

Comparison of Average Pumping Head and Booster Pumps per km Performance Metrics

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Glossary

APH	Average Pumping Head
APR	Annual Performance Report
B2D	Boost to distribution
B2S	Boost to storage
BpK	Number of booster pumping stations per 1,000km of water network
BWL	Bottom Water Level
DI	Distribution Input
mAOD	Metres Above Ordnance Datum
PCA	Price Control Area
PS	Pumping station
TWD	Treated Water Distribution
TWL	Top Water Level
WTW	Water Treatment Works

Summary

i Reasons

Average pumping head (APH) is one of a number of performance metrics that water companies in England and Wales are required to report to Ofwat as part of the Annual Performance Report process. APH can act as a proxy for energy requirements and, for this reason, Ofwat has used APH as a key variable in its econometric models for operating expenditure up until PR14. At PR19 Ofwat used the number of water booster pumping stations per 1,000km of water network (BpK) as a measure of the cost of pumping across a network. There is some concern across the water industry that BpK may not be fair measure of operational efficiency as it may not directly reflect the impact of local topography, historical network configurations or company policies.

ii Objectives

South Staffordshire Water has asked WRc to undertake an impartial comparison of these two metrics to ascertain whether BpK is a reasonable alternative to APH for use within econometric models of operational efficiency. The objective of the project was to theoretically quantify both metrics under a number of reasonable distribution network configuration and operational scenarios and compare outcomes.

iii Approach

A number of hydraulic modelling scenarios were devised that described a set of treated water distribution networks containing features or characteristics that will influence both APH and BpK, specifically topography and the number and size (rating) of pumping stations. The scenarios were designed to allow topography to be varied and pumping adjusted to meet the system requirements. All other components, such as length of main and population demand, remained fixed, allowing the impact on APH and BpK to be observed.

Two core types of systems were selected as the basis for these scenarios; supply boosted directly into distribution and supply boosted via storage (service reservoir). Within these two core types of system, four scenarios were devised to represent variations in system elevation, giving a total of eight scenarios.

The networks described in the scenarios were all theoretical, but the values used to define the networks were taken from ‘real world’ situations, where possible. All the values and parameters used in the scenarios were developed by the WRc team, based on engineering judgment and expertise and standard industry data. As this was an impartial assessment, no data or network information were requested from South Staffs Water.

iv Conclusions

- The APH and BpK metrics both respond to changes in topography, but their responses are different in the majority of scenarios modelled in this study. The undulating demand topography scenario in particular illustrates the influence of topography on these two metrics, regardless of whether a network includes storage or not. More PS would be required to overcome local changes in elevation, but their contribution to the overall TWD APH value would be small as they only serve discrete demand centres.

- The number of pumping stations per km (BpK) in a network could be used as an approximation for the relative capital maintenance costs of pumping, reflecting in some part the cost of maintaining each station as well as any costs associated with collecting and transmitting performance data. However, this metric does not take account of the rating or size of each pump and therefore the greater maintenance costs for larger pumps and pumping stations, nor the energy costs associated with operating each station.

- APH gives an accurate measure of the total work done by pumping stations in the network and is therefore a good indication of the total energy costs. Although it takes into account the total lift across a network (and therefore total changes in elevation), it does not account for other site variations such as pump and motor efficiency. The product of volume and lift at each individual pumping station gives a good indication of its size and potential maintenance costs. The number of pumping stations is not taken into account for the overall APH metric, but in producing the metric each pumping station is considered and could be reported alongside the APH.

- Neither metric takes account of age of equipment (wear and tear), accessibility to sites, distances from depots, or level of automation and control, all of which may impact operational and capital costs.

- This work demonstrates the measures are not equivalent and neither APH nor BpK as reported will accurately provide a full picture of the pumping costs of a supply system. However, APH could be considered a more versatile measure if the component parts of the calculation relating to the individual pumping stations are considered alongside the overall APH figure, as discussed above, e.g. size of pumps correlating to maintenance requirements.

- The aim of this study was to assess the influence of topography on both pumping metrics. The validity of using either metric within economic cost modelling has not been undertaken. Although this study demonstrates that the two metrics are not equivalent, further work would be needed to model correlations of each metric to cost.

1. Introduction

1.1 Project appreciation

Average pumping head (APH) is one of a number of performance metrics that water companies in England and Wales are required to report to Ofwat as part of the Annual Performance Report (APR) process. The derivation of APH is described in a standard formula detailed in the Ofwat APR guidance (RAG 2.08) (Ofwat, 2021). APH is derived for each of the following Price Control Areas (PCA): raw water abstraction; raw water transport; water treatment and treated water distribution (TWD). It is calculated as the sum of the pumping head (lift * volume) for each pumping station (PS) in the PCA (the numerator of the APH formula) divided by the total volume entering the PCA (denominator of the APH formula).

APH can act as a proxy for energy requirements and, for this reason, Ofwat has used APH as a key variable in its econometric models for operating expenditure up until PR14. At PR19 Ofwat used the number of water booster pumping stations per 1,000km of water network (BpK). This alternative metric is supposed to measure the cost of pumping across a network, but there is some concern that this is not a fair measure of operational efficiency as it may not directly reflect the impact of local topography, historical network configurations or company policies.

1.2 Objectives and scope

South Staffordshire Water has asked WRc to undertake an impartial comparison of these two metrics to ascertain whether BpK is a reasonable alternative to APH for use within econometric models of operational efficiency. The objective of the project was to theoretically quantify both metrics under a number of reasonable distribution network configuration and operational scenarios and compare outcomes.

1.3 Overview of approach

In order to meet the objectives of the project a number of scenarios were devised that describe a set of TWD networks (post treatment) containing features or characteristics that will influence both APH and BpK. These scenarios represent a range of network configuration and operational situations that the WRc team have observed, whilst allowing a fair comparison to be undertaken.

Synergi Water™ network modelling software was used to build and run the scenario simulations to ensure a consistent mechanism for generating and exporting the data required to calculate the APH and BpK metrics. This approach also provided the hydraulic information that underpins the results from each scenario.

The networks described in the scenarios in this study were all theoretical, but the values used to define the networks were taken from ‘real world’ situations, where possible. All the values and parameters used in the scenarios were developed by the WRc team, based on engineering judgment and expertise and standard industry data. Furthermore, each scenario was ‘sense checked’ against a back catalogue of known supply networks held by the WRc team, to confirm that these types of systems do exist in the UK supply network.

As this was an impartial assessment, **no data or network information were requested from South Staffs Water**.

1.4 This report

This report has the following structure:

- Section 2 presents the detailed methodology followed in this study together with the analysis of the APH and BpK metric outputs.

- Section 3 presents key findings and conclusions.

2. Methodology

In order to meet the objectives of this project, the following process was followed:

- A set of network and operational scenarios were devised that describe a range of theoretical TWD configurations, describing characteristics or parameters that are most likely to influence both APH and BpK.

- A set of conceptual hydraulic models were built using Synergi Water to describe each scenario and run across a 24 hour period.

- The outputs from the models were then used to calculate the APH and BpK metrics for each scenario.

- These calculated metrics were analysed and compared.

The details of each of these steps are presented below.

2.1 Scenario development

A number of scenarios were devised for use in the subsequent hydraulic modelling step (Section 2.2). These scenarios were based on a set of theoretical TWD networks that enable both metrics to be calculated and compared. These TWD networks were defined using the following key components:

- Number and size (rating) of PS
- Topography/ relative elevation
- Length, diameter and material of mains
- Size of demand centres/ demand profiles

Of these components, topography and the number and size of the PS will have the greatest influence on APH and BpK. The scenarios were therefore designed to allow these components to be varied, whilst keeping the other components fixed, as far as possible.

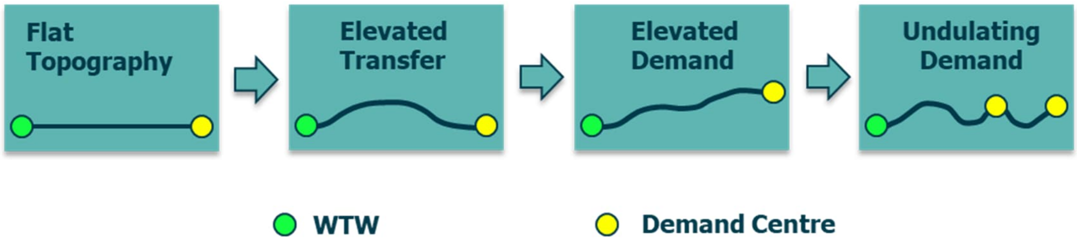
Two core types of systems were selected as the basis for these scenarios:

- Boost to distribution (B2D): supply from the water treatment works (WTW) is pumped directly to the demand centres.

- Boost to storage (B2S): supply from the WTW is pumped to the demand centres via service reservoir(s).

Within these two core types of system, four scenarios were devised to represent variations in system elevation, as illustrated in Figure 2.1 below.

