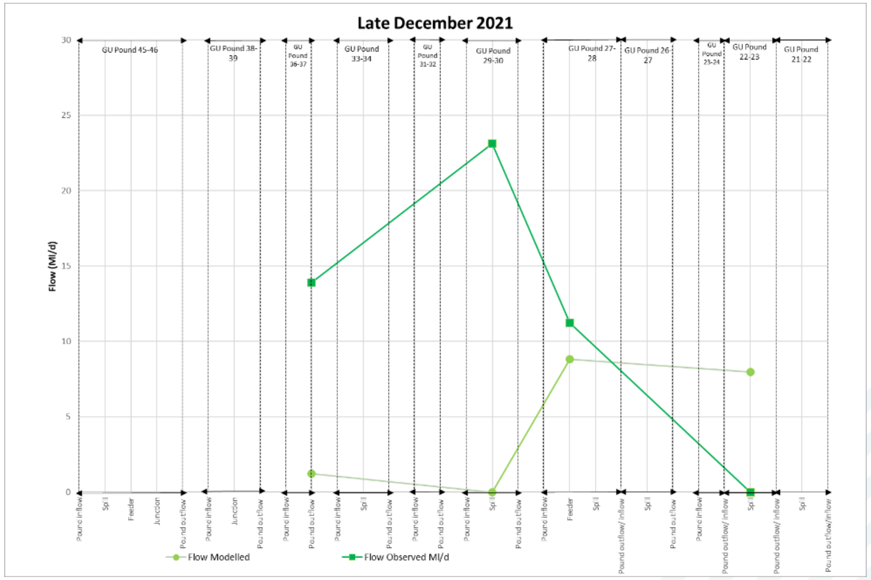


Figure 5-7; Long section of observed and modelled flows along the Tring Summit to Fenny Stratford Trough Reach

5.1.4 Summary and conclusions

It should be noted when reviewing the comparison of results that flow magnitudes are very difficult to replicate between spot and modelled Aquator flows, this is due to several factors:

- Limitations in the model representation of structures such as by weirs and spills.
- Local controls on flow within the canal affecting flows which cannot be replicated within the model.
- Spot flows are instantaneous measurements of flow, whereas the model results represent average daily flow.

Model results are therefore assessed within this context.

Overall, Aquator model results along key reaches of the transfer route show a realistic pattern in line with the spot flow measurements from summit to trough. Response to wet and dry periods is largely replicated between the model and observed (i.e., flow magnitudes increase in wetter periods). The model is generally spilling at a higher volume across all reaches.

5.2 Trust Gauge Data- flows

The below sections compare gauged canal system flows and modelled flows. While it is unlikely that the model would be able to replicate exact flows through the system, modelled performance has been based on if the model replicated seasonal and annual patterns in flows as well as more general trends. To remove some of the noise and make it easier to see patterns and trends in both the modelled and observed data a 7-day moving average has been applied.

5.2.1 CC Pound 1-1: Atherstone Lock Bypass flow

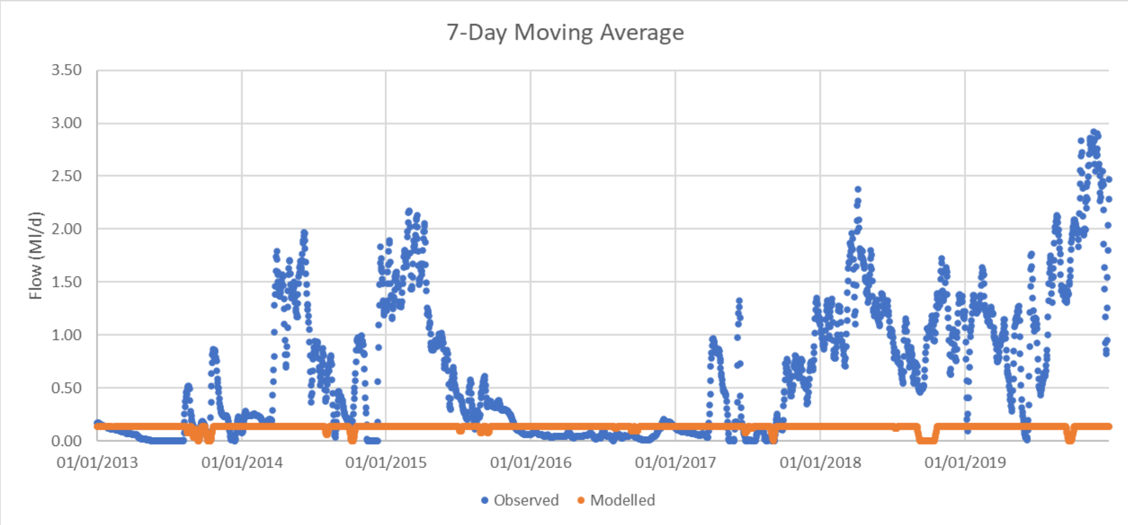


Figure 5-8; Comparison of gauged and modelled flows bypassing Atherstone Lock (Lock 1) (Aquator component CC Locks 1-7)

As shown in Figure 5-8, the model is presently spilling a roughly constant value of 0.14Ml/d over the Atherstone by-weir. This is not consistent with observed data which shows variable by-weir flow ranging from 0 to 3 Ml/d. The upstream pound has a control curve set at 100% meaning that the pound is kept consistently full and as such creates a relatively constant flow over the by-weir, it is likely that in reality the canal level is more variable causing the observed to be much more variable.

5.2.2 GU Pound 6-7: Lock 6 Bypass flow

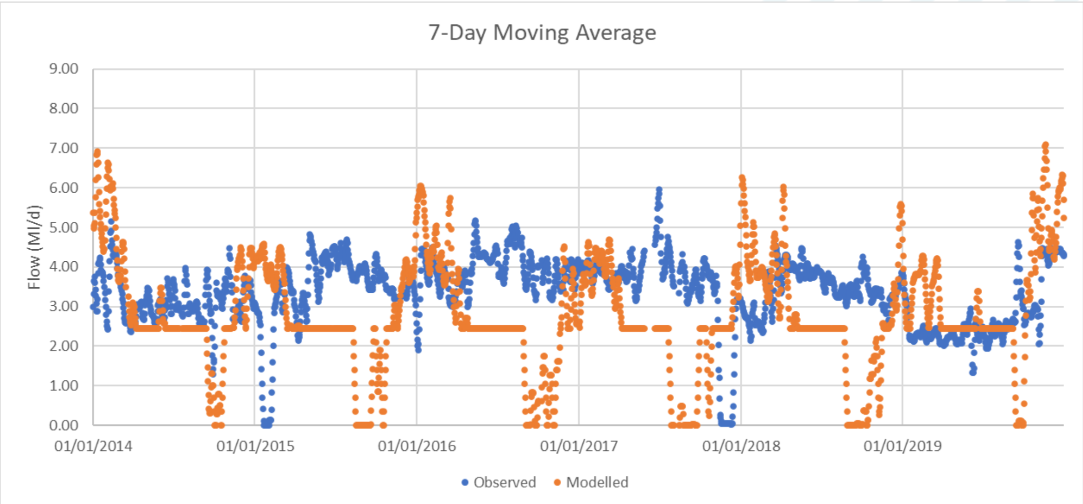


Figure 5-9; Comparison of gauged and modelled flows bypassing Lock 6 (Aquator component GU Locks 6-1)

As shown in Figure 5-9, the model is presently spilling a variable by-weir flow ranging from 0 to 7 Ml/d. The model is not replicating observed flow patterns likely due to the control curve of the upstream pound. Modelled and observed flow magnitudes compare well however, with the average model flow being 2.7Ml/d and the average observed flow being 2.4Ml/d.

5.2.3 GU Pound 6-7: Inflow from Daventry Reservoir

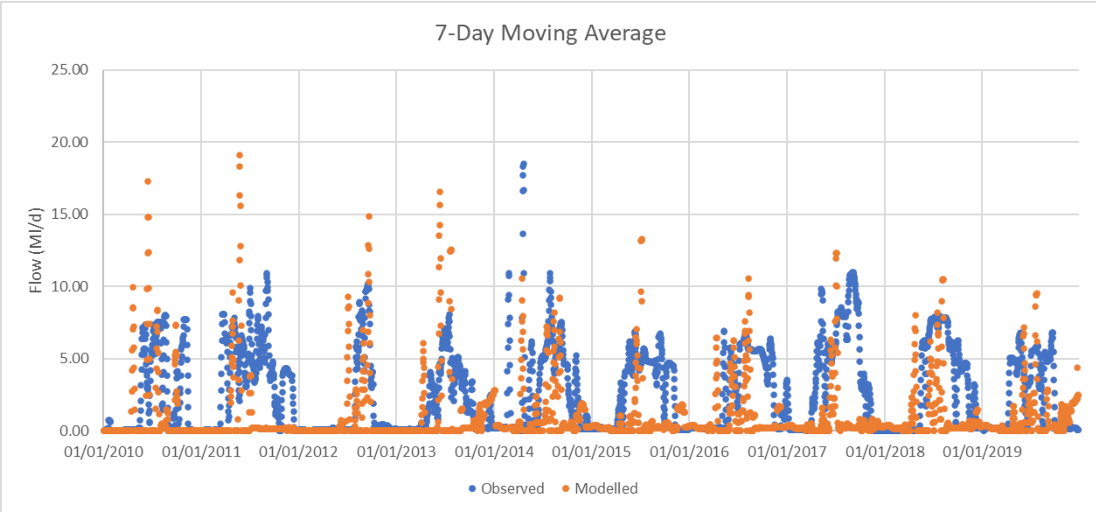


Figure 5-10; Comparison of gauged and modelled flows at the inflow from Daventry Reservoir

As shown in Figure 5-10, the model is replicating annual trends in flow well at the inflow from Daventry Reservoir, with seasonality and absolute values being comparable. The model is generally underestimating the flow from Daventry reservoir to the canal compared to the observed with the average flow bring 2Ml/d less than the observed.

5.2.4 GU Pound 6-7: Inflow from Drayton Reservoir

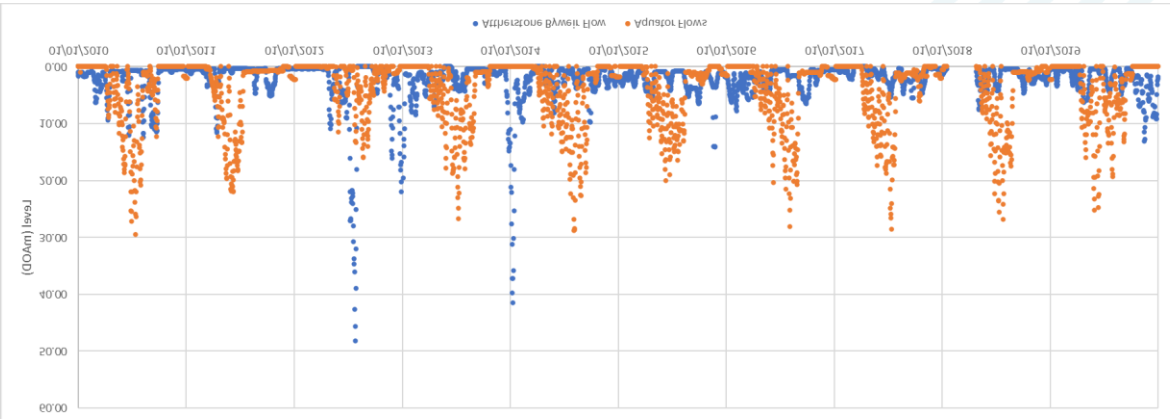


Figure 5-11; Comparison of gauged and modelled flows at the inflow from Drayton Reservoir

As shown in Figure 5-11, the model does not replicate long term or annual trends in flows very well. The modelled results show a distinctly seasonal pattern in flows which is not shown in the observed which seems to spill more regularly. The model is generally overestimating the flow from Drayton reservoir to the canal compared to the observed with the average flow bring 1 Ml/d higher than the observed.

5.2.5 GU Pound 20-21: Flow through the River Tove pump station

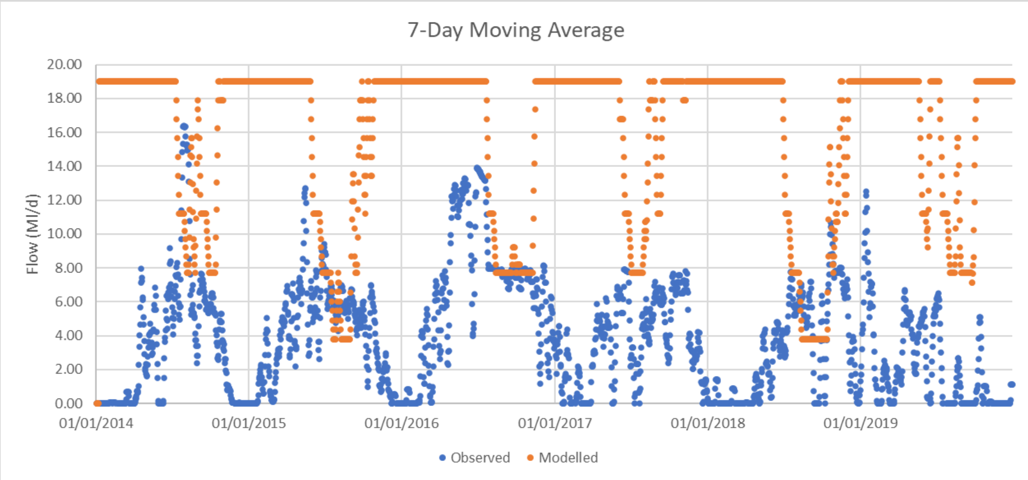


Figure 5-12; Comparison of gauged and modelled flows from the river Tove

As shown in Figure 5-12, model replicates long term and annual trends in flows adequately for the Tove inflow. The modelled total annual volume comparison suggests that in total the modelled volume is less than the observed by about 20%.

5.2.6 GU Pound 21-22: Flow through the River Ouse pump station

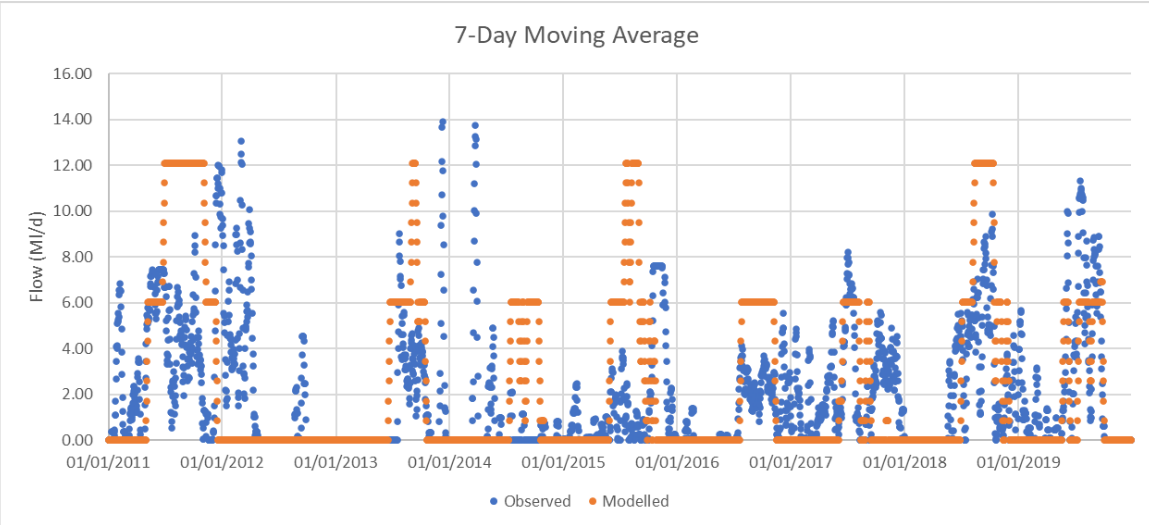


Figure 5-13; Comparison of gauged and modelled flows from the River Ouse

As shown in Figure 5-13, the model replicates long term trends in flows relatively well at the River Ouse inflow. The Ouse abstraction is related to flows in the Tove. The modelled flow magnitude is similar to the observed, but the model does not supply flow from the Ouse as often as is observed through the pump.

5.2.7 GU Pound 22-23: Flow over the Stoke Hammond Waste weir

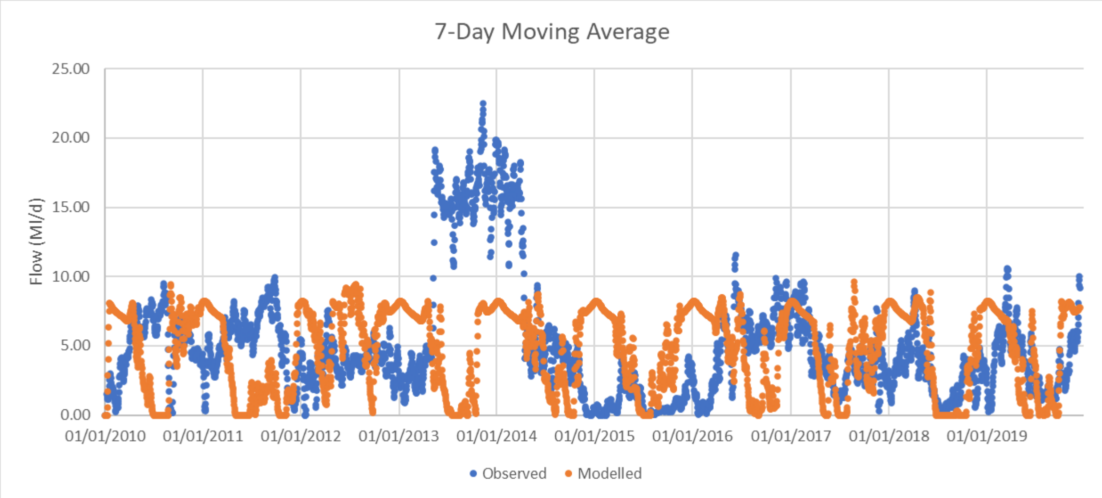


Figure 5-14; Comparison of gauged and modelled flows over the Stoke Hammond Waste Weir

As shown in Figure 5-14, the model does not replicate long term or annual trends in flows very well at the stoke Hammond Waste Weir. The modelled results show a constant flow over the waste weir with a seasonal dip around August September. This is likely related to control curve set up in the pound component. Modelled and observed flow magnitudes compare well though, with the average model flow being 4.8 Ml/d and the average observed flow being 5 Ml/d.

5.2.8 GU Pound 38-39: Flow from Marsworth and Startopsend Reservoirs

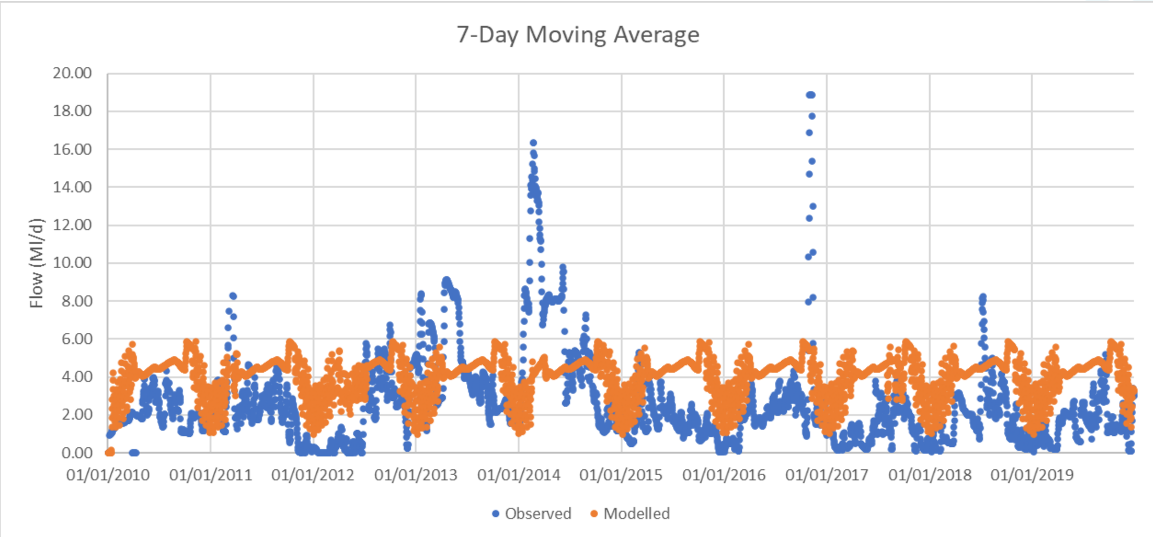


Figure 5-15; Comparison of gauged and modelled flows Marsworth and Startopsend Reservoirs

As shown in Figure 5-15, the model replicates seasonal and long-term trends in flows relatively well, though shows considerably less variability which is to be expected. The model is generally overestimating flow compared to the observed, with the average model flow being 4Ml/d and the average observed flow being 2.6Ml/d.

5.3 Trust Gauge Data- back pumping

The below sections compare modelled and observed back pump flow rates, with particular attention paid to annual average volumes. To remove some of the noise and make it easier to see patterns and trends in both the modelled and observed data a 7-day moving average has been applied.

5.3.1 Hillmorton back pump (OX Pound 8-7)

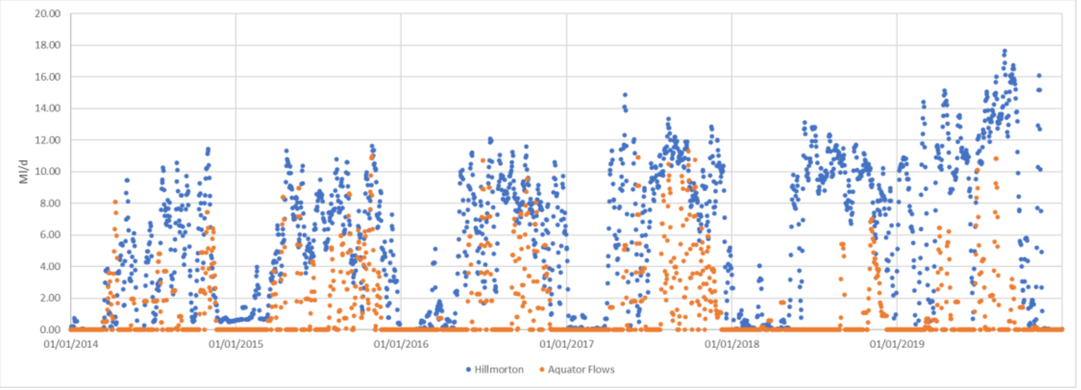


Figure 5-16; Comparison of gauged and modelled flows at the Hillmorton back pump

As shown in Figure 5-16, the model replicates seasonal and long-term trends in flows relatively well, and similar variability in flows. Modelled flow magnitudes are similar to the observed however, within the model the back pump is operated much less frequently than in the observed and as such the model is consistently underestimating total annual volumes as demonstrated in Figure 5-17. It should be noted that the modelled flows represent back pumping between several locks, whereas the observed is the back pumping around one lock so the comparison is not exactly like for like.

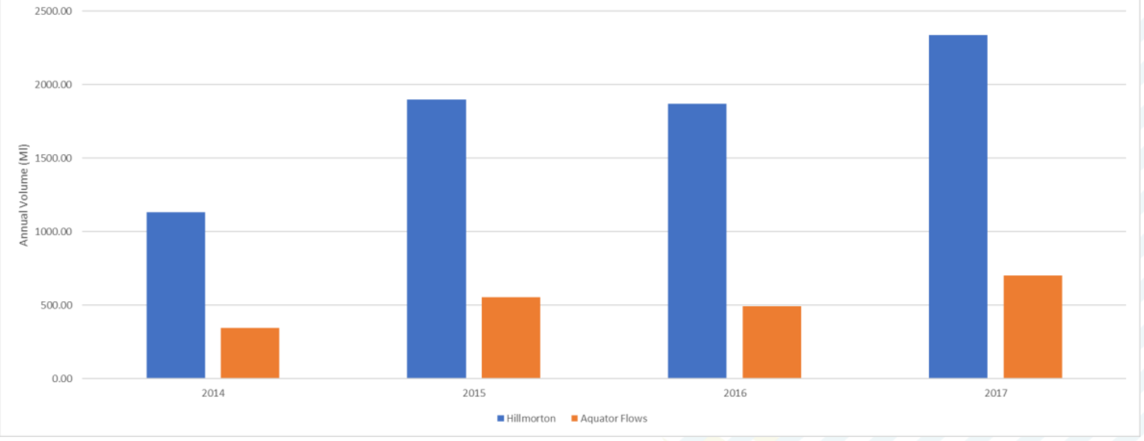


Figure 5-17; Gauged and modelled annual flow volumes at the Hillmorton Lock pump

5.3.2 Braunston lock back pump (GU Pound 6-7)

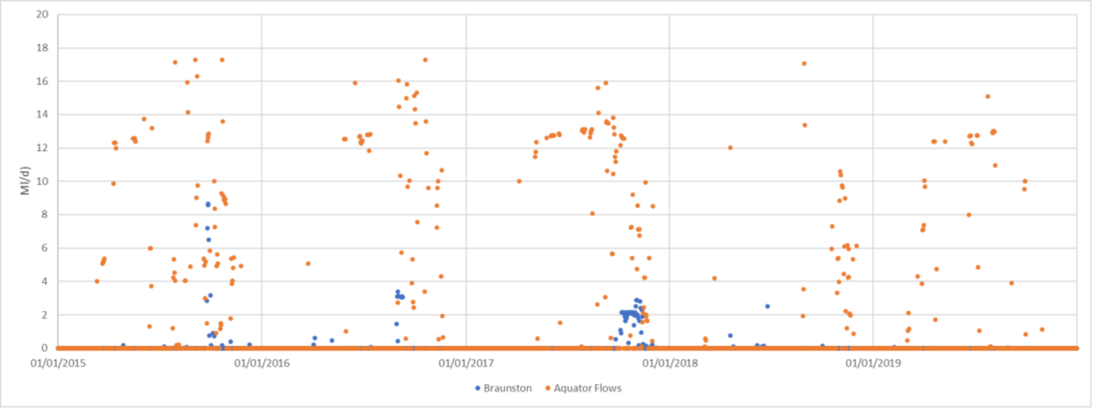


Figure 5-18; Gauged and modelled flows at the Braunston Lock back pump

As shown in Figure 5-18, the model is overestimating back pump flow around the lock. It should be noted that the modelled flows represent back pumping between several locks, whereas the observed is the back pumping around one lock so the comparison is not exactly like for like which may be the cause of this discrepancy.

5.3.3 Buckby Upper back pump (GU Pound 6-7)

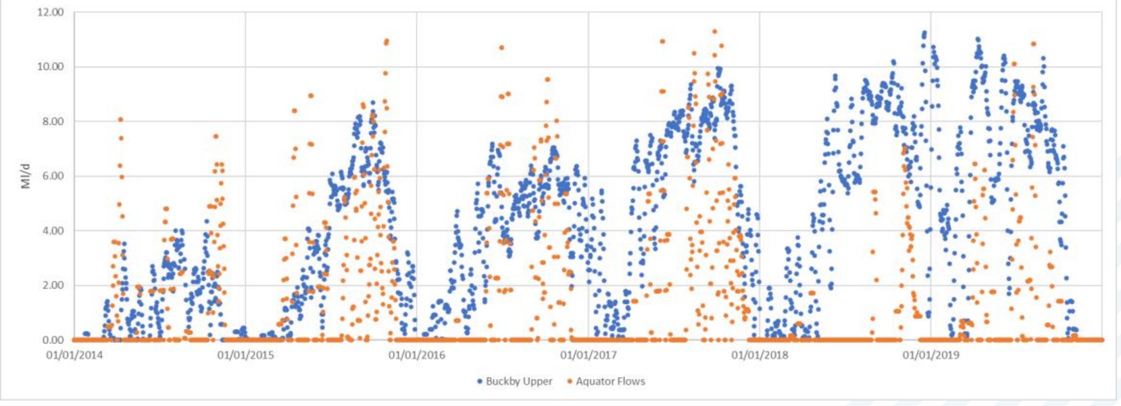


Figure 5-19; Gauged and modelled flows at the Buckby Upper back pump

As shown in Figure 5-19, the model replicates seasonal and long-term trends in flows relatively well and shows similar variability in flows. Modelled flow magnitudes are similar to the observed however, within the model the back pump is operated much less frequently than in the observed and as such the model is consistently underestimating total annual volumes as demonstrated in Figure 5-20.

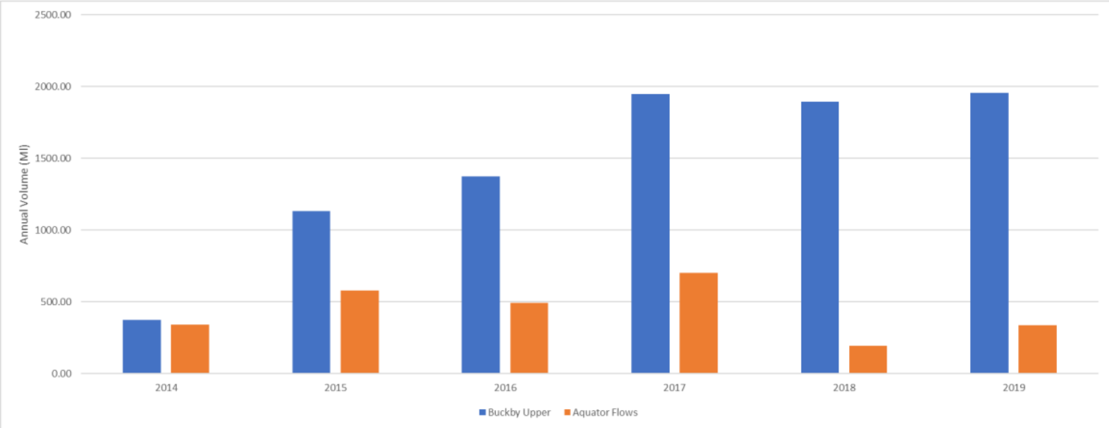


Figure 5-20; Gauged and modelled annual flow volumes at the Buckby Upper back pump

5.3.4 Stoke Hammond

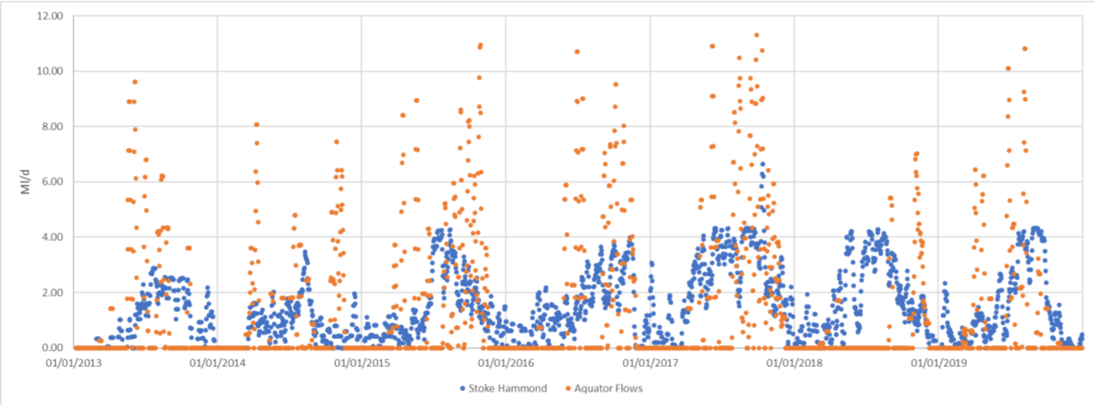


Figure 5-21; Gauged and modelled flows at the Buckby Upper back pump

As shown in Figure 5-21, the model replicates seasonal and long-term trends in flows relatively well and shows similar variability in flows. Modelled flow magnitudes are similar to the observed however, generally within the model the back pump is operated much less frequently than in the observed. It should be noted however that the model is generally replicating annual total flows within the first three years, as demonstrated in Figure 5-22.

