Improving Ofwat’s cost models for use at PR24

Severn Trent input into the PR24 cost modelling consultation

January 2023

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1. Executive Summary

- We welcome the opportunity to submit econometric models for the PR24 base cost assessment to contribute to the development of improved models for assessing companies costs at PR24.
- We are submitting 110 models that both increase the engineering coherence and predictive capability relative to the models used at PR19. This has been done in a way that conforms to Ofwat's five principles relevant to cost models that Ofwat set out in the PR24 final methodology.
- We have sought to build on the PR19 models and taken the following approach to model development. We have:
    - set out prior engineering expectations for primary cost drivers by sub service;
    - identified plausible explanatory driver choices to generate a long list of models;
    - identified a model short list using engineering logic forcing groups and predictive capability of models run;
    - reduced the short list through a review of driver significance and counterintuitive coefficients;
    - tested sensitivity of short list models; and
    - selected final models with reference to their ability to satisfy the prior engineering expectations, proximity to PR19 models and number of parameters.
- We have clearly identified a set of engineering expectations based on expert engineering input and assured by external engineering consultants. Taking account of these engineering expectations has improved the coherence of the models.
- We have focused on models for the four wholesale subservices (WRP, TWD, SWC and SWT). This level of aggregation provides the best opportunity to clearly focus on cost: cost driver relationships (without complex trade-offs) given the information available. We have then merged the inherent logic that we have identified in those sub-service models to develop improved water wholesale and waste network plus models.
- We have explored some more novel explanatory drivers (AMP years and spatial drivers). Whilst we are aware there is a trade-off between model simplicity and more highly specified models, we have shown that there can be opportunities for additional complexity to improve the base cost assessment models.
- External engineering and economic specialists have assured our models to make sure that the engineering assumptions and econometric analysis that underpins this work is robust.

Table 1: Summary of the number of models submitted by Severn Trent

	WRP	TWD	SWC	SWT	WW	WWWNP	BR	Retail	Total
Simple models*	16	8	6	10	16	15	4	4	79
More novel models**	5	9	10	7					31
Total	21	17	16	17	16	15	4	4	110

**Models with primary cost drivers only*

***Models with additional time and special effects and smoothed capex*

The following documents accompany this report:

- Ofwat’s requested modelling proforma
- Modelling datasets (x4)
- Efficiencies calculation spreadsheets (x8)
- Model .do files (x8)
- Weather dataset
- Assurance statement from Frontier Economics (supported by Atkins and Professor Ron Smith)

2. Improving Coherence and Performance of Base Cost Models for PR24

2.1 Ofwat's Cost Assessment Principles

We have sought to improve the coherence and performance of the base cost models with reference to cost assessment principles 1-5 as confirmed in Ofwat's PR24 final methodology (figure 1).

Figure 1: Ofwat's cost assessment principles. * Principles 6 and 7 are less relevant for the purpose of econometric cost modelling, but form part of our overall approach to base cost assessment.

1. Data used is good quality	2. Consistent with engineering, operational and economic rationale
3. Sensibly simple and transparent	4. Focus on exogenous cost drivers
5. Robust econometric cost models	6. Set a stretching but achievable cost efficiency challenge*
7. A coherent cost assessment approach that drives the right incentives*	

In doing so we have considered the following:

- Good quality data is a fundamental requirement for coherent models (principle 1). There are cases where less optimal models / variables are required due to data constraints.
- We understand the premise and desirability of both principle 2 and principle 3. However, we consider that there will be an element of dynamic tension between them. Therefore, we have attempted to develop valid models across this continuum. We consider that if increasing the amount of engineering logic included in models leads to an increase in parameters, this should be considered acceptable where the robustness of the model is maintained or improved (principle 5) until we reach a point where the additional parameters start to become problematic and increase the risk of over-fitting (i.e. they are no longer suitably simple and transparent).
- The need for econometric models to be robust (i.e. to accurately describe the costs included in the data panel) is clear (principle 5). We consider that this should be a check applied to models that have good engineering logic and are sensibly simple / transparent (principle 2 and principle 3). In doing this it is desirable to consider a wide range of tests rather than relying too heavily on one metric such as the R^2 performance.
- We understand the desirability of exogenous variables as only costs that are outside of management control should be allowed for in efficiency analysis (principle 4). However (as acknowledged by Ofwat), where variables that describe sunk assets provide a material increase in explanatory power relative to exogenous equivalents, they should be used where there are no opportunities for short term management control.

We have set out how we have satisfied Ofwat's principles throughout our model development process (set out in figure 2) in table 2.

2.2 Our model development approach

Figure 2: Our approach to model development.

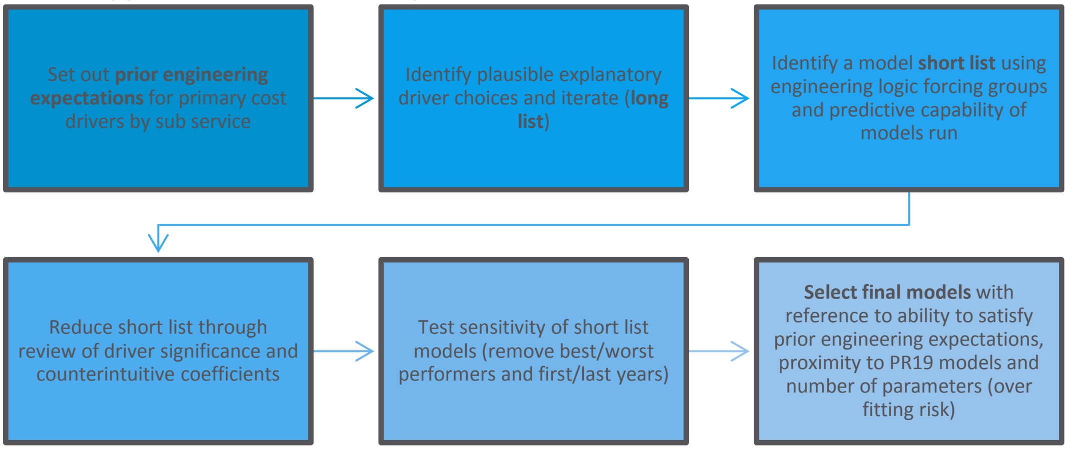


Table 2: How we have adhered to Ofwat's principles when developing alternative cost models

Ofwat Principle	How we have adhered to Ofwat's principle
1. Data used is good quality	**WRP:** Whilst we have no reason to doubt the veracity of treatment complexity band data, we do not consider that the data is correctly describing differences in cost as a result of treatment complexity. We note that pumping head data has previously not been used in models potentially as a result of data consistency issues. Since PR19, efforts have been made to improve data quality and consistency. Given the significant explanatory power of pumping head data, we consider that there is now a strong case to use this data but agree that more steps can be taken to improve the data going forward. **TWD:** As above, we consider that there is now a strong case to use pumping head data but agree that more steps can be taken to improve the data going forward. **SWC:** Sewage network models at PR19 used the length of legacy and PDAS sewers. Whilst length of sewer will be a strong scale driver, we are concerned that the PDAS length is subject to significant uncertainty. PDAS assets are a driver of costs, therefore, using only legacy length is also imperfect. The connected properties data does not suffer from this issue. We consider that there is significant uncertainty with sewer network pumping data. This has not had the same regulatory scrutiny as water APH data, therefore could be a major source of uncertainty if included in the models.
2. Consistent with engineering, operational and economic rationale	We have set out prior engineering expectations which have been the fundamental basis for selecting our final set of models and which have been reviewed by external engineering specialists.
3. Sensibly simple and transparent	There is a clear interaction between this principle and principle 2. We have presented a series of 'simple' models across this continuum of a trade of between principle 2 and principle 3. Our models contain: a scale driver; a measure of economies of scale/density; one or more complexity variables; and potentially a weather variable. All of the variables we have used can be explained and interpreted from an engineering perspective. As model parameters increase, we have sought to test that additional parameters are being justified with a corresponding predictive improvement using the Akaike Information Criterion (AIC) to prevent over-fitting. We have also presented some more novel models that seek to account for variances across time (AMP cycle) and space (spatial models). Whilst these models are more complex, they are supported by our prior expectations and model performance (including AIC).
4. Focus on exogenous cost drivers	We have used only explanatory cost drivers that are either exogenous or endogenous only in the long term.
5. Robust econometric cost models	We have tested the models we have selected against a wide range of criteria. Our models outperform the predictive capability of the PR19 models (R^2). We have considered R^2unit, distribution of residuals and AIC in addition to the tests that Ofwat have stipulated. This gives us confidence that the models we are presenting are robust.

3. Prior Engineering Expectations

In this section we highlight our engineering expectations for both water and waste models. These are then used to underpin the development and selection of our final cost models.

We have focused on the four subservices (WRP, TWD, SWC and SWT). These are summarised in tables 3 and 4 below. We have prioritised this level as we believe that the engineering rationale is clearest here. Each engineering expectation is elaborated on in the relevant sections below, with each expectation coded as 'EE[x]'.