Figure 2.1 Variations in system elevation



This gave a total of eight different TWD network scenarios, as follows:

- Boost to Distribution (Flat Topography)
- Boost to Distribution (Elevated Transfer)
- Boost to Distribution (Elevated Demand)
- Boost to Distribution (Undulating Demand)
- Boost to Storage (Flat Topography)
- Boost to Storage (Elevated Transfer)
- Boost to Storage (Elevated Demand)
- Boost to Storage (Undulating Demand)

In each scenario, the only direct change is elevation. The output from the WTW (equivalent to Distribution Input (DI)), the diameter, material and length of the trunk main systems and the total customer demand all remain fixed. The number and performance (size) of each PS was adjusted to support the system requirements of each TWD network scenario, allowing the impact on APH and BpK to be observed. In each scenario, either one or both pumping variables will therefore show a consequential adjustment to reflect the impact topography is having on the operation of that system.

2.2 Model construction and scenario modelling

A total of 8 individual hydraulic models were created, one for each of the scenarios discussed above. The network scenario models were built and run in the Synergi Water version 4.9.4.3 modelling software.

The devised scenario models depict a skeletonized network. This means the scenario models are relatively simple in design, consisting of a relatively small number of facilities (pipe, valves, tanks etc). Using a simplified network for the scenario modelling allows for a more efficient means to model the required scenarios. An all-mains model would be far more complex than required for a piece of work of this nature.

The material chosen for the pipes within the network models was ductile iron, roughness values for these pipes were set using standard industry roughness values.

Pump performance curves for the numerous pumps within the scenario models were created using an inhouse pump curve generator tool that has been used by the WRc modelling team on several modelling frameworks. The tool uses the Design Point 'Flow' and 'Head' required for each pump to generate a pump curve. The formula for this pump curve generator was taken from EPANET, which is a free piece of hydraulic modelling software.

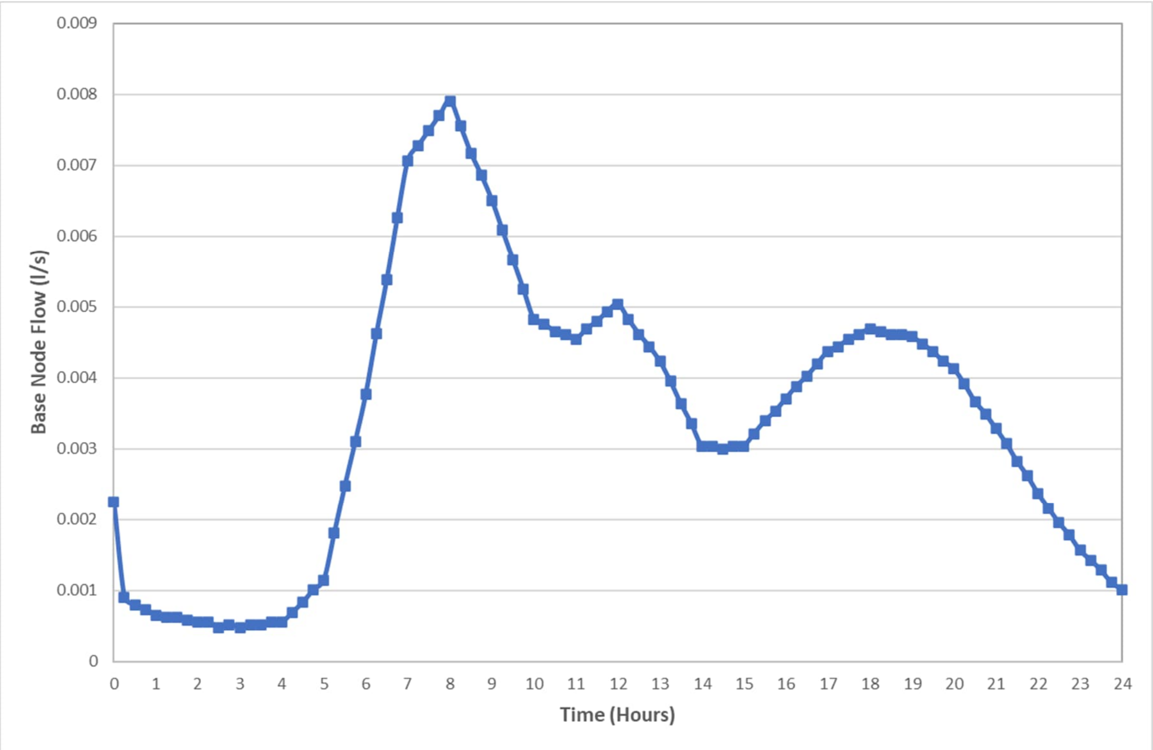
Reservoir sizes were calculated to ensure a good turnover of water during a 24hour simulation period.

All elevations stated in the scenarios are above sea level (mAOD).

2.2.1 Demand allocation

A generic Domestic Profile was used for assigning population demand to the model. The domestic profile used is shown below in Figure 2.2.

Figure 2.2 Domestic Consumption (Demand) Profile



An assumed domestic consumption figure of ***300 l/prop/day*** was used in the scenario models, with property occupancy assumed to be 2.5 people per property. Therefore, a population of 100k would have an average consumption of 12000m^3/day.

Each of the eight scenario models were set to run to simulate a 24-hour period using the demand profile shown above (demand period).

2.2.2 Boost to distribution scenarios

An overview of the four boost to distribution scenario models is described below:

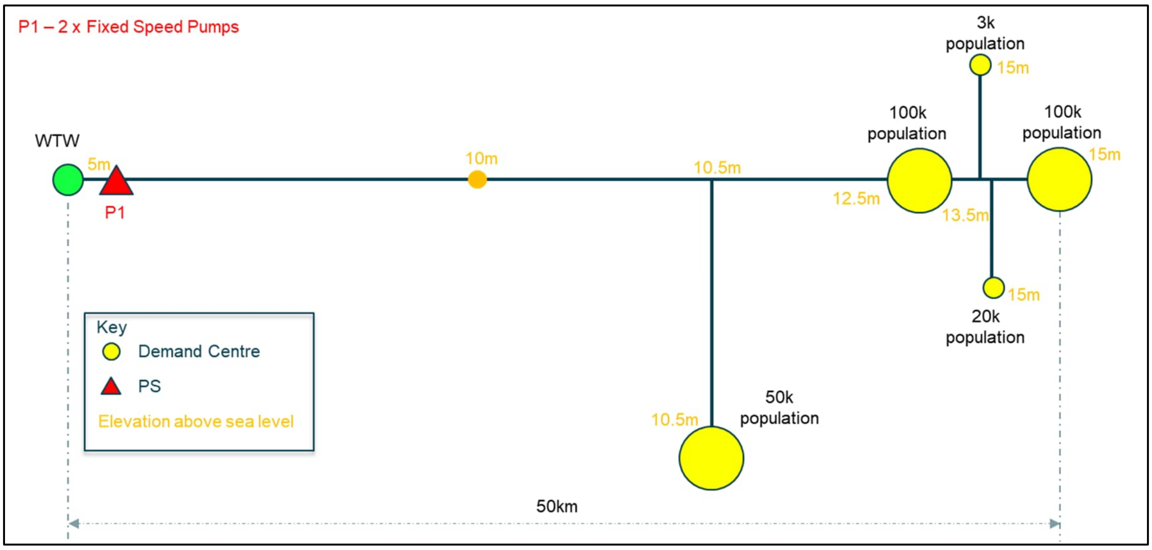
The source of the boost to distribution scenario models was modelled with a fixed pressure of 2m on the source node (WTW). From here a short length of 1200mm ductile iron pipework supplies the first PS (P1), which consists of two operational pumps. The two pumps at P1 are both modelled as fixed speed pumps, working to pump curve 'Pump1QvsH'. From P1 water is boosted to distribution along two parallel ductile iron mains, these pipes act as the spine of the network model, sized at 1100mm diameter and reducing after approximately 28km to two parallel 900mm diameter ductile iron. Demand nodes (demand centres) are located on smaller diameter mains that tee-off from the main spine of the network. The diameters of these pipes are as follows:

- Main supplying '50k population' demand centre – 700mm ductile iron
- Main supplying '3k population' demand centre – 250mm ductile iron
- Main supplying '20k population' demand centre – 500mm ductile iron

Flat topography model

The network for the boost to distribution (flat topography) model is shown in the following schematic (Figure 2.3).