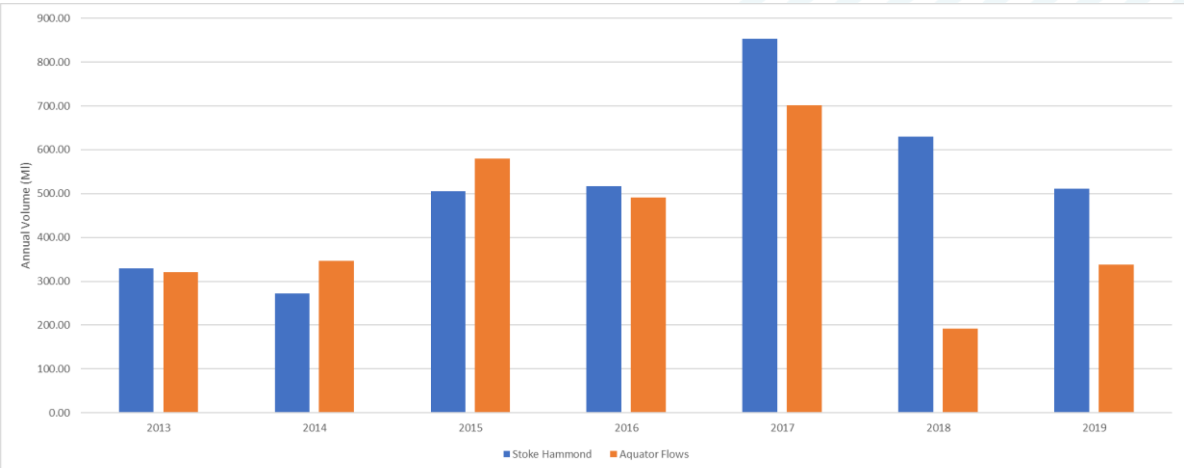


Figure 5-22; Gauged and modelled annual flow volumes at the Stoke Hammond back pump

5.3.5 Soulbury Back pump (GU Pound 23-24)

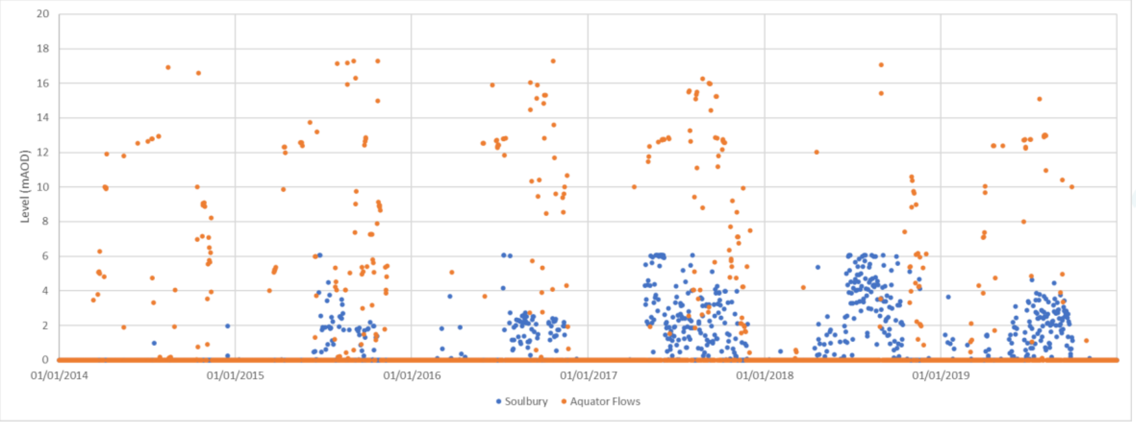


Figure 5-23; Comparison of gauged and modelled flows at the Soulbury back pump

As shown in Figure 5-23, the model replicates seasonal and long-term trends in flows relatively well. Modelled flow magnitudes are much higher than the observed and the model is consistently overestimating total annual volumes as demonstrated in Figure 5-24, with the exception 2018 where the model is underestimating the total annual volume. It should be noted that the modelled flows represent back pumping between several locks, whereas the observed is the back pumping around one lock so the comparison is not exactly like for like.

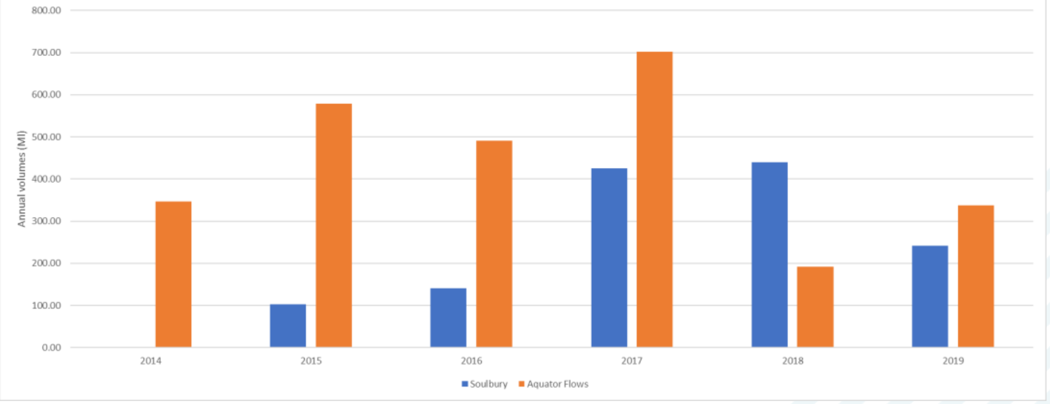


Figure 5-24; Gauged and modelled annual flow volumes at the Soulbury Back pump

5.4 The Trust gauge data – reservoir storages

The section compares observed and modelled storages for key Trust Reservoirs along the transfer route.

As recommended by the Trust Hydrologists reservoir storages have been assessed by reservoir group. The Braunston Summit group includes Daventry and Drayton Reservoirs, and the Tring Summit Reservoir Group includes the Tringford, Startopsend, Marsworth and Wilstone Reservoirs.

5.4.1 Braunston Summit Group

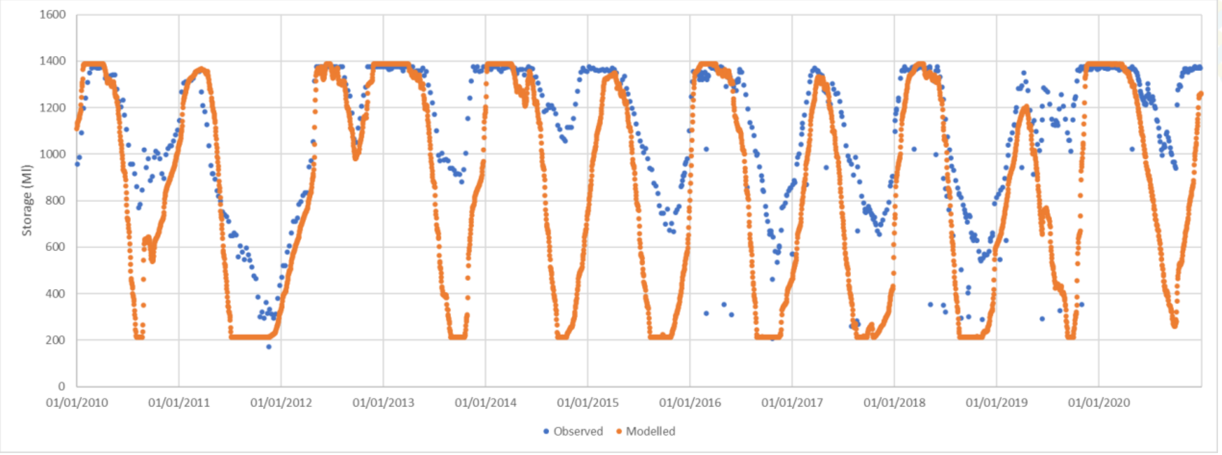


Figure 5-25; Comparison of observed and modelled reservoir storage for the Braunston Summit Reservoir Group.

As shown in Figure 5-25, the model replicates seasonal and long-term trends in reservoir storages relatively well, though is overestimating drawdown in summer. Both reservoirs are drawing down to their emergency storage levels most years. Modelled volumes are comparable with the observed and the model is showing similar annual average storage volumes to the observed (Figure 5-26).

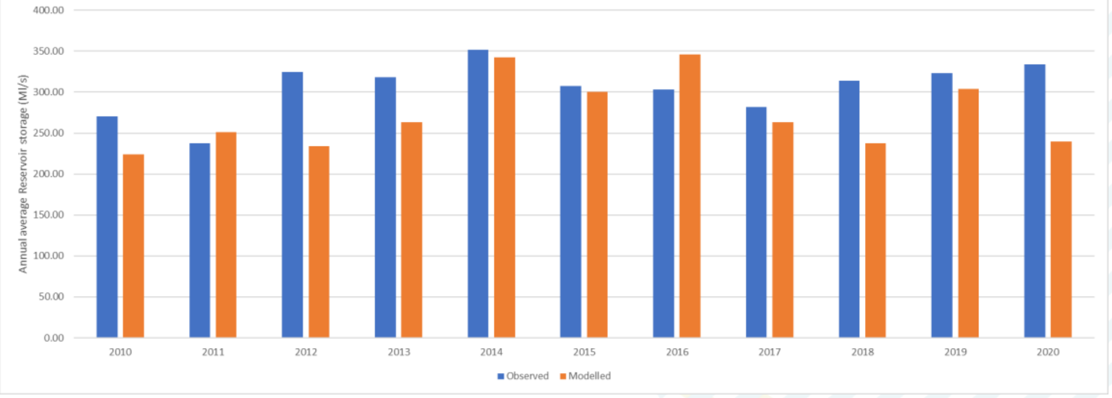


Figure 5-26; Gauged and modelled average annual flow volumes for the Braunston Summit Reservoir Group.

5.4.2 Tring Summit Reservoir Group

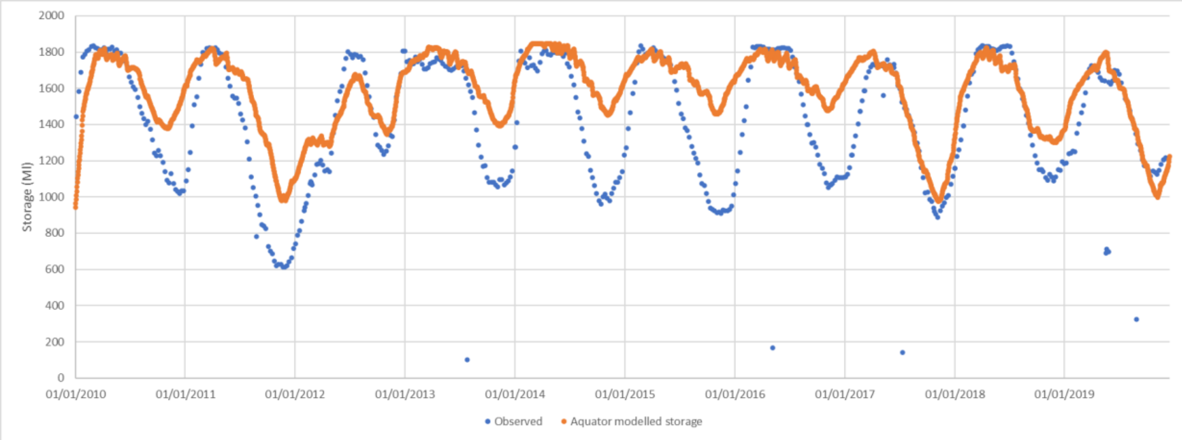


Figure 5-27; Comparison of observed and modelled reservoir storage for the Tring Summit Group

As shown in Figure 5-27, the model replicates seasonal and long-term trends in reservoir storages relatively well, though is generally underestimating drawdown in summer. Modelled volumes are comparable with the observed and the model is showing similar annual average storage volumes to the observed (Figure 5-28).

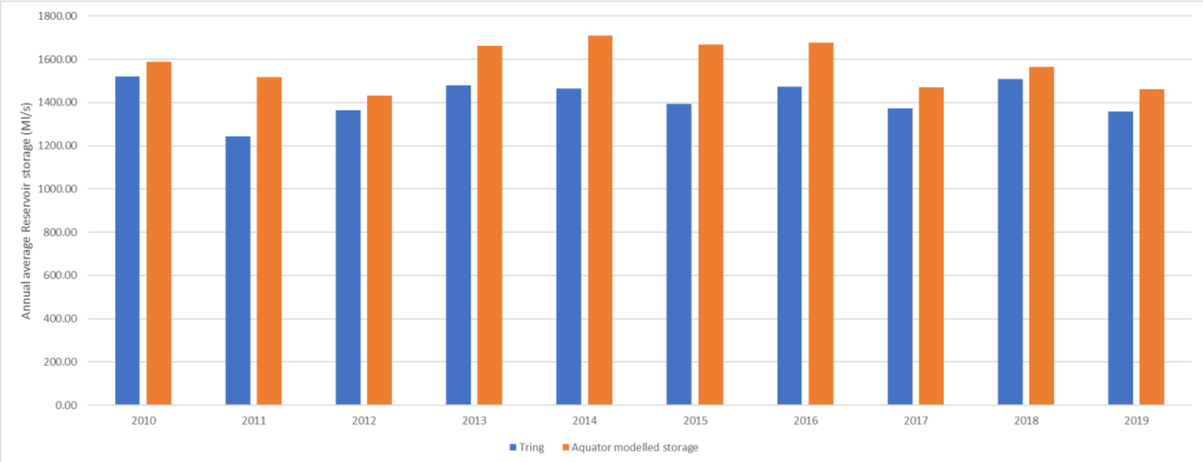


Figure 5-28; Gauged and modelled average annual flow volumes for the Tring Summit Group The Trust gauge data – reservoir storages

5.5 The Trust gauge data – annual lockage volumes

The section compares observed and modelled total annual lockage values for several key locks along the transfer route.

5.5.1 Ox Locks 7-3

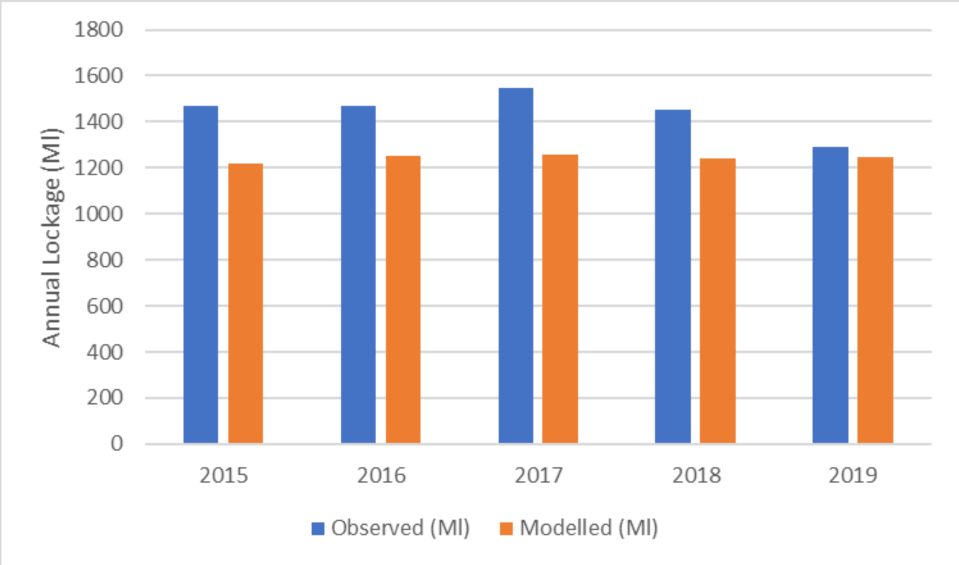


Figure 5-29; Gauged and modelled annual lockage volumes for Ox Locks 7-3

As shown in Figure 5-29, the model is generally representing total lockage flow well with modelled and observed values being comparable, the modelled total annual volume comparison suggests that on average the observed volume is greater than the modelled by about 20%.

5.5.2 Ox Locks 6-2

Figure 5-30; Gauged and modelled annual lockage volumes for Ox Locks 6-2

As shown in Figure 5-30, the model is generally representing total lockage flow well with modelled and observed values being comparable. The modelled total annual volume comparison suggests that on average the observed volume is less than the modelled by about 20% aside from in the first and last years of the gauge record where volumes compare well.

5.5.3 GU Lock 7

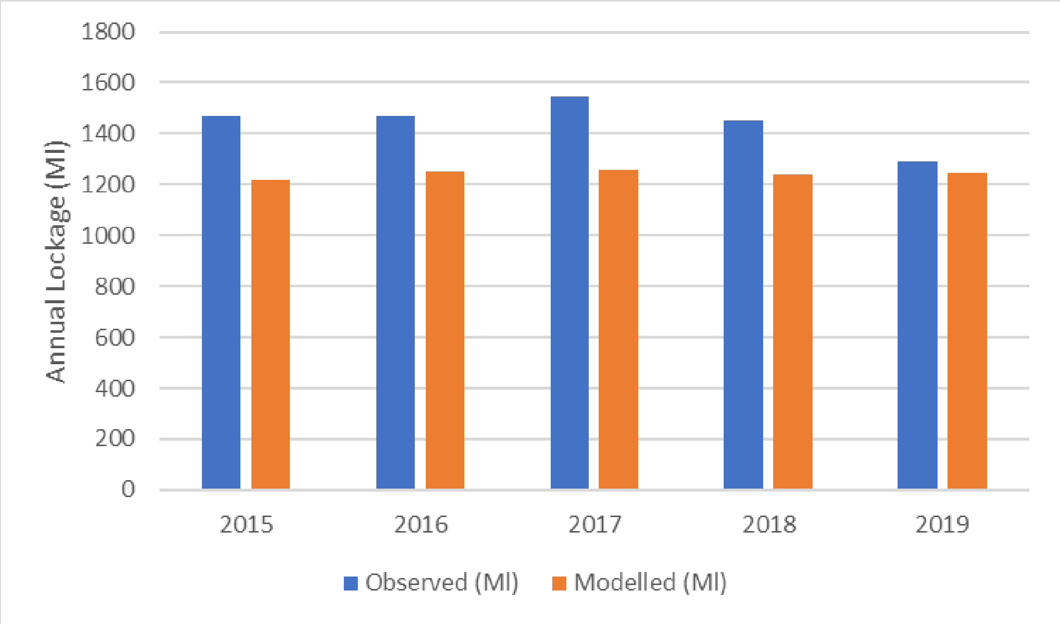


Figure 5-31; Gauged and modelled annual lockage volumes for GU Lock 7

As shown in Figure 5-31, the model is generally representing total lockage flow well with modelled and observed values being comparable. The modelled total annual volume comparison suggests that on average the observed volume is greater than the modelled by about 20% aside from in the last year of the gauge record where volumes compare well.

5.5.4 GU Lock 37

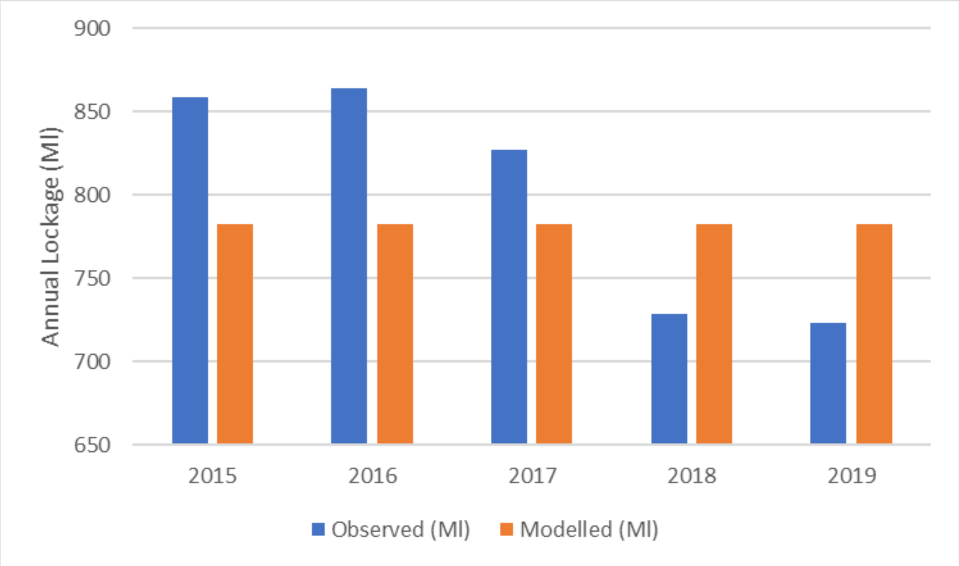


Figure 5-32; Gauged and modelled annual lockage volumes for GU Lock 37

As shown in Figure 5-32, the model is generally representing total lockage flow well with modelled and observed values being comparable.

5.6 Summary

Revised inflows have been inserted in the Aquator model and a validation exercise was undertaken comparing modelled flows to spot flow gaugings and continuous gauge data. The main conclusions are:

- The Aquator flows at pounds suggest a realistic pattern in line with the spot flow measurements from summit to trough. When rainfall has fallen in the previous days, the response is replicated both from observed and from modelled in the same way.
- With reference to spot gaugings and Trust flow data at pounds and weir spills, there is variability to the flow estimate comparisons, with spills from pounds often being higher than the spot gaugings. This is to be expected as the daily flow estimates for pound spills are based on weir equations based on British Standards, which make assumptions of smooth flow over weir and generally are likely to estimate more flow for a given level than what has been observed. It is noted that these are aged structures and as such it is hard to model.
- The reservoir outflows from the key Trust reservoirs along the transfer route compare generally well to the observed outflows. Reservoir storages also compare well to the observed. There is a clear signature to the modelled flows that is dictated by the reservoir curves, which is to be expected as reservoir operation in Aquator is subject to the control curves being below or above specific thresholds.
- Aquator does not represent flow from by weirs adequately, as the flow calculation is dependent on whether respective levels have been set within the model and the control curve of the canal pound upstream. The best workaround for this is to compare observed flow from by-weir to modelled flows downstream of lock. This is a known and accepted limitation of Aquator. However, JBA have additional topographic survey data which could be used to specify suitable levels over the by-weirs at key locations to improve the model.
- Most back-pumps work in line with observed data and replicate seasonal patterns well, although generally the back pumps in the model tend to be activated less frequently than in the observed. The pattern of yearly variability is in line with the rule curve at the respective pound driving the pump activation, which is to be expected as it is the rule triggering the activation of the pumps.
- Water level predictive performance of modelled versus observed pound levels has not been reported here. A comparison on modelled level data from Aquator at pounds versus observed gauge locations has been made and generally the model performs reasonably well, but the level data from Aquator is a secondary parameter based on volumes at pounds and rule curves, therefore it is not good practice to validate the model based on levels. The hydraulic model will do the validation of pound levels more accurately and compare against spot measurements and Trust level data more comprehensively.

6 Modelling of historical droughts

6.1 Overview

To stress test the Aquator model during drought conditions and understand if the hydrological calibration and approach adopted for the hydrological analysis using donors results to underestimation of drought impacts, observed flows have been used and scaled where applicable to model notable drought periods and compare the findings against the results of the Aquator model.

This is to test if the current rainfall-runoff models replicate the complex processes that contribute to drought, particularly in catchments with a moderate to high groundwater component. To make best use of the work carried out under Phase 3 to identify suitable donor catchments, the donors used for rainfall-runoff modelling have been maintained and scaled to feeder catchments.

This section outlines the identification of a suitable drought period and the derivation representative drought hydrology for use as input to the combined Aquator XV model.

6.2 Drought scenario selection

Notable drought events to choose from in recent history include the 1975-76 (perhaps the most well-known drought of recent decades), 1984, 1995-1998, 2003-2006, 2011-2012 and 2018-2019 droughts. Selection of the drought scenario took into consideration several factors including, severity and data availability.

The number of gauges in the UK significantly increased in the early 2000's, and as such it was decided to choose a drought event that occurred after this event to increase the availability of suitable gauges to use as donors. From this a 90-day moving average was calculated from the gauges used as donors in the original hydrology and used to work out return periods for droughts occurring in the last 20 years to assess which was the consistently the driest across catchments. The results are shown in Table 6-1 (overleaf). This table shows that aside from at Wendover, the 2018-2019 event and the 2011-2012 events are consistently the driest. The 2018-2019 event has been chosen as the final scenario as this was a more prolonged drought with a 2-year duration.

Table 6-1; Return periods of 90-day average annual minimum flows for donor gauges, for the 2003-2006, 2011-2012 and 2018-2019 drought events.

Gauge	Year	90-day Annual Minimum Flow (Ml/d)	Return Period
Tove at Cappenham Bridge	2011	12.1	37
	2019	14.7	8
	2012	17.1	5
	2006	17.3	5
	2018	17.5	4
	2005	18.3	3
Clipstone Brook at Clipstone	2019	0.9	27
	2018	1.4	10
	2011	1.6	6
	2006	1.7	4
	2005	2.9	2
	2012	3.8	1
Wendover Springs at Wendover	2012	2.9	5
	2006	3.4	4
	2011	3.5	4
	2019	3.8	3
	2005	4.1	2
	2018	5.6	1
Mease at Clifton Hall	2018	19.2	34
	2011	19.5	12
	2005	24.4	7
	2012	29.7	5
	2006	34.9	3
	2019	44.6	1
Nene/Kislingbury at Dodford	2011	13.4	3
	2018	13.5	3
	2005	15.0	3
	2012	15.1	3
	2019	16.5	2
	2006	17.3	2
Sence at South Wigston	2018	11.9	10
	2011	12.6	8
	2012	16.5	4
	2005	18.6	2
	2006	20.5	2
	2019	28.1	1
Swift at Churchover	2011	3.3	14
	2018	4.2	8
	2012	7.0	5
	2006	7.5	2
	2005	9.5	2

Gauge	Year	90-day Annual Minimum Flow (Ml/d)	Return Period
	2019	10.0	1

6.3 Donor catchments

Most feeder catchments are small and ungauged, requiring the use of analogue or donor gauges as discussed in section 4.3. Two additional gauges were used as donors for the PDM calibration that were not carried forward for use in the drought analysis, Tring Drainage, and the Bedford Ouse at Thornbrough Mill. The Tring Drainage gauge has a very short record (2020 onwards), and this gauge was not operational during 2018/2019 which is the focus of this study. The Wendover at Wendover Springs has been used in place of this gauge as the two have similarities in the catchment descriptors and a baseflow dominated regime. Rainfall-runoff modelling was originally used to represent the flow on the Tring feeder and Tring Drainage as these gauges have a significant urban component at high flows. However, as shown on Figure 6-1 mean scaling the Wendover arm series gives comparable baseflows to the observed and therefore as these catchments are small using Wendover to represent the flows is acceptable.

The Bedford Ouse at Thornbrough Mill was decommissioned in 1991 and therefore cannot be used to represent flows in the drought scenario. After investigation of different gauges nearby, on the catchment and on adjacent catchments to determine which was most appropriate. The Flow duration curves for Thornborough Mill, Tove at Cappenham, Bedford Ouse at Brackley and the Ouzel at Willen were all normalised by mean and compared to determine which was the most representative (Figure 6-2). This showed that the Tove at Cappenham was the most suitable to represent flows on this watercourse.

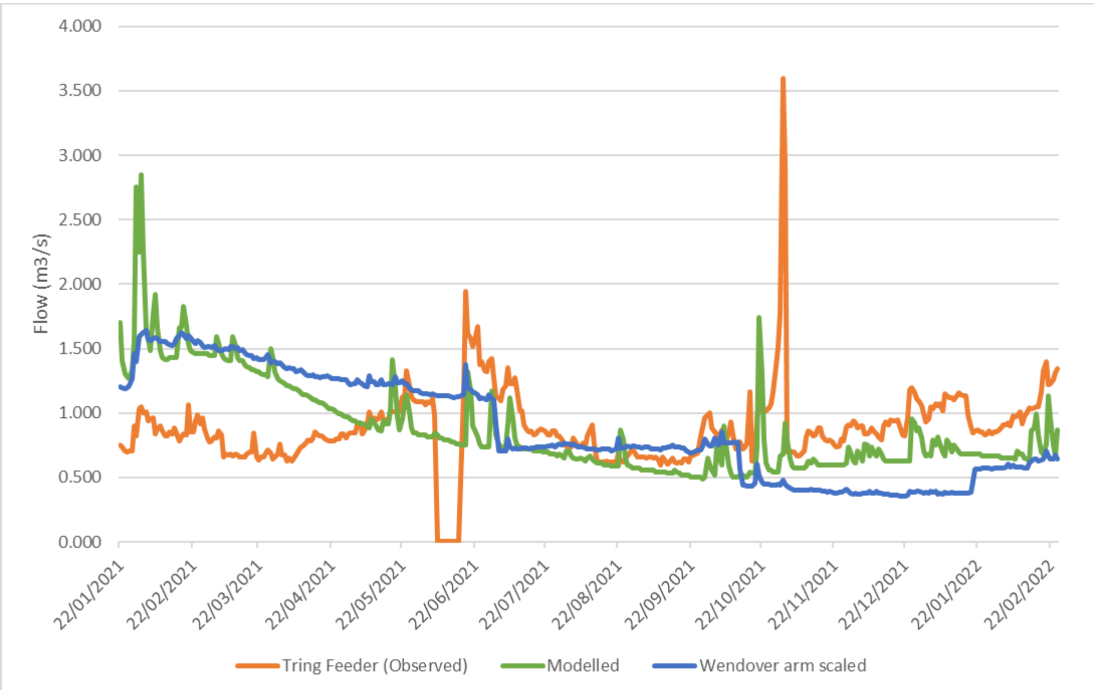


Figure 6-1; Comparison of observed modelled and mean scaled Wendover Springs series for comparison.

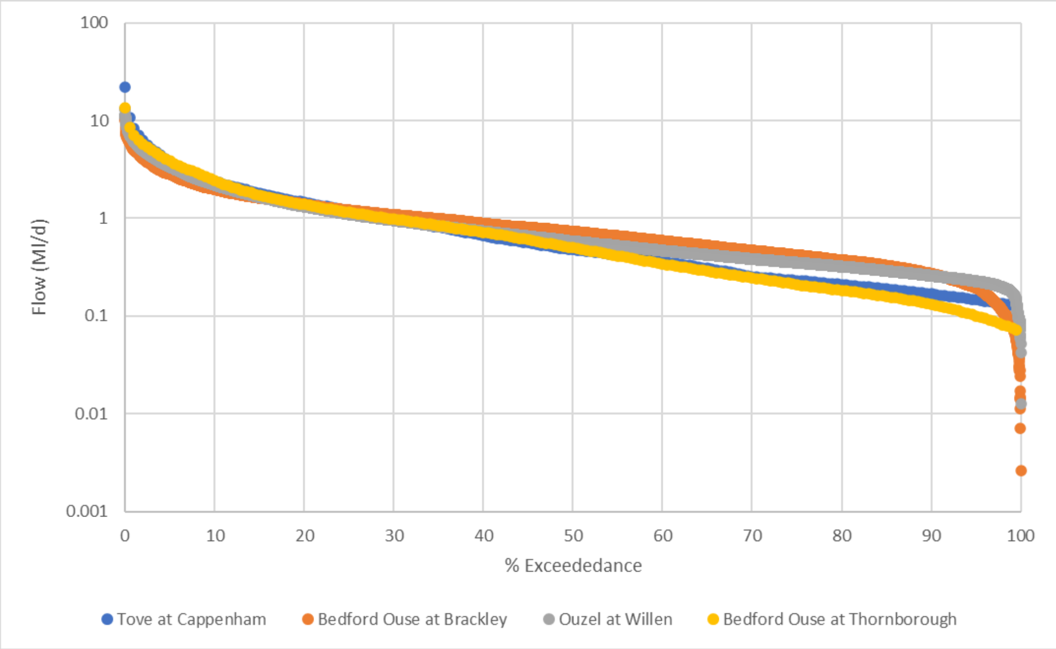


Figure 6-2; Normalised flow duration curves for the Tove at Cappenham, Bedford Ouse at Brackley, Ouzel at Willen shown compared to the normalised flow duration curve for the Bedford Ouse at Thornbrough Mill.