At the wholesale level it can sometimes be less obvious whether a variable should have a positive coefficient, a negative coefficient, or be insignificant. In some cases, a variable might be associated with higher costs in one of the subservices, but may provide opportunities to decrease costs in the other. An example of this might be density in water which in WRP we consider to be a proxy for treatment works size. We expect higher densities, and therefore larger works, to provide a benefit for companies. However, on the network side, we expect that higher densities are associated with increased costs because of congestion effects and the difficulty of making repairs in densely-populated areas. It is therefore not clear at the wholesale level what the sign on this coefficient should be. In anticipation of developing wholesale water and wastewaster network plus models we have also set out our expectations of how the identified subservice engineering expectations are likely to interact.

Finally, we have also set out separate expectations for both bioresources and retail as these are likely to be more discrete to our water wholesale / waste network plus expectations.

Table 3: Prior engineering expectations 'EEs' in water (WRP and TWD).

Area	WRP (Water resources and Treatment)	TWD (Water distribution)
Scale	**EE1.** Properties is an uncontentious explanatory variable	**EE1.** There is a logical case to use both length and properties as a scale driver: • Length – Traditional scale driver that describes the size of the asset base. • Properties – The number of physical connections to the network drive cost. Point of failure and additional complexity that drive cost despite potentially having limited impact on the network length. It is also a stronger proxy for volume.
Economies of Scale (population density)	**EE2.** Size of WTWs is the most appropriate explanatory variable, however the inability to differentiate between groundwater (GW) and surface water (SW) mean that population density accounting for GW% is pragmatic. **EE3.** No clear engineering basis for including a non-linear density term in WRP models (i.e. density^2) since opportunities for economies of scale do not diminish at higher densities.	**EE2.** There is a strong theoretical basis for population density as an explanatory variable. TWD costs are driven by density and rurality, therefore population / area is a more appropriate metric because local authority densities (LAD) are weighted by population which will skew to higher density areas, therefore putting less weight on costs incurred in rural areas that the squared term is intended to capture.
Complexity (driven by Geography / Geology)	**EE4.** Ofwat's treatment complexity bands do not appear to be good explanatory variables. **EE5.** Water treatment APH is the most appropriate proxy to differentiate between treatment complexity.	Boosters/length and TWD APH provide coherent and complementary explanatory power relating to the complexity of providing potable water to the supply area: **EE3.** Booster/length: Increased pumping assets (driven by geography and population location) increase cost, irrespective of the pumping lift (capital maintenance).

	EE6. Raw water APH will allow for differences in water resource opportunities (and make sure that all pumping from source to tap is accounted for).	**EE4.** TWD APH: Increased pumping lift has a direct impact on network opex costs.
Weather effects	**EE7.** Weather is a proxy for peak demand & asset use intensity.	**EE5.** Weather is a proxy for peak demand & asset use intensity.
AMP effects	**EE8.** Capex costs vary materially according to the AMP cycle.	**EE6.** Capex costs vary materially according to the AMP cycle.

Table 4: Prior engineering expectations in wastewater (SWT and SWC).

Area	SWT (Waste Treatment)	SWC (Waste Network)
Scale	**EE1.** Load is an uncontentious explanatory variable.	**EE1.** Properties provides a way of moving away from PDAS data which is subject to much uncertainty.
Economies of Scale (population density)	**EE2.** We consider that the best variable is a weighted average scale based on industry-wide costs incurred at sewage works within each band. Opportunities for economies of scale are much reduced at band 6 than they are at bands 1-3. There is a significant difference in cost per unit of load between bands 1-3 and 4+, but much less differentiation between band 6 and bands 4/5. As a result if a weighted average scale driver is not included, we have a preference for a band 1-3 driver over a band 6 driver.	**EE2.** There is a strong theoretical basis for population density as an explanatory variable. Population / length is a more appropriate metric because Local Authority (LAD) densities are weighted by population which will skew to higher density areas, therefore putting less weight on costs incurred in rural areas that the squared term is intended to capture.
Complexity (driven by Geography / Geology)	**EE3.** Wastewater treatment complexity is driven by the consents that need to be delivered. This was allowed for by using an explanatory variable of NH_3 load <3mg/l. However, as consents tighten across multiple parameters, costs increase further. Therefore, additional or composite explanatory variables are required, particularly to account for tight P consents which are very expensive to treat to.	**EE3.** The specification of the network complexity driver is important: • Whilst pumping capacity / length has logical appeal, the data quality is poor and therefore may be providing spurious explanatory power. • Rising mains and combined sewers provide legitimate alternative complexity drivers.
Weather effects	**EE4.** Weather less likely to be a material driver of cost than with WRP, TWD and SWC.	**EE4.** Weather describes cost – High intensity rainfall in urban areas should increase sewerage costs (more pumping, managing sewer flooding / CSO spill events).
AMP effects	**EE5.** AMP years are logical but over fitting issues are an increased risk with wastewater models due to the reduced number of companies in the data panel.	**EE5.** AMP years are logical but over fitting issues are an increased risk with wastewater models due to the reduced number of companies in the data panel.

3.1 The basis for scale drivers (EE1 for WRP, TWD, SWT & SWC)

Water Resources Plus (WRP)

- **Properties served** is a strong and uncontentious cost driver for treatment costs that is outside of company control.
- As properties served increases, so too does the size of our asset base and the volume of water that flows through it. This drives both capital maintenance and operating costs.

Treated Water Distribution (TWD)

- **Mains length** – Traditional scale driver that describes the size of the asset base.

- **Properties** – The number of physical connections to the network drives cost. Connections increase the asset base and are a major point of failure. This drives additional complexity that incurs cost despite potentially having limited impact on the network length.

Sewage Treatment (SWT)

- **Load** is a strong and uncontentious cost driver outside of company control.
- As load increases, so too does the size of our asset base and the effort needed to treat the sewage we receive. This drives both capital maintenance and operating costs.

Sewage Collection (SWC)

- Sewer length is a natural choice of scale driver. However, this is significantly complicated by the inclusion of PDaS assets. PDaS length data is largely modelled (using the WRC assessments during the adoption process) rather than measured empirically.
- **Properties served** provides a way of moving away from the material uncertainty associated with PDAS sewer lengths.

PDAS Note

We do not consider that PDAS sewers being included in the sewer length calculation adheres to Ofwat's first principle of "data used is good quality". As a result, we have also removed this from the denominator in other variables. For example, pumping capacity per sewer length is now pumping capacity per legacy sewer length.

It should be noted that this is detrimental to companies that have a greater certainty of their total sewer length (including Severn Trent), and as such have a higher proportion of their network length outside of the PDAS estimation. This is because companies with a longer assumed PDAS length relative to their total length will be seen to be relatively denser (by properties/sewer length) and have a relatively more complex network as a result. This may also result in some perverse incentives for companies that have a long PDAS network relative to their total network length who will now not be incentivised to survey the full length of their network which will need to be managed.

Considering future data requirements, we believe there is a strong case to move to a position where there is a greater empirical understanding of PDAS sewer lengths across the sector.

3.2 Economies of Scale and Use of a Density Proxy

Size and dispersion of assets is a cost driver, this provides opportunities for economies of scale for individual assets.

In non-infra (WRP and SWT), the greater the population density served, the larger the opportunities to develop large treatment assets which in turn benefit from economies of scale.

In infra (TWD and SWC), very low levels of population density require longer network lengths, a larger asset base, and long travel times between assets to operate and maintain the network. In contrast, at very high levels of population density congestion effects increase cost because of the time taken to travel to operate or maintain assets, the intensity of asset utilisation, and the increased difficulty of repairing assets in built up areas.

Population density can be considered an exogenous proxy for economies of scale in assets. We will refer to this as *economies of density*. For non-infra subservices asset sizes are a more appropriate explanatory variable than density proxies. This is because the size of assets is impacted by more than just population density – primarily, the geography and geology of the supply area. For waste treatment assets (SWT), asset size data is readily available and coherent explanatory variables can be made. For water treatment assets (WRP), fundamental differences between groundwater (GW) and surface water (SW) treatment assets (driven by geography / geology, rather than population density) mean that whilst the size of each asset type is strongly correlated with cost, when considered together, this clear signal is distorted. Consequently, WTW asset size does not currently make a satisfactory explanatory variable. This means that the population density proxy should be preferred for the WRP, TWD and SWC subservices.

3.2.1 Choice of Density Measure

Different density measures are describing different things, and as such where density is attempting to explain some specific characteristics in one model but something different in another, it would be logical to consider different measures of density to account for this.

LAD and MSOA measures are population weighted and are therefore describing more heavily the density of the most populated areas, which in practice are also the densest areas, of a company. We consider that these measures are best used as a proxy for economies of scale in individual assets, e.g. in WRP models, because opportunities to benefit from economies of density will be heightened in these dense, highly populated areas.

Population per area (water) and properties per length of sewer (waste) are giving an overall picture of the direct average density within a company, i.e. they are accounting for rural areas and dense areas equally. It would make sense to consider these measures where there are costs associated with both dense and rural areas, e.g. in TWD models. It would also make sense to consider this measure in SWC models given waste networks are highly localised.

Where differing density measures are used in the bottom-up models, the top-down models will become more ambiguous as to the preferred density driver. In such a case we can either let the model fit decide or create two models that triangulate over these different measures of density.