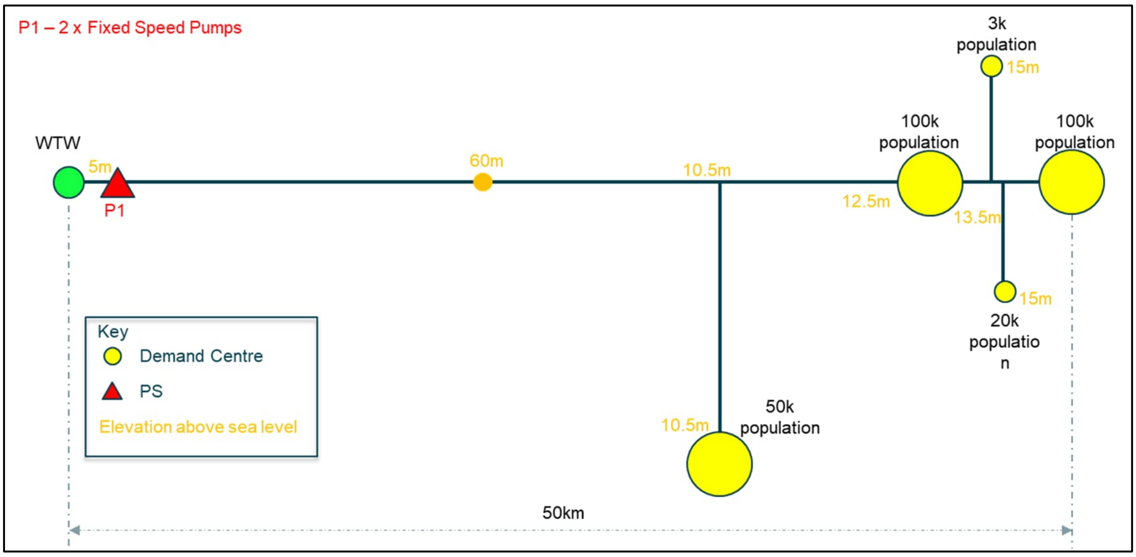
Figure 2.3 Boost to Distribution (Flat Topography) Model Schematic



The system was modelled with a fixed pressure of 2m set as the driving head on the source node (i.e. WTW). The P1 PS boosts water into the network, ensuring minimum pressures in the system do not fall below 20m.

Elevated transfer model

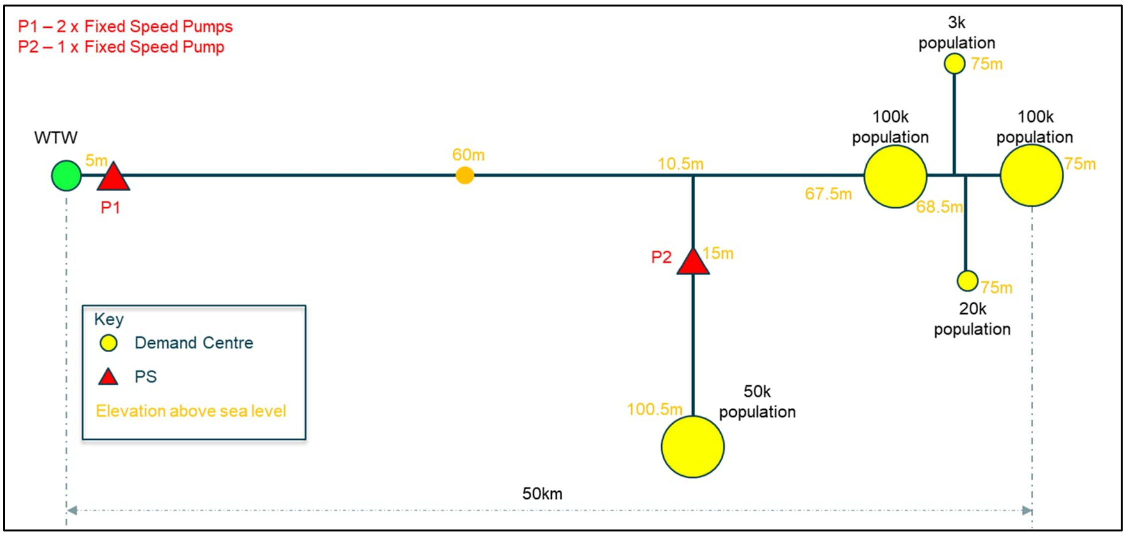
Figure 2.4 Boost to Distribution (Elevated Transfer) Model Schematic



The system was modelled with a fixed pressure of 2m set as the driving head on the source node (WTW). The P1 PS boosts water into the network, ensuring there is enough pressure to lift the water over the elevated node (60m elevation) located along the main spine of the network.

Elevated demand model

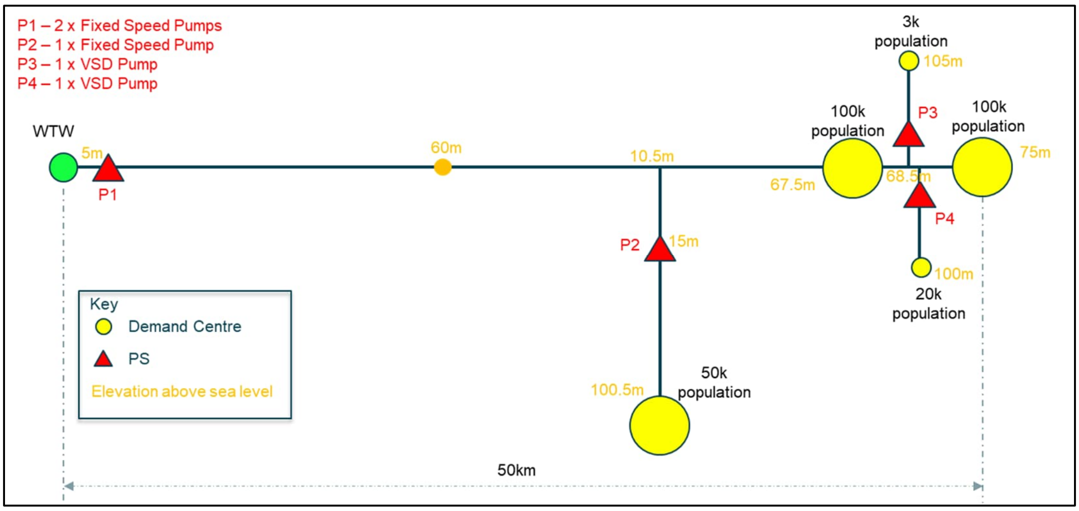
Figure 2.5 Boost to Distribution (Elevated Demand) Model Schematic



The system was modelled with a fixed pressure of 2m set as the driving head on the WTW node. The P1 PS boosts water into the network, ensuring minimum pressures in the system do not fall below 20m. As the elevation at the 50k population node has increased significantly more than the remaining population nodes, a second PS (P2) was added to the model to lift water up to the 50k population demand centre, ensuring the minimum pressure at this node does not fall below 20m.

Undulating demand model

Figure 2.6 Boost to Distribution (Undulating Demand) Model Schematic



The system was modelled with a fixed pressure of 2m set as the driving head on the WTW node. The P1 PS boosts water into the network, ensuring minimum pressures in the system do not fall below 20m. The operation of the P2 PS has not changed from the boost to distribution - elevated demand model. It is lifting water up to the 50k population demand centre, ensuring minimum pressures at this node do not drop below 20m.

As the elevation at the 3k and 20k population demand centres have increased to 105m and 100m respectively, two further PS were added to the model, as follows:

- P3 PS has been modelled as a variable speed pump set to deliver 60m on the pump delivery node. This ensures pressure at the 3k population demand centre does not drop below 20m.

- P4 PS has been modelled as a variable speed pump set to deliver 53m on the pump delivery node. This ensures pressure at the 20k population demand centre does not drop below 20m.

2.2.3 Boost to storage scenarios

The source of the boost to storage scenario models has been modelled with a fixed pressure of 2m on the source node (WTW). From here a short length of 1200mm ductile iron pipework supplies the first PS (P1), which consists of two operational pumps. The two pumps at P1 are both modelled as fixed speed pumps, working to pump curve ‘Pump1QvsH’. From P1 water is boosted up to a reservoir (DSR 1) along two parallel 900mm ductile iron mains. The capacity of DSR1 is 50Ml and the depth (difference between top and bottom water levels) of the reservoir is 5m. The pumps at P1 work to a level control maintaining the level of water in DSR1 between 70% and 90%.

From DSR1 there are two parallel 900mm ductile iron mains that supply the population demand centres further in the system. In the flat topography model water is boosted into distribution by a 2nd PS (P2) due to the low elevation of DSR1 in this scenario. P2 consists of two pump elements which work to pump performance curve ‘Pump2QvsH’.