Observed time series for each of the donor gauges for the period 2017-2019 were extracted from the gauged daily flow record and checked to ensure the data looked realistic, any periods of missing data were infilled. Only very small periods of missing data were found in each of the gauge record (periods of one to two days) and were infilled using of the gauge records either side.

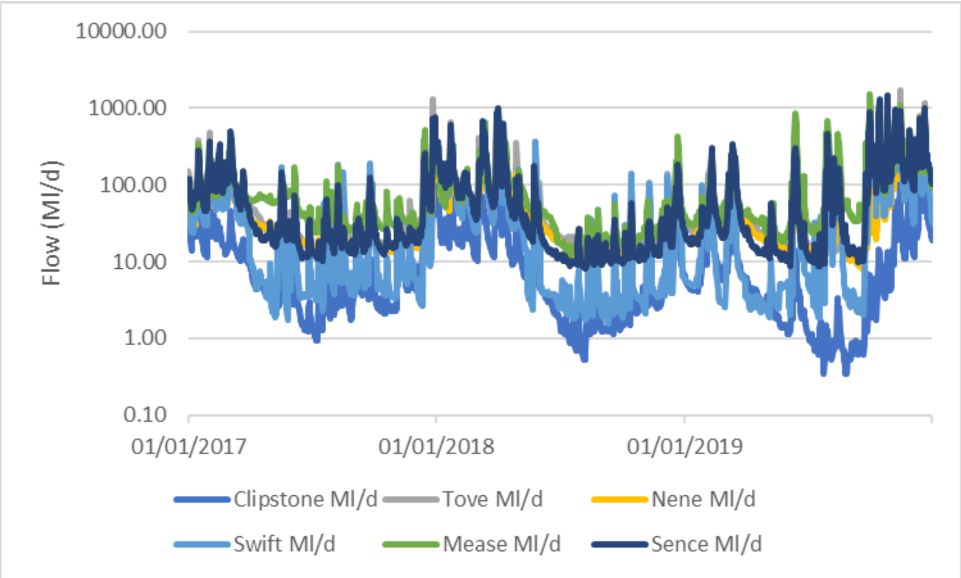


Figure 6-3; Timeseries for the 2017-2019 period at donor gauges.

The resulting timeseries derived for each donor catchment has been scaled using either catchment area (scaled using the ratio of target and donor catchment areas) or mean flow scaling (scaled using the ratio of target and donor catchment mean flows as derived from the LowFlows 2 software). Where possible mean flow scaling has been used in place of catchment area scaling as this accounts for differences in catchment characteristics between the donor and target feeder catchment. Where catchments have similar characteristics and catchment areas catchment area scaling has been used. A summary of which method and donor has been used for each catchment is given in Table 4-6.

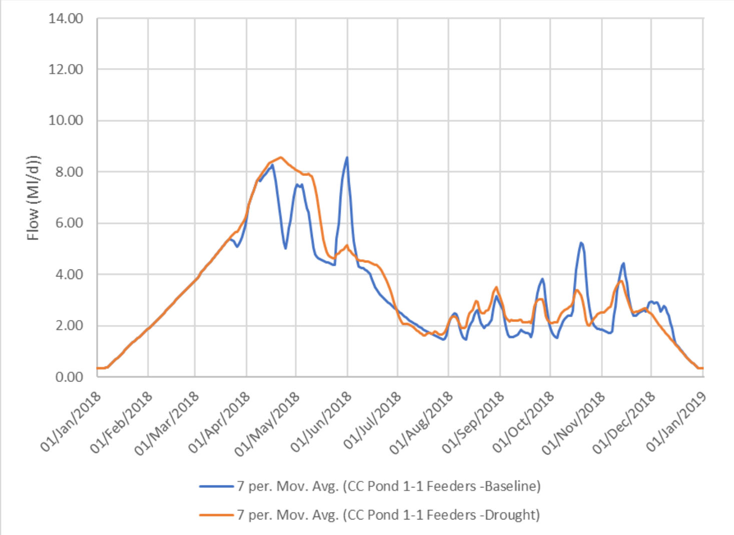
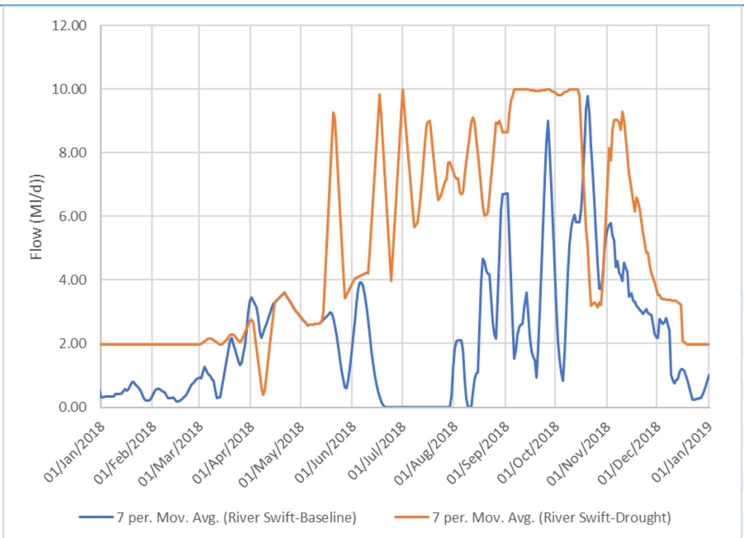
Table 6-2; Summary of method for inflow derivation

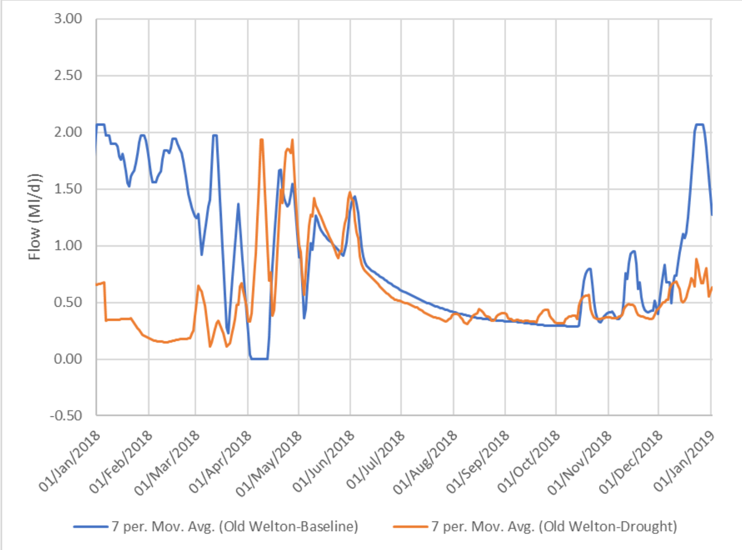
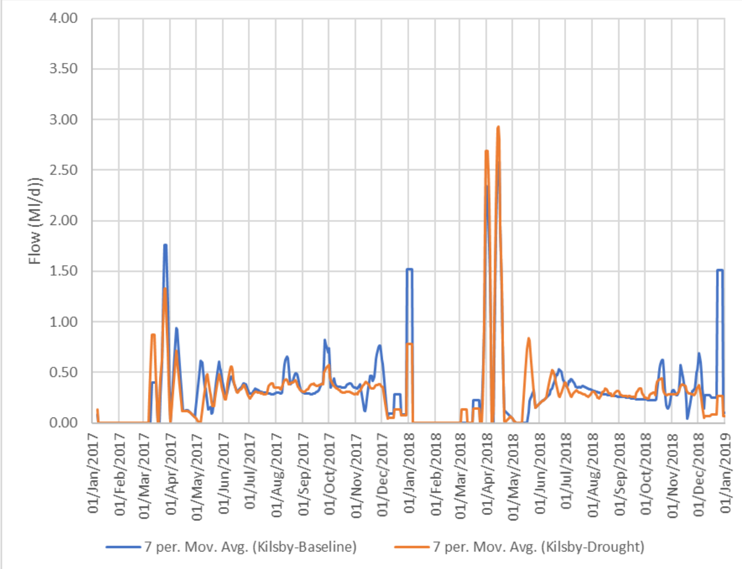
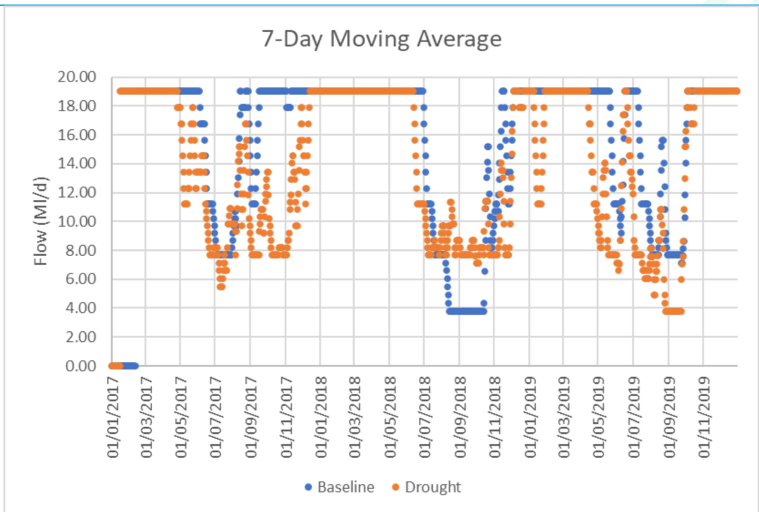
Feeder	Area	Donor	Method
River Ouse	505.9	Tove	Mean scaled
River Cherwell, Aynho	276.0	Tove	Mean scale
River Tove	171.9	Tove	Area scaled
River Cherwell Cropredy Mill	148.2	NA	Feeder inflow hydraulically constrained, constant inflow of 1.5Ml/d in model maintained.
River Swift Feeder	68.0	Swift	Area scaled
Ledburn Brook	34.5	Clipstone	Area scaled
Boddington Feeder	19.6	Clipstone	Mean scale
Burton Brook	15.4	Sence	Area scaled
Watford Feeder	11.2	Nene	Mean scale
Grendon Feeder	10.2	Mease	Mean scale
Griff Arm	9.3	Mease	Mean scale
Wem Brook Feeder	8.7	Mease	Mean scale
Sulby Feeder	8.4	Sence	Mean scale
Daventry Feeder	8.4	Nene	Mean scale
Tring Summit Feeder	7.6	Wendover	Mean scale
Wendover	7.3	Wendover	Infilled flows from Wendover Springs
Tring Drainage	6.5	Wendover	Mean scale
Saddington Feeder	6.3	Sence	Mean scale
Naseby Feeder	4.7	Sence	Mean scale
Wormleighton Feeder	4.7	Clipstone	Mean scale
Old (Welton) Feeder	3.4	Nene	Mean scale
Gumley Feeder	3.2	Sence	Mean scale
Merevale Feeder	3.0	Mease	Mean scale
Kilsby	2.9	Nene	Mean scale
Wilstone Feeder	2.7	Wendover	Mean scale
Bulbourne Stream	2.2	Wendover	Area scale
Clattercote Feeder	1.9	Mease	Mean scale
Drayton Feeder	1.8	Nene	Mean scale
Hartshill	1.5	Mease	Mean scale
Rawn hill Feeder	1.3	Mease	Mean scale
Mancetter Feeder	1.2	Mease	Mean scale
Tunnel Feeder	1.1	Mease	Mean scale
Welford	0.5	Sence	Mean scale

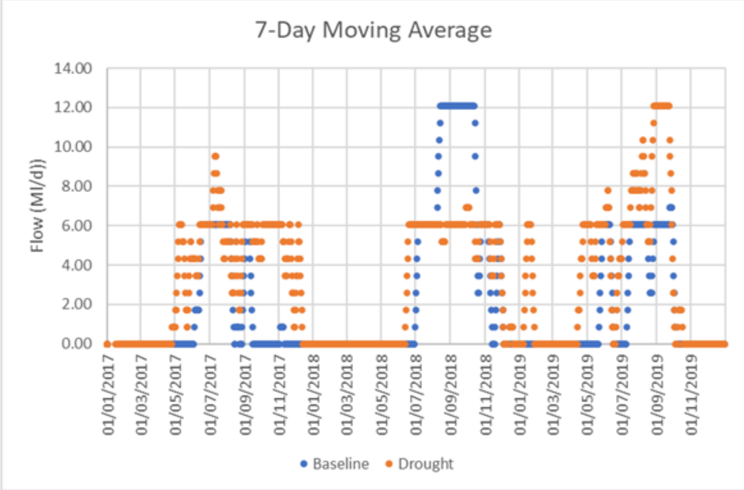
6.4 Historical drought run Aquator modeling results

The historical drought flows have been imported into the baseline Aquator model to assess the impact of the historical drought flows on the storages and abstractions. The below sections compare baseline and drought flows for the 2017-2018 period. To remove some of the noise and make it easier to see patterns and trends in both the baseline and drought runs a 7-day moving average has been applied. 2017 is a warm-up year and where results are shown for summer of 2017, these are not for comparison.

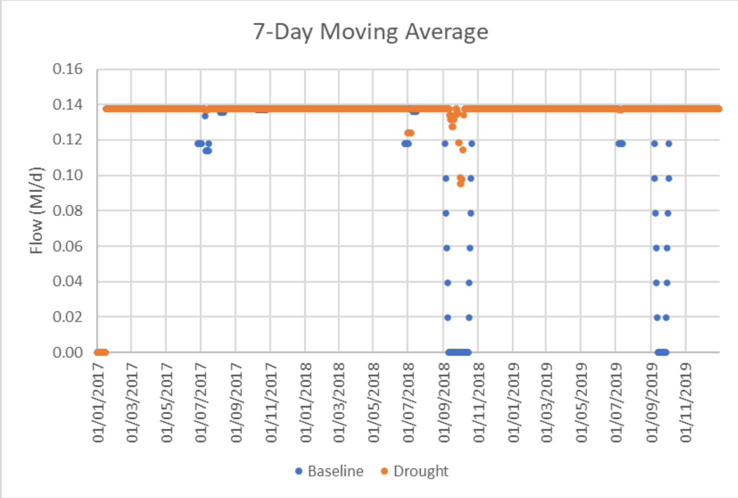
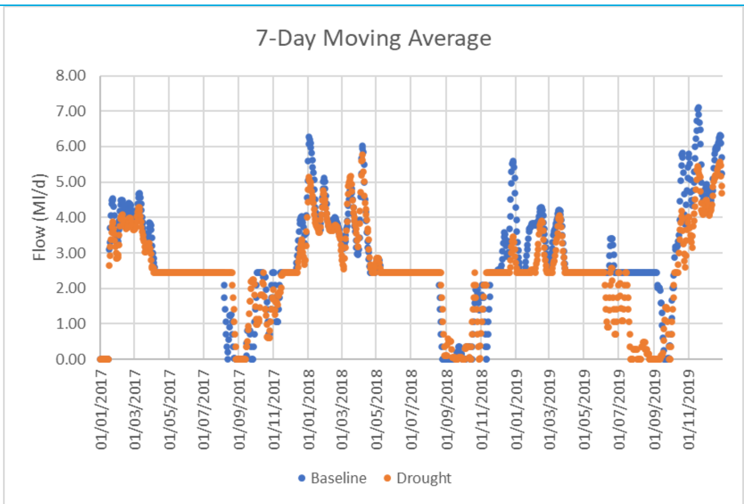
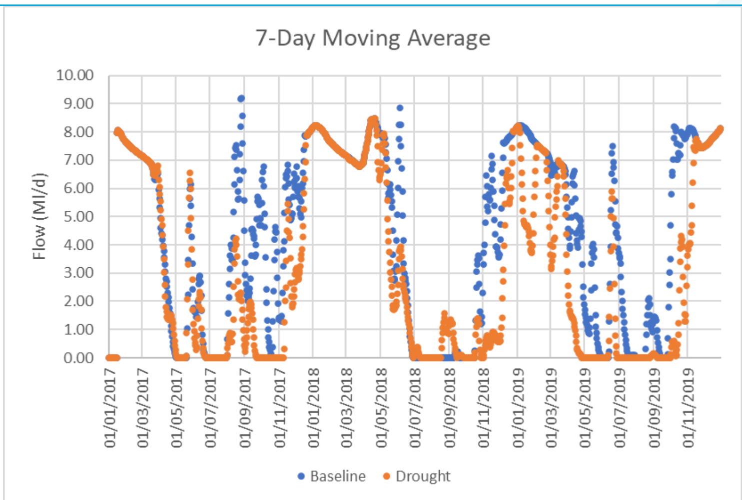
6.4.1 Abstractions

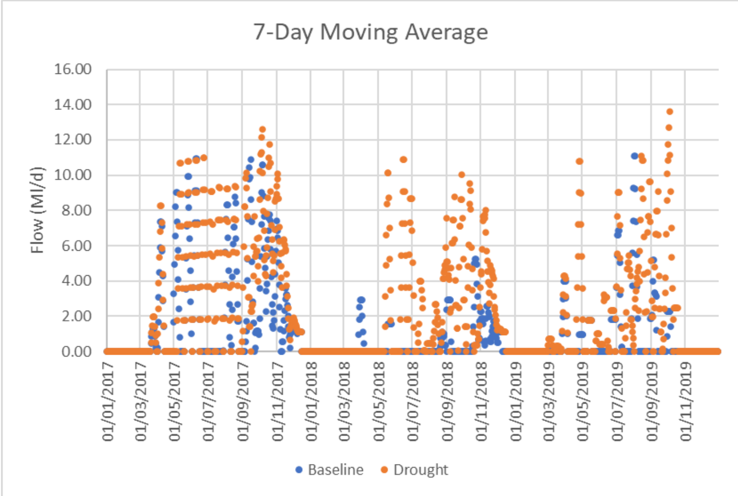
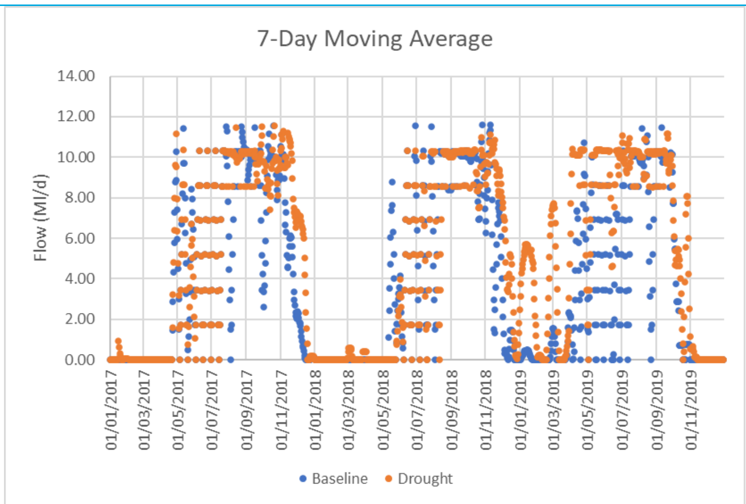
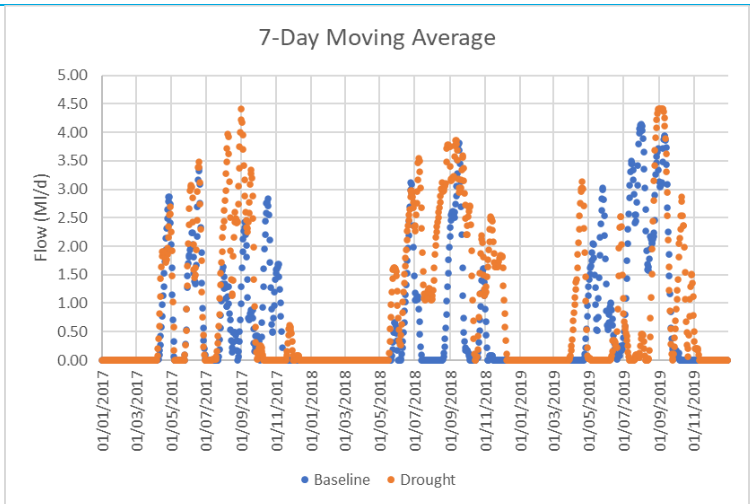
Location: component	Comparison Plot	Comments
Abstraction from CC Pound 1-1 feeders.		Minimal change.
Abstraction from River Swift		Abstraction increased in the drought scenario, Baseline modelled inflows lower, therefore more conversative than the observed. Likely to be due to both baseline feeder flows being more conversative than the observed.

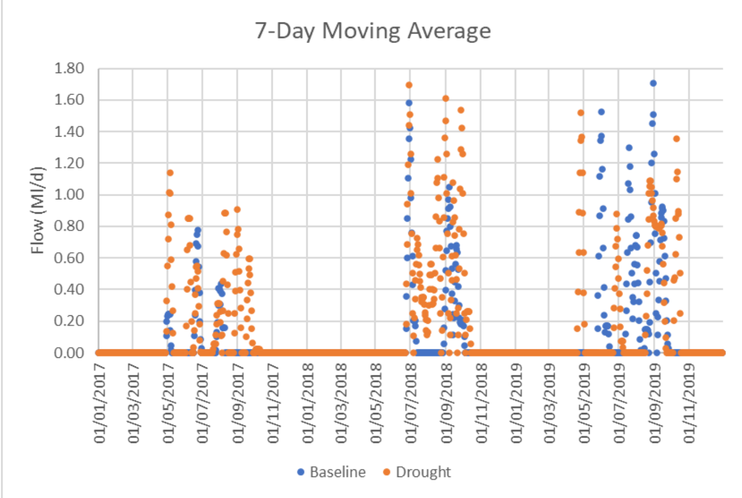
Abstraction from Old Welton		Minimal change.
Abstraction from Kilsby		Minimal change.
GU Pound 20-21: Flow through the River Tove pump station		The Tove abstraction is reduced to its minimum limit in the summer 2018 in the baseline but not in the drought. This is because the rainfall-runoff model flows appear to be more conservative during this period than the observed. The abstraction is reduced more and for a longer period in 2019. This is likely because the model does not replicate the second year of drought as well as the first.

GU Pound 21-22: Flow through the River Ouse pump station		The flow through the Ouse pump abstraction is interlinked to flows and the abstraction from the Tove. Despite the monthly volumes being less than 5% different, the Ouse abstraction is increased in 2019 compared to the baseline, likely to make up the shortfall from the Tove abstraction in these years.

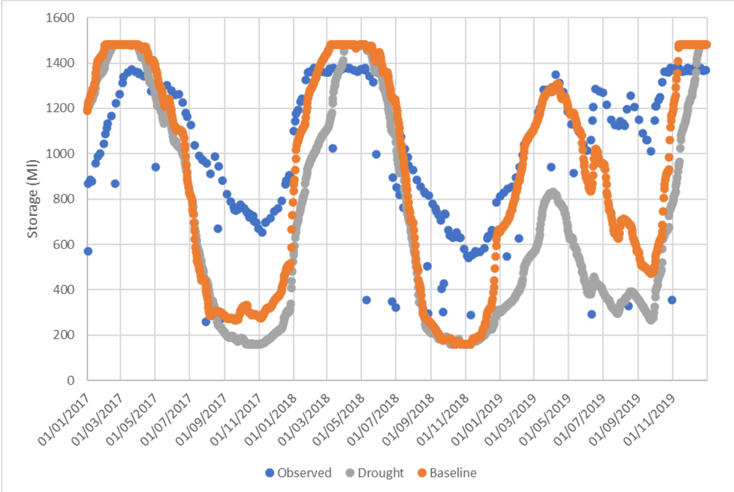
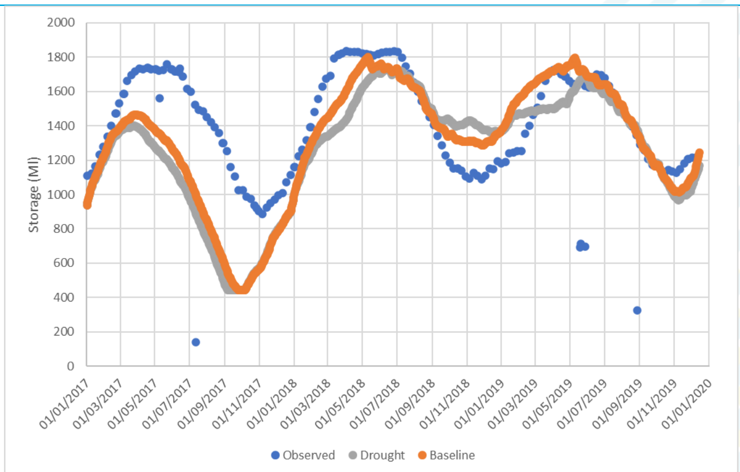
6.4.2 Canal flow

Location: component	Comparison Plot	Comments
Atherstone Locks (CC Pound 1-1): Bypass Flow		Minimal change.
GU Pound 6-7: Lock 6 Bypass flow		Minimal change in 2018. Some small reductions to bypass flow during Summer 2019. Likely due to reduced recharge of the Branston Summit Reservoirs limiting the refill of the Braunston summit pound causing pound levels to drop below the bypass weir level.
GU Pound 22-23 (Stoke Hammond Waste weir): Pound Spill		Largest changes occur during August to November, where less water is available for spill than in the baseline. This is particularly true in Winter 2018-2019. This is likely as the rainfall-runoff models representing the flows around Tring in the baseline model appear to overestimate feeder flows during this period, as the hydrological model is challenged when replicating the complex groundwater processes occurring in the catchments around

		this area.
Hillmorton back pump (OX Pound 8-7)		Flow through the back pumps is slightly increased, although monthly volume totals are very comparable for both runs(less than 5% difference). The discrepancies are likely due to small imbalances within the system caused by reduced refill and lower pound storages into the Braunston Summit Pound.
Buckby Upper back pump (GU Pound 6-7		Flow through the back pumps is slightly increased in 2019(around 5% of total monthly volumes) . Likely due to the imbalances within the system caused by reduced refill and lower pound storages into the Braunston Summit Pound. Volumes 2018 are similar between drought and baseline runs(less than 2% difference) .
Stoke Hammond back pump (GU Pound 22-23)		Flow through the back pumps is increased although monthly total volumes are very comparable (within 3%). This is likely due to the imbalances within the system caused by reduced refill of the GU Pound 27-28 from Ledburn Brook.

Soulbury Back pump (GU Pound 23-24		Flow through the back pumps is increased although monthly total volumes are very comparable (within 3%). This is likely due to the imbalances within the system caused by reduced refill of the GU Pound 27-28 from Ledburn Brook.

6.4.3 Reservoir storages

Location: component	Comparison Plot	Comments
Braunston Summit reservoirs		In winter 2018-2019 reservoir recharge is limited in the drought scenario leading to much lower modelled storages in summer 2019. Comparing this with the observed however shows that this is not necessarily representative of reality as the storages did not empty as the model predicts.
Tring Summit reservoirs		Minimal changes

6.5 Historical drought modelling discussion

The exercise that was undertaken to compare drought to baseline model runs for the 2018-2019 period has concluded the following:

- The effect of drought scenario flows on Aquator model results is spatially variant. The biggest changes are associated with the reduced refill of the Braunston Summit from Daventry and Drayton Reservoir. This reduced refill causes a system imbalance in the reaches descending from this pound.
- There is a small impact of the storage of the Daventry and Drayton Reservoir in the drought scenario due to reduced recharge in the winter of 2018-2019. Comparison with the observed indicates that this did not happen.
- Some changes to abstraction flows are observed in the Tove, Ouse and Ledburn catchments. In these catchments the rainfall-runoff model struggles to suitably replicate the soil moisture and groundwater conditions in the second consecutive drought year in this groundwater dominated catchments, causing it to overestimate winter baseflows. This has a knock-on impact on the abstractions from these watercourses. In any case, abstractions never exceed the licenced amounts as these are placed as constraints in the Aquator model.
- In other catchments across the system the changes to abstractions are very small.
- Overall, the changes across the system using the drought flows are relatively minor. This gives confidence to the performance of the rainfall runoff timeseries as suitable for simulating periods of low flows in the GUC transfer canal system.

7 With scheme Aquator modelling

This section documents the findings from the Aquator model amendments and runs with the SRO transfer scheme in place. Additions to the model to represent the transfer are discussed, as well as result comparisons between baseline and with scheme scenario in place. The section focuses on documenting the scenario of the highest flow transfer (115Ml/d maximum flow, as described in the section below), which would see the largest impact to the canal network.

7.1 The transfer

The SRO transfer will be coming into the canal system into the Atherstone pound (Figure 7-1). The inflow is reliant on treated effluent discharge and is therefore very predictable and dependent on the demand, unlike natural catchment flow. The transfer will move water through the canal network and water will be extracted in Leighton Buzzard, treated, and used to cover demand in the Affinity Water Central Supply Area.

The SRO transfer uses a monthly profile which is based on the utilization report produced by Affinity Water. All three scenarios have been modelled, using a 115 Ml/d max, 57 Ml/d max and 20 Ml/d max[11].

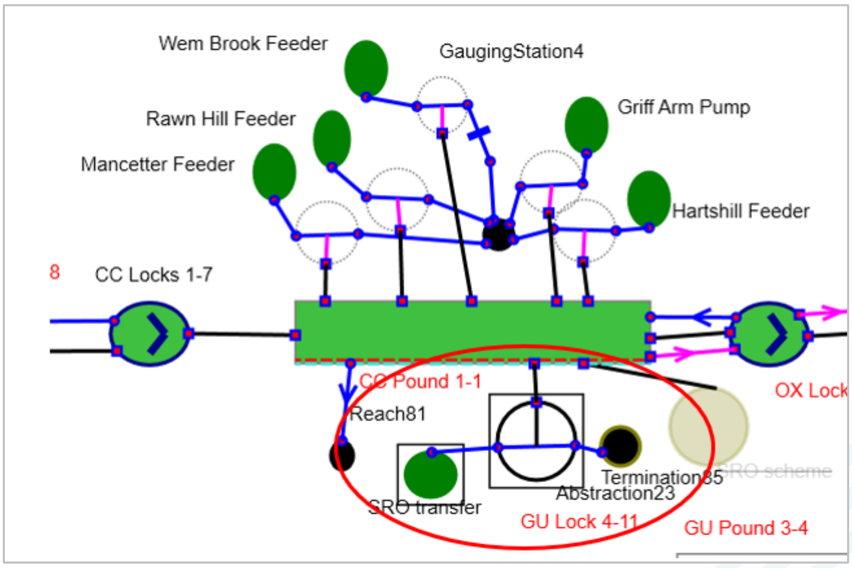


Figure 7-1: Aquator modelling-SRO transfer representation within the Atherstone Pound

7.2 Aquator model amendments

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[11] Evaluation of scheme utilization report, 17/02/2022 by Affinity Water

The baseline model requires some amendments for the transfer to go through at the max rate of 115 Ml/d to allow this volume to pass through the system. This is because there are limitations to the capacity of the by-weirs, lockage volumes and backpumps, as well as the pound capacity and the operational rules associated with the activation of the backpumps. There are several constriction points either due to limitations to the lock component dimensions or due to operational rules which dictate levels of spill, levels of operation etc. The latter is harder to change in the model as the model operation is based on resource state in the pounds, which is in turn is decided from the control curves present in the pounds.

The SRO transfer has been modelled as a bulk transfer, representing the SRO flow as an abstraction. For this modelling option to be as close to reality as possible, the pounds must be allowed to be used for supply and refill, as this will be happening with the water moving through the canal system. Conceptually the model can allow water to be transferred through without changing the levels if this option is not selected which means demand would be met from this specific source all year round without failures. However, the additional flow will affect the pound levels and as a result the operating levels for backpump activation where backpumps are used. Therefore, the pounds are also used for supply and refill as supply sources that can be used for demand. Alongside the introduction of the SRO abstraction, a series of changes were made along the transfer route within the model to facilitate the transfer.