3.2.2 Linear / Non-Linear Density Expectations

The addition of a non-linear density term ($density^2$) can allow for two effects:

- Allow for diminishing (or increasing) economies of density (assuming the turning point of the curve is before the observation with the lowest density).
- Allow for increasing and decreasing economies of density at the extremes of density (assuming the turning point of the curve is within the range of the observations).

There is no expectation for diseconomies of scale in water treatment (WRP) assets at large population densities. Therefore, either a linear population density or non-linear population density where the turning point is outside of the observed range is required.

In TWD, there is a clearer engineering expectation for diseconomies over economies of density. We anticipate that the diseconomy of density (i.e. increased costs in very urban areas) is more powerful than the economy of density (i.e. increased costs in rural areas). Therefore, the minimum of the curve should be closer to the rural rather than urban end of the distribution. Where a problem arises, the asset intervention is always more costly than the travel, but there are increased travel costs in very rural areas. The reduced travel costs in moderately urban areas are quickly outweighed by the substantially increased costs of the asset intervention and congestion.

In SWC, whilst the same processes apply, we consider that the effect of diseconomies of density in rural areas is reduced. This is because wastewater networks tend to be much more localised than water – Severn Trent have approximately 100 water treatment assets and more than 1000 wastewater treatment assets. In addition, there may be increasing problems with blockages in dense areas, and therefore more problems to fix, and it is also more difficult and more costly to address these problems when they arise. This is in part a function of the complexities of pumping sewage long distances and the increasing need to blend water sources.

Therefore, our expectations are:

- **TWD:** Non-linear density expected, provided the minimum is within and towards the rural end of the distribution.
- **SWC:** The case for non-linear density is reduced as diseconomies of density are likely to dominate. However, a non-linear density term may be included if the minimum of the density function lies below the minimum observed density value.
- **WRP:** Continuing economies of density are expected. Therefore, a linear density term, or a squared density term where the minimum is above the highest observed population density should be expected. In areas of very high density, cost adjustment claims (CACs) may be more appropriate for assets too big to fail.

3.2.3 WRP EE2 & EE3: WTW Economies of Scale

Using Severn Trent WTW opex and depreciation data, there is clear evidence of economies of scale at both GW and SW WTWs at the Ofwat size band level (figure 3).

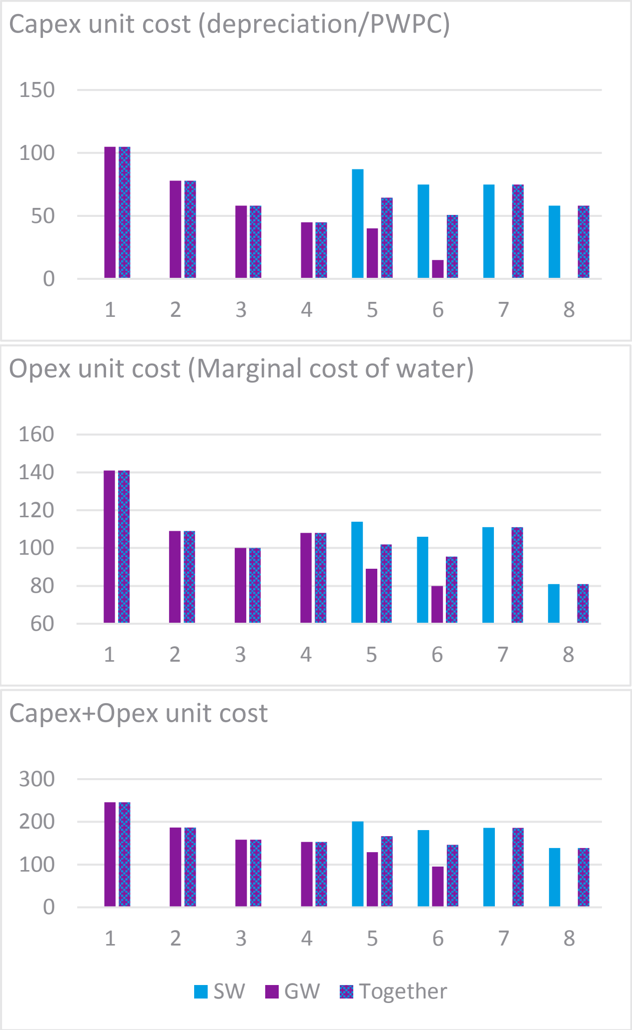
However, if shown together, this pattern becomes confused. This is because whilst both exhibit clear economies of scale, this is only relative to equivalent WTWs and there is a difference in size (GW WTWs are generally smaller than SW with only an overlap in size bands 5 and 6).

Given that Ofwat size band information does not differentiate between SW and GW, the different bands should be weighted at an industry level such that they can vary between each other and reflect economies of scale at both SW and GW WTWs

Note: Where we have used depreciation we have summed the 1st year of depreciation of all components which remain on our asset register. This means that all assets which are operational will be included irrespective of whether they have been fully depreciated. This should be a good proxy for long term capital maintenance.

Opex is shown through the 'marginal cost of water' analysis.

Figure 3: Economies of scale at water treatment works for Severn Trent.

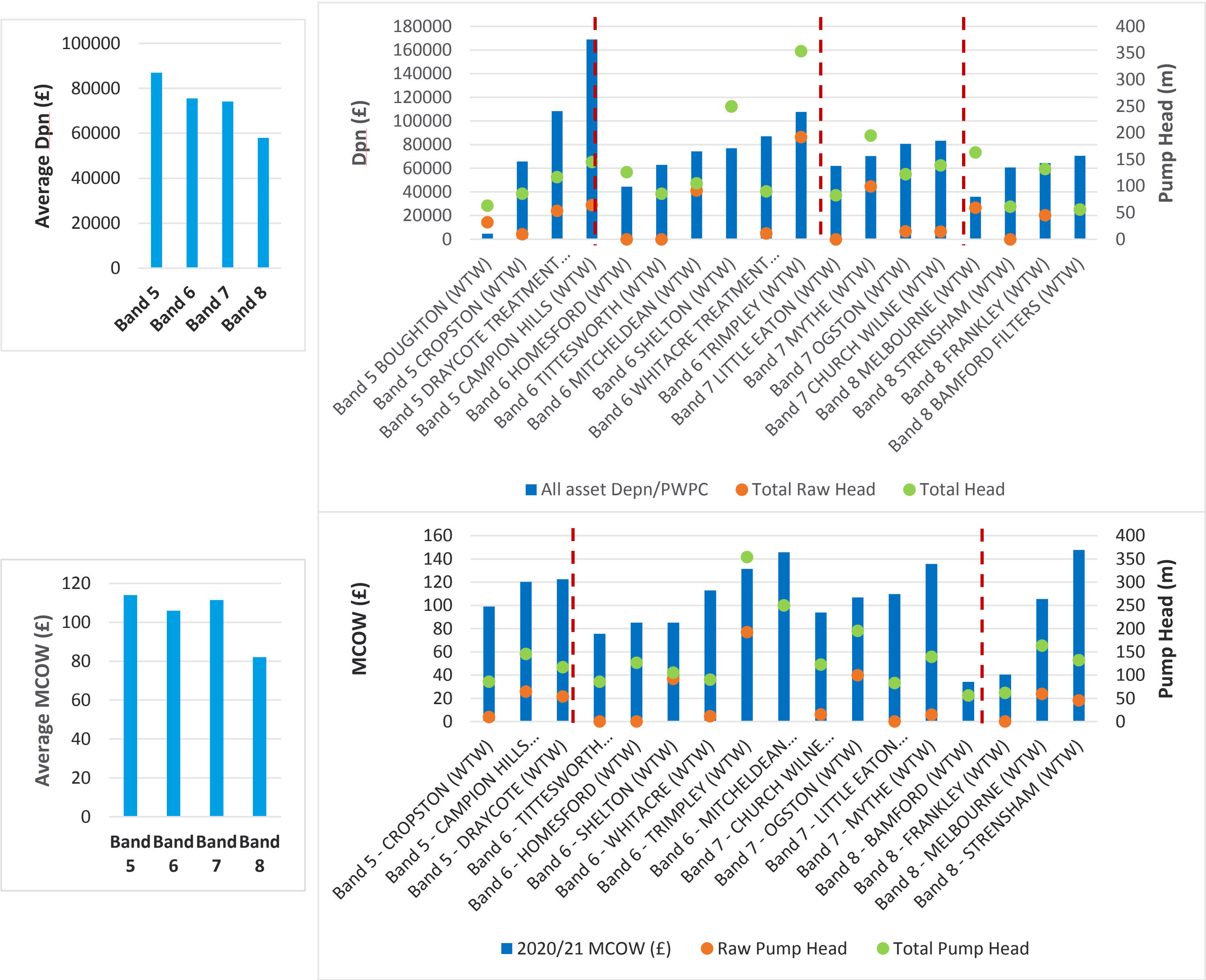


3.2.4 WRP EE2 & EE3: Cost Variances Within Size Bands

When reviewing cost at a more granular level, there is material variance between WTWs in the same size band (figure 4 and 5). This suggests that there are other material cost drivers in addition or economies of scale. If not robustly accounted for, this variance will increase the amount of modelling noise.