Demand nodes (demand centres) are located on smaller diameter mains that tee-off from the main spine of the network. The diameters of these mains are as follows:

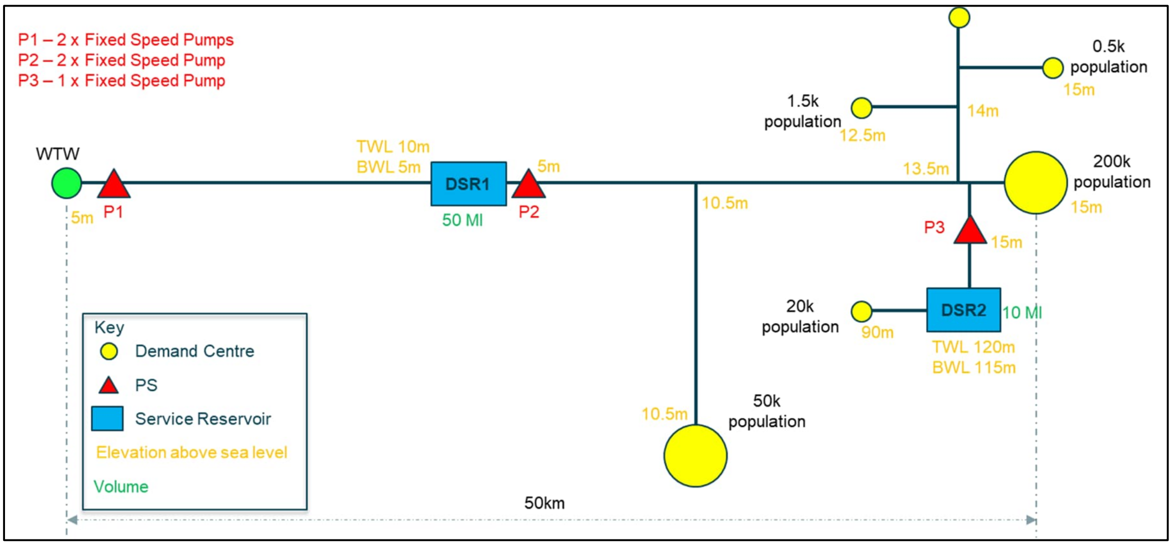
- Main supplying ‘50k population’ demand centre – 700mm ductile iron.

- Mains supplying 1.5k, 1k and 0.5k population demand centre – 200mm and 150mm ductile iron.

There is a 2nd reservoir (DSR2) located in the boost to storage scenario models which provides a gravity supply to the 20k population demand centre. Reservoir DSR2 is supplied along a 500mm diameter ductile iron main and receives a boosted supply from P3. DSR2 has a capacity of 10Ml and depth of 5m (difference between top and bottom water level). P3 is set to a level control that maintains the level of DSR2 between 70% and 90%.

Flat topography model

Figure 2.7 Boost to Storage (Flat Topography) Model Schematic



The system was modelled with a fixed pressure of 2m set as the driving head on the WTW node. From here, water is boosted by PS P1 to reservoir DSR1. The elevation of the top water level (TWL) and bottom water level (BWL) for DSR1 is 10mAOD and 5mAOD respectively.

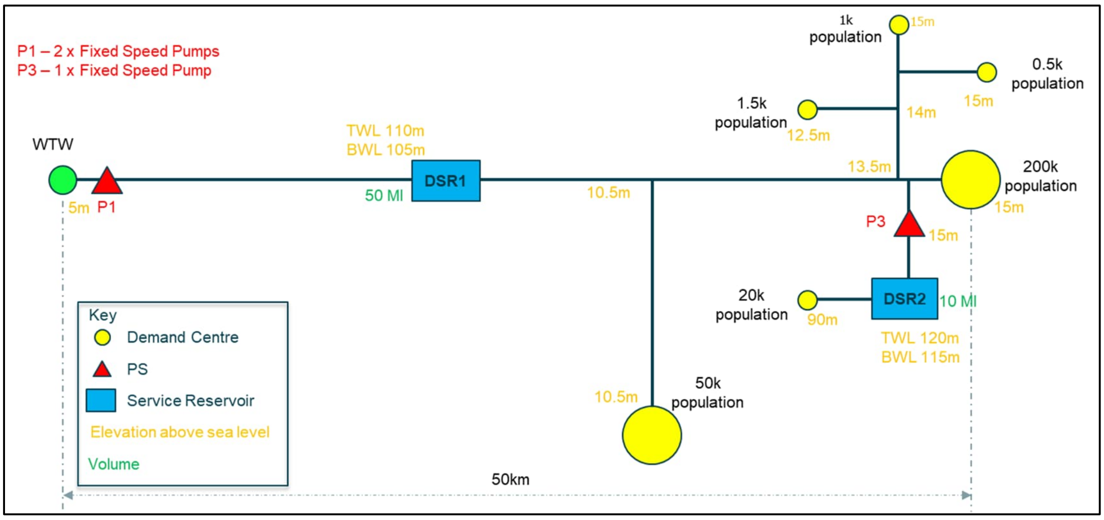
As DSR1 is low level, a second PS is located on the outlet of the reservoir which boosts water up to the population demand centres, ensuring minimum pressures do not drop below 20m. There is a second reservoir located in the network, DSR2, which is at a much higher elevation than the rest of the system, as follows:

- TWL elevation: 120mAOD
- BWL elevation: 115mAOD

A third PS, P3, is located on the main that supplies DSR2. The PS is modelled as a fixed speed pump, operating to a level control that maintains the water level of DSR2 between 70% and 90% full. Water from DSR2 provides a gravity supply to the 20k population demand centre.

Elevated transfer model

Figure 2.8 Boost to Storage (Elevated Transfer) Model Schematic



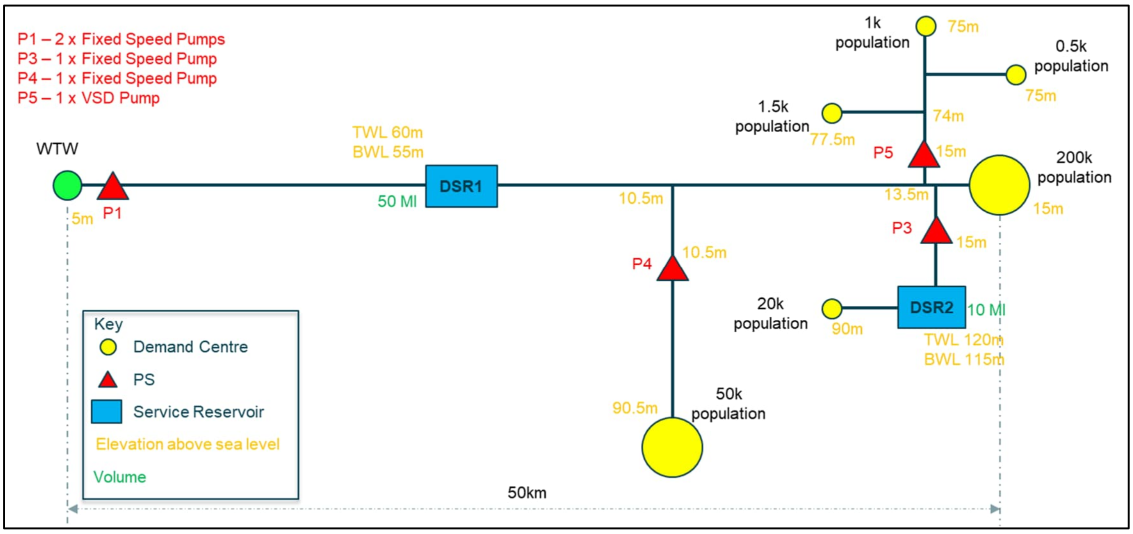
The system was modelled with a fixed pressure of 2m set as the driving head on the WTW node. From here, water is boosted by PS P1 to reservoir DSR1, the elevation of which has been increased (TWL elevation of 110mAOD and BWL elevation of 105mAOD).

As the elevation of DSR1 has increased significantly there is no requirement for a booster PS on the outlet of the reservoir in this scenario. As such, P2, which was included in the flat topography model is no longer required as the gravity supply from DSR1 is sufficient to maintain network pressures at the 1.5k, 1k, 0.5k and 200k population demand centres above 20m.

P3 is still required to lift water up to DSR2. The elevation of the TWL and BWL of DSR2 remains unchanged from the flat topography model, as do the pump control, set to maintain the level of DSR2 between 70% and 90% full.

Elevated demand model

Figure 2.9 Boost to Storage (Elevated Demand) Model Schematic



In this scenario model the elevations of the TWL and BWL of DSR1 have been reduced to 60mAOD and 55mAOD respectively.