More specifically:

- A demand centre (DC5) was introduced at Leighton Buzzard which was set to be supplied from all abstractions and the route canal pounds (which would be moving the water along the canal). The reservoirs in the model are not set to directly be used as a source for supplying this demand centre, however, they will be impacted as they will need to be used where available to refill the pounds where they get low.
- Backpump capacity: Canal lock backpump capacity for CL20, CL17, CL7, CL51, CL52, CL53 and CL54 were increased to a 115 Ml/d capacity. These locks are along the stretches of the transfer route.
- By-weirs: Increasing capacity at by-weirs at locks CL14, CL18 and CL19. This is to allow the transfer to move through gravity from higher to lower pounds if there is not enough water movement through the lockage and the other components of the locks.
- Lowering control curves, using either a 90% full control or a 95% control curve to allow the water to be stored for the day. This is to help the model move the water to avoid excessive spills. The changes were made to the following pounds: CP21, CP22, CP23, CP24, CP25, CP56, CP57, CP58, CP59. There are pounds along the transfer route that are typically operated as full, with either a 100% or a 99% control curve rule to achieve positive resource state and be part of the operation. The knock-on effect of the pounds not having a healthy resource state is that they are not used for supply.
- Emergency storage: For the same pounds that the control curves were lowered, the emergency storage was also lowered to be below the control curve level. This is because the model does not use emergency storage from the pounds and therefore if there was an emergency storage value above the control curve value the model would not use the water for supply, as it would think it is to be used for emergency storage purposes.

As a result of introducing these changes, the advance order of several components along the route changed, as this is relevant to proximity of a supply to a demand centre.

7.3 With scheme results

This section documents the results from the full model run including any failures from demand not met for DC5 and changes to the volumes of water drawn from supplies. In theory the SRO is a steady supply driven by amounts of demand within the scheme. It is expected to have some variation to the amount of water drawn from different sources particularly closer to the route and the demand centre due to the changes to the order in the advance order.

7.3.1 Demand failures

The failures of the model to meet demand in the period between 1961-2022, for which the model is run have been analysed. There have been some erroneous isolated failures lasting 1-2 days observed which are not justifiable by the water supply available and have been traced back to resource state of pounds and as a result backpumps shutting off. This is because the control curves in one or more of the transfer route pounds has fallen below the level that assigns a 'healthy' resource state and has therefore stopped sending flow to the next upstream pound. These occurred during winter/spring when the scheme is operating with a maintenance flow and therefore are not real failures. A rule to exclude this has been applied to the results and a summary plot of the flow supplied to the demand centre DC5 (SRO transfer) is shown below.

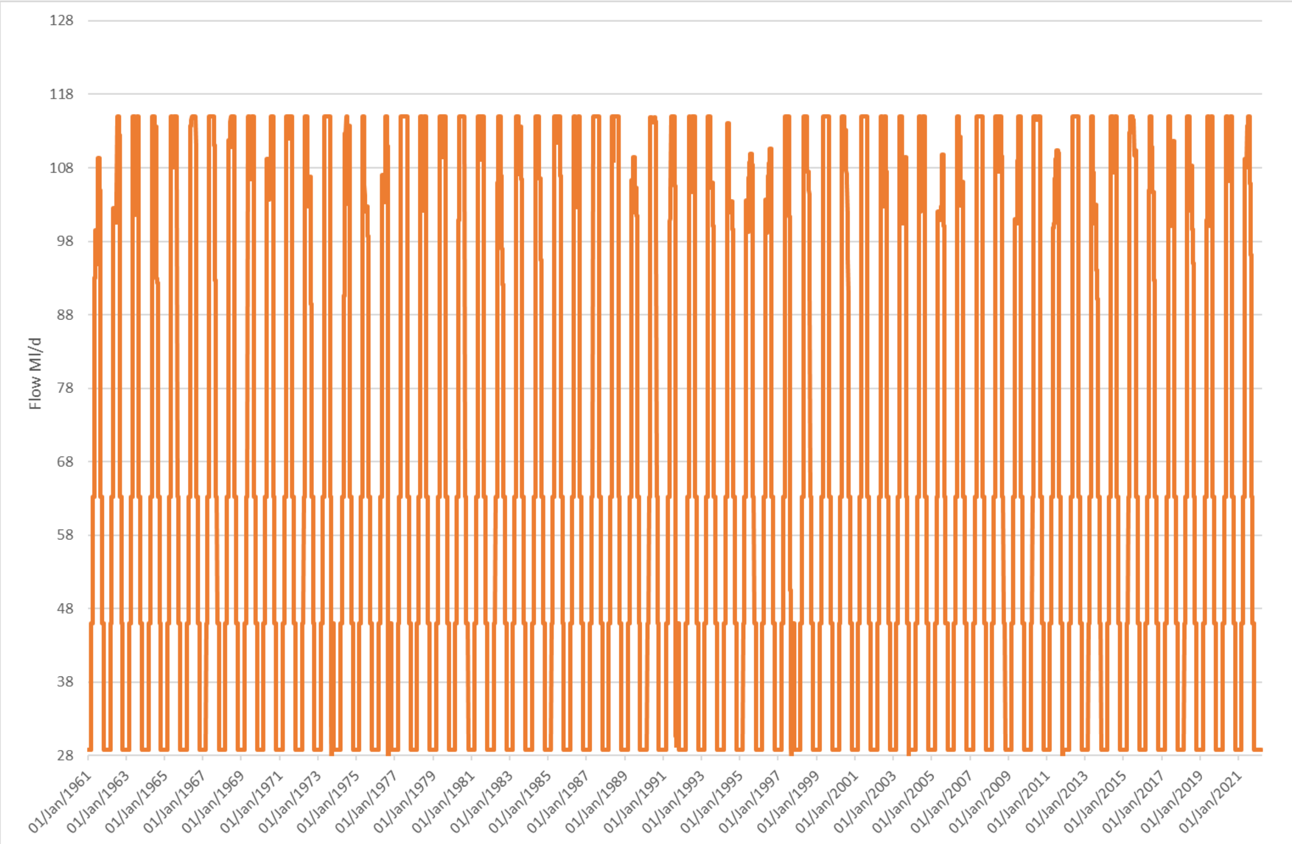


Figure 7-2: Supply to SRO demand centre

1961 is excluded from the analysis as a warm-up year. There are 12 years where failures have been observed which are shown on Table 7-1. These are summer failures when the maximum demand of 115 Ml/d is required.

Table 7-1: Duration of demand failures

Year	1975	1976	1982	1991	1996	1997	2005	2006	2013	2016	2017	2018
Days	28	24	12	3	11	7	11	24	4	6	4	12

A review of when these failures occur suggests these are real failures of the system to provide supply as water is held for emergency storage, compensation flows and other prioritised uses before supplying demand. In addition, the levels in the pounds are not high enough to activate backpumping to move the SRO flow through the lower pounds to the higher.

Several of the years identified though are in line with national hydrological droughts. For example, 1975-1976, 1991, 1996-1997, 2005-2006 and 2018 were all years that several regions in the UK had a hydrological drought. This suggests that although the rules for the operation of pounds and activation of backpumps can be fine-tuned, there will always be occurrences where a national drought means that the demand is not met, even if the SRO flow is supplied by the Minworth treatment works.

In terms of duration of droughts, in three out of the 12 years the duration is close to one month, but for the remaining failures, the period does not exceed 2 weeks. If the model rules are refined, it is expected that these durations are reduced further.

7.3.2 Atherstone pound feeders

The Atherstone pound is a large pound with five feeders (controlled feeders modelled via abstraction) already present in the system prior to introduction of the SRO Transfer. The volume of water extracted after the scheme is in place from these sources appears largely unaffected, as seen in Figure 7-3. There are some small changes because of the day-to-day control level variabilities, but the annual volumes are largely unchanged.

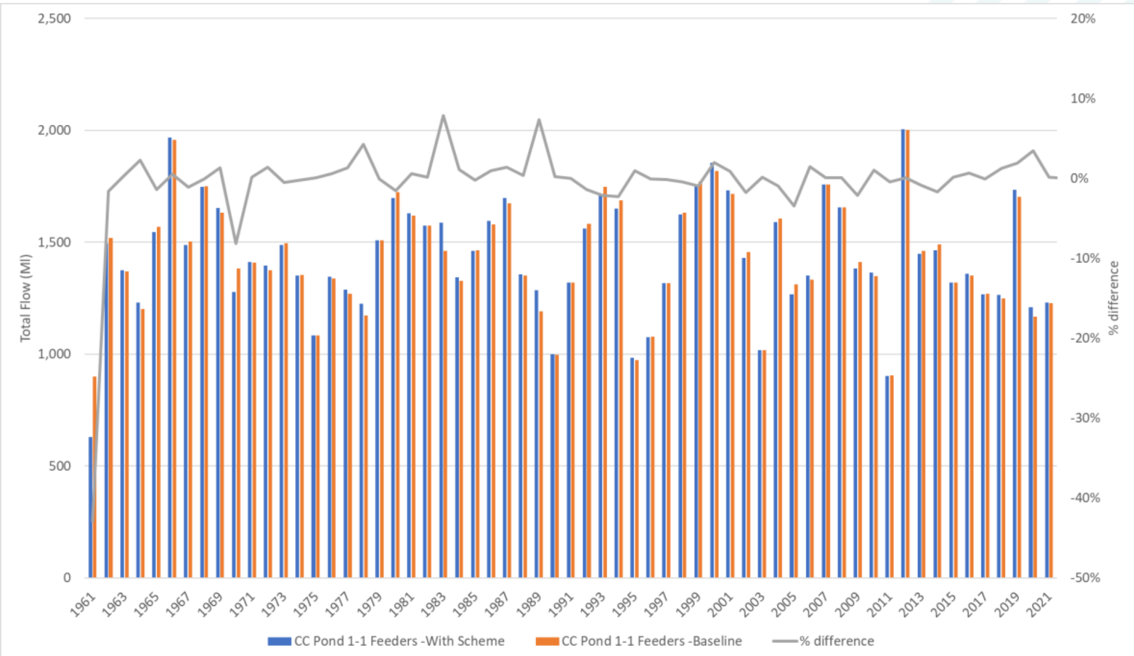


Figure 7-3: Atherstone pound feeder abstractions annual flow comparison -baseline vs with SRO scheme

7.3.3 River Swift Feeder

The River Swift feeder (controlled feeder modelled via an abstraction) discharges into Ox Pound 2-1, which is the pound just upstream of Atherstone (Figure 7-4) and the first pound to receive transfer flow before it moves through to the Oxford Summit.

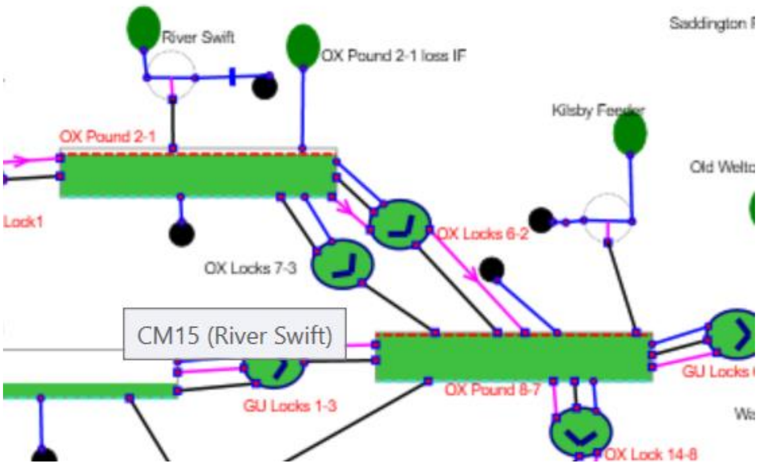


Figure 7-4: River Swift feeder abstraction and pound system

The control curve for this pound has been lowered as part of the model changes and this has triggered changes to the amount of flow required from the River Swift abstraction (as shown in Figure 7-5) and the rules triggering the backpumps. The backpump is activated more often, therefore moving more water through the system. This increases the need for more supply and as the River Swift feeder takes priority for pound refill in relation to other neighbouring sources this increases the amount of flow requested from the River Swift Feeder. The lowering of the control curves was somewhat arbitrary to allow for the transfer to move without spilling and, the operations of the pound will be fine-tuned to avoid over-using the Swift abstraction. There is a limit to the abstraction which is 10 Ml/d which is never allowed to be exceeded. Additionally, The Trust are required to leave a minimum of 2Ml/d in the river Swift after our abstraction and this is included within the model and is always required to be passed forward.

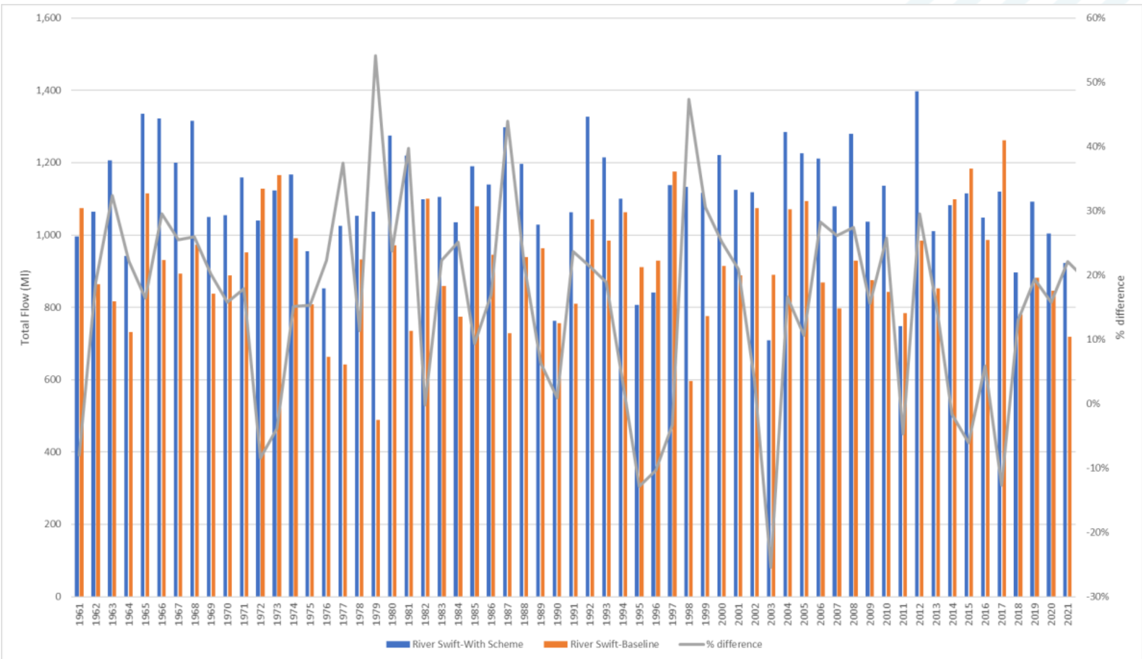


Figure 7-5: River Swift abstraction annual flow comparison -baseline vs with SRO scheme

7.3.4 River Tove and River Ouse feeder abstractions

The feeder flows from these abstractions do not appear to have been affected by the transfer in terms of their annual volumes. Although small variations to the daily flows were present the total volume remains largely unaffected. This is because there are strict constraints to these 2 abstractions with multiple thresholds and there is not much flexibility in terms of how much water can be drawn from the source.

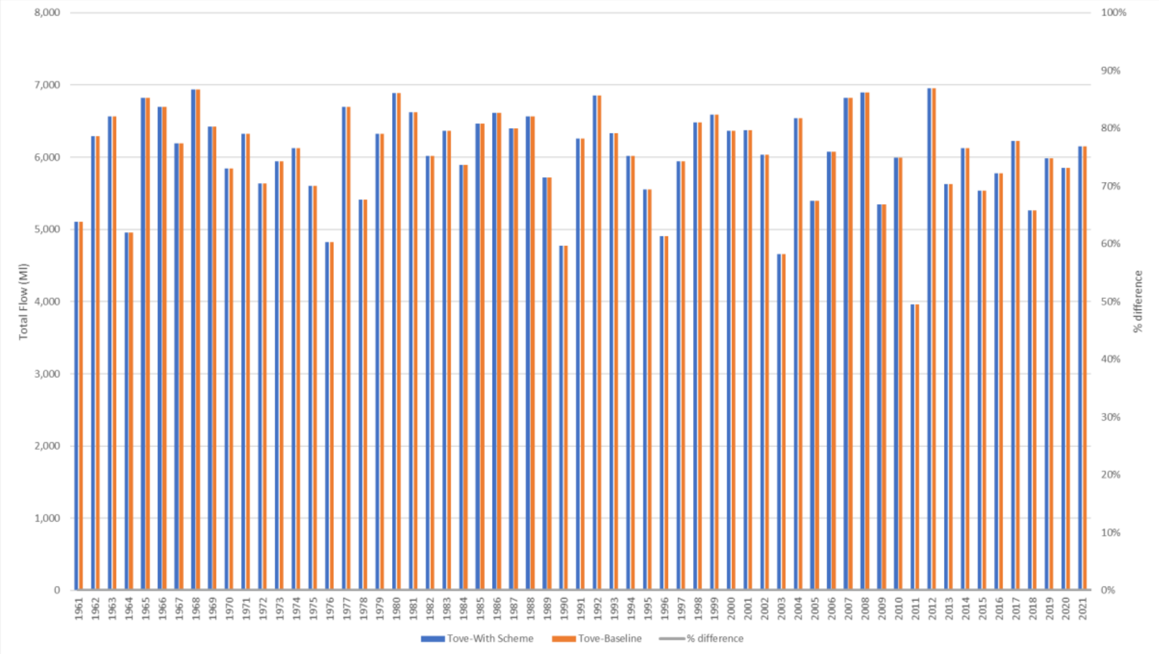


Figure 7-6: River Tove abstraction annual flow comparison -baseline vs with SRO scheme

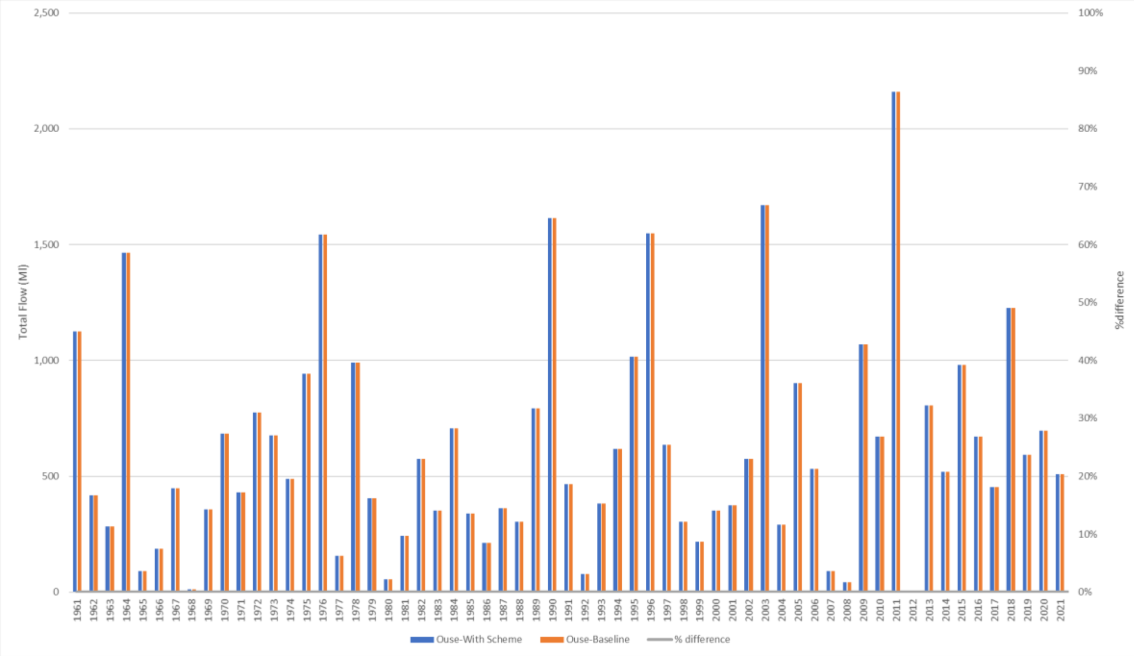


Figure 7-7: River Ouse abstraction annual flow comparison -baseline vs with SRO scheme

7.3.5 Drayton and Daventry reservoir storages

These are the reservoirs used to feed Braunston Summit and have been assessed as a group. Annual average storage values for these reservoirs have significantly decreased to an average of 40% of the total reservoir storage in the with scheme model, though this is thought to be a limitation of the modelling rather than an actual impact of the SRO transfer.

In the with scheme model the Braunston Summit by-weir capacities have been increased and the control curve has been amended to allow more backpumping to occur and the transfer the SRO water over the summit through to Leighton Buzzard. Backpumping is reliant on pound levels being above the control curve levels though to allow the resource state to be healthy, so that the backpump is activated. This means that the supply from the reservoirs to the summit is increased to feed the SRO demand if the backpumps are not activated. The pound draws more water from these sources as they are the closest and are the highest priority in refilling the Braunston Summit Pound.

This has been balanced to a certain extent by lowering the control curves but there is still an over-use of these reservoirs in the modelled system which happens because the water arriving in the summit from the adjacent pounds through back pumping is delayed as the supply from the reservoirs is prioritised. This is an issue that needs to be balanced further during the next Phase of modelling when control curves are refined to balance canal operations and the SRO transfer to minimize spills and maximize the transfer.

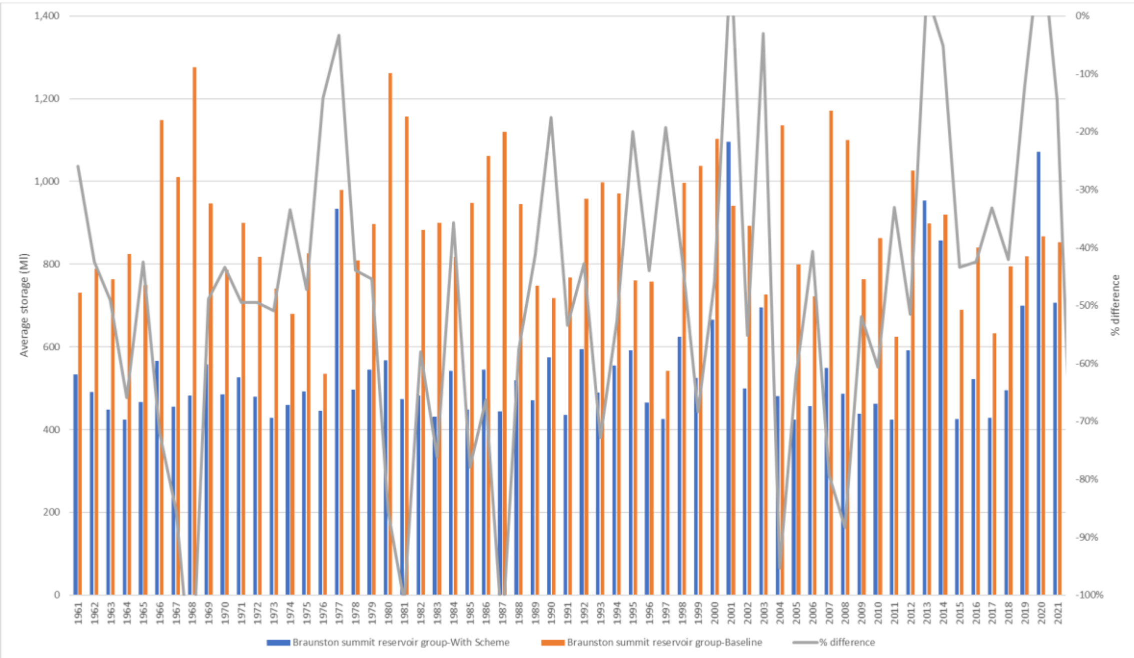


Figure 7-8 Drayton and Daventry annual average storage comparison -baseline vs with SRO scheme

7.3.6 Tring summit reservoir Storages

These reservoirs have been assessed as a group. Annual average storages appear to be decreased by an average of 20% in the with scheme model compared to the baseline. This is again because they are nearer to the scheme so as a balanced approach, the model selects these reservoirs to refill the pounds upstream of the transfer if they are emptied prior to getting water from a further away resource.

As discussed, backpumping is reliant on pound levels and this is an issue that needs to be balanced further during the next Phase of modelling when control curves are refined to balance canal operations and the SRO transfer to minimize spills and maximize the transfer.

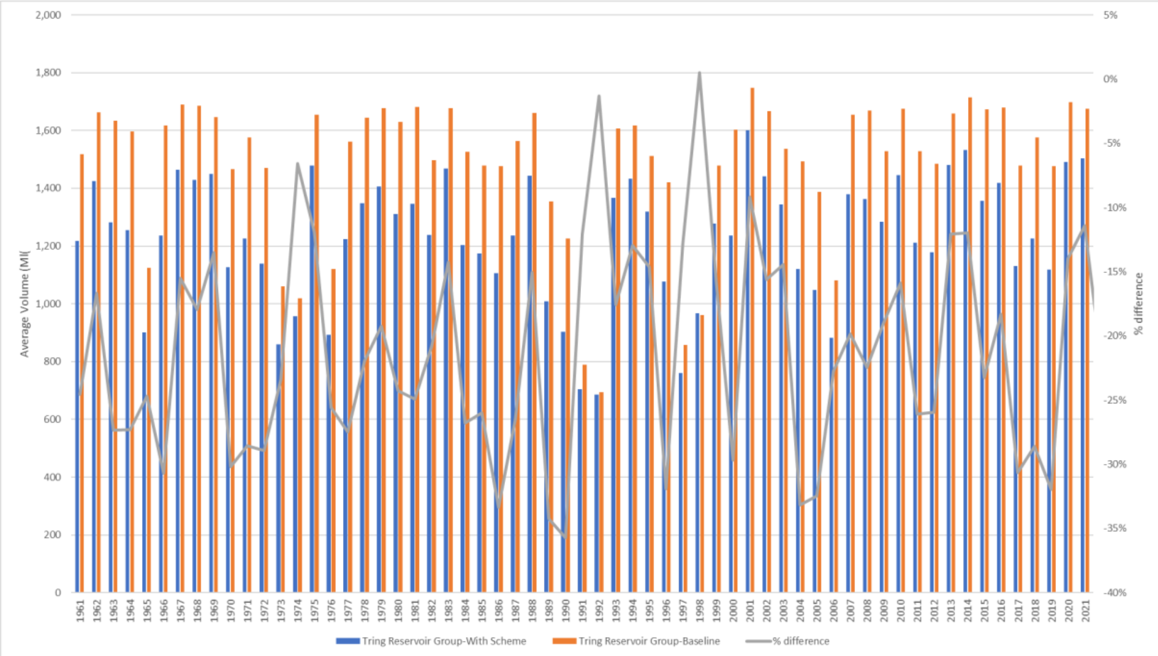


Figure 7-9: Tring summit reservoirs- annual average storage comparison -baseline vs with SRO scheme

7.3.7 Other model components

The impact of the scheme to pound spills has also been assessed and there are instances where there is significant spill in the Atherstone pound when water cannot be moved through the backpump to the upstream pound. This is because of the limitations on the control curve levels as discussed in the sections above. In these instances, there may be failures to the SRO demand centre or water will be pulled from other sources to increase the levels in the pounds that have been impacted. These are not real failures of the system to supply but rather are because of model constraints. A comparison of volume drawn from the reservoirs versus spills in the source suggest suggests that this mainly occurs when the SRO transfer water cannot move through the Atherstone or subsequent pounds through backpumping and therefore spills and the reservoir sources are activated to meet the SRO demand. The spill is not necessarily observed in the hydraulic modelling in the same locations (Annex A.2) because aspects such as head difference between upstream to downstream pound and velocities of flow are modelled and therefore the level driven processes of the water movement through the system are more accurately represented. The way the transfer is represented has generated drops in heads closer to the pumps. Aquator model is not able to represent this either.

7.3.8 With scheme modelling results - discussion

Key conclusions from the above analysis are that the model shows that the system can move through the transfer at the max required demand of 115 Ml/d.

- Key changes to the operations of the canal to activate backpumps would need to be made.
- Engineering solutions to allow for increased flow to by-weirs need to be undertaken.

- Although an attempt was made to amend the control curves for the pounds along the SRO transfer route to operate more seamlessly and minimise spillage, this needs more work. The activation of backpumps is reliant on these levels and as the system currently works, it shows more of an impact on The Trust reservoirs as these are the sources that are used to fill the pounds to bring them back to a 'healthy' resource based on the current control curve rules. If this is addressed, there will not be as much water pulled from the reservoirs as it is not needed.
- The failures identified in the summer are real and they are a result of restricted supply from the system. If the control curves are refined, possibly the duration of these failures will decrease but there will be still some years (in line with historical droughts) that a widespread drought in the UK means there is limited scope to balance the systems supplies to meet demand.

8 Conclusions and recommendations

8.1 Conclusions

Work undertaken under Phase 3 of this study has involved updating and improving the Aquator model, with updated hydrology of feeder catchments and validating the Aquator model performance a key focus of this process.

Inflows for feeder catchments have been derived for the period 1961-2022 using a combination of rainfall-runoff modelling and matched pairs analysis. The resulting timeseries have been validated against spot flows and continuous gauge data (where available) and benchmarked against LowFlows estimates for each feeder catchment to ensure the flows were representative. Overall, all derived feeder flows are considered to representative and appropriate for use in Aquator modelling. Limitations and uncertainty associated with the methods applied to derive flow series should be considered when using the Aquator model for modelling the baseline and with scheme scenarios.

These inflows have been inserted into the Aquator model and the baseline model has been validated by comparing modelled flows to spot flow gaugings and the Trust continuous gauge data. These comparisons concluded that the model performance is reasonable, but there are still some limitations associated with modelling back-pump operation and by-weir flow movement. Most comparisons made are based on volume and flow estimates as level is not a primary variable that Aquator estimates with sufficient accuracy. The validation of pound water levels was carried out using the hydraulic model .(Annex A2.2).

The effect of the drought scenario flows on Aquator model results is minimal. Generally, the changes to the abstractions from Tove, Ouse and Ledburn are small (less than 5% change compared to baseline scenario). Also, changes to the reservoir recharges broadly appear to be very small. This lends confidence to the calibrated flows used for the updated Aquator model and their ability to simulate drought conditions in the GUC canal system.

Key conclusions from the above analysis are that the validated Aquator model adequately represents the canal system and is fit for the purpose of this study. In addition, modelling results show that the system can move through the transfer at the maximum required demand of 115 Ml/d under normal canal operating procedures. Recommendations for further work required at Gate 3 are provided in section 8. Some of the supply sources of the Trust appear to be impacted if the operations of the canal remain the same, as constrictions in the system mean that water is lost to weirs in specific pounds and therefore needs to be replaced further downstream. There are locations, such as pounds and back-pumps, where ,operationally, the management of the canal will need to be changed to accommodate the volume of the transfer.

The Aquator simulations identify 12 years where summer failures are predicted, when the maximum demand of 115 Ml/d is not met. Several of the years identified are in line with national hydrological droughts. The deficit is between 10-30 Ml/d depending on the drought incident and typically last between 1-3 weeks. These occur because during these periods, normal operating procedures in the canal are not occurring due to the canal levels dropping below normal operating levels. So, although the water is still supplied from Minworth, it is not possible to move through the canal due to lower-than-normal levels. It is envisaged that this issue may be possible to overcome by developing an integrated control strategy combining the objectives of the canal and the transfer.