Marginal treatment costs are driven by geography, geology, circumstance of demand centres and raw water quality risks faced. These have previously been proxied using treatment complexity bandings, but we consider that they relate more clearly to pumping requirements – or at least that pumping requirements help to differentiate between treatment processes, complexity, and intensity within each band – and the way in which processes are used (rather than the processes themselves).

Figure 4: Charts to show the cost variances in both depreciation (top) and operating costs (bottom) within surface water treatment works size bands. This suggests that there are other material cost drivers in addition or economies of scale.



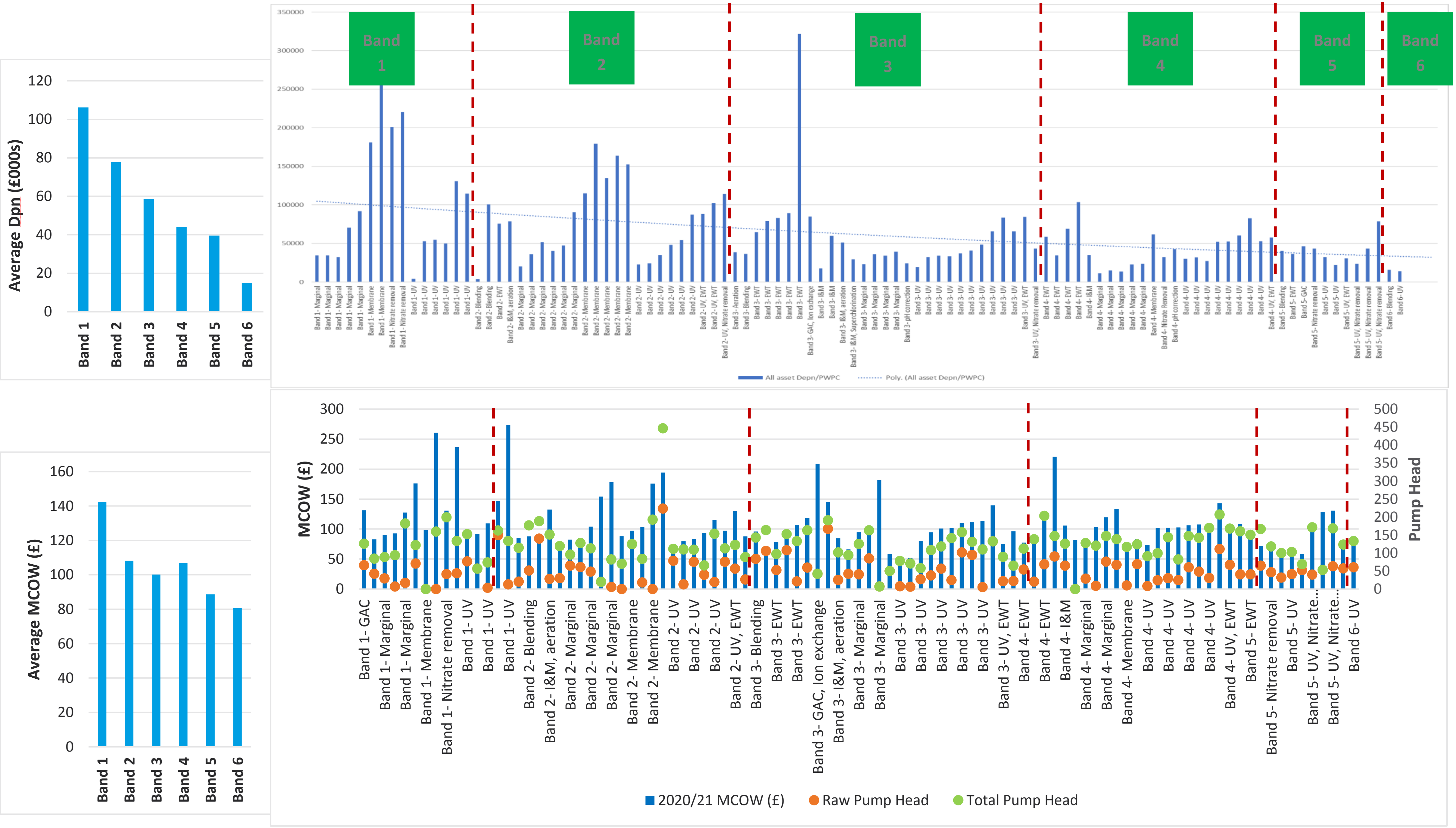


Figure 5: Charts to show the cost variances in both depreciation (top) and operating costs (bottom) within groundwater treatment works size bands. This suggests that there are other material cost drivers in addition or economies of scale.

3.2.5 WRP EE2 & EE3: Economies of Scale at Treatment Works are the True Cost Driver Rather than Density

The relative size of WTWs is a fundamental driver of costs. This relates to the opportunities for economies of scale.

Population density has a strong theoretical linkage with the opportunity to benefit from treatment economies of scale and all else constant, population density will act as an exogenous proxy for opportunities for them. Supplying more urban areas should give the opportunity to create larger water / sewage treatment works. This was acknowledged as the basis for selection of density as a driver in treatment models at PR19.

However, the geography (availability/quality of surface water) and geology (availability/quality of groundwater) are also powerful drivers that determine the optimal selection of how and where to source and treat water. These undermine the quality of population density as a proxy for treatment economies of scale:

- Large WTWs require large water resources (or large/costly raw water transfers) to feed them. Water resources fundamentally constrains WTW size not population density.
- Treatment costs vary due the different attributes of GW and SW WTWs. Therefore, measures of economies of scale should be able to better describe costs than population density.
- Unfortunately, the industry wide WTW size data does not differentiate between GW and SW. We have attempted to identify a weighted metric that accounts for both GW and SW, but this confuses the clear picture that is seen when looking at GW and SW separately. Collection of this data separately should be a clear next step for Ofwat as it is likely to materially improve the predictive capability of WRP models.

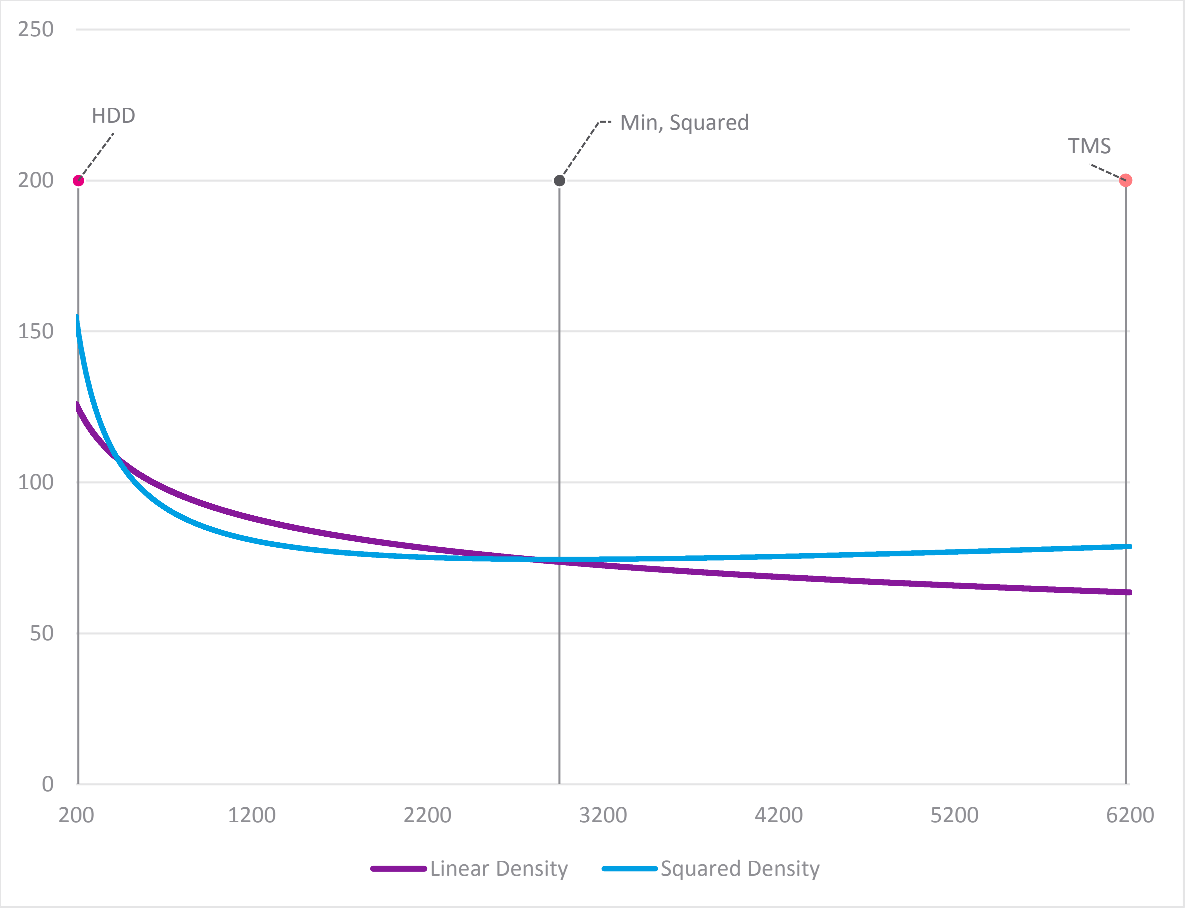
Therefore, pragmatically, population density should be used in conjunction with some allowance for the GW asset base. This could be:

- The impact of GW relative to SW on opportunities for scale can be accounted for by adding % of DI supplied by GW as an additional explanatory variable alongside population density
- The interaction term between GW and population density can also be used. This sets the expectation that the effect of population density is reduced for each additional % of DI supplied by GW.