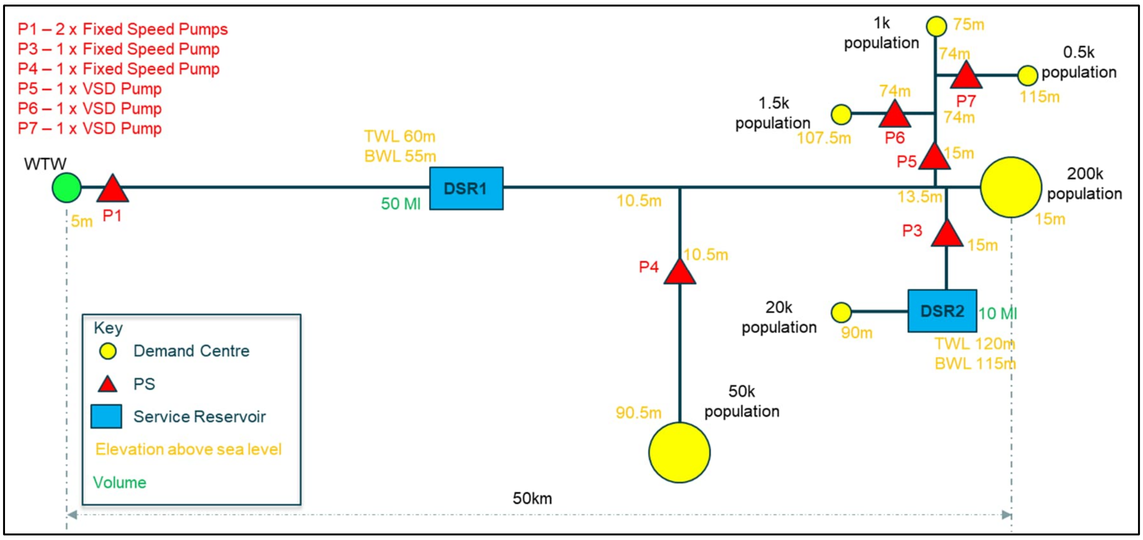
The elevations of the 50k, 1.5k, 1k and 0.5k population demand centres have been increased so that the gravity supply (head) provided by DSR1 cannot maintain the pressures at these nodes above 20m. As these population nodes are at a higher elevation, a further two PS have been added to this scenario model, as follows:

- P4 boosts pressure to the 50k population demand centre, operating as a fixed speed pump.
- P5 boosts pressure to the 1.5k, 1k and 0.5k population demand centre, operating as a variable speed pump. This PS is set to deliver a pressure of 86.5m on the pump delivery node.

The system was modelled with a fixed pressure of 2m set as the driving head on the WTW node. From here, water is boosted by P1 to reservoir DSR1. Water from DSR1 gravitates to directly supply the 200k population demand centre. The operation of P3, DSR2 and the 20k population demand centre remain unchanged from the previous boot to storage models.

Undulating demand model

Figure 2.10 Boost to Storage (Undulating Demand) Model Schematic



This model is an evolution of the elevated demand model (previous model description). The following two changes have been made to the model:

- The elevation of the 1.5k population demand centre is increased to 107.5mAOD.
- The elevation of the 0.5k population demand centre is increased to 115mAOD.

To ensure pressures at the 1.5k and 0.5k population demand centres remain above 20m a further two PS have been added to this model, as follows:

- P6 is modelled as a variable speed pump and lifts water to the 1.5k population demand centre. It is set to deliver a pressure of 55m on the pump delivery node.
- P7 is modelled as a variable speed pump and lifts water to the 0.5k population demand centre. It is set to deliver a pressure of 62m on the pump delivery node.

The remainder of the model network is unchanged. The system was modelled with a fixed pressure of 2m set as the driving head on the WTW node. From here, water is boosted by P1 to reservoir DSR1. Water from DSR1 gravitates to directly supply the 200k population demand centre. The operation of P3, DSR2, P4 and P5 remain as modelled in the elevated demand model.

2.2.4 Model outputs

The following table presents the parameters available to calculate APH and BpK from the hydraulic modelling.

Table 2.1 Model outputs used to calculate APH and BpK

Performance metric	Parameter	Definition
APH	F_{15}	Pump flow (l/s) at 15 minute interval for each PS
	DH_{15}	Total Dynamic head (m) at 15 minute intervals for each PS, the difference between the discharge and suction pressure, derived at the outlet and inlet of the PS respectively
BpK	*NBp*	Total number of PS within each TWD network (scenario)
	L	Total length of trunk main (km) in each TWD network

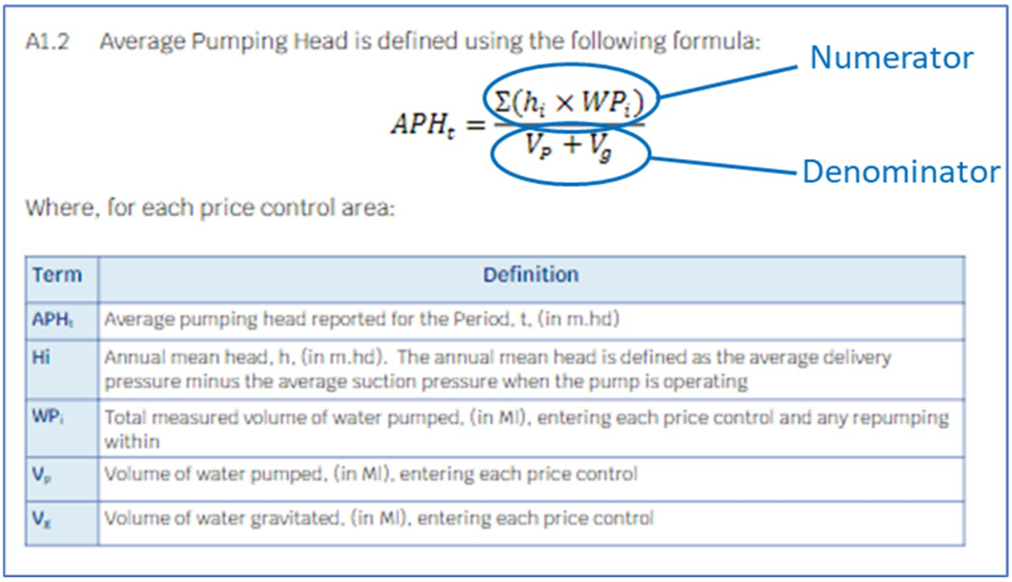
2.3 Calculation of APH and BpK

2.3.1 Average Pumping Head

The average pumping head was calculated using the standard formula detailed in the Ofwat APR guidance, RAG 2.08 (Ofwat, 2021). The following figure (Figure 2.11) shows the APH formula as presented in RAG-2.08_App A1. For clarity, the numerator and denominator for this formula have been highlighted.

The APH value was calculated for the demand period (*t*) modelled in the scenarios (24 hours).

Figure 2.11 APH formula as detailed in the RAG-2.08_App A1



A1.2 Average Pumping Head is defined using the following formula:

$$APH_t = \frac{\Sigma(h_i \times WP_i)}{V_p + V_g}$$

Where, for each price control area:

Term	Definition
APH_t	Average pumping head reported for the Period, t, (in m.hd)
Hi	Annual mean head, h, (in m.hd). The annual mean head is defined as the average delivery pressure minus the average suction pressure when the pump is operating
WP_i	Total measured volume of water pumped, (in Ml), entering each price control and any repumping within
V_p	Volume of water pumped, (in Ml), entering each price control
V_g	Volume of water gravitated, (in Ml), entering each price control

Calculating the numerator

The total volume lifted by each PS across the 24 hour period (WP_i) was calculated as:

$$WP_i = \sum V_{15}$$

Where V_{15}, the volume lifted in each 15 minute interval (Ml), is calculated as:

$$V_{15} = \frac{(F_{15} \times 60 \times 15)}{1{,}000{,}000}$$

The mean head (h_i) for each PS across the 24 hour demand period (i) was calculated as the average of the 15 minute total dynamic head (DH_{15}), calculated using only periods where the PS is operational ($F_{15} > 0$).

A value for pumping head (h_i x WP_i) was then calculated for each PS and then summed to give the numerator for each network scenario.

Calculating the denominator

For the TWD PCA, the denominator ($V_p + V_g$) is equivalent to the total volume of Distribution input (DI).

For the purpose of this project the value for DI was taken to be the volume of water supplied by the WTW, i.e. the volume of water delivered by the P1 PS.

2.3.2 Booster Stations per 1000 km

The BpK metric for each scenario was calculated using the following formula:

$$BpK = \left(\frac{NB_p}{L}\right) \times 1000$$

2.4 Results

The outputs from the scenario modelling are presented in Appendix A, together with the detailed calculations of APH and BpK for each scenario.

A sense check of the calculated values was undertaken by comparing to the APH values and numbers of booster pumping stations reported by companies in their APR. The data used to undertake this sense check is detailed in Appendix B, together with a summary of key statistics relating to this data that the scenario modelling results were compared to.

The values for APH derived in this project are within the envelope of values reported by Water Companies. BpK is more difficult to compare because the model outputs do not include distribution mains length.

In terms of the values derived for each of the scenarios (shown in Table 2.2 and Table 2.3), as expected, either one or both metrics change as a result of the impact topography is having on the operation of the system.

2.5 Analysis

The following sections present an analysis of the results of the scenario modelling by each of the core system types to enable the impact of topography to be observed.

Table 2.2 presents the values for APH and BpK for each scenario in the boost to distribution core supply system.

Table 2.2 Key outputs from the Boost to Distribution Scenarios

Parameter	Scenario			
	Flat	Elevated Transfer	Elevated Demand	Undulating Demand
APH (m.hd)	46.8	60.1	107.0	108.3
BpK (No/'000km)	8.3	8.3	16.6	33.3

It can be seen that both metrics generally increase as the topography of the network becomes more complex. It is interesting to note that the value of BpK for both the flat topography and elevated transfer scenarios remains the same, as the number of PS in these two scenarios remains the same. APH however, increases from the flat to the elevated transfer scenario as a result of the greater pump performance required to overcome the elevated terrain between the WTW and the demand centres (see Figure 2.4).