8.2 Recommendations for Phase 4 Hydrology and Aquator

Further work will be required at Gate 3 to address:

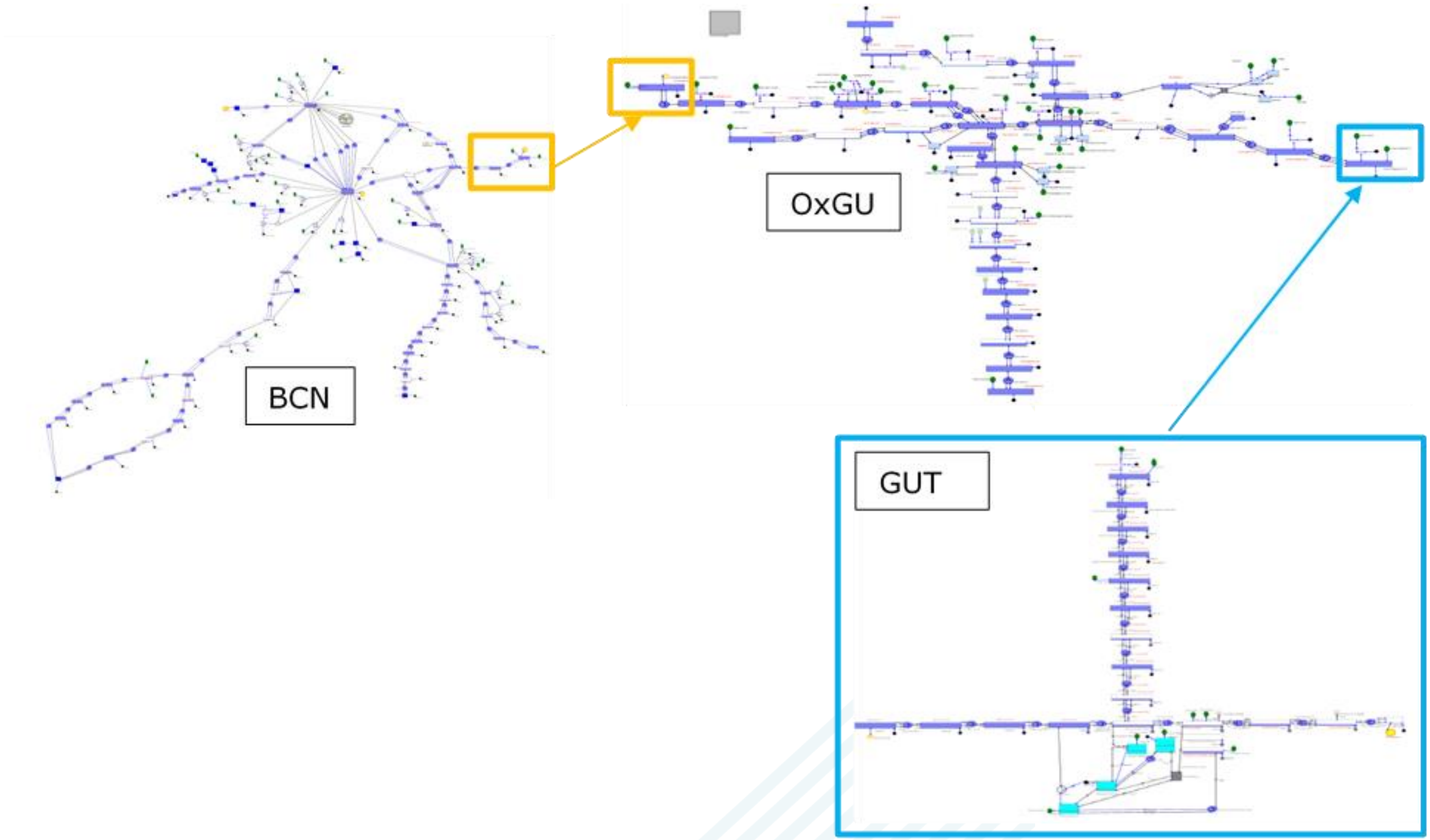
- Location and magnitude of changes to the operations of the canal to activate back-pumps.
- Location and nature of engineering solutions to allow for increased flow to by-weirs needs to be added to the model.
- Operational rules to manage levels for the pounds along the SRO transfer route to operate more seamlessly and minimise spillage. The activation of back-pumps is reliant on these levels and as the system currently works, it shows more of an impact on The Trust's reservoirs as these are the sources that are used to fill the pounds to bring them back to a 'healthy' resource based on the current control curve rules. If this is addressed, there will not be as much water pulled from the reservoirs as it is not needed.
- Additional hydrometric survey of key locks and pounds at summits and troughs are also recommended, or alternatively (or in combination) installation of telemetered gauges to help validate changes to canal operations to accommodate the transfer volume in the canal pounds.
- Flood hydrology estimates will be required to support the FRA for the DCO (see main Report 2.1).

A Appendix A- Feeder catchment Rainfall derivation

Feeder name	Gauge name	Catchment (FEH) area (km2)	Area of catchment in Thiessen	% Catchment
Boddington Reservoir	Byfield STW Auto	19.6	19.6	100
Bulbourne Stream	Dancers End Reservoir	2.2	2.2	100
Burton Brook	Kibworth	15.4	11.0	72
	Fleckney	15.4	4.4	28
Cherwell @ Aynho	Knightcote	276.49	24.891	9
	Brackley RG	276.49	13.462	5
	Preston Capes	276.49	25.186	9
	Byfield STW Auto	276.49	101.109	37
	Grimsbury R31	276.49	112.04	41
Cherwell @ Cropredy	Knightcote	148.22	12.406	8
	Preston Capes	148.22	25.186	17
	Byfield STW Auto	148.22	101	68
	Grimsbury R31	148.22	9.735	7
Clattercote Reservoir	Knightcote	1.9	0.6	32
	Grimsbury R31	1.9	1.3	68
Daventry Reservoir	Daventry	8.0	8.0	100
Drayton Reservoir	Braunston Leam	1.6	0.8	49
	Daventry	1.6	0.8	52
Grendon Feeder	Atherstone	9.7	8.6	89
	Lea Marston	9.7	1.1	11
Griff Arm	Corley	9.5	9.3	98
	Hinckley	9.5	0.2	2
Gumley feeder	Kibworth	3.3	2.5	78
	Husbands Bosworth	3.3	0.7	22
Hartshill	Atherstone	1.5	1.5	100
Kilsby	Braunston Leam	2.9	2.9	100
Ledburn Brook	Drayton Parslow S Wks	34.5	32.2	93
	Dancers End Reservoir	34.52	0.006	0
	Aylesbury STW TBR	34.5	2.3	7
Mancetter	Atherstone	1.2	1.2	100
Merevale	Atherstone	3.0	2.9	100
Naseby Reservoir	Stanford Reservoir	5.1	0.1	2
	Ravensthorpe	5.1	2.8	55
	Great Oxendon	5.1	1.7	33
	Husbands Bosworth	5.1	0.5	9
Old Welton	Braunston Leam	3.4	1.6	47
	Daventry	3.4	1.8	53

Rawn Hill	Atherstone	1.2	1.2	100
River Ouse	Brackley RG	504.1	148.2	29
	Foxcote T	504.1	228.3	45
	Towcester S Wks	504.1	15.4	3
	Drayton Parslow S Wks	504.1	60.6	12
	Bicester STW TBR	504.1	31.1	6
	Aylesbury STW TBR	504.1	20.8	4
River Swift	Stanford Reservoir	66.7	42.1	63
	Kings Newnham	66.7	8.3	12
	Littlethorpe Rain	66.69	1.013	2
	Husbands Bosworth	66.7	15.4	23
River Tove	Brackley RG	171.9	14.4	8
	Towcester S Wks	171.9	102.5	60
	Quinton	171.9	8.1	5
	Preston Capes	171.9	15.4	9
	Byfield STW Auto	171.9	7.5	4
	Litchborough	171.9	24.1	14
Saddington Reservoir	Kibworth	6.3	1.8	28
	Fleckney	6.3	1.4	23
	Husbands Bosworth	6.3	3.1	49
Sulby Reservoir	Great Oxendon	8.3	1.5	18
	Husbands Bosworth	8.3	6.8	82
Tring Feeder	Dancers End Reservoir	7.6	10.4	137
Tunnel	Braunston Leam	1.1	1.1	100
Watford Feeder	Braunston Leam	11.1	11.1	100
	Daventry	11.1	0.004	0
Wem Brook	Corley	8.6	1.9	22
	Hinckley	8.6	6.8	78
Wendover	Prestwood Reservoir TBR	9.6	0.6	6
	Dancers End Reservoir	9.6	8.9	93
Wilstone Reservoir	Dancers End Reservoir	2.7	2.7	100
Wormleighton Res	Knightcote	4.7	4.7	100

B Appendix B- Aquator Model Schematic



C Appendix C – Rainfall-runoff model calibration

C.1 River Ouse Calibration

C.1.1 Initial Model set up

This model has been set-up to calibrate to observed flow data from Thornbrough Mill[12]. This gauge was removed in 1991, however this gauge represents the only reliable gauge record on the Bedford Ouse upstream of the confluence with the Tove and Ouse. The Passenham Ultrasonic Gauge is located just downstream of Thornbrough Mill and has records from 2003-2022 however its gauged flow record is unreliable and is prone to step changes and dropping out. For this reason, the River Ouse Model has been calibrated to Thornbrough Mill for the period 1980-1990, the model has then been validated against the entire gauge record. The catchment is flat and lies mainly on the Great Oolite. One large tributary drains an area of Oxford Clay. Gauge decommissioned in 1991, gauge record in 1990-1991 judged to be suspect.

Rainfall and PET derived for the Ouse Catchment have been used as an input to the PDM.

C.1.2 Model Parameters

The PDM model has been calibrated to observed flow data by adjusting parameters, informed by the lag response to rainfall, and the geology and soils of the catchment. The model has been calibrated using the parameters in the table below. The focus for calibration has been matching baseflows.

Table C-1; Parameter values used in calibration of the Ouse PDM model

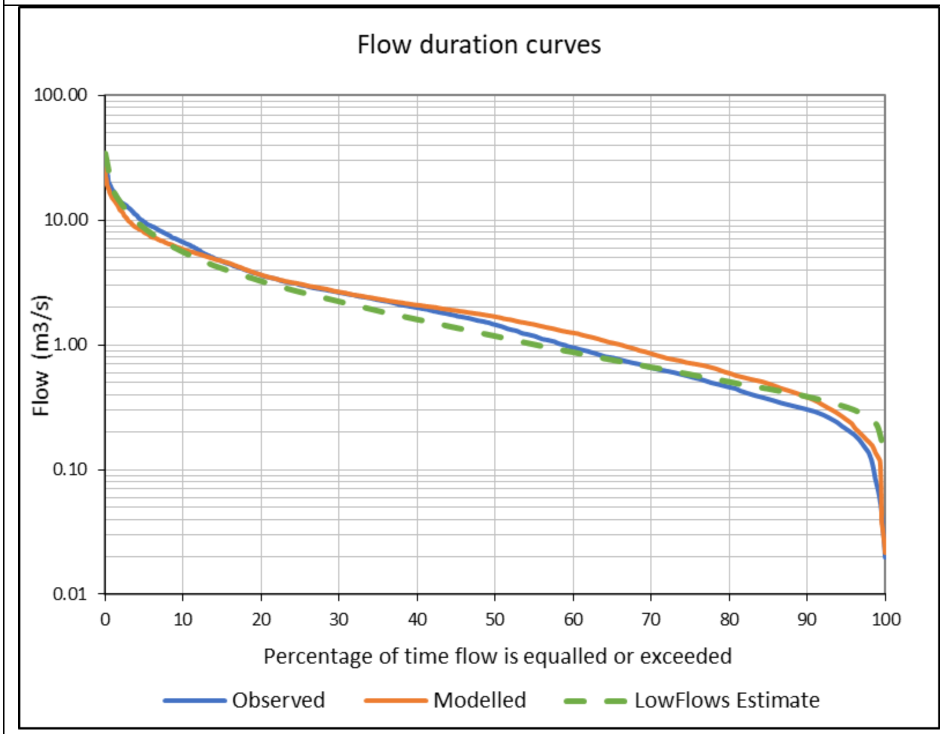
Parameter	Value	Parameter definition	Typical range
f_c	1	Rainfall factor	0.8-1.2
c_{min}	30	Minimum store capacity	0-30
c_{max}	190	Maximum store capacity	40-300
b	1	Exponent of Pareto distribution	0.5-2.5
B_e	3	Exponent of evaporation function	0.5-3
K_g	90,000	Groundwater recharge time constant	100-100,000
B_g	1.8	Exponent of recharge function	0.5-2.5
St	0	Soil tension storage capacity	0
K_1	7	Time constants of cascade of linear reservoirs	0.5-24
K_2	40		
K_b	1000000	Baseflow time constant	125 – 100,000,000
Q_{const}	0	Constant flow representing abstractions	n/a
T_{dly}	0	Time delay	n/a

This model uses the extended groundwater model with a spring factor (Alpha) of 0.4

[12] https://nrfa.ceh.ac.uk/data/station/info/33005

C.1.3 Calibration Performance (1980-1990)

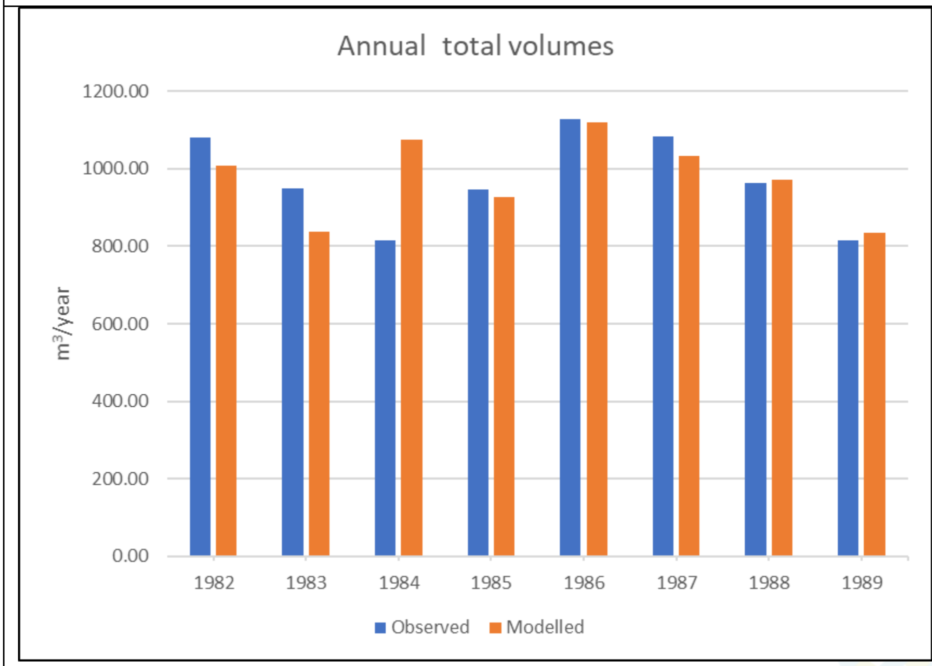
Flow Duration Curve



Comment

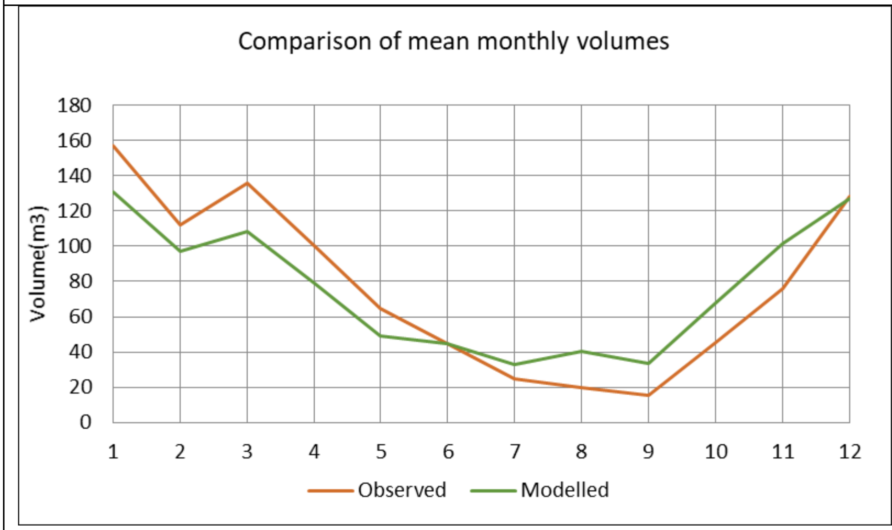
Overall, modelled flows compare reasonably well to the observed flow, though the model tends to slightly over predict flows between Q40 and Q90. The observed and modelled values also compare well to the LowFlows Estimate of the catchment, giving further confidence that the model is representative of the overall catchment flow regime.

Annual Total Volumes



Comment

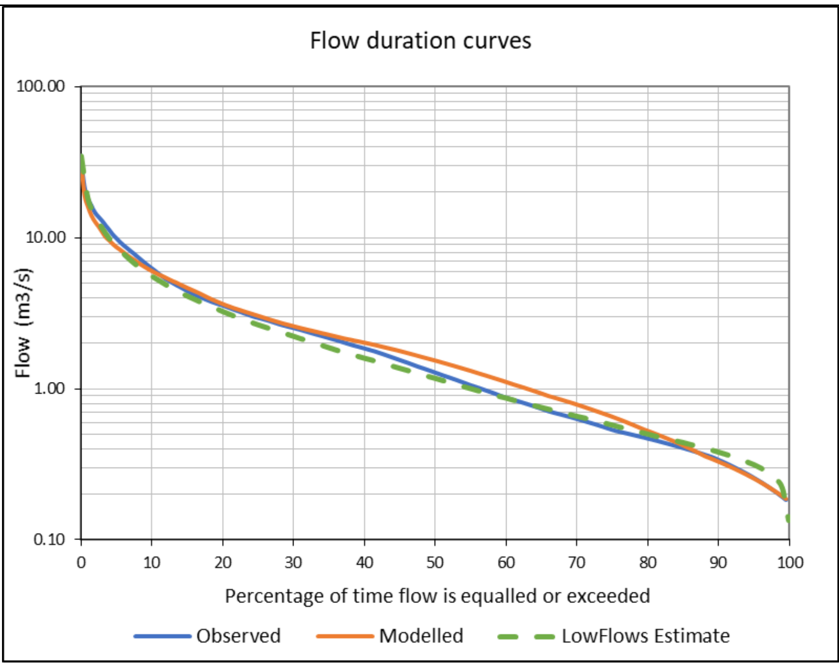
Annual Total Volumes s compare well to the observed, aside from in 1984, the model is over predicting volumes. This is due to the model overpredicting peak flows in this year, this is likely caused by the rainfall used as an input.

Mean Monthly Volumes	Comment
	Mean monthly values compare well to the observed, though indicate that the model generally overpredicts baseflows between July and September.

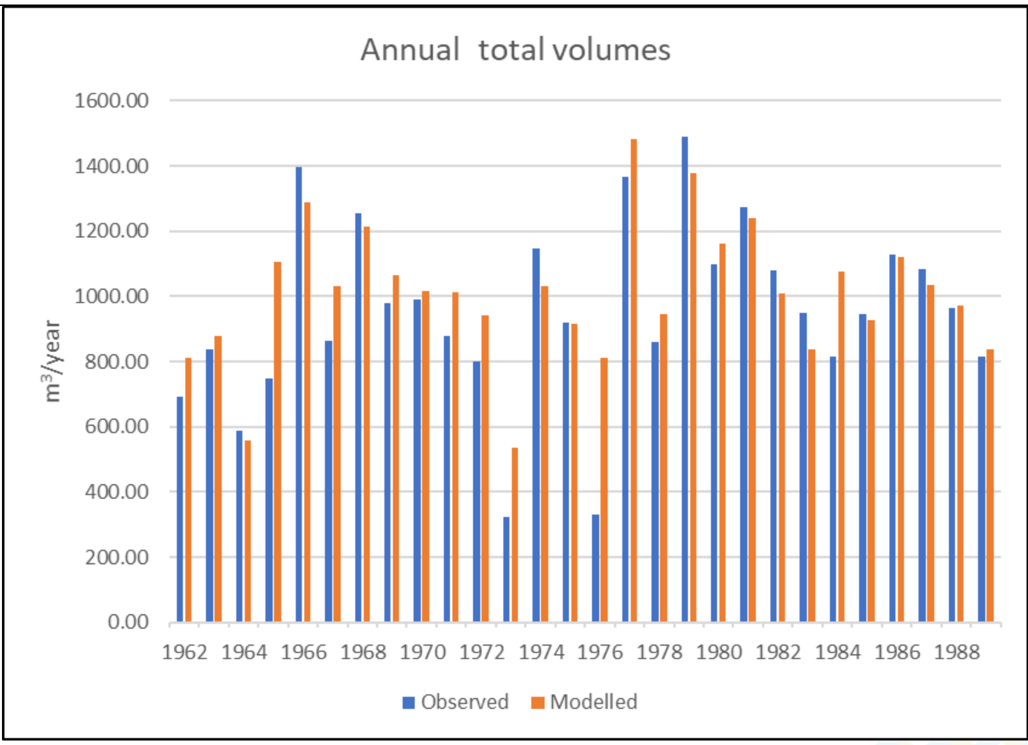
Statistical model fit			Comment
STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*	Model performance statistics are good and give confidence to the performance of the model relative to the observed.
NSE	0.998	Very good	
PBIAS	1.181	Very good	
R^2	0.613	Good	
RSR	0.047	Very Good	

C.1.4 Validation performance

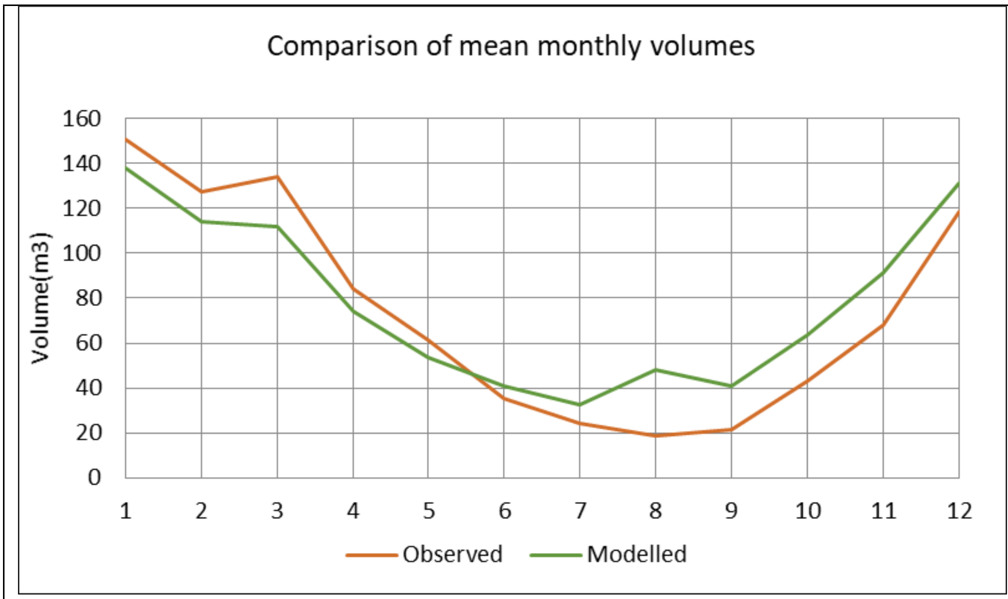
Flow Duration Curve



Annual Total Volumes



Mean Monthly Volumes



Statistical model fit

STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*
NSE	0.992	Very good
PBIAS	-7.167	Very good
R^2	0.608	Good
RSR	0.090	Very Good

C.2 River Tove Calibration

C.2.1 Initial Model set up

This model has been set-up to calibrate to observed flow data from Cappenham Bridge for the period 2010-2019. The gauge is reliable, draining a predominantly rural chalk catchment overlain with boulder clay.

Rainfall and PET derived for the Tove Catchment have been used as an input to the PDM.

C.2.2 Model Parameters

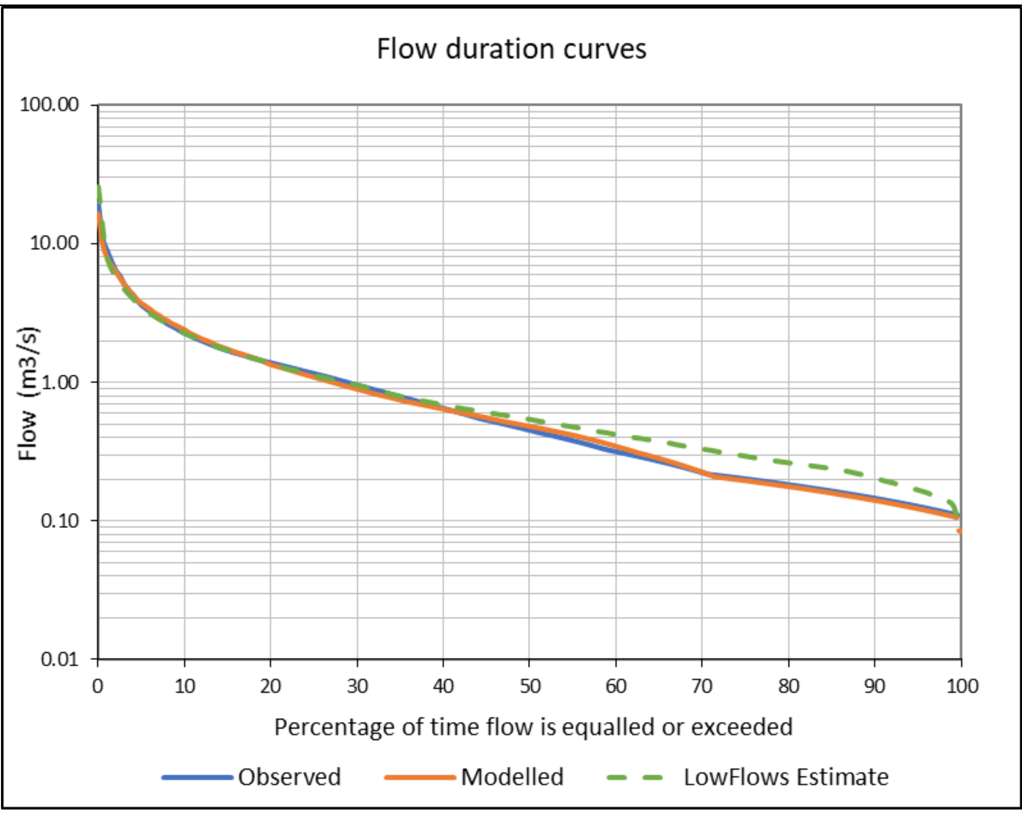
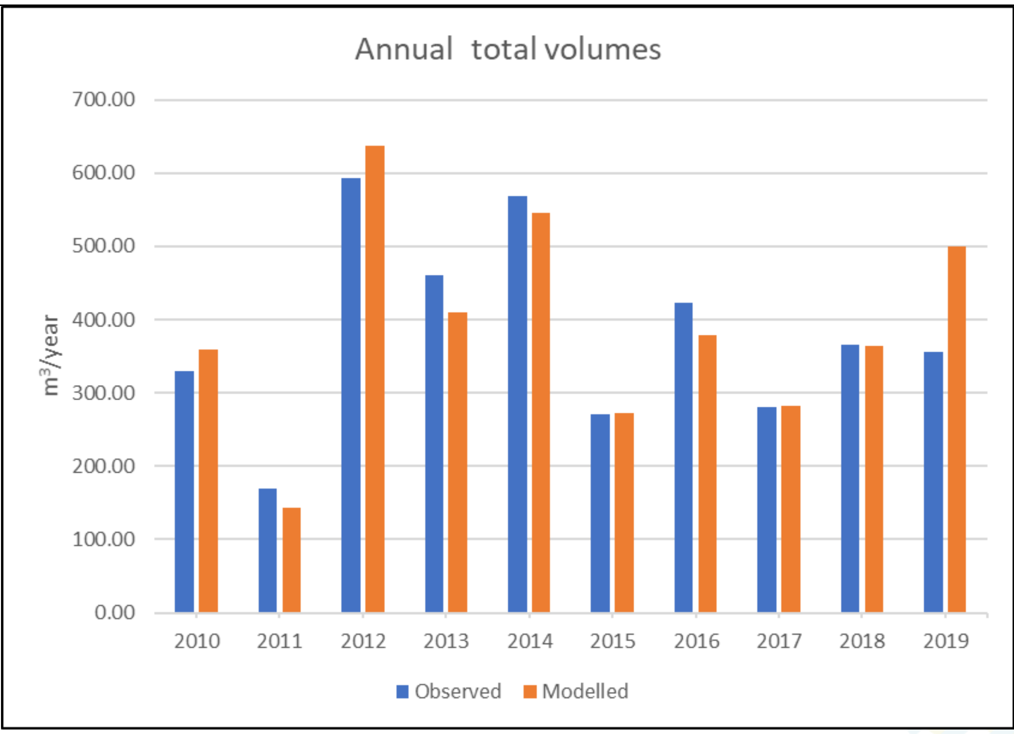
The PDM model has been calibrated to observed flow data by adjusting parameters, informed by the lag response to rainfall, and the geology and soils of the catchment. The model has been calibrated using the parameters in the table below. The focus for calibration has been matching baseflows. It should be noted this model uses a linear baseflow store rather than the default cubic.

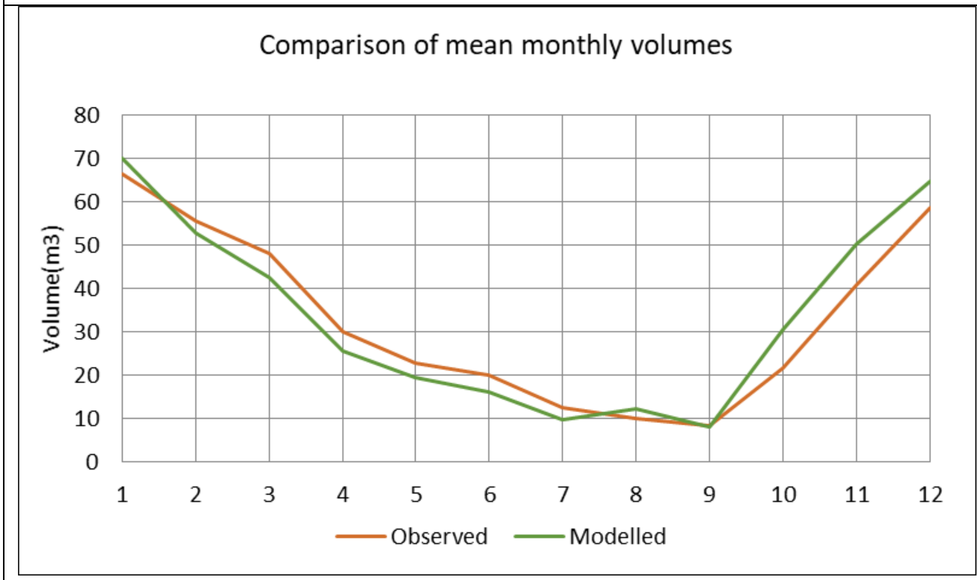
Table C-2; Parameter values used in calibration of the Tove PDM model

Parameter	Value	Parameter definition	Typical range
f_c	1	Rainfall factor	0.8-1.2
c_{min}	30	Minimum store capacity	0-30
c_{max}	120	Maximum store capacity	40-300
b	0.5	Exponent of Pareto distribution	0.5-2.5
B_e	3	Exponent of evaporation function	0.5-3
K_g	30,000	Groundwater recharge time constant	100-100,000
B_g	1.5	Exponent of recharge function	0.5-2.5
St	0	Soil tension storage capacity	0
K_1	30	Time constants of cascade of linear reservoirs	0.5-24
K_2	30		
K_b	1000	Baseflow time constant	125 – 100,000,000
Q_{const}	0	Constant flow representing abstractions	n/a
T_{dly}	0	Time delay	n/a

This model uses the extended groundwater model with a spring factor (Alpha) of 0.2.

C.2.3 Calibration Performance (2010-2019)

Flow Duration Curve	**Comment**
	Overall, modelled flows compare very well to the observed flow. The observed and modelled values also compare well to the LowFlows Estimate of the catchment, giving further confidence that the model is representative of the overall catchment flow regime. LowFlows is slightly higher than both the observed and modelled values below Q40.
Annual Total Volumes	**Comment**
	Annual Total Volumes s compare well to the observed, aside from in 2019, where the model is over predicting volumes. This is likely due to the 2018-2019 drought, the model is unable to replicate the soil moisture and groundwater conditions in the second consecutive drought year, causing it to overestimate winter baseflows.