3.2.6 WRP EE2 & EE3: Expected Economies of Density in Water Treatment

In WRP, we believe there is a case for dropping the squared density term and using a linear density specification to describe costs (figure 6). For WRP models, density is being considered as a proxy for economies of scale at treatment works. As population centres grow opportunities for economies of scale at treatment works should continue to grow, rather than reduce at elevated levels of population density. There is a possible limit when assets become too big to fail and incur resilience costs. However, this should limit continuing opportunities for economies of scale rather than suggest that costs will eventually increase at very high densities. As a result, we consider a linear density specification to be most appropriate here.

Figure 6: Graph showing the effect of using density and density squared in Ofwat's PR19 WRP1 model. Data for other variables is for the average company. HDD and TMS are displayed as the least and most dense company respectively, as per weighted average LAD density.

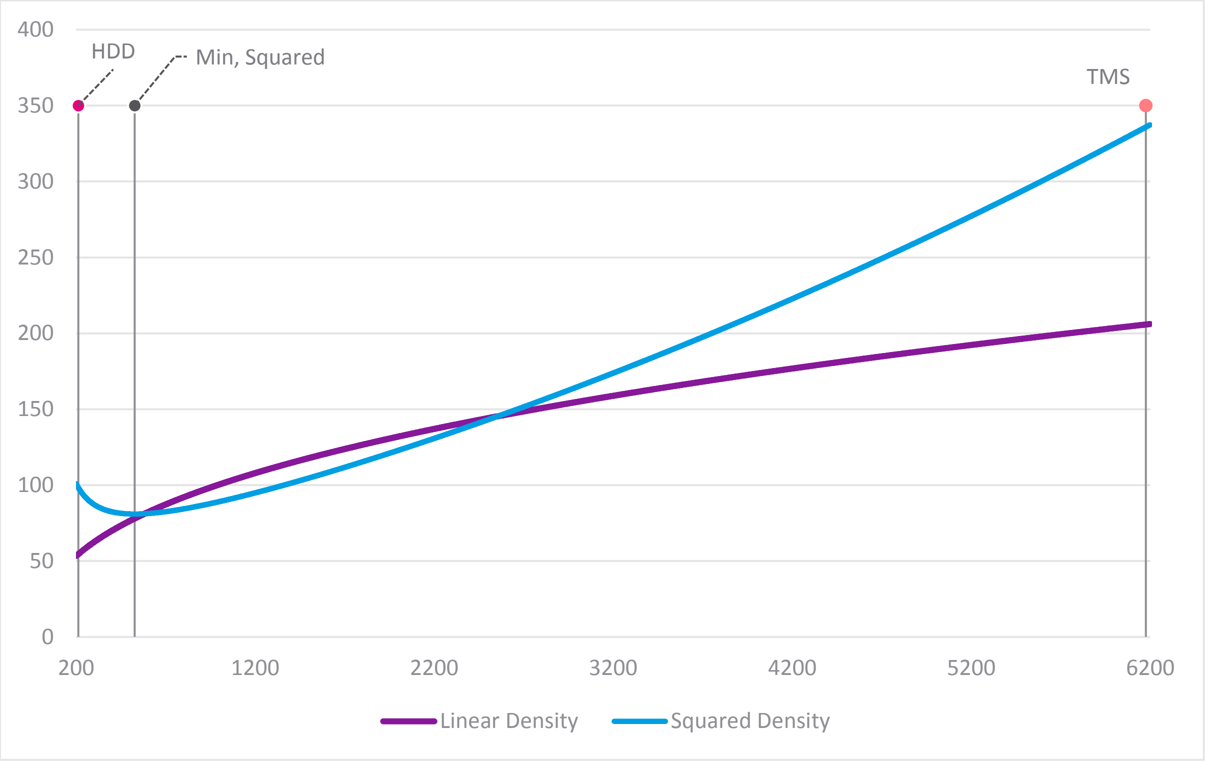


3.2.7 TWD EE2: Expected Economies of Density in Water Networks

We expect unit costs to increase in both rural areas given increased costs associated with increased distance to address any network issues and to take water from the treatment works to a property, and urban areas because of congestion effects. In spite of our initial hypothesis that boosters per length and APH account for the effects of rurality, they do not seem to give a full picture.

We found that models with squared density performed significantly better than those without squared density and there is engineering logic to justify this. Therefore, we consider the squared density specifications to be the most appropriate (see figure 7).

Figure 7: Graph showing the effect of using density and density squared in Ofwat's PR19 TWD model. Data for other variables is for the average company. HDD and TMS are displayed as the least and most dense company respectively, as per weighted average LAD density.



3.2.8 SWT EE2: Economies of Scale at Treatment Works

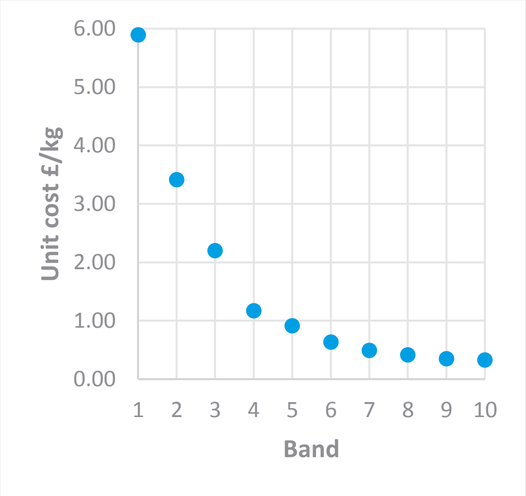
Figure 8 shows that the opportunities for economies of scale are far smaller where a company has a lot of band 1-3 works relative to the other bands.

While it also suggests that economies of scale exist at very large works, we do not think it would be easy to successfully account for these in a model given the lack of observations within these bands.

We can show using a paired t-test that while there may be some differences in economies of scale between Ofwat's band 6 and band 9, there are too few observations to form any real conclusion about band 10, and Ofwat's 'above band 5' is no different to bands 7 or 8. In the other direction there may be some diseconomies of scale in the band 6 on the left relative to Ofwat's 'above band 5' that aren't fully captured.

Looking at the differences between companies means for the largest works where there are very few observations isn't ideal because a single high (or low) performance works not reflective of the whole can tip the balance between a statistically significant difference in cost and otherwise.

Figure 8: Graph showing economies of scale at waste treatment works in 2021.



Regardless, given the vast differences in opportunities for economies of scale between bands we consider the appropriate economies of scale driver to be a weighted size variable, as shown in section 3.3.5 (lnwas2).

3.2.9 SWC EE2: Expected Economies of Density in Waste Networks

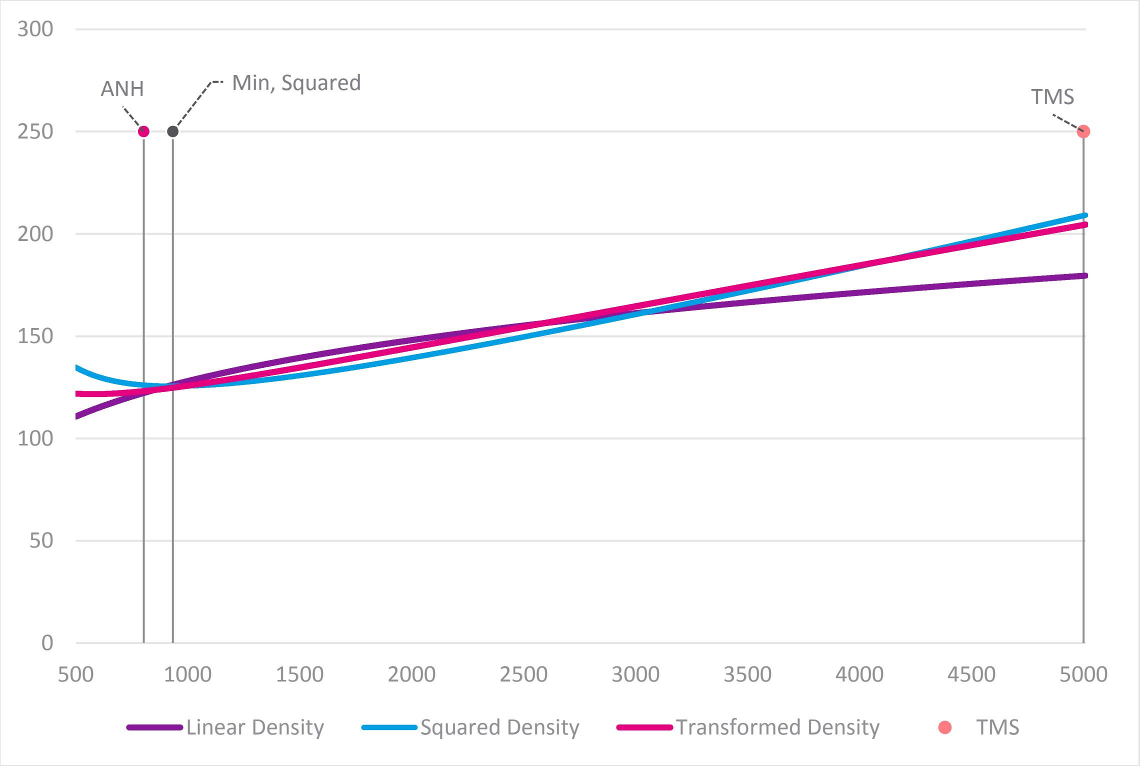
We do not expect there to be an increase in unit costs in rural areas because of the localised nature of networks.