This trend is reversed for the other two scenarios, with only a small increase in APH between the elevated and undulating demand scenarios, and near twofold increase in BpK. A greater number of PS are required in the undulating demand scenario to overcome the changes in elevation across this network and ensure the different demand centres receive supply at the requisite level - two PS in the elevated demand scenario (Figure 2.5) compared to four in the undulating demand scenario (Figure 2.6).

However, as only a limited amount of additional pumping is required in the undulating demand scenario to serve the smaller demand centres, the contribution of these PS to the overall APH value is relatively small. This point is illustrated in Figure 2.12 below, which shows the pumping head component *(h_i x WP_i)* of each PS compared to the BpK value for each scenario in the boost to distribution supply system type. It is worth noting that it is possible that large demand centres could be located towards the end of a network, but this is unusual because water companies will tend to use sources as close to large demand centres as possible to minimise pumping.

This figure is useful for illustrating that a single PS in these scenarios contributes to the majority of the overall APH value. This concurs with the finding from the Ofwat APH project that observed that the pumping asset base is often dominated by a small number of larger PS which generate a greater proportion of APH, followed by a larger number of smaller rated PS generating relatively small proportions of APH (Turner & Townsend and WRc, 2022).

Figure 2.12 Lift x Volume per Pumping Station v BpK – Boost to Distribution Scenarios

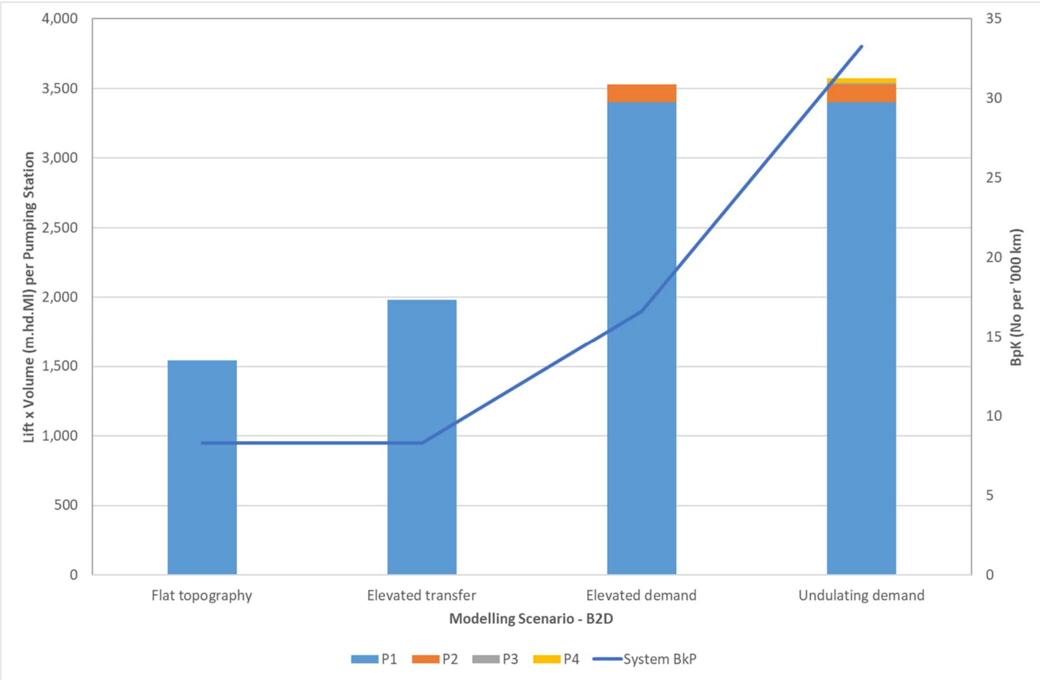


Table 2.3 presents the values for APH and BpK for each scenario in the boost to storage core system type.

Table 2.3 Key outputs from the Boost to Storage Scenarios

Parameter	Scenario			
	Flat	Elevated Transfer	Elevated Demand	Undulating Demand
APH (m.hd)	66.3	117.3	82.5	82.7
BpK (No/'000km)	22.6	15.1	30.3	45.5

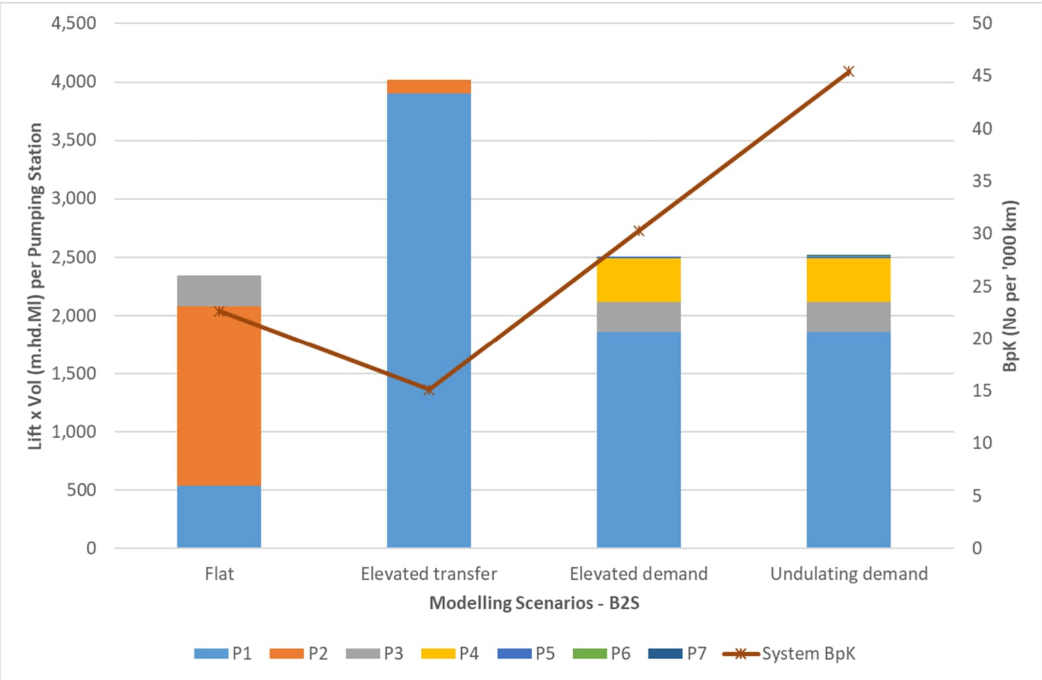
The trends in the change in APH and BpK across the scenarios modelled in the TWD network system that includes storage assets are different to those observed in the boost to distribution scenarios. For APH in particular there is no clear relationship between the values derived and the changes in the complexity of the topography. This is due to the benefits of gravity supply that the DSR's provide.

The APH values are similar for the flat topography, elevated demand and undulating demand scenarios. However, the APH value for the elevated transfer scenario is significantly higher at 117.3m.hd. In contrast, this scenario generated the lowest value of BpK. This is due to the influence of DSR1 which, in this scenario is situated at a high enough elevation to supply the downstream network without the need for the additional pumping that the other scenarios require. The reason for the higher APH value in the elevated transfer scenario is due to the large rating of P1 needed to supply DSR1 at this elevated location.

The values calculated for both metrics in the elevated transfer scenario can be compared to those derived for the flat topography scenario. The flat scenario resulted in the lowest APH value, whilst BpK is higher than for the elevated transfer scenario (although not the largest overall). The reason for this switch in relative values is due to the necessity of an additional PS on the outlet of DSR1 in the flat topography scenario needed to boost supply into the downstream network as a result of the lower elevation of the reservoir.

As with the boost to distribution set of scenarios, the pumping head component *(h_i x WP_i)* of each PS compared to the BpK value for each boost to storage scenario is shown in Figure 2.13. In particular, the influence of P1 on the overall APH value for the elevated transfer scenario can be clearly seen.

Figure 2.13 Lift x Volume per Pumping Station v BpK – Boost to Storage Scenarios



It can also be seen from Figure 2.13 that the APH and BpK metrics in the elevated and undulating demand scenarios are performing similarly to those in the boost to distribution network scenarios. Again, the reason for these trends is the same – a greater number of smaller PS are required in the undulating demand scenario to ensure the various demand centres receive supply at the requisite pressure.

Figure 2.13 again illustrates that, in all but the flat topography scenario, a single PS is contributing to the majority of the APH value, with a larger number of PS making a smaller contribution.