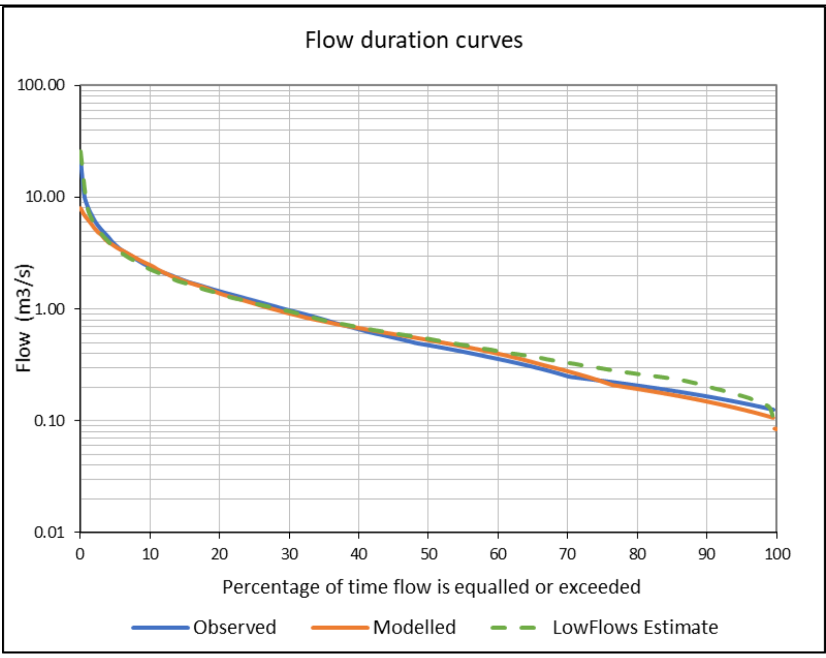
Mean Monthly Volumes	Comment
	The model replicates mean monthly values well, particularly in the summer months.

Statistical model fit — **Comment**: Model performance statistics are good and give confidence to the performance of the model relative to the observed.

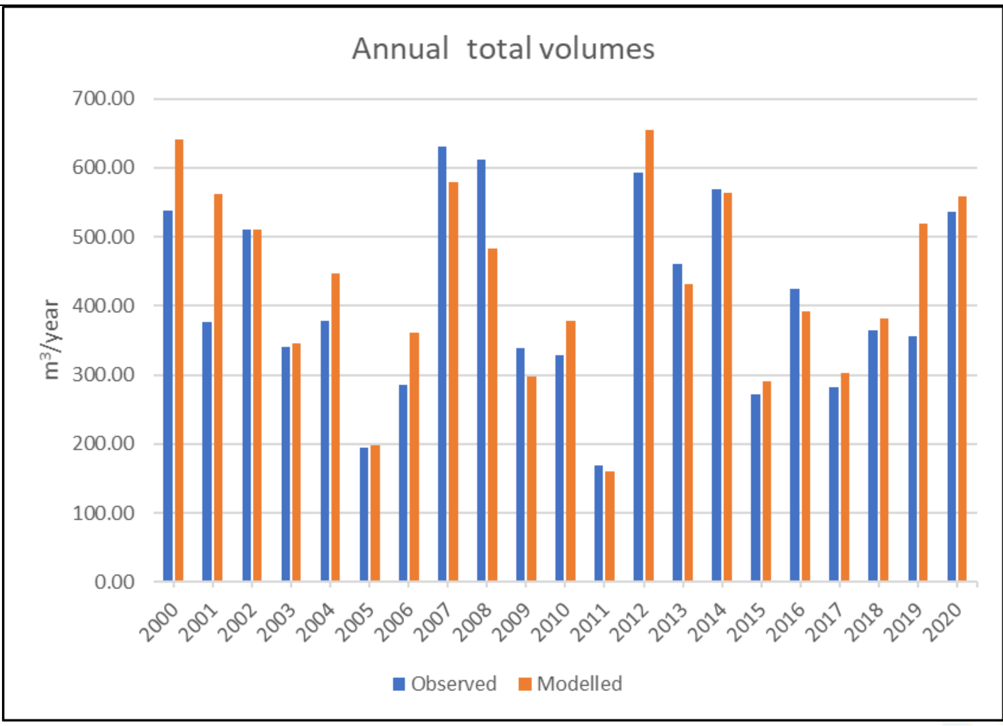
STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*
NSE	0.998	Very good
PBIAS	-1.806	Very good
R^2	0.776	Very good
RSR	0.046	Very good

C.2.4 Validation performance

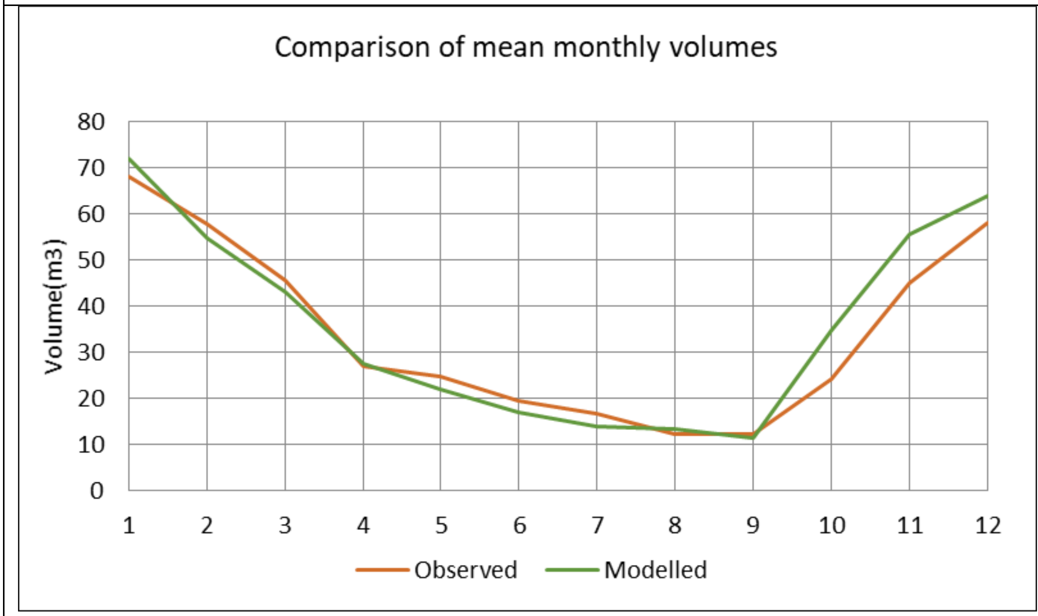
Flow Duration Curve



Annual Total Volumes



Mean Monthly Volumes



Statistical model fit

STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*
NSE	0.995	Very good
PBIAS	-3.900	Very good
R^2	0.727	Very good
RSR	0.070	Very Good

C.3 Clipstone Brook Calibration

C.3.1 Initial Model set up

This model has been set-up to calibrate to observed flow data from Clipstone (new weir) for the period 2010-2019. The gauge is reliable, draining a predominantly rural greensand catchment. The gauge has some artificial influences on flow.

Rainfall and PET derived for the Ledburn Catchment have been used as an input to the PDM.

C.3.2 Model Parameters

The PDM model has been calibrated to observed flow data by adjusting parameters, informed by the lag response to rainfall, and the geology and soils of the catchment. The model has been calibrated using the parameters in the table below. The focus for calibration has been matching baseflows. It should be noted this model uses a quadratic baseflow store rather than the default cubic.

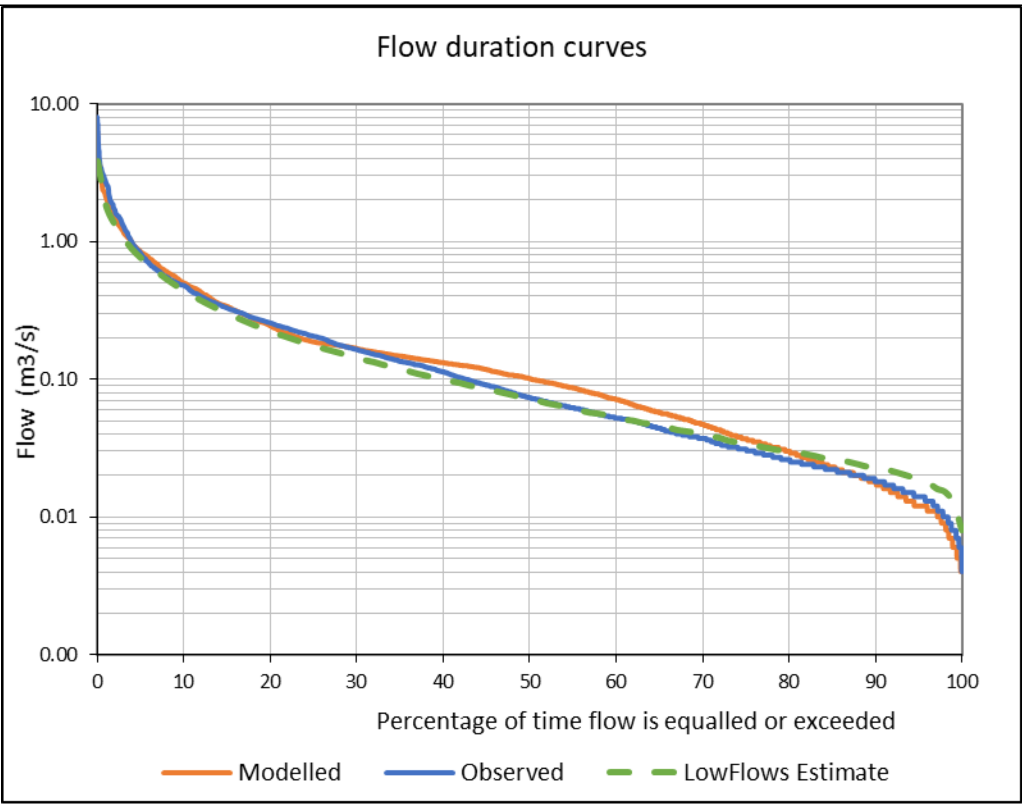
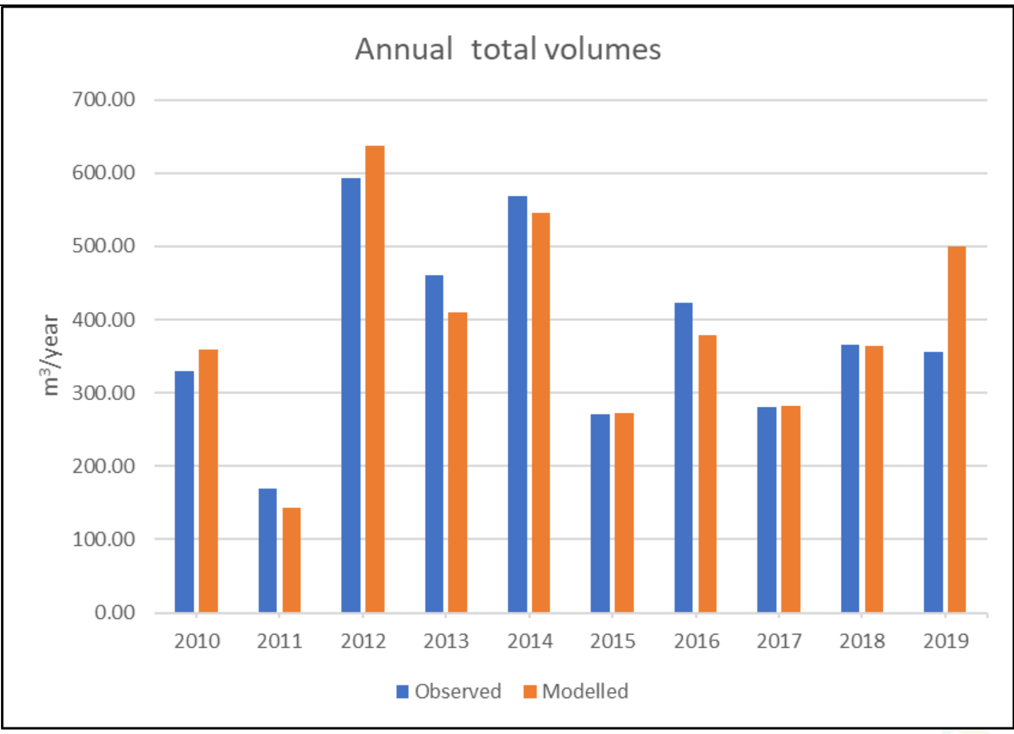
Table C-3; Parameter values used in calibration of the Clipstone PDM model

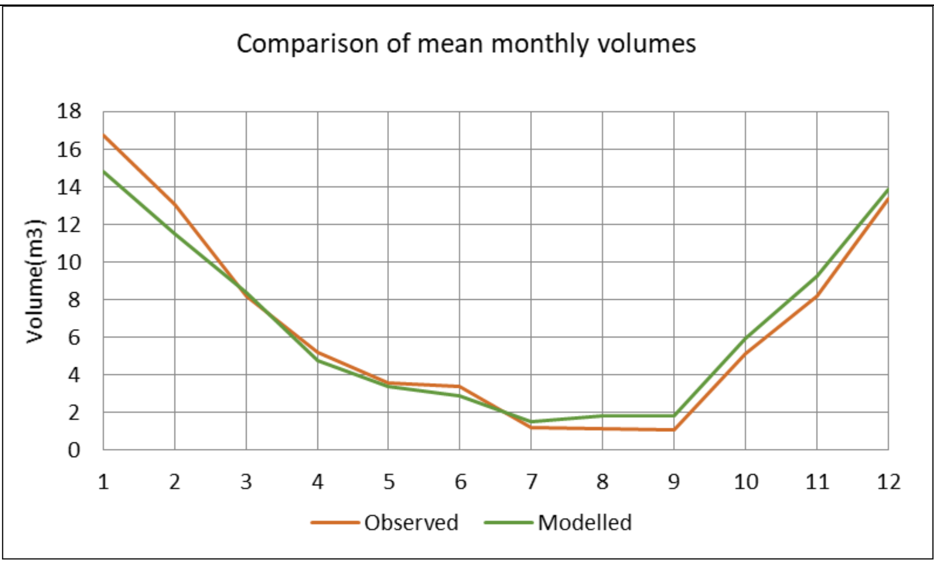
Parameter	Value	Parameter definition	Typical range
f_c	1	Rainfall factor	0.8-1.2
c_{min}	30	Minimum store capacity	0-30

c_{max}	200	Maximum store capacity	40-300
b	0.5	Exponent of Pareto distribution	0.5-2.5
B_e	3	Exponent of evaporation function	0.5-3
K_g	60,000	Groundwater recharge time constant	100-100,000
B_g	1.5	Exponent of recharge function	0.5-2.5
St	0	Soil tension storage capacity	0
K_1	5	Time constants of cascade of linear reservoirs	0.5-24
K_2	10		
K_b	5000	Baseflow time constant	125 – 100,000,000
Q_{const}	0	Constant flow representing abstractions	n/a
T_{dly}	0	Time delay	n/a

This model uses the extended groundwater model with a spring factor (Alpha) of 0.2.

C.3.3 Calibration Performance (2010-2019)

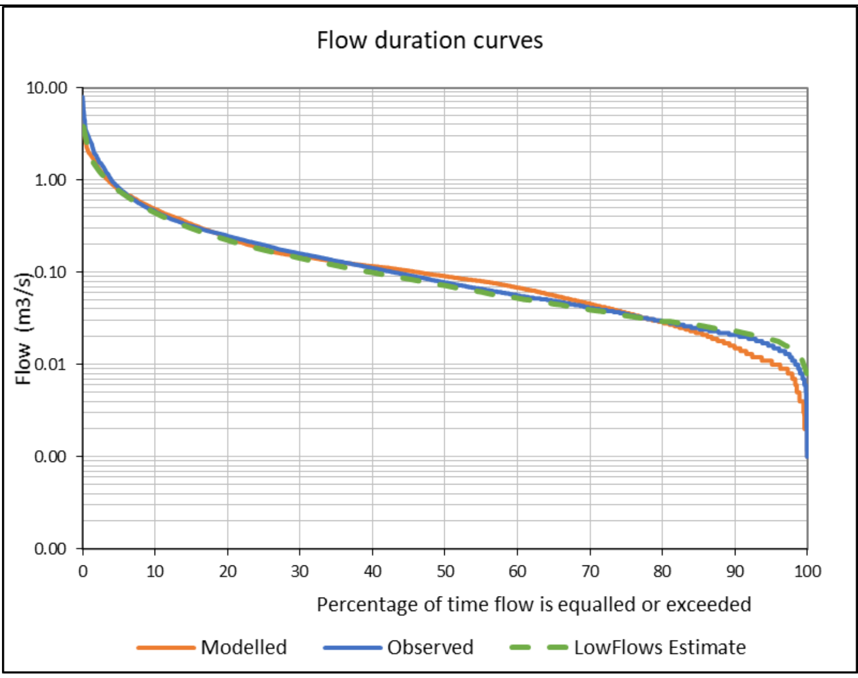
Flow Duration Curve	Comment
	Overall, modelled flows compare reasonably well to the observed flow, though the model tends to slightly over predict flows between Q35 and Q85. The observed and modelled values also compare well to the LowFlows Estimate of the catchment, giving further confidence that the model is representative of the overall catchment flow regime.
Annual Total Volumes	**Comment**
	Annual Total Volumes s compare well to the observed, aside from in 2019, where the model is over predicting volumes. This is likely due to the 2018-2019 drought affecting catchment flows, the model is unable to replicate the soil moisture and groundwater conditions in the second consecutive drought year, causing it to overestimate winter baseflows.

Mean Monthly Volumes	Comment
	The model replicates mean monthly values well, particularly in the summer months.

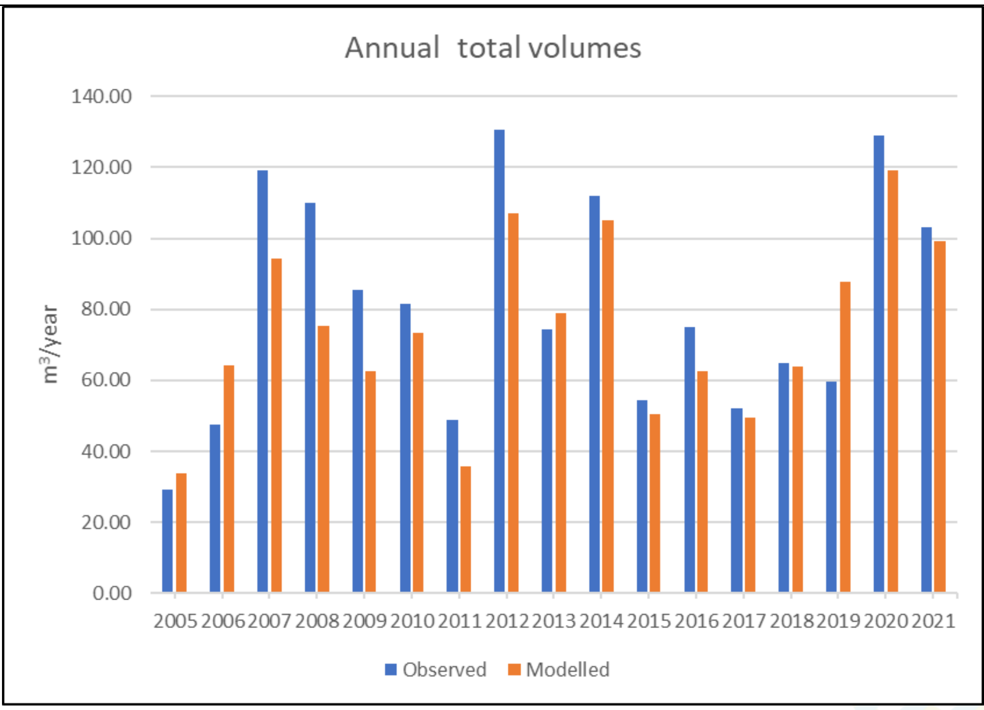
Statistical model fit			Comment
STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*	Model performance statistics are good and give confidence to the performance of the model relative to the observed.
NSE	0.991	Very good	
PBIAS	0.365	Very good	
R^2	0.543	Satisfactory	
RSR	0.096	Very Good	

C.3.4 Validation performance

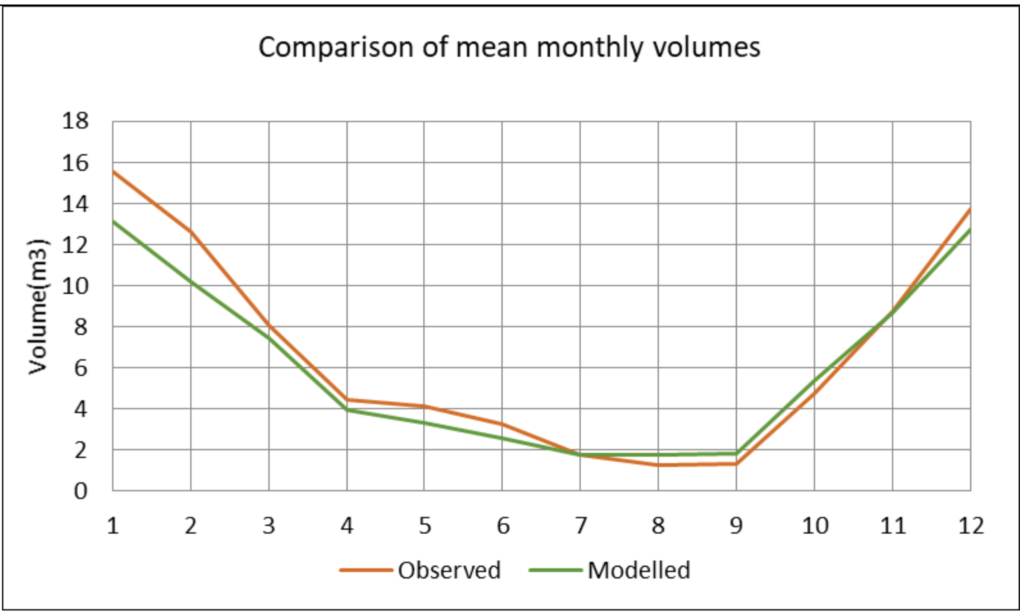
Flow Duration Curve



Annual Total Volumes



Mean Monthly Volumes



Statistical model fit

STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*
NSE	0.984	Very good
PBIAS	8.485	Very good
R^2	0.494	Satisfactory
RSR	0.128	Very Good

C.4 River Nene Calibration

C.4.1 Initial Model set up

This model has been set-up to calibrate to observed flow data from Dodford for the period 2010-2019. The gauge is reliable, gauging a predominantly clay catchment, rural land use and with some significant artificial influences.

Rainfall and PET derived for the Watford Catchment have been used as an input to the PDM.

C.4.2 Model Parameters

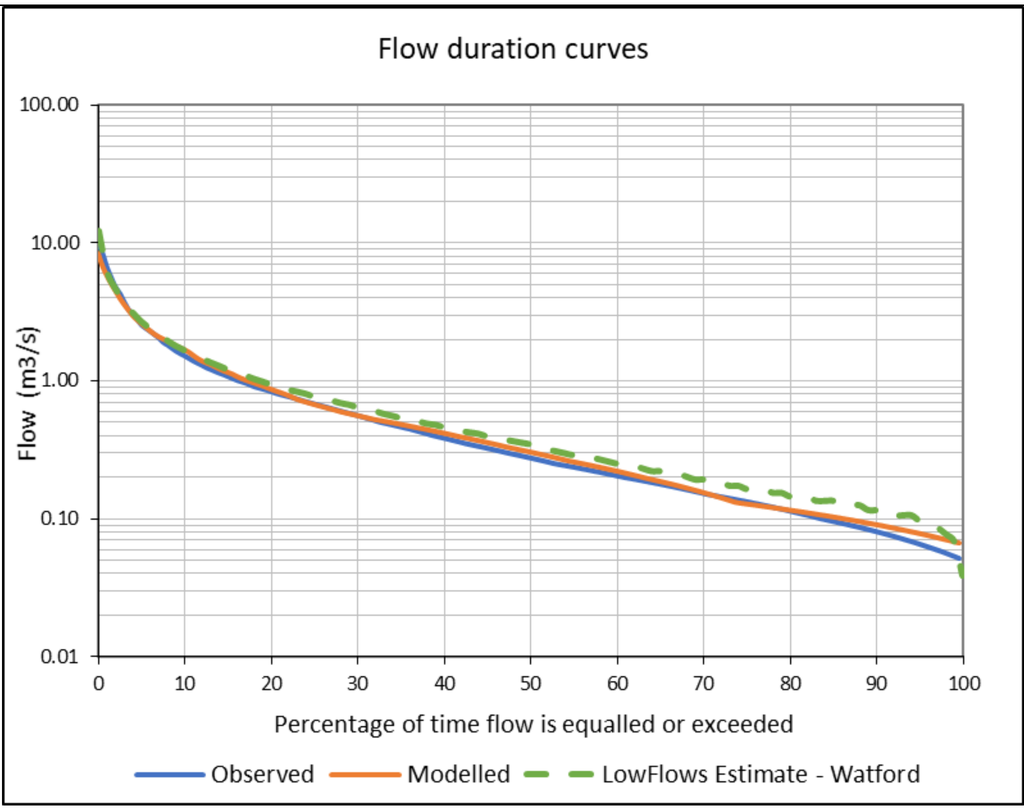
The PDM model has been calibrated to observed flow data by adjusting parameters, informed by the lag response to rainfall, and the geology and soils of the catchment. The model has been calibrated using the parameters in the table below. The focus for calibration has been matching baseflows.

Table C-4; Parameter values used in calibration of the Nene PDM model

Parameter	Value	Parameter definition	Typical range
f_c	0.993	Rainfall factor	0.8-1.2
c_{min}	30	Minimum store capacity	0-30
c_{max}	100	Maximum store capacity	40-300
b	0.5	Exponent of Pareto distribution	0.5-2.5
B_e	3	Exponent of evaporation function	0.5-3
K_g	65,000	Groundwater recharge time constant	100-100,000
B_g	1.7	Exponent of recharge function	0.5-2.5
St	0	Soil tension storage capacity	0
K_1	24	Time constants of cascade of linear reservoirs	0.5-24
K_2	24		
K_b	10,000,000	Baseflow time constant	125 – 100,000,000
Q_{const}	0	Constant flow representing abstractions	n/a
T_{dly}	0	Time delay	n/a

C.4.3 Calibration Performance (2010-2019)

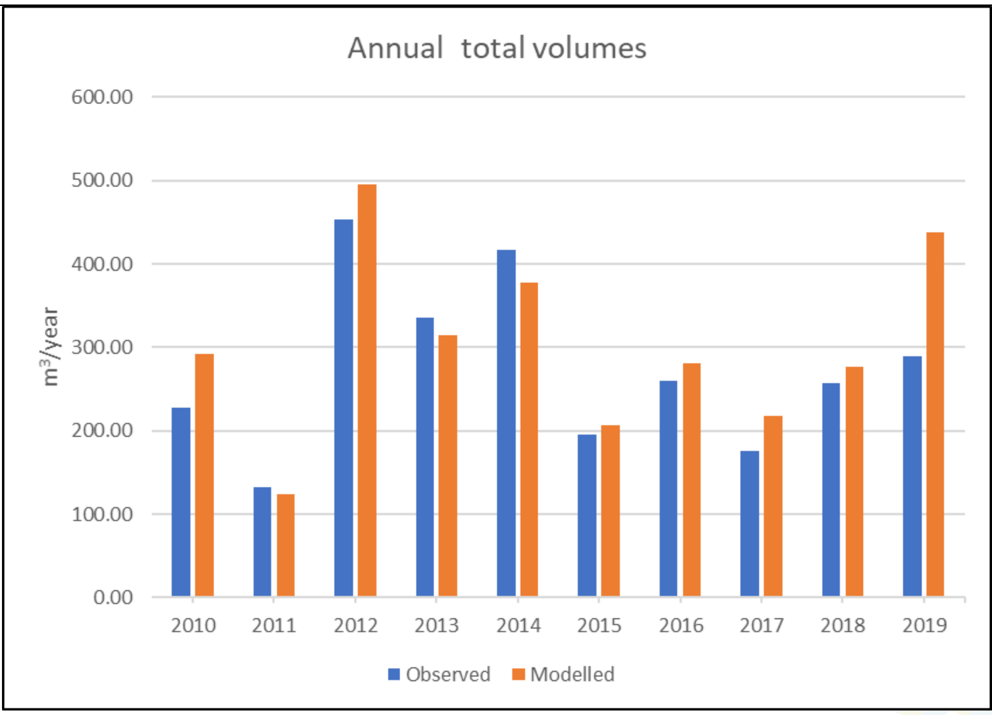
Flow Duration Curve



Comment

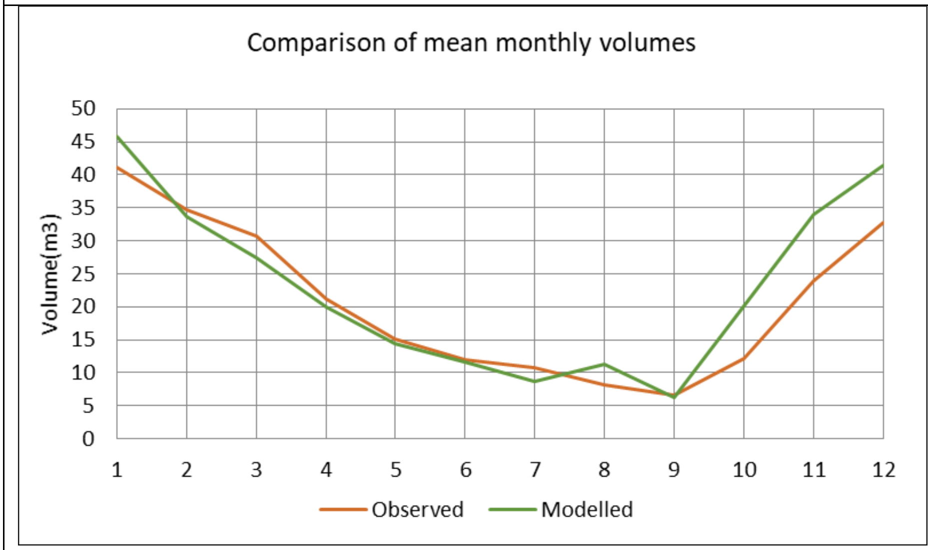
Overall, the modelled FDC matching the observed across the whole range of flows. The observed and modelled values also compare well to the LowFlows Estimate for the Watford catchment, giving further confidence that the model is representative of the overall catchment flow regime. The slope of the curve of the LowFlows Estimates below Q20 is flatter than both the observed and modelled flows.

Annual Total Volumes



Comment

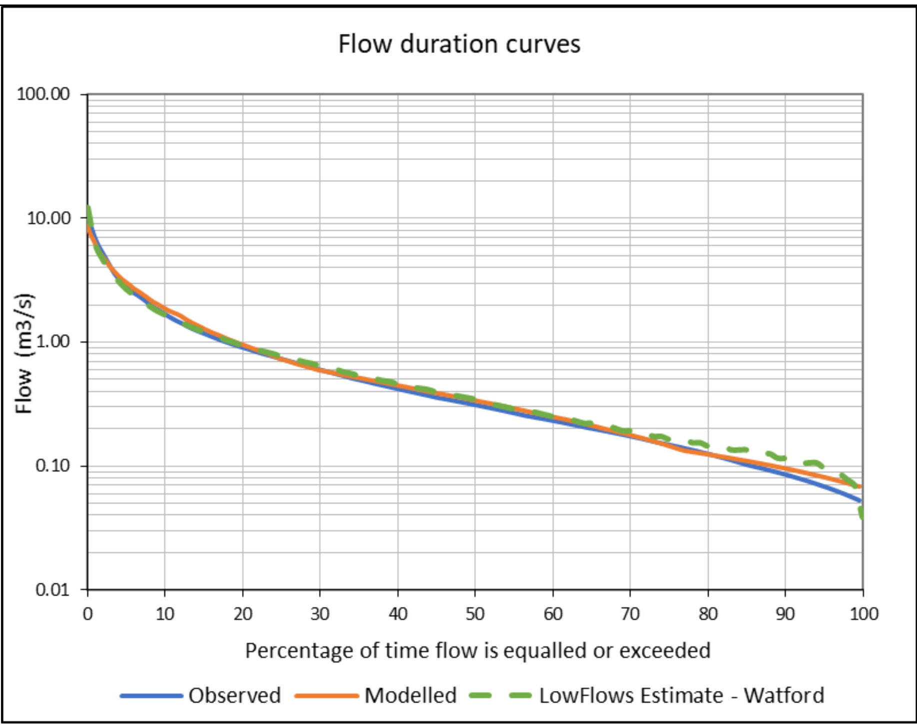
Annual Total Volumes s compare well to the observed, aside from in 2019, where the model is over predicting volumes. This is likely due to the 2018-2019 drought affecting catchment flows, the model is unable to replicate the soil moisture and groundwater conditions in the second consecutive drought year, causing it to overestimate winter baseflows.