We expect diseconomies to be increasing in density because of the increased likelihood of problems with the network (e.g. blockages) and the increased difficulty of repairing them (e.g. larger more critical sewers in urban areas).

Therefore, we do not consider a linear density specification to be appropriate given that we consider that the % increase in costs should continue to rise.

We also do not consider a squared density specification to be entirely appropriate given the increases in unit costs for more rural companies (see figure 9).

Figure 9: Graph showing the effect of using density and density squared in Ofwat's PR19 SWC1 model. Data for other variables is for the average company. ANH and TMS are displayed as the least and most dense company respectively, as per weighted average LAD density.



We have presented an alternative 'transformed density' specification that uses:

$$lnaltlad2 = (ln(lad) - ln(min(lad)))^2$$

This is interpreted as the squared percentage change from the minimum density in the dataset, which gives increasing unit costs for higher densities, but does not allow for increased unit costs in rural areas.

3.3 Complexity Engineering Expectations

3.3.1 WRP EE4: Existing Treatment Complexity Bands are not appropriately differentiating where increased costs are incurred

Ofwat’s current treatment complexity bands do not appear to be good explanatory variables for describing how and where treatment costs are incurred.

To demonstrate this, we have optimised R^2 replacing weight average complexity in Ofwat’s WRP2 model allowing weight to float freely (see table 5).

Table 5: Unconstrained weightings given to complexity bands when R^2 is optimised with a gradient descent algorithm and WAC (Weighed Average [treatment] Complexity) is replaced in PR19 WRP2.

Ofwat Complexity band / Scenario	Simple	1	2	3	4	5	6
GW separately	21	21	21	21	21	21	21
SW separately	16	17	21	21	21	21	21
GW and SW together	9	9	9	9	9	9	9

For groundwater, whilst there is some differentiation by process types, this is not exposed by the complexity bands. Marginal chlorination (simple), Arsenic removal ‘EWT’ and Membrane filtration (both band 4) do appear to differentiate. But UV (categorised as band 4) confuses the distribution. UV appears to be of varying cost – sometimes analogous with simple, but systematically less expensive than Arsenic and Membrane. This should be given more consideration in future data reporting for use in PR29.

For surface water, the bandings do not distinguish the major treatment cost outputs. No surface water WTWs in the industry are below band 3, and very few are in band 6, with the vast majority in band 4. For SVE, the differences determining whether WTWs are in band 3,4 or 5 are not the major differentiator in cost between WTWs. For SVE, Band 3 categorisations relate to WTWs without GAC (Granular Activated Carbon); band 4 to WTWs with GAC and band 5 to WTWs with GAC *and* either UV or Ozone.

Treatment costs are highly sensitive to pumping requirements which are not explicitly reflected in treatment complexity bands. Treatment APH is primarily driven by interstage pumping. This is in turn largely a function of two things.

- The topography of the site – sites with a helpful slope can better use gravity for the processes and transfers between them.
- The subsequent requirement for additional processes. For example, GAC has typically been retrofitted to WTWs in response to pesticide risks. In most cases the hydraulics of the WTW have meant that additional interstage pumping is required to allow it to be installed alongside the existing processes.

In the sections below we set out analysis from our own asset base that highlights the lack of differentiation across the treatment complexity bands for different categories of water treatment cost (Groundwater opex, Groundwater capex and Surface Water totex).

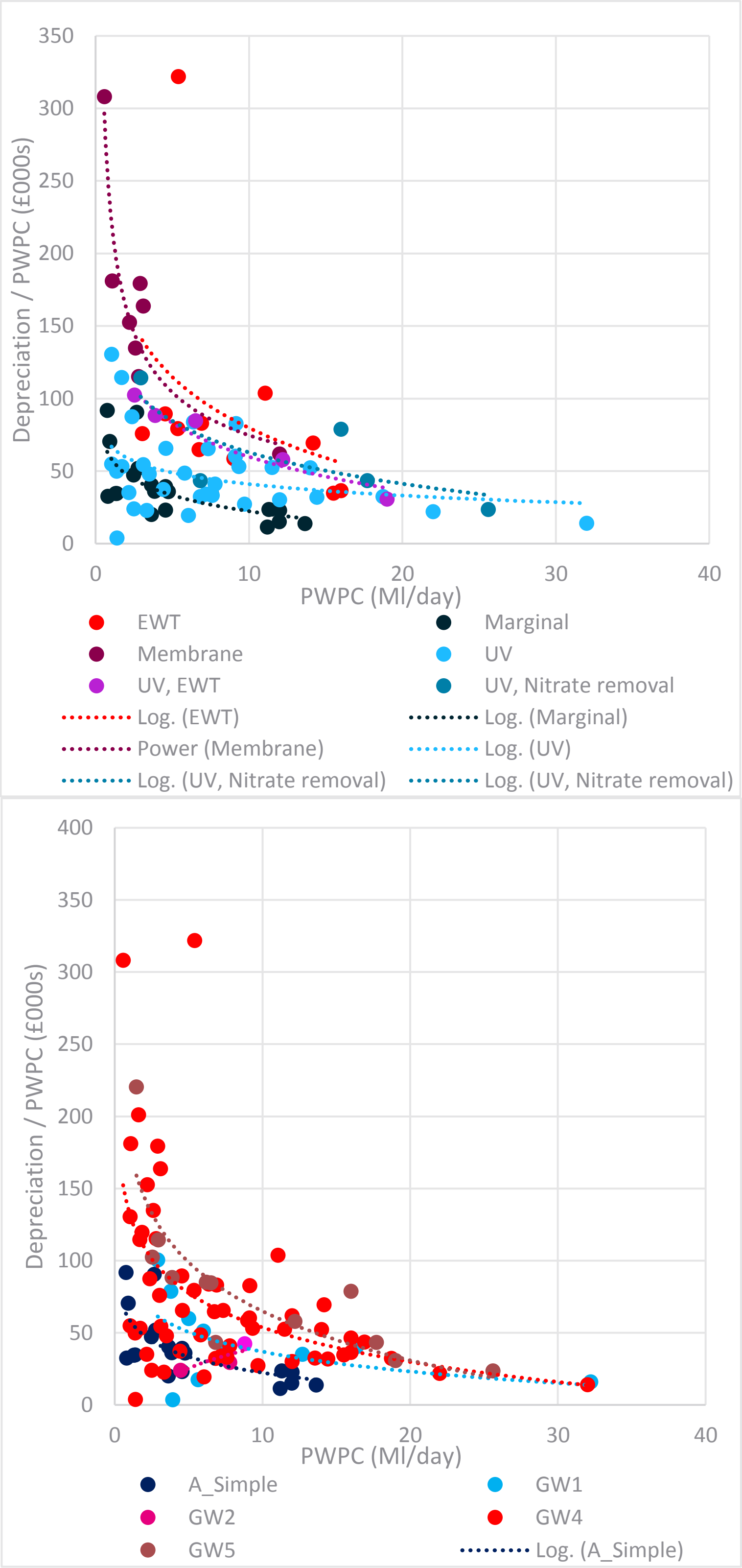
Comparing treatment complexity with groundwater capex

Figure 10 (top) shows there is a clear relationship between size, depreciation and installed processes. From cheapest to most expensive, the processes appear to be: Marginal Chlorination, UV, UV+, EWT (arsenic), Membrane Filtration.

However, this is not as clear with complexity bands (figure 10 bottom). UV is categorised as one of the more complex processes but for our own sites, appears to be the second cheapest process.

Simple and GW1 appear towards bottom of distribution, GW5 towards top. However, GW4 dominates and is very broad (both high and low cost).

Figure 10: Graphs showing depreciation by installed processes (top) and Ofwat complexity band (bottom) at groundwater treatment works. PWPC is Peak Weak Production Capacity, it describes the capacity of a WTW that can be sustained for one week.



Comparing treatment complexity with groundwater opex

In figure 11, we cannot see a very strong relationship between opex and installed groundwater processes or Ofwat complexity bands.

Opex marginal cost of water (MCOW) includes pumping costs. These should not be impacted by the complexity of treatment. Therefore, we have attempted to remove the impact of pumping costs. However, this does not appear to significantly improve the relationship.