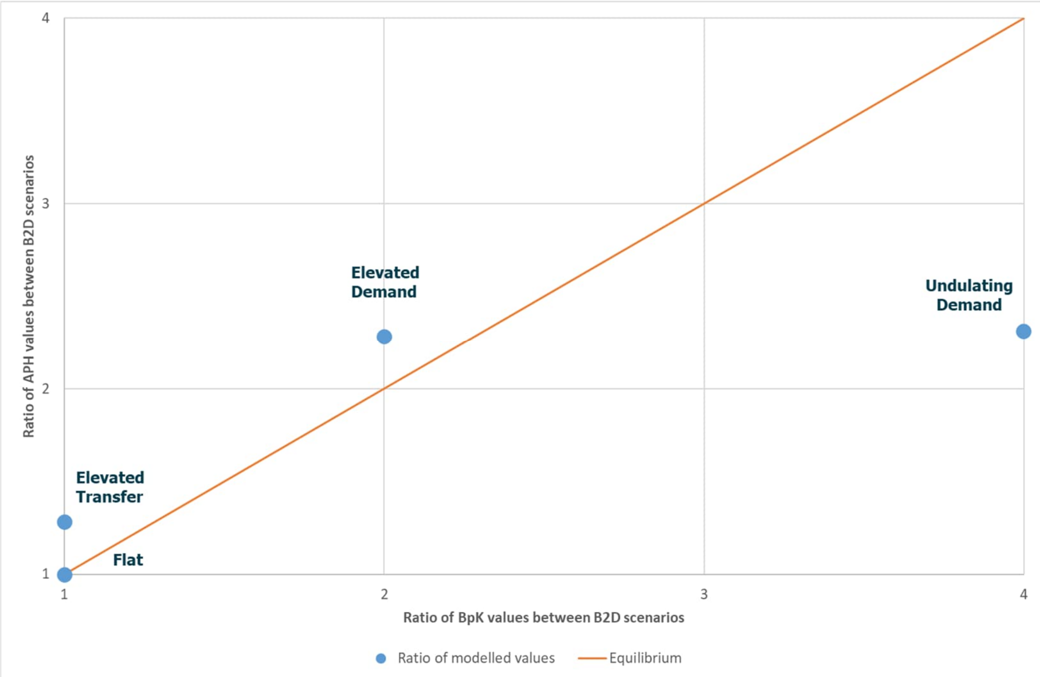
The above analysis illustrates how each metric changes across the different topography scenarios, but not how the metrics deviate from each other within these scenarios. To explore this further, the ratios of the change in each metric relative to the flat topography scenario have been calculated. Table 2.4 presents the ratio of APH and BpK across all scenarios in both the boost to distribution and boost to storage supply systems.

Table 2.4 Ratio of APH v Ratio of BpK – Boost to Distribution Scenario

	Flat Topography	Elevated Transfer	Elevated Demand Centres	Undulating Demand Centres
APH Ratio	1.00	1.28	2.29	2.31
BpK Ratio	1.00	1.00	2.00	4.00

Figure 2.14 shows the ratios for both metrics per scenario, plotted against an “equilibrium” line (the point at which both metrics are equal) to illustrate how the metrics differ from each other.

Figure 2.14 APH and BpK Ratios – Boost to Distribution



As can be seen, the metrics are different from each other under every scenario. The metrics for the elevated transfer and elevated demand scenarios are consistently different to each other – consistent offset from the equilibrium line – with the APH ratio being larger than the BpK in both cases. However, the metrics derived for the undulating demand scenario are significantly different from each other, with the ratio of flat : undulating demand topographies for BpK being nearly twice as much as the ratio for APH.

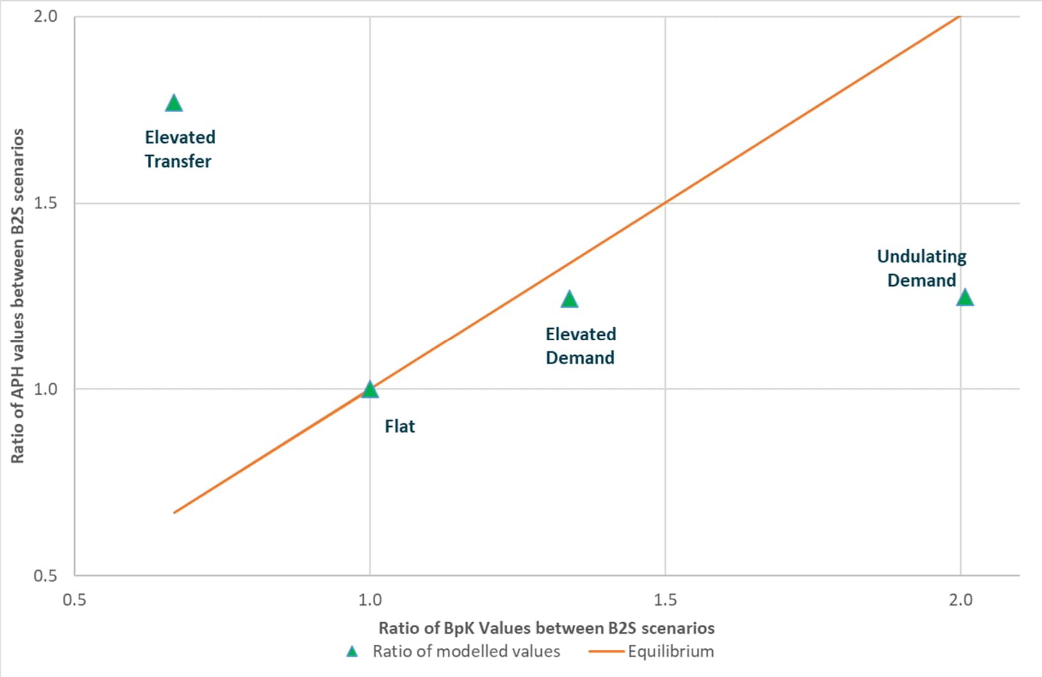
Table 2.5 presents the ratio of APH and BpK across each scenario in the boost to storage supply system, relative to the flat topography scenario.

Table 2.5 Ratio of APH v Ratio of BpK – Boost to Storage Scenarios

	Flat Topography	Elevated Transfer	Elevated Demand Centres	Undulating Demand Centres
APH Ratio	1.00	1.77	1.24	1.25
BpK Ratio	1.00	0.67	1.34	2.01

Again, these ratios have been plotted against an "equilibrium" line to identify difference within scenarios (Figure 2.15).

Figure 2.15 APH and BpK Ratios – Boost to Storage



As can be seen, the ratios between the two metrics in each of the scenarios are all different to each other. The elevated demand scenario is the only one where the two metrics are close to equilibrium, with the BpK ratio being slightly higher than that for APH.

The metric ratios are significantly different in the elevated transfer and undulating demand scenarios. In the case of the former, the APH ratio is much greater than the BpK ratio, and visa versa for the latter. It is interesting to note that the difference in the ratios for the undulation demand scenario are similar to those in the boost to distribution supply system scenario.

Overall the comparison of the ratios of APH and BpK relative to the flat topography scenarios in both system types has demonstrated that there are a small number of topographical scenarios where the metrics are close to equilibrium. This is true for the elevated demand scenario in both the system types and for the elevated transfer scenario in the boost to distribution system. However, there are more scenarios in which the ratios are significantly different to each other, illustrating that the two metrics are not comparable. The undulating demand scenario in particular stands out as the metrics are very different in both system types, with the metrics performing in the same way in both.

3. Key Findings and Conclusions

3.1 Key findings

The following is a summary of the key findings from the comparison of APH and BpK metrics derived from a set of reasonable distribution network configuration and operational scenarios, simulated as a set of conceptual hydraulic models.

- The TWD network scenarios devised for use within the study were all theoretical but were based on the range of network configurations and operational situations that the WRc team have observed. This study has not favoured any particular supply system or water company, but still provide a sensible basis for comparing APH and BpK.

- The scenarios have been configured such that they have produced the expected outcomes in terms of generating varying values of both APH and BpK in response to the range of modelled topographies. This has enabled a thorough comparison of the two metrics to be undertaken.

- In the scenarios based on TWD networks without storage (boost to distribution), both metrics generally increase as the topography of the network becomes more complex (flat topography through to undulating demand centres). However, there is no clear trend between either of the metrics and the complexity of the topography in the TWD networks that do include storage assets (boost to storage). This is due to the benefits of gravity supply that these storage assets provide.

- The scenario outcomes show there are clear differences between the responses of both metrics to the changes in network topography.

  - There is a slight increase in the APH value between the elevated demand and undulating demand scenarios in both TWD network types, whereas the value for BpK increases significantly. This is because a greater number of PS are required in the undulating demand scenarios to overcome the changes in elevation across this type of network and ensure the different demand centres receive supply at the requisite pressure. The rating (size) of these extra PS is small, however, as they are serving discrete section of the network. They therefore do not significantly contribute to the overall APH value.

  - For the boost to distribution network type the value of BpK remains static between the flat topography and elevated transfer scenarios, whereas the APH value increases between the two. The number of PS is the same in both these scenarios (as is the length of main), therefore the BpK remains unchanged. However, the first PS (at the WTW) in the elevated transfer scenario is required to 'work harder' to overcome the elevated terrain between the WTW and the demand centres, thus increasing the APH value.