Mean Monthly Volumes	Comment
	The model replicates mean monthly values well, particularly in the summer months.

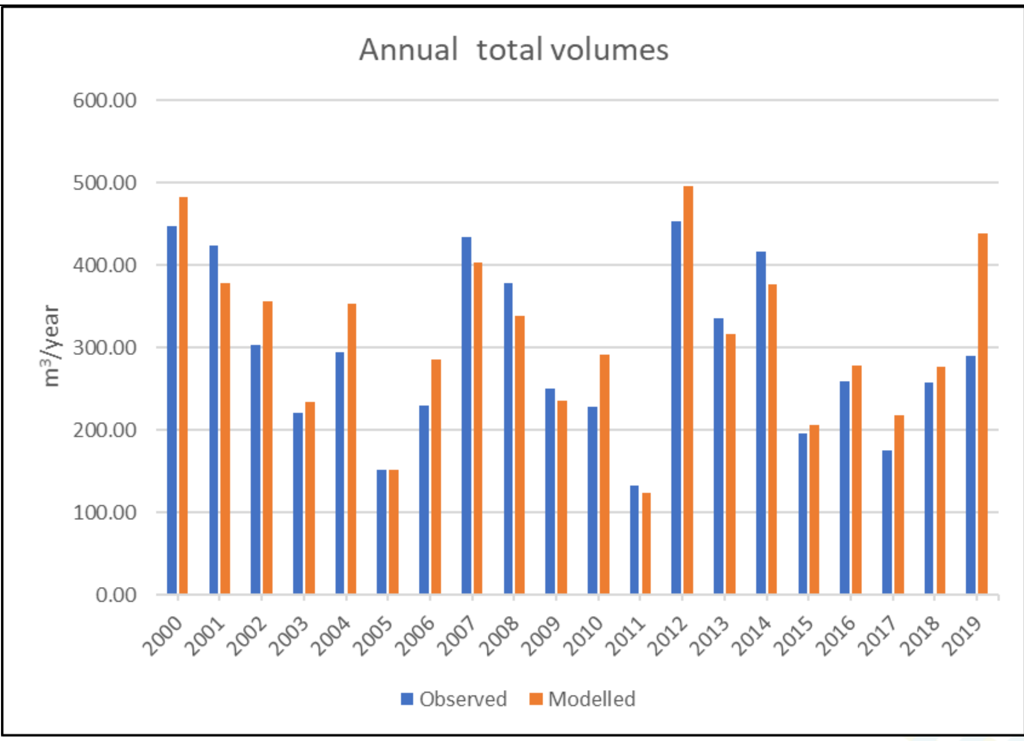
Statistical model fit			Comment
STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*	Model performance statistics are good and give confidence to the performance of the model relative to the observed.
NSE	0.997	Very good	
PBIAS	-9.258	Very good	
R^2	0.736	Very good	
RSR	0.053	Very good	

C.4.4 Validation performance

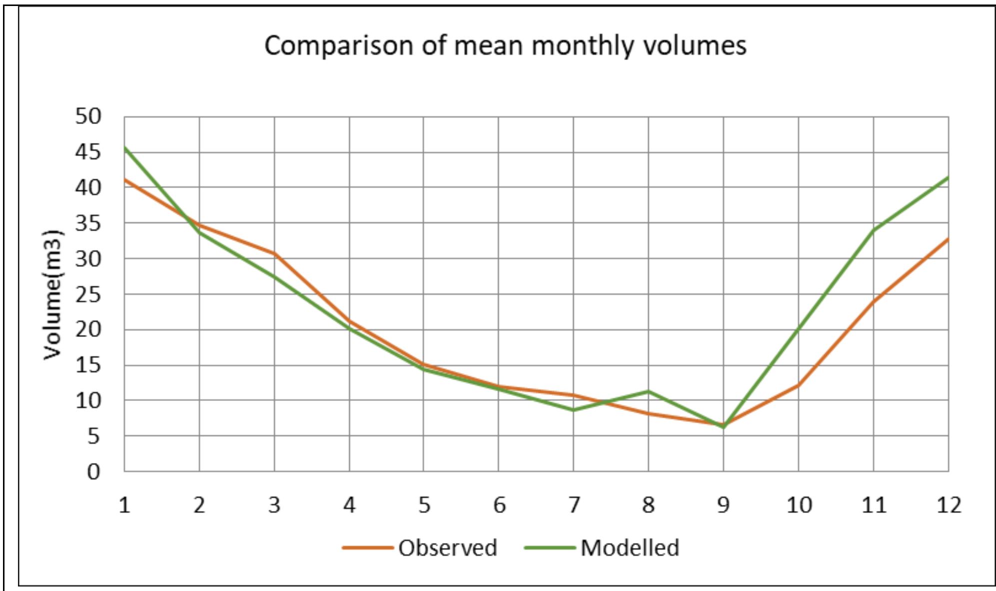
Flow Duration Curve



Annual Total Volumes



Mean Monthly Volumes



Statistical model fit

STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*
NSE	0.995	Very good
PBIAS	-5.681	Very good
R^2	0.716	Good
RSR	0.071	Very Good

C.5 River Swift Calibration

C.5.1 Initial Model set up

This model has been set-up to calibrate to observed flow data at Churchover for the period 2010-2019. The gauge is reliable, though flows are affected by the sluice gate just upstream of the gauge controlling the abstraction to the GUC. The Trust have previously noted this gauge to be affected by siltation. The observed flow data for this gauge shows a distinct pattern of flow al illustrated in the figure below, with prolonged periods of high flow in winter characteristic of high tributary input. In summer peaks are shorter and more responsive to rainfall.

Rainfall and PET derived for the Watford Catchment have been used as an input to the PDM.

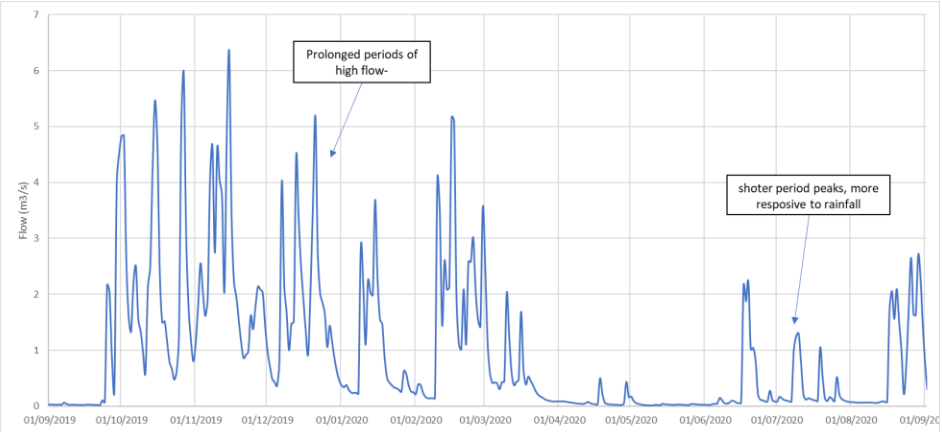


Figure C-1; Hydrograph of flow at the Swift at Churchover showing characteristic seasonal patterns of flow.

Ideally this would be represented with a seasonal PDM, however as the focus of this calibration is matching baseflows and overall flow volumes a compromise calibration has been used to represent flow at this gauge.

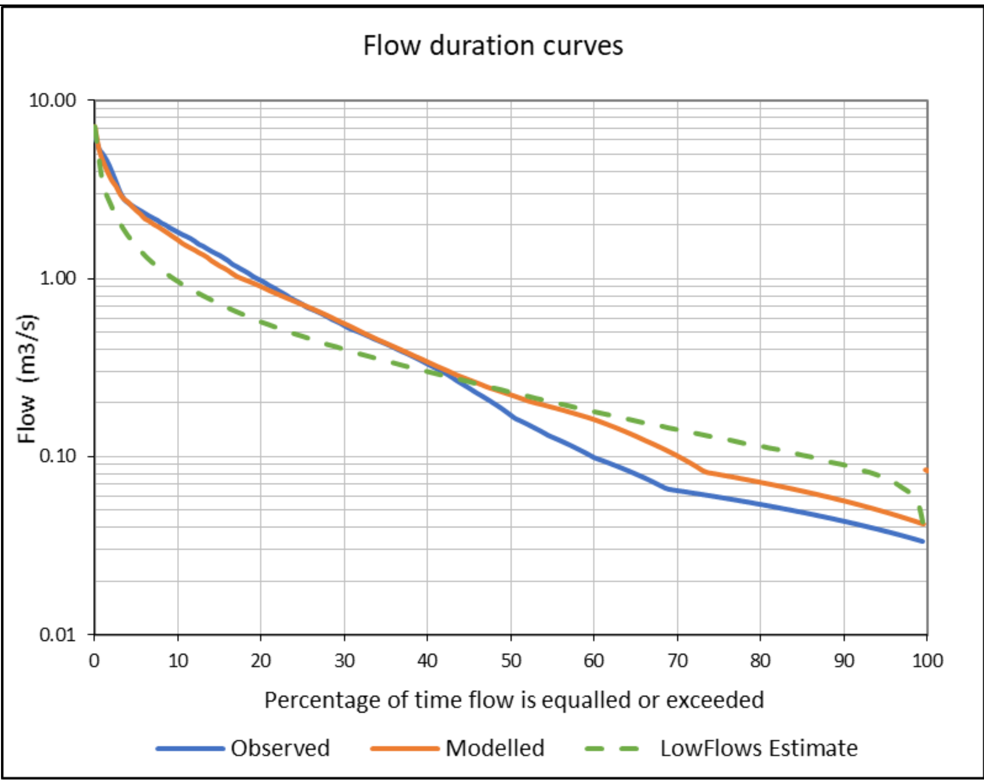
C.5.2 Model Parameters

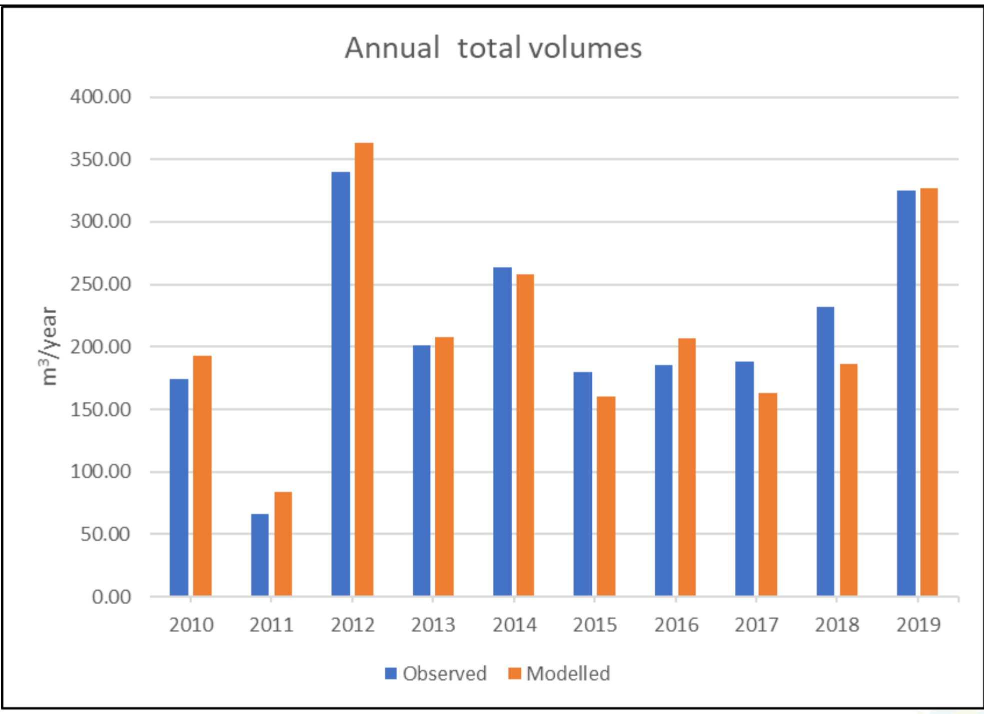
The PDM model has been calibrated to observed flow data by adjusting parameters, informed by the lag response to rainfall, and the geology and soils of the catchment. The model has been calibrated using the parameters in the table below. The focus for calibration has been matching baseflows.

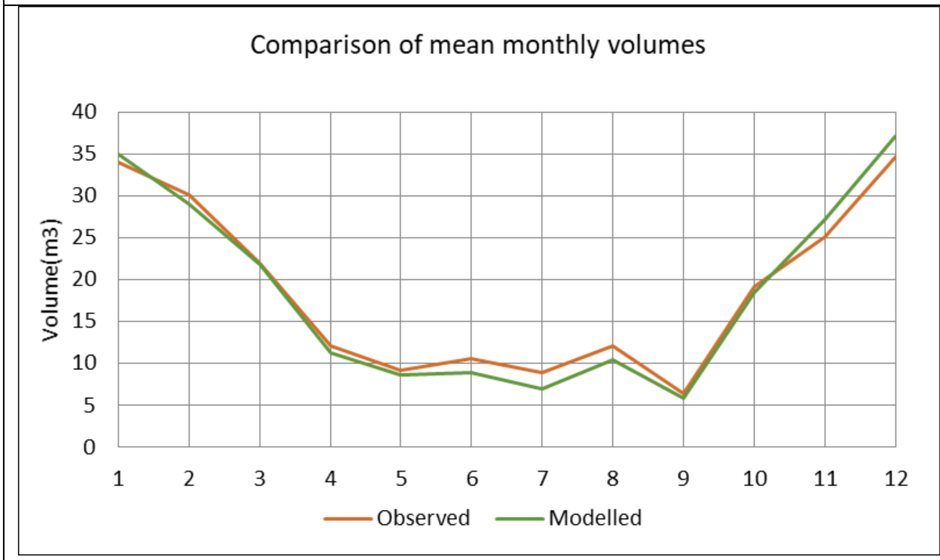
Table C-5; Parameter values used in calibration of the Swift PDM model

Parameter	Value	Parameter definition	Typical range
f_c	0.993	Rainfall factor	0.8-1.2
c_{min}	10	Minimum store capacity	0-30
c_{max}	175	Maximum store capacity	40-300
b	1	Exponent of Pareto distribution	0.5-2.5
B_e	3	Exponent of evaporation function	0.5-3
K_g	70,000	Groundwater recharge time constant	100-100,000
B_g	1.5	Exponent of recharge function	0.5-2.5
St	0	Soil tension storage capacity	0
K_1	10	Time constants of cascade of linear reservoirs	0.5-24
K_2	32		
K_b	10	Baseflow time constant	125 – 100,000,000
Q_{const}	0	Constant flow representing abstractions	n/a
T_{dly}	0	Time delay	n/a

C.5.3 Calibration Performance (2010-2019)

Flow Duration Curve	Comment
	Modelled flows compare well to the observed for the range Q10 to Q40. The model overestimates flow below this range though it should be noted that the differences in flow are only in the range of 0.1m^3/s. The LowFlows estimate does not compare well to either the modelled or the observed flows.

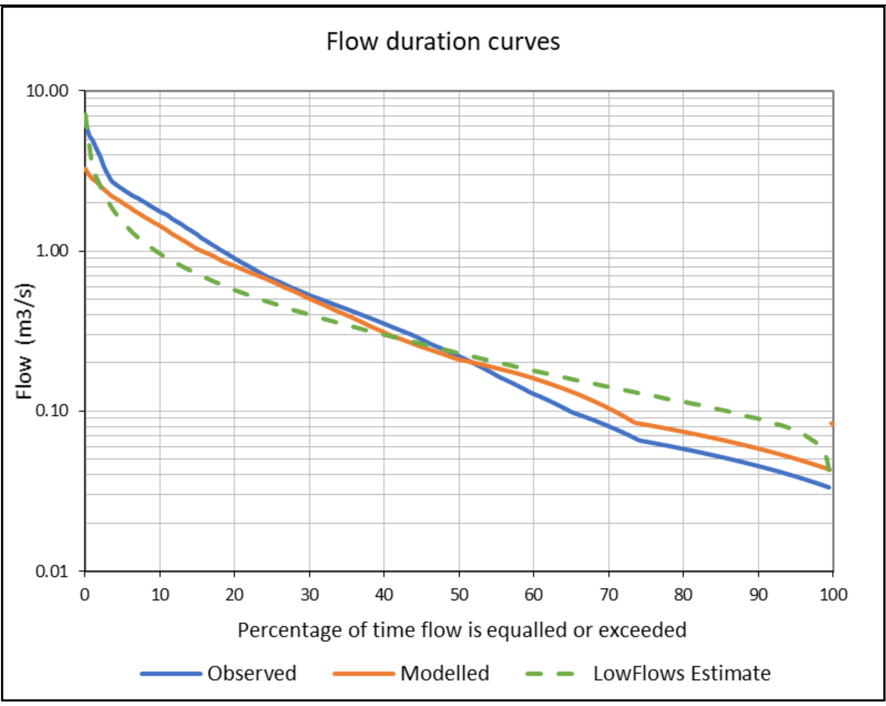
Annual Total Volumes	Comment
	Annual Total Volumes s generally compare well to the observed.

Mean Monthly Volumes	Comment
	The model replicates mean monthly volumes well, though tends to overestimate volumes in Spring and Summer.

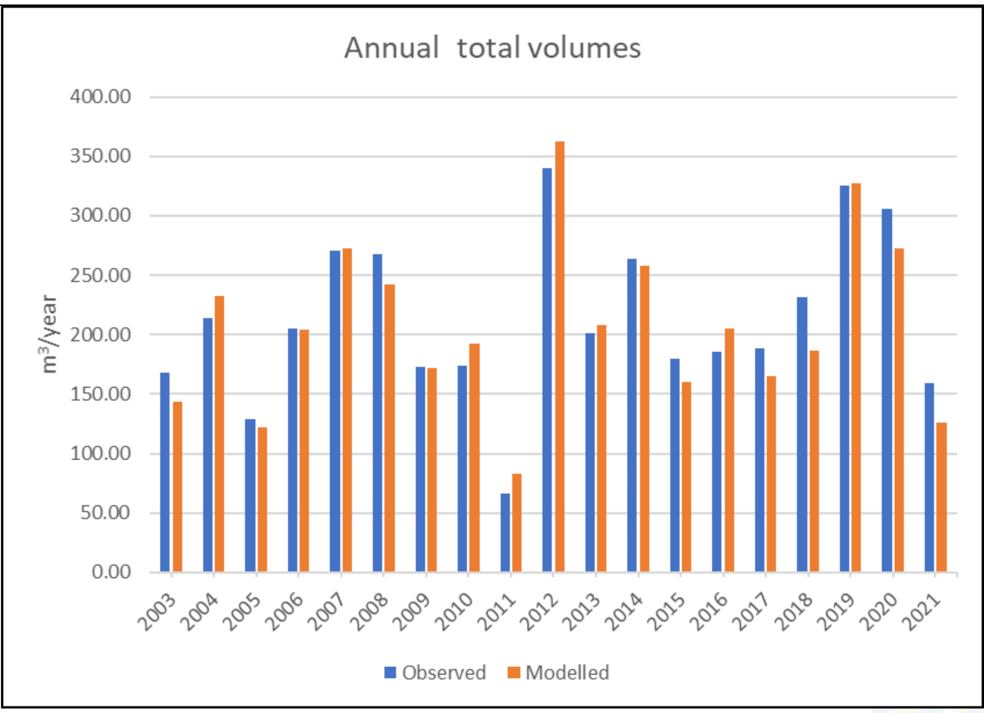
Statistical model fit			Comment
STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*	Model performance statistics are good and give confidence to the performance of the model relative to the observed.
NSE	0.999	Very good	
PBIAS	1.66	Very good	
R^2	0.837	Very good	
RSR	0.040	Very good	

C.5.4 Validation performance

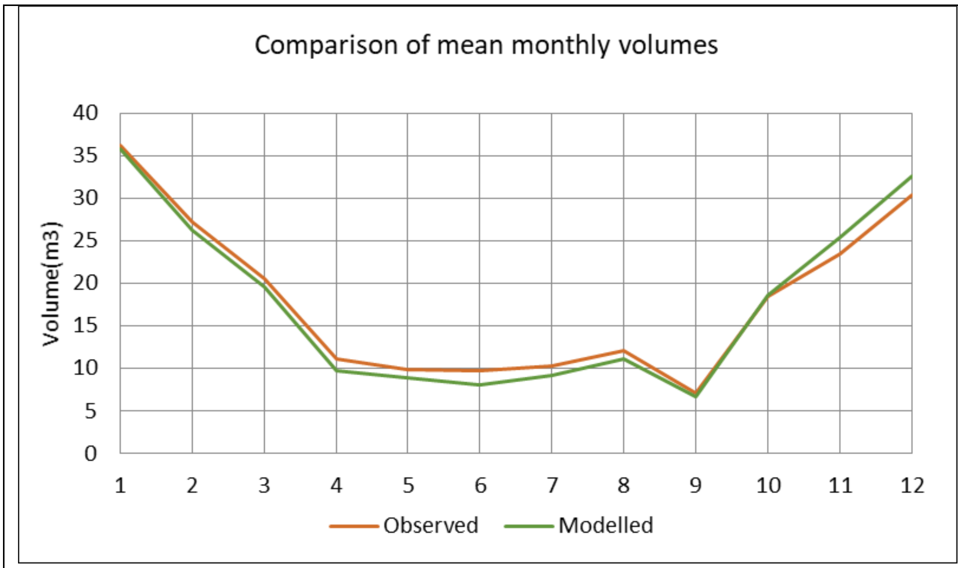
Flow Duration Curve



Annual Total Volumes



Mean Monthly Volumes



Statistical model fit

STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*
NSE	0.996	Very good
PBIAS	2.883	Very good
R^2	0.787	Very good
RSR	0.061	Very Good

C.6 River Sence Calibration

C.6.1 Initial Model set up

This model has been set-up to calibrate to observed flow data at South Wigston for the period 2010-2019. LaserFlow ultrasonic gauge post 2017, previously electromagnetic gauge set in 1:1 formalised banks and flood embankment 20m downstream of the control. Gauges a moderate to low relief catchment to E and S of Leicester. Catchment geology is predominantly mudstones and limestones overlain with boulder clay.

Rainfall and PET derived for the Burton Catchment have been used as an input to the PDM.

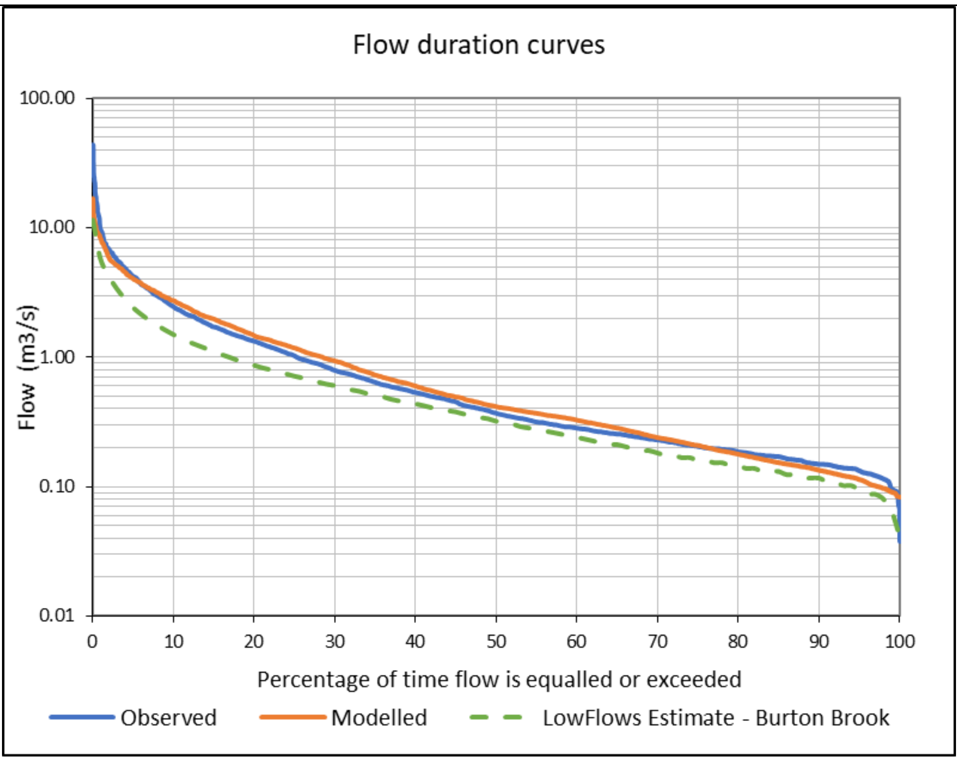
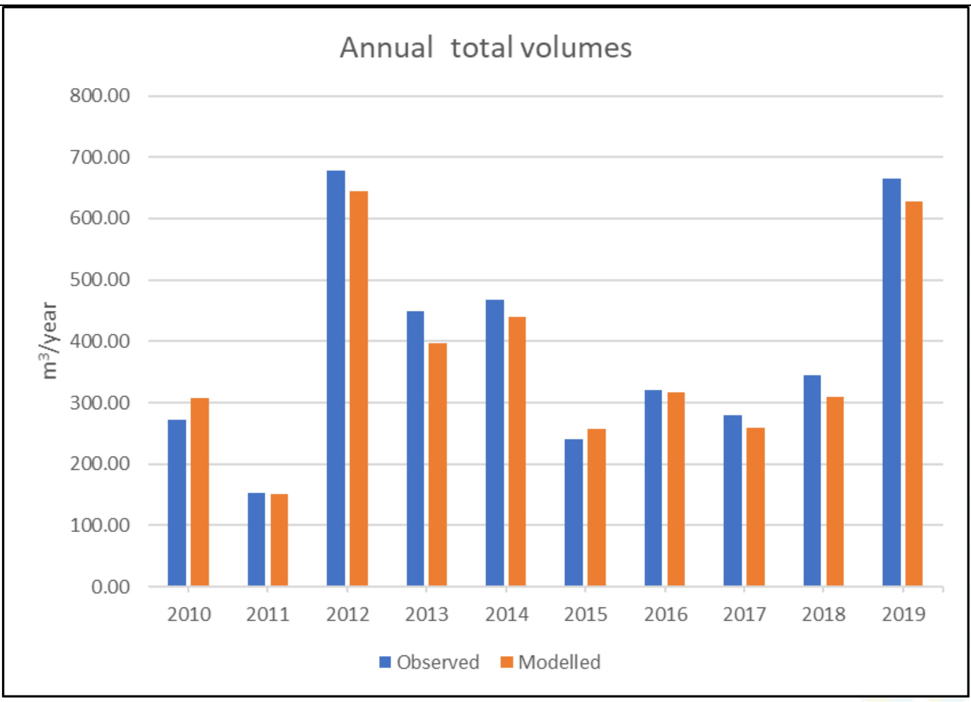
C.6.2 Model Parameters

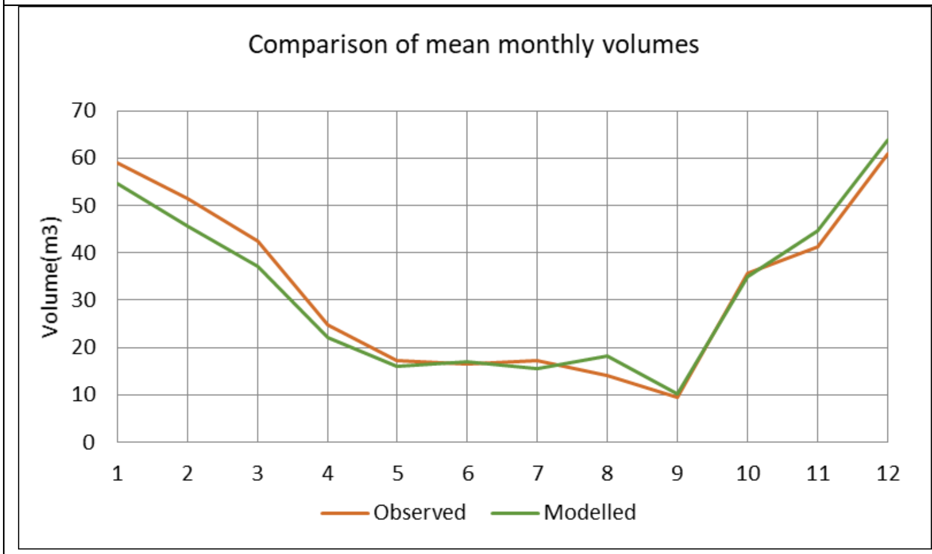
The PDM model has been calibrated to observed flow data by adjusting parameters, informed by the lag response to rainfall, and the geology and soils of the catchment. The model has been calibrated using the parameters in the table below. The focus for calibration has been matching baseflows.

Table C-6; Parameter values used in calibration of the Swift PDM model

Parameter	Value	Parameter definition	Typical range
f_c	0.993	Rainfall factor	0.8-1.2
c_{min}	20	Minimum store capacity	0-30
c_{max}	130	Maximum store capacity	40-300
b	0.8	Exponent of Pareto distribution	0.5-2.5
B_e	3	Exponent of evaporation function	0.5-3
K_g	6000	Groundwater recharge time constant	100-100,000
B_g	1	Exponent of recharge function	0.5-2.5
St	0	Soil tension storage capacity	0
K_1	2	Time constants of cascade of linear reservoirs	0.5-24
K_2	50		
K_b	1,000,000	Baseflow time constant	125 – 100,000,000
Q_{const}	0	Constant flow representing abstractions	n/a
T_{dly}	0	Time delay	n/a

C.6.3 Calibration Performance (2010-2019)

Flow Duration Curve	Comment
	Modelled flows compare reasonably well to the observed, though the model slightly overestimates lower magnitude peak flows and underestimates high magnitude peak flows. The LowFlows estimate compares reasonably well to the observed and modelled though seems to be generally lower then both the modelled and observed.
Annual Total Volumes	**Comment**
	Annual Total Volumes s generally compare well to the observed. Modelled volumes tend to be higher than the observed.

Mean Monthly Volumes	Comment
	The model replicates mean monthly volumes well, though tends to overestimate volumes in Spring and Summer.