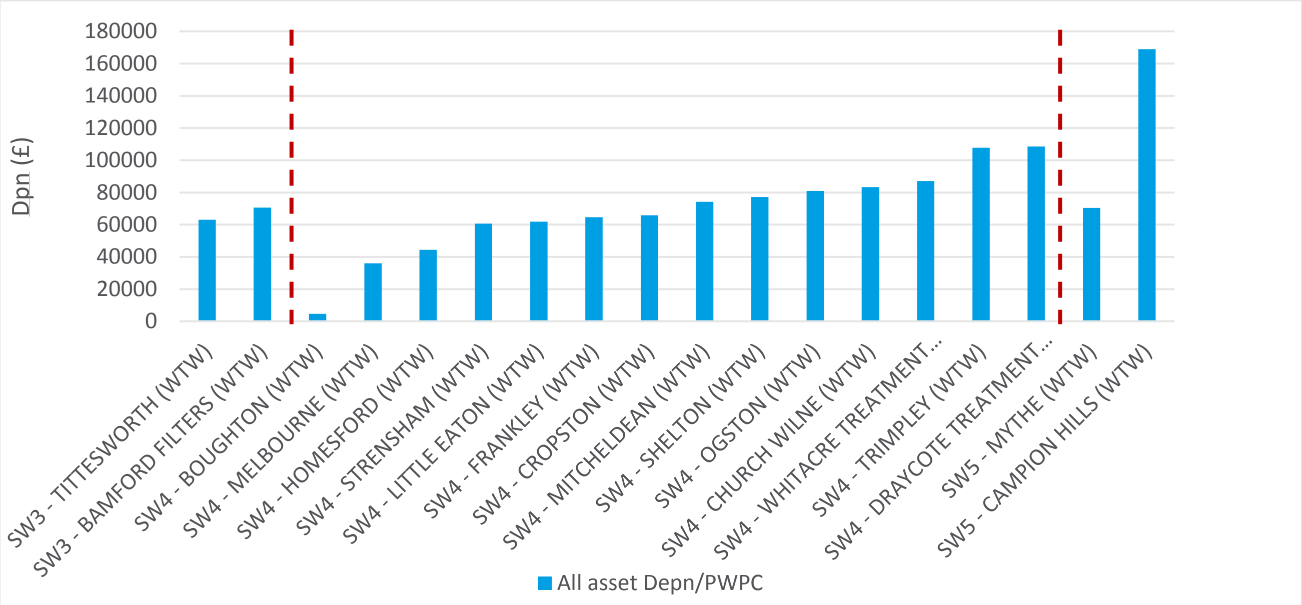
This suggests that either, treatment complexity is not a strong driver of opex costs, or the explanatory variables considered do not reflect the complexity cost drivers.

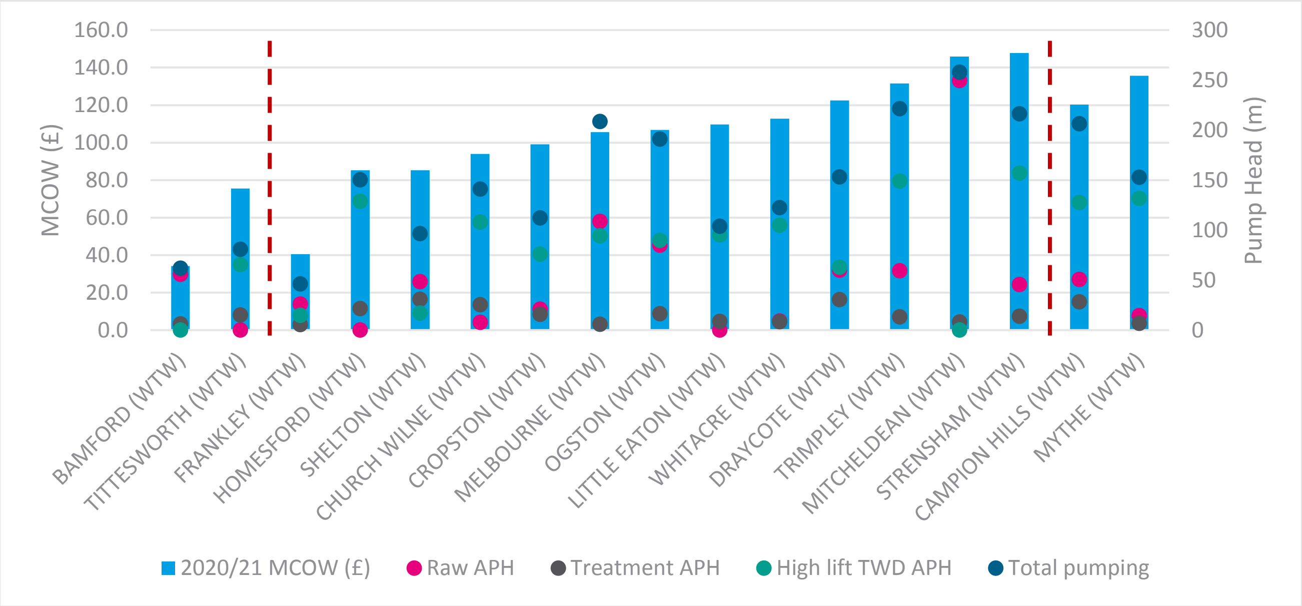
Figure 11. Treatment complexity at SVE groundwater WTWs by process complexity band

Comparing treatment complexity with surface water totex

As shown in figure 12, Ofwat’s complexity bands do not sufficiently differentiate between costs at our SW WTWs. The only determinant of complexity in the SVE assets is the absence of GAC at Tittesworth and Bamford WTWs meaning that they are band 3 and the inclusion of ozone/UV at Campion and Mythe WTWs making them band 5.

Figure 12: Charts showing depreciation and operational costs at treatment works (including high lift pumping) by Ofwat treatment band.





Most SW WTWs follow a similar process path:

- Clarification (Coagulation/Flocculation e.g. DAF (Dissolved Air Flotation), HBC (Hopper Bottomed Clarification) or SBL (Sand Ballasted Lamella),
- Filtration (e.g. RGF (Rapid Gravity Filter)),
- Chlorination

- Further processes can also be added where there are specific risks such as pesticides or coliforms (e.g. GAC (Granular Activated Carbon), UV, Ozone, Arsenic removal) but in themselves do not describe a complete picture of treatment challenges faced.

Within these common processes, there is a wide range of raw water qualities treated. Different types of clarification relate to different treatment challenges. DAF/ SBL are easier to vary in response to changing raw water conditions but have increased operating complexity. HBC has fewer mechanical and electrical (M&E) processes but is less effective at managing fluctuating water quality.

Ofwat's complexity bands are built around these high-level processes, but there are major differences in cost driven by the way in which similar treatment assets are operated or configured which will not be accounted for if only the presence/absence of a process is considered. For example, WTWs that require more clarification (lowland sources, river abstractions direct from rivers without bankside storage) will have the same processes but require more dosing of polymers.

We do not consider that the bands are a sufficient differentiator of costs at any of our SW WTWs. This is because the fundamental processes used remain the same across WTW's that are treating differing levels of raw water complexity. We consider that missing key cost drivers are:

- the amount of pumping (but this must consider all pumping);
- the type of assets and the opportunities for natural filtration (i.e. raw water reservoirs / bankside storage); and
- the way in which assets are used as determined by the external environment (e.g. amount of polymer required).

To illustrate the richness of these drivers we have set out data in table 6 which shows how they vary across our SW WTW assets.

Table 6: WRP EE4 & EE5: WTW and Raw Water Complexity Data

Name of WTW Site	2020/21 MCOW (£)	2021/22 PWPC (ML/D)	Complexity band	Size Band	Clarification	Filtration	Additional processes	Interstage pumping?	Raw APH	Treatment APH	High lift TWD APH	Total pumping	Water resource
Bamford	34.2	181	3	8	DAF	RGF	None	no	56	6	0	62	Impounding Reservoir
Tittesworth	75.5	39	3	6	DAF	RGF	None	no	0	15	65	81	Impounding Reservoir
Frankley	40.5	417	4	8	DAF / SBL	RGF	GAC	no	26	6	15	46	Impounding Reservoir
Homesford	85.2	46	4	6	Membrane		GAC	no	0	22	129	150	Adit
Shelton	85.2	41	4	6	HBC	RGF	GAC	yes x2	48	31	17	96	River (Direct)
Church Wilne	94.0	116	4	7	DAF / HBC	RGF	GAC	yes	8	25	108	141	River (Bankside storage)
Cropston	99.1	28	4	5	DAF	RGF	GAC	yes	21	16	76	112	Impounding Reservoir
Melbourne	105.6	225	4	8	DAF	RGF	GAC	no	109	6	94	209	Pumped Reservoir
Ogston	106.8	68	4	7	DAF / HBC	RGF	GAC	yes x 2	85	16	90	191	Pumped Reservoir
Little Eaton	109.7	79	4	7	Lamella	RGF	GAC	yes	0	9	95	104	River (Direct)
Whitacre	112.8	38	4	6	HBC	RGF	GAC	yes	9	8	105	122	Pumped Reservoir
Draycote	122.5	25	4	5	DAF	RGF	GAC	yes	60	30	63	153	Pumped Reservoir
Trimpley	131.5	55	4	6	DAF / HBC	RGF	GAC	yes	59	13	149	221	River (Bankside storage)
Mitcheldean	145.8	48	4	6	HBC	RGF	GAC	yes	250	8	0	258	River (Bankside storage)
Strensham	147.8	163	4	8	HBC	RGF	GAC	yes	45	14	157	216	River (Direct)
Campion Hills	120.3	17	5	5	HBC	RGF	GAC, Ozone	yes x2	51	28	127	206	River (Bankside storage)
Mythe	135.6	106	5	7	HBC	RGF	GAC, UV	yes x2	14	7	132	153	River (Direct)
All SW Works									47	11	69	127	
All GW Works (Boreholes)			0-5	1-6					42	11	73	126	
Additional network pumping (after initial high lift at WTW)											24		

3.3.2 WRP EE5: Treatment APH Proxying Complexity Summary

Given the issues raised when considering the existing treatment complexity bands and the historical interaction of pumping head as additional processes have been installed, we consider that water treatment APH is the most appropriate proxy to differentiate between treatment complexity cost pressures. As processes are retrospectively increased which were not known when the hydraulics of the WTW was originally designed (e.g. GAC, UV and membrane plants requiring interstage/process pumping that would otherwise not be required) pumping becomes a requirement and major cost driver. For SVE most interstage pumping was installed in the 1990s alongside GAC which was driven by DWI requirements coupled to growth (e.g. at Strensham WTW). Even if complexity bands are also used, treatment APH is still significant, so it appears to provide a better differentiation between the processes defined above and retrofitting.

3.3.3 WRP EE6: Raw Water APH Proxying Water Resources Cost Drivers

Different water resources asset assemblages will have different cost pressures. Some of these will have knock on effects to treatment complexity. However, treatment complexity variables will at best only partially account for water resource cost drivers.

Raw water pumping relative to TWD pumping can be entirely a function of the location of the WTW. Water typically needs to be pumped from source to DSR (Distribution service reservoir) via a WTW. If TWD models account for pumping (either through boosters/length as at PR19, or through the including of an APH explanatory variable) this will account for pumping after WTWs, but not before, despite this split being relatively arbitrary. For example, Mitcheldean and Bamford WTWs have relatively large raw water pumping (not accounted for in WRP modelling) then no treated water high lift pumping; whereas Strensham and Mythe WTWs have very little raw water pumping but significant treated water high lift pumping (likely to be accounted for in TWD modelling).

The disparity of size between GW and SW WTWs is discussed above. However, the inclusion of raw water pumping head would account for different depths of aquifer which would otherwise be considered as the same.

Figure 13: Chart showing pumping to, at, and from Severn Trent surface water treatment works.

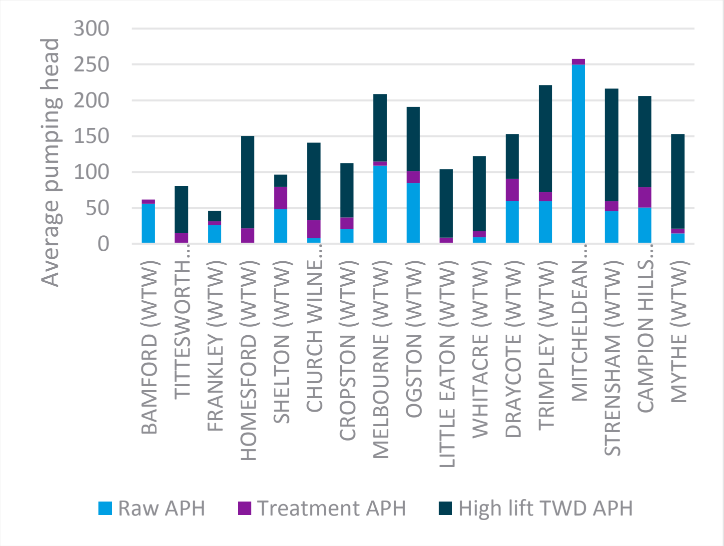


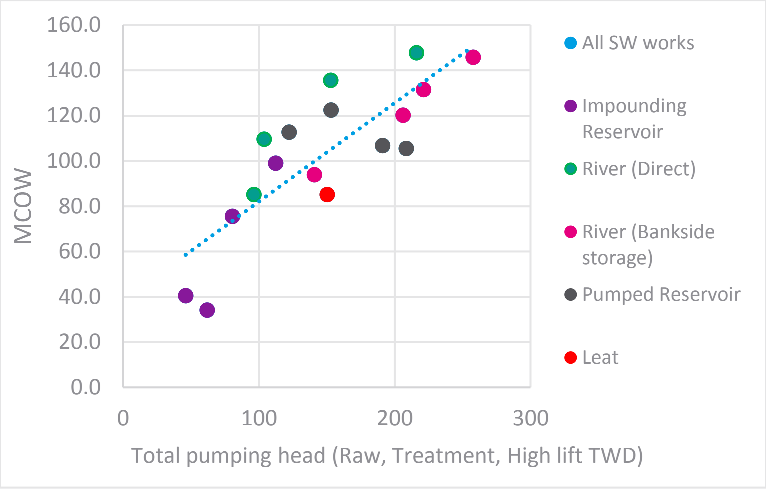
Figure 13 shows that there is a wide range of pumping across our surface water WTWs. The absolute and relative sizes of Raw and Treated water pumping is a function of:

- the challenges of the water resource being used;
- the characteristics of the population centres being served; and
- where the WTW is located relative to the water resource and population centre (contrasting Mitcheldean with Strensham WTWs as shown in the figure).

Raw APH was not accounted for in PR19 models but is often increased to minimise treatment complexity. For example Melbourne WTW which sources its water from the more distant but higher quality River Dove with associated pumping costs, rather than the closer River Trent. Currently raw water pumping is assumed to be the same at all WTWs.

Figure 14 shows that there is a strong relationship between total pumping head and WTW MCOW (opex). This relationship is much clearer than complexity band or water resource type. However, we note that the residual of the relationship between total pumping and opex may also reflect opportunities for natural filtration. Direct river WTWs appear more expensive relative to WTWs that have bankside storage. Therefore, there is a need to account for the pumping head that is not currently accounted for (Raw water) and consider better ways of accounting for treatment APH given the significance of the cost driver.

Figure 14: Relationship between total pumping head and ST WTW marginal cost of water by treatment type



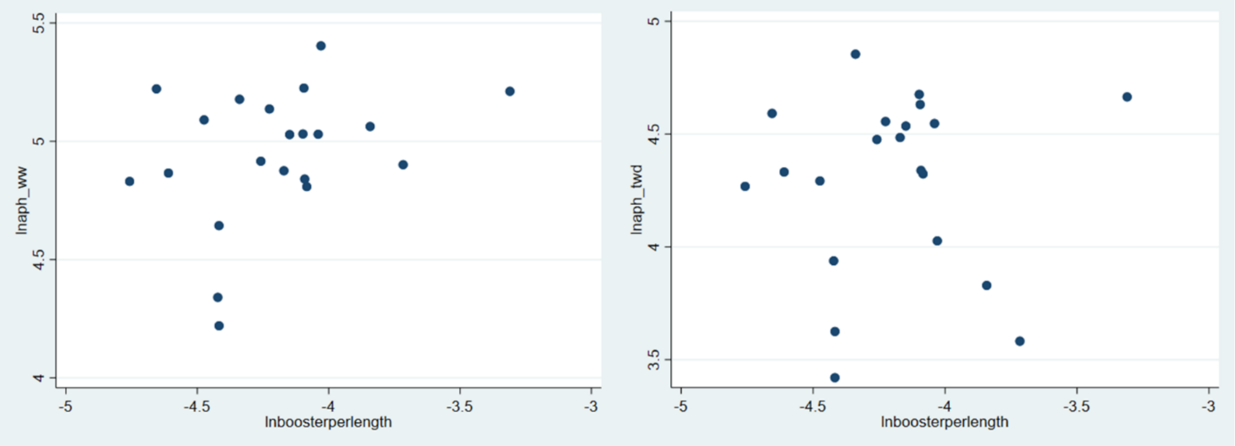
3.3.4 TWD EE3 & EE4: Network Complexity drivers

Currently, only ‘booster pumping stations per km of mains’ is considered to account for network complexity. Some water companies want to see boosters per length replaced with average pumping head, others want to see boosters per length retained.

We are of the opinion that they should both be included in the models, and that from a statistical perspective it is acceptable, and even preferable from a model performance standpoint, to do so.

In figure 15, we show graphically that there is not a strong relationship between these variables across companies, and this is supported by the low to moderate correlations between them. Including APH in the TWD and WW models alongside boosters per length produces coefficients that are significant and robust (i.e. they don’t change much regardless of which other variables are present). We therefore consider that the two explanatory variables measure different elements of cost (boosters per length is more strongly associated with capex, APH with opex), but it might also be that different solutions are used in different areas – APH describes a total and may be increased with lots of small pumps or a few large pumps.

Figure 15: Scatter graphs showing the relationship between Boosters per Length and APH across the industry. Left, wholesale water AHH; right, treated water distribution APH.



3.3.5 SWT EE3: Tight P consents driving incremental costs in sewage treatment