- For the boost to storage network type there is a significant difference between the values derived for both metrics in the flat topography and elevated transfer scenarios. There is a large increase in APH as the topography becomes more complex but a reduction in BpK. These trends are as a direct result of the topography, specifically the elevation of the first storage reservoir. In the elevated transfer scenario the reservoir has sufficient elevation to enable the downstream network to be supplied via gravity, therefore not requiring any further booster pumping. The WTW PS is large so as to ensure this reservoir can be supplied. In the flat topography scenario, additional pumping is required on the outlet of the first reservoir to overcome the lack of elevation between the reservoir and the demand centres.

- The outcomes from all but one of the scenarios concur with an observation from the Ofwat APH project conducted by WRc and Turner in Townsend in 2022 (Turner & Townsend and WRc, 2022) that the pumping asset base is often dominated by a small number of larger PS which generate a greater proportion of APH, followed by a larger number of smaller rated PS generating relatively small proportions of APH

- Overall the comparison of the ratios of APH and BpK relative to the flat topography scenarios in both TWD network types has demonstrated that there are a small number of topographical scenarios where the metrics are similar. This is true for the elevated demand scenario in both the boost to distribution and boost to storage system types and for the elevated transfer scenario in the boost to distribution system type. However, there are more scenarios in which the ratios are significantly different to each other, illustrating that the two metrics are not comparable. The undulating demand scenario in particular stands out as the metrics are very different in both supply system types, with the metrics performing in the same way in both.

3.2 Conclusions

The following conclusions can be made based on the key findings presented above.

- The APH and BpK metrics both respond to changes in topography, but their responses are different in the majority of scenarios modelled in this study. The undulating demand topography scenario in particular illustrates the influence of topography on these two metrics, regardless of whether a network includes storage or not. More PS would be required to overcome local changes in elevation, but their contribution to the overall TWD APH value would be small as they only serve discrete demand centres.

- The number of pumping stations per km (BpK) in a network could be used as an approximation for the relative capital maintenance costs of pumping, reflecting in some part the cost of maintaining each station as well as any costs associated with collecting and transmitting performance data. However, this metric does not take account of the rating or size of each pump and therefore the greater maintenance costs for larger pumps and pumping stations, nor the energy costs associated with operating each station.

- APH gives an accurate measure of the total work done by pumping stations in the network and is therefore a good indication of the total energy costs. Although it takes into account the total lift across a network (and therefore total changes in elevation), it does not account for other site variations such as pump and motor efficiency. The product of volume and lift at each individual pumping station gives a good indication of its size and potential maintenance costs. The number of pumping stations is not taken into account for the overall APH metric, but in producing the metric each pumping station is considered and could be reported alongside the APH.

- Neither metric takes account of age of equipment (wear and tear), accessibility to sites, distances from depots, or level of automation and control, all of which may impact operational and capital costs.

- This work demonstrates the measures are not equivalent and neither APH nor BpK as reported will accurately provide a full picture of the pumping costs of a supply system. However, APH could be considered a more versatile measure if the component parts of the calculation relating to the individual pumping stations are considered alongside the overall APH figure, as discussed above, e.g. size of pumps correlating to maintenance requirements.

- The aim of this study was to assess the influence of topography on both pumping metrics. The validity of using either metric within economic cost modelling has not been undertaken. Although this study demonstrates that the two metrics are not equivalent, further work would be needed to model correlations of each metric to cost.

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Appendix A Scenario Modelling Results

Table A.1 Scenario Modelling Results – Boost to Distribution

Pumping Station	Parameter	Flat topography	Elevated transfer	Elevated demand	Undulating demand
WTW_Pump Station	Average head (m) (h_i)	46.84	60.06	103.06	103.06
	Total Vol (Ml) (WP_i)	32.98	32.98	32.98	32.98
	$h_i * WP_i$	1544.72	1980.81	3398.98	3398.98
PUMP2	Average head (m) (h_i)	NA	NA	21.65	21.65
	Total Vol (Ml) (WP_i)	NA	NA	6.04	6.04
	$h_i * WP_i$	NA	NA	130.75	130.75
PUMP3	Average head (m) (h_i)	NA	NA	NA	21.20
	Total Vol (Ml) (WP_i)	NA	NA	NA	0.36
	$h_i * WP_i$	NA	NA	NA	7.68
PUMP4	Average head (m) (h_i)	NA	NA	NA	14.75
	Total Vol (Ml) (WP_i)	NA	NA	NA	2.42
	$h_i * WP_i$	NA	NA	NA	35.63
PUMP5	Average head (m) (h_i)	NA	NA	NA	NA
	Total Vol (Ml) (WP_i)	NA	NA	NA	NA
	$h_i * WP_i$	NA	NA	NA	NA
PUMP6	Average head (m) (h_i)	NA	NA	NA	NA
	Total Vol (Ml) (WP_i)	NA	NA	NA	NA
	$h_i * WP_i$	NA	NA	NA	NA
PUMP7	Average head (m) (h_i)	NA	NA	NA	NA
	Total Vol (Ml) (WP_i)	NA	NA	NA	NA
	$h_i * WP_i$	NA	NA	NA	NA
Numerator (Ml.m)	$\Sigma (h_i * WP_i)$	1544.72	1980.81	3529.73	3573.04
APH (m.hd)	$\Sigma (h_i * WP_i) / DI$	46.84	60.06	107.02	108.34

Pumping Station	Parameter	Flat topography	Elevated transfer	Elevated demand	Undulating demand
Number of PS (*NBp*)		1	1	2	4
Network length (*L*) (km)		120.24	120.24	120.24	120.27
BpK (No. per ‘000 km)		8.3	8.3	16.6	33.3

Table A.2 Scenario Modelling Results – Boost to Storage

Pumping Station	Parameter	Flat	Elevated transfer	Elevated demand	Undulating demand
WTW_Pump Station	Average head (m) (h_i)	15.14	113.87	61.20	61.20
	Total Vol (Ml) (WP_i)	35.42	34.26	30.39	30.39
	h_i * WP_i	536.12	3900.72	1859.65	1859.63
PUMP2	Average head (m) (h_i)	45.54	35.35	NA	NA
	Total Vol (Ml) (WP_i)	33.94	3.29	NA	NA
	h_i * WP_i	1545.65	116.31	NA	NA
PUMP3	Average head (m) (h_i)	78.51	NA	75.35	75.75
	Total Vol (Ml) (WP_i)	3.38	NA	3.43	3.40
	h_i * WP_i	265.21	NA	258.29	257.78
PUMP4	Average head (m) (h_i)	NA	NA	61.65	61.65
	Total Vol (Ml) (WP_i)	NA	NA	6.04	6.04
	h_i * WP_i	NA	NA	372.37	372.37
PUMP5	Average head (m) (h_i)	NA	NA	45.27	43.76
	Total Vol (Ml) (WP_i)	NA	NA	0.36	0.36
	h_i * WP_i	NA	NA	16.41	15.86
PUMP6	Average head (m) (h_i)	NA	NA	NA	29.76
	Total Vol (Ml) (WP_i)	NA	NA	NA	0.18
	h_i * WP_i	NA	NA	NA	5.39

Pumping Station	Parameter	Flat	Elevated transfer	Elevated demand	Undulating demand
PUMP7	Average head (m) (h_i)	NA	NA	NA	36.94
	Total Vol (Ml) (WP_i)	NA	NA	NA	0.06
	h_i * WP_i	NA	NA	NA	2.23
Numerator (Ml.m)	Σ (h_i * WP_i)	2346.98	4017.03	2506.71	2513.26
APH (m.hd)	Σ (h_i * WP_i) / DI	66.26	117.26	82.50	82.71
Number of PS (*NBp*)		3	2	4	6
Network length (*L*) (km)		132.46	132.11	132.00	131.98
BpK (No. per '000 km)		22.6	15.1	30.3	45.5

Appendix B Deriving Industry Values

A sense check of the calculated values was undertaken by comparing to the APH and BpK values reported by water companies in England and Wales.

WRc were given access to the Ofwat APH Dataset- clean 19th Nov 2021.xlsx dataset by Ofwat (Ofwat, 2021) in order to deliver the APH Data Quality Improvement project for Ofwat (Turner & Townsend and WRc, 2022). This dataset contains the reported TWD APH values for each water company in England and Wales between 2011 and 2021. This dataset also contains the number of booster pumping stations, per year per company.

In order to derive a value for BpK, the total length of mains report by each company, each year was required. This was obtained from the serviceability performance data spreadsheet published annually by Ofwat (Ofwat, 2020).

Table B.1 presents summary statistics for the APH and BpK metrics calculated using the above stated sources. The statistics have been calculated for all water companies in England and Wales, using performance information reported between 2011 and 2022.

Table B.1 Reported performance - all water companies in England and Wales (2011 to 2022)

Parameter	APH (m.hd)	BpK (no per '000 km)
Average	76.5	17.8
Min	18.2	9.4
Max	131.4	36.5
SD	29	7.6