Statistical model fit

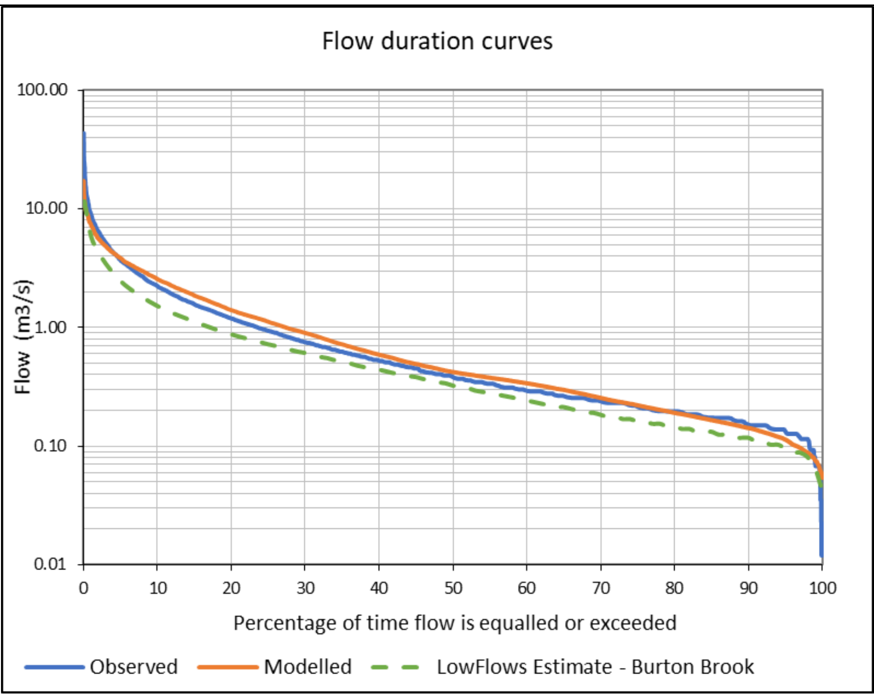
STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*
NSE	0.995	Very good
PBIAS	2.792	Very good
R^2	0.691	Very good
RSR	0.074	Very good

Comment

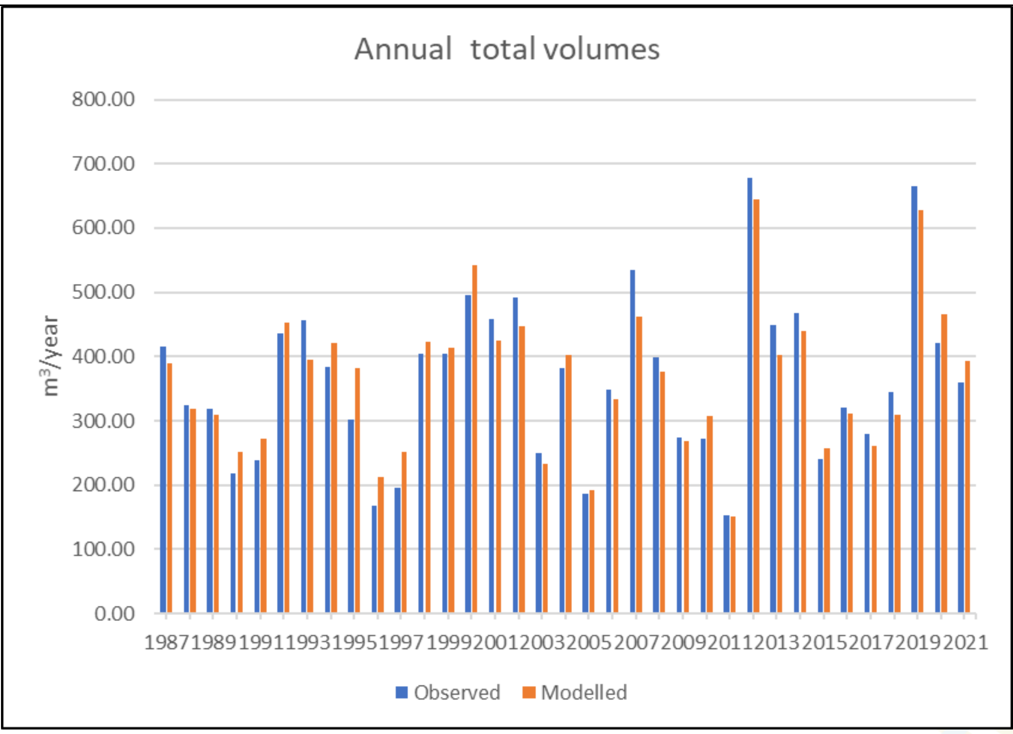
Model performance statistics are good and give confidence to the performance of the model relative to the observed.

C.6.4 Validation performance

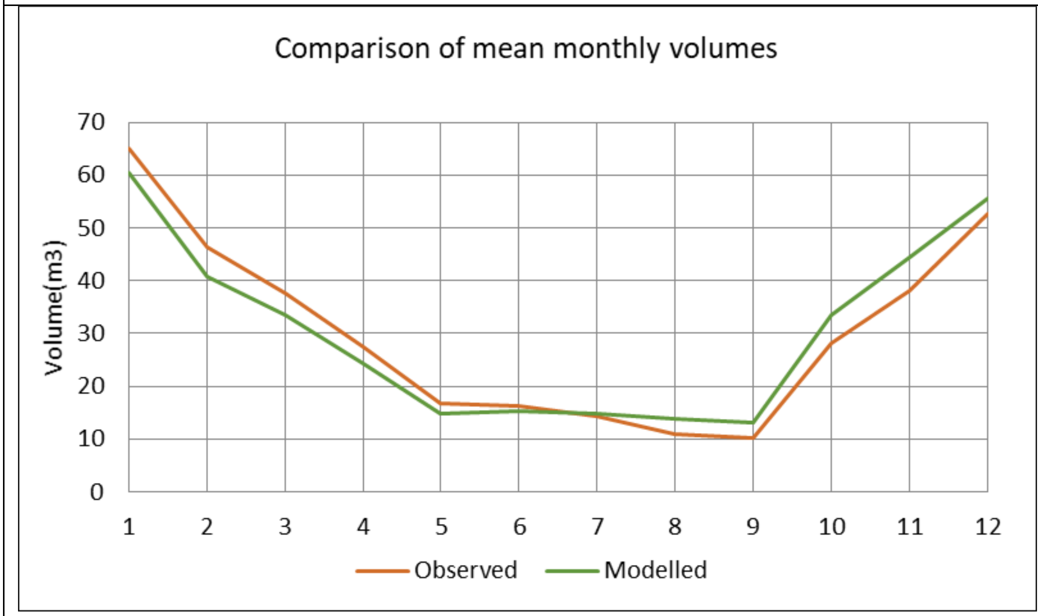
Flow Duration Curve



Annual Total Volumes



Mean Monthly Volumes



Statistical model fit

STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*
NSE	0.983	Very good
PBIAS	-5.273	Very good
R^2	0.655	Very good
RSR	0.132	Very Good

C.7 River Mease Calibration

C.7.1 Initial Model set up

This model has been set-up to calibrate to observed flow data at Clifton Hall for the period 2010-2019. The gauge is reliable draining a predominantly rural, lowland clay catchment.

Rainfall and PET derived for the Burton Catchment have been used as an input to the PDM.

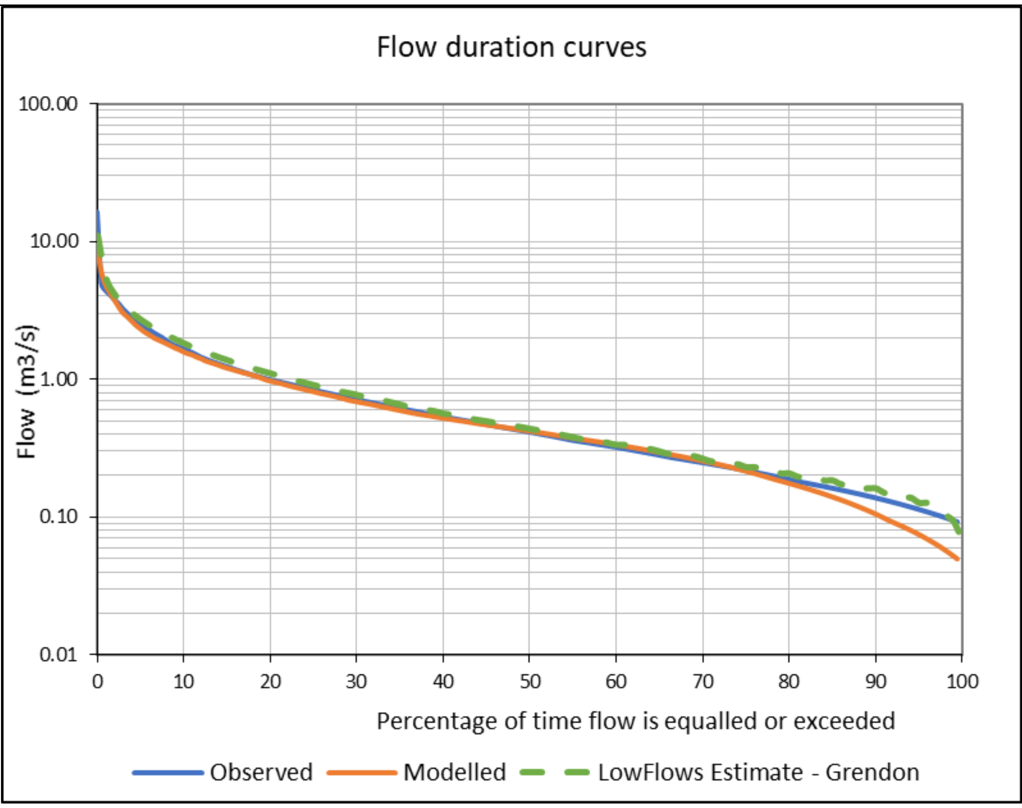
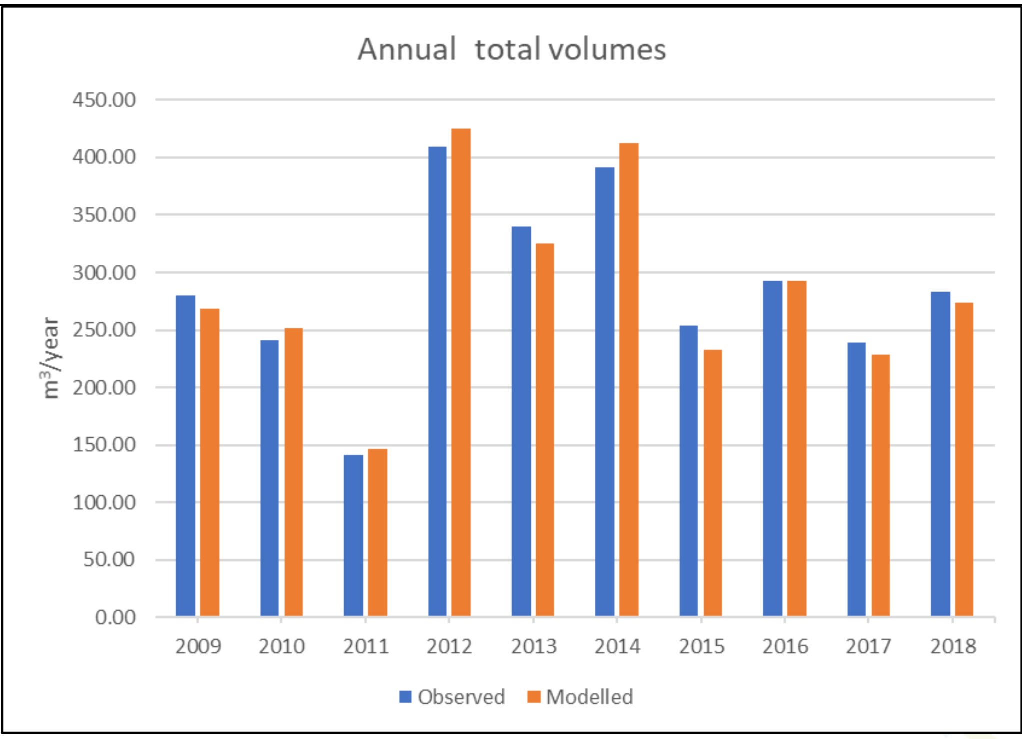
C.7.2 Model Parameters

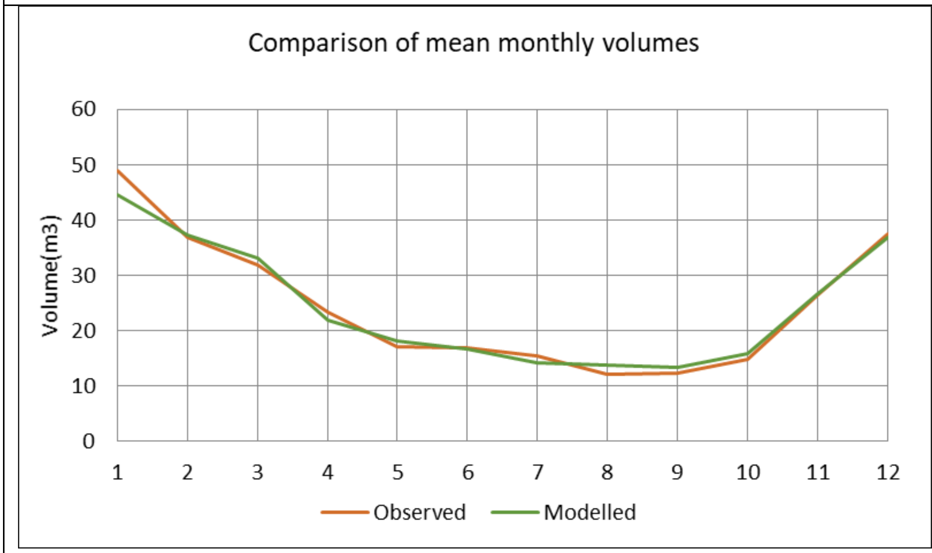
The PDM model has been calibrated to observed flow data by adjusting parameters, informed by the lag response to rainfall, and the geology and soils of the catchment. The model has been calibrated using the parameters in the table below. The focus for calibration has been matching baseflows.

Table C-7; Parameter values used in calibration of the Swift PDM model

Parameter	Value	Parameter definition	Typical range
f_c	0.98	Rainfall factor	0.8-1.2
c_{min}	1	Minimum store capacity	0-30
c_{max}	200	Maximum store capacity	40-300
b	0.5	Exponent of Pareto distribution	0.5-2.5
B_e	3	Exponent of evaporation function	0.5-3
K_g	4000	Groundwater recharge time constant	100-100,000
B_g	0.9	Exponent of recharge function	0.5-2.5
St	0	Soil tension storage capacity	0
K_1	1	Time constants of cascade of linear reservoirs	0.5-24
K_2	50		
K_b	1,000,000	Baseflow time constant	125 – 100,000,000
Q_{const}	0	Constant flow representing abstractions	n/a
T_{dly}	0	Time delay	n/a

C.7.3 Calibration Performance (2008-2019)

<table>
<tr><th>Flow Duration Curve</th><th>Comment</th></tr>
<tr><td>
</td><td>Modelled flows compare reasonably well to the observed, though the model slightly underestimates flows below Q80. The LowFlows estimate compares reasonably well to the observed and modelled giving further confidence that the model is representative of the overall catchment flow regime of the feeder catchments.</td></tr>
<tr><th>Annual Total Volumes</th><th>Comment</th></tr>
<tr><td>
</td><td>Annual Total Volumes s generally compare well to the observed. Modelled volumes tend to be higher than the observed.</td></tr>
</table>

Mean Monthly Volumes	**Comment**
	The model replicates mean monthly volumes well, though tends to overestimate volumes in Spring and Summer.

Statistical model fit

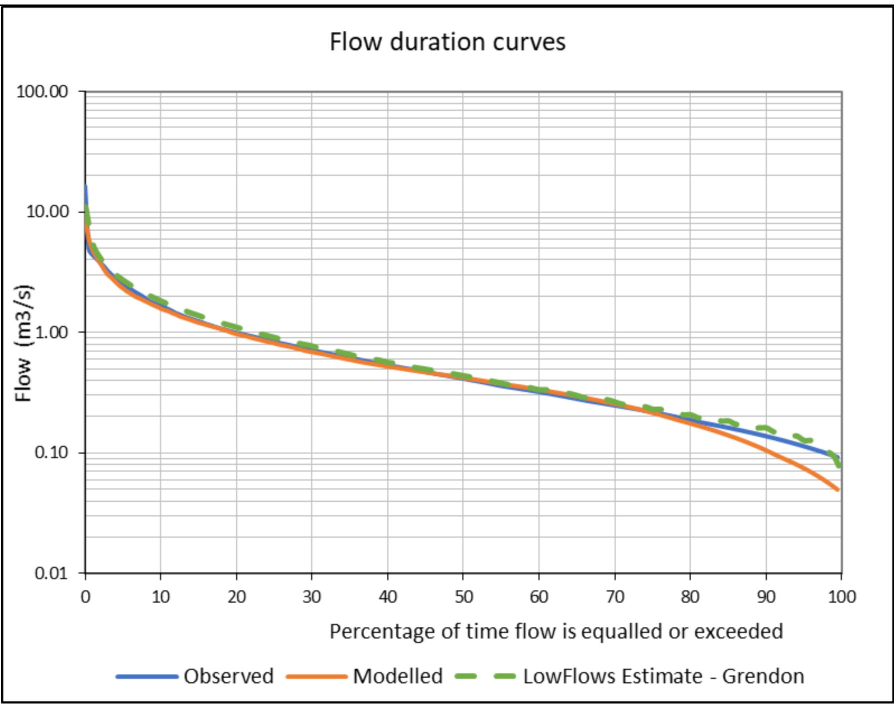
STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*
NSE	0.999	Very good
PBIAS	0.388	Very good
R^2	0.805	Very good
RSR	0.030	Very good

Comment

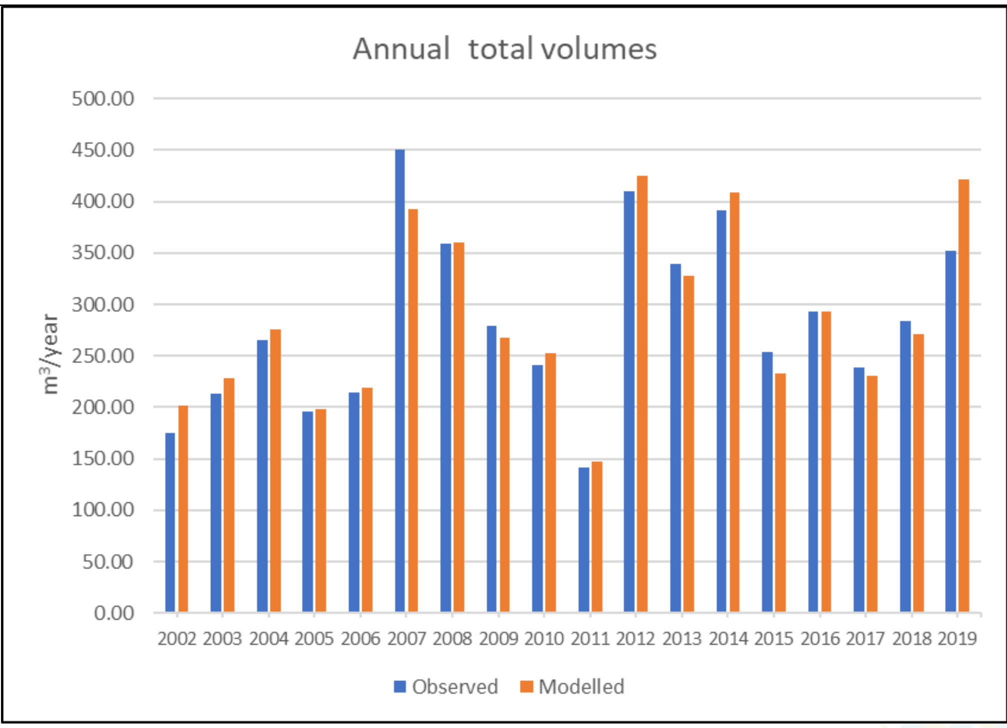
Model performance statistics are good and give confidence to the performance of the model relative to the observed.

C.7.4 Validation performance

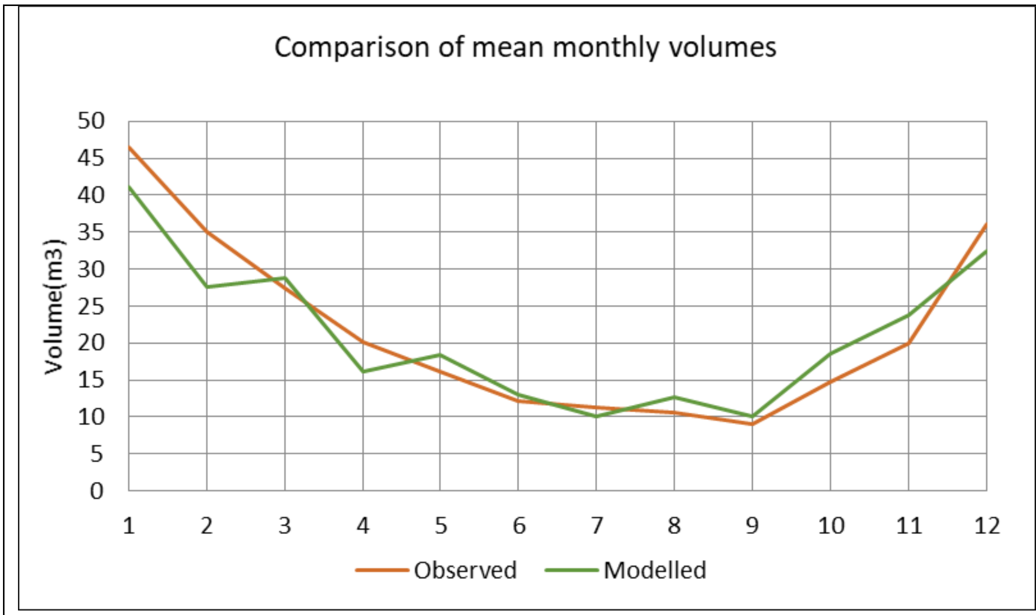
Flow Duration Curve



Annual Total Volumes



Mean Monthly Volumes



Statistical model fit

STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*
NSE	0.997	Very good
PBIAS	0.247	Very good
R^2	0.759	Very good
RSR	0.051	Very Good

C.8 Tring Drainage Rainfall-runoff model calibration

C.8.1 Initial Model set up

This model has been set-up to calibrate to observed flow data at the Tring Drainage Gauge. The exact catchment area of this gauge is uncertain. The original HYSIM model of the Tring Drainage Feeder used a catchment area of 6.5 km^2 and this area has been maintained for use in this model.

Rainfall and PET derived for the Wendover Catchment have been used as an input to the PDM.

C.8.2 Model Parameters

The PDM model has been calibrated to observed flow data by adjusting parameters, informed by the lag response to rainfall, and the geology and soils of the catchment. The model has been calibrated using the parameters in the table below. The focus for calibration has been matching baseflows. It should be noted this model uses a quadratic baseflow store rather than the default cubic.

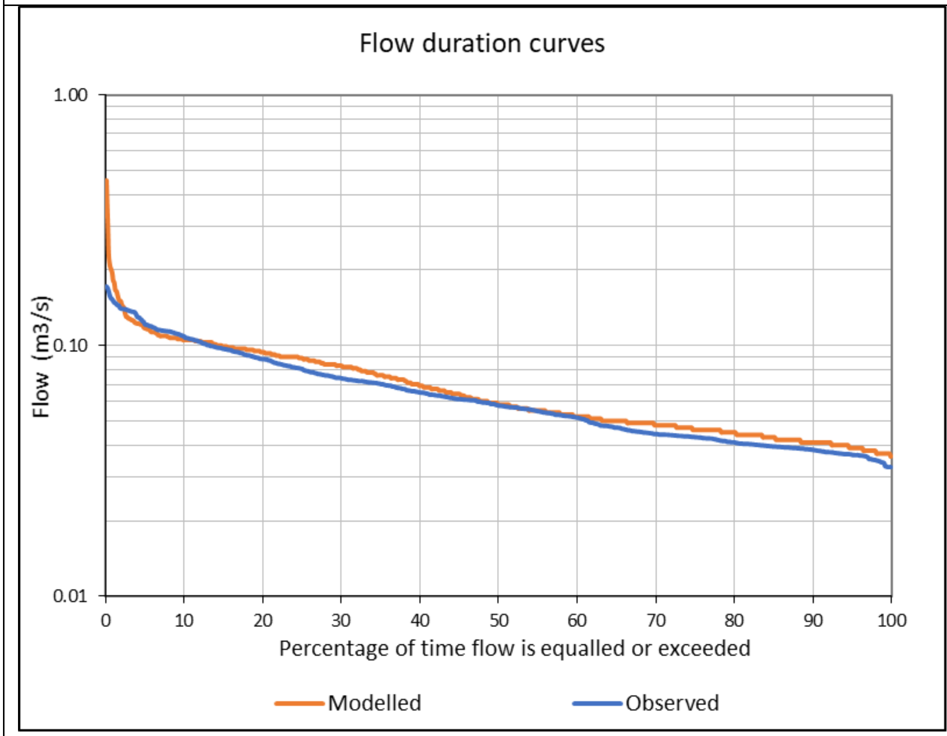
Table C-8; Parameter values used in calibration of the Tring Drainage PDM model

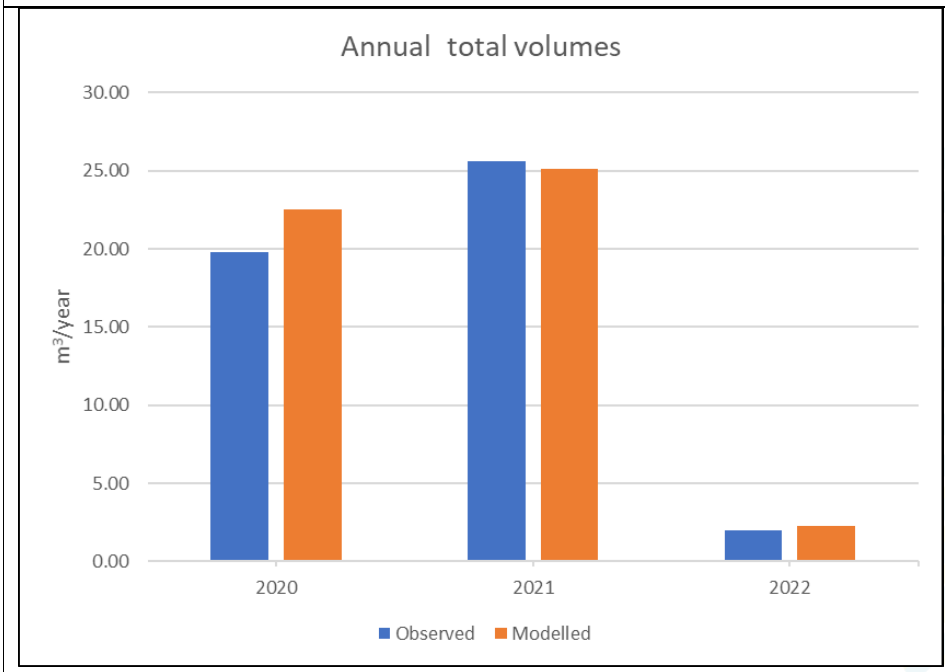
Parameter	Value	Parameter definition	Typical range
f_c	0.9	Rainfall factor	0.8-1.2
c_{min}	30	Minimum store capacity	0-30
c_{max}	350	Maximum store capacity	40-300
b	0.5	Exponent of Pareto distribution	0.5-2.5
B_e	3	Exponent of evaporation function	0.5-3
K_g	50000	Groundwater recharge time constant	100-100,000
B_g	1.8	Exponent of recharge function	0.5-2.5
St	0	Soil tension storage capacity	0
K_1	48	Time constants of cascade of linear reservoirs	0.5-24
K_2	48		
K_b	1,000,000	Baseflow time constant	125 – 100,000,000
Q_{const}	0	Constant flow representing abstractions	n/a
T_{dly}	0	Time delay	n/a

This model uses the extended groundwater model with a spring factor (Alpha) of 0.4.

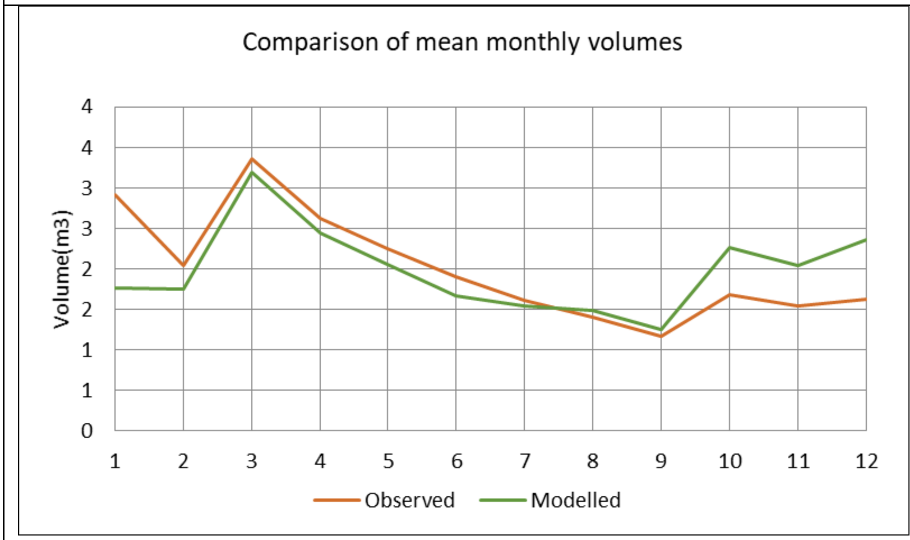
C_{max} has been extended beyond the typical range of this parameter to achieve a better fit to the Flow Duration curve.

C.8.3 Calibration Performance (2020-2022)

<table>
<tr><th>Flow Duration Curve</th><th>Comment</th></tr>
<tr><td>


</td><td>Modelled flows compare reasonably well to the observed, those the model overestimates high magnitude peak flows (above Q5). As these are outside of the range of consideration for this study this is acceptable but should be kept in mind when validating the results of the Aquator model.</td></tr>
<tr><th>Annual Total Volumes</th><th>Comment</th></tr>
<tr><td>


</td><td>Annual Total Volumes s generally compare well to the observed.</td></tr>
</table>

Mean Monthly Volumes	Comment
	The model replicates mean monthly volumes well, though tends to overestimate volumes between January and July and underestimate volumes between July and December.

Statistical model fit

STATISTICAL MEASURE	*VALUE*	*PERFORMANCE RATING*
NSE	1.000	Very good
PBIAS	-5.167	Very good
R^2	0.541	Satisfactory
RSR	0.009	Very good

Comment

Model performance statistics are good and give confidence to the performance of the model relative to the observed.

D Appendix D – List of feeder catchments, catchment descriptors and choice of donor.

Feeder	Area	BFI	SAAR	URBEXT	Choice of Donor
River Ouse	505.9	0.45	652	0.01	Ouse
River Cherwell, Aynho	276.0	0.42	663	0.03	Ouse
River Tove	171.9	0.38	655	0.01	Tove
River Cherwell Cropredy Mill	148.22	0.361	669	0.0113	
River Swift Feeder	68.0	0.36	657	0.04	Swift
Ledburn Brook	34.5	0.34	651	0.01	Clipstone
Boddington Feeder	19.6	0.34	667	0.01	Clipstone
Burton Brook	15.4	0.35	648	0.00	Sence
Watford Feeder	11.2	0.36	665	0.00	Nene
Grendon Feeder	10.2	0.54	665	0.09	Mease
Griff Arm	9.3	0.37	675	0.06	Mease
Wem Brook Feeder	8.7	0.38	653	0.06	Mease or Swift
Sulby Feeder	8.4	0.35	681	0.00	Sence
Daventry Feeder	8.4	0.50	676	0.30	Nene
Tring Summit Feeder	7.6	0.87	726	0.12	Wendover
Wendover	7.3	0.85	745	0.04	
Tring Drainage	6.5				Wendover
Saddington Feeder	6.3	0.31	652	0.00	Sence
Naseby Feeder	4.7	0.40	684	0.03	Sence
Wormleighton Feeder	4.7	0.26	654	0.00	Clipstone
Old (Welton) Feeder	3.4	0.45	670	0.00	Nene
Gumley Feeder	3.2	0.25	650	0.00	Sence
Merevale Feeder	3.0	0.40	683	0.04	Mease
Kilsby	2.9	0.34	649	0.06	Swift
Wilstone Feeder	2.7	0.90	681	0.00	Wendover
Bulbourne Stream	2.2	0.86	685	0.00	Wendover
Clattercote Feeder	1.9	0.54	653	0.00	Mease
Drayton Feeder	1.8	0.36	674	0.33	Nene
Hartshill	1.5	0.44	689	0.06	Mease
Rawn hill Feeder	1.3	0.50	689	0.00	Mease
Mancetter Feeder	1.2	0.51	692	0.02	Mease
Tunnel Feeder	1.1	0.30	672	0.00	Mease
Welford	0.5	0.35	681	0.00	Sence

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Registered Office
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+44(0)1756 799919
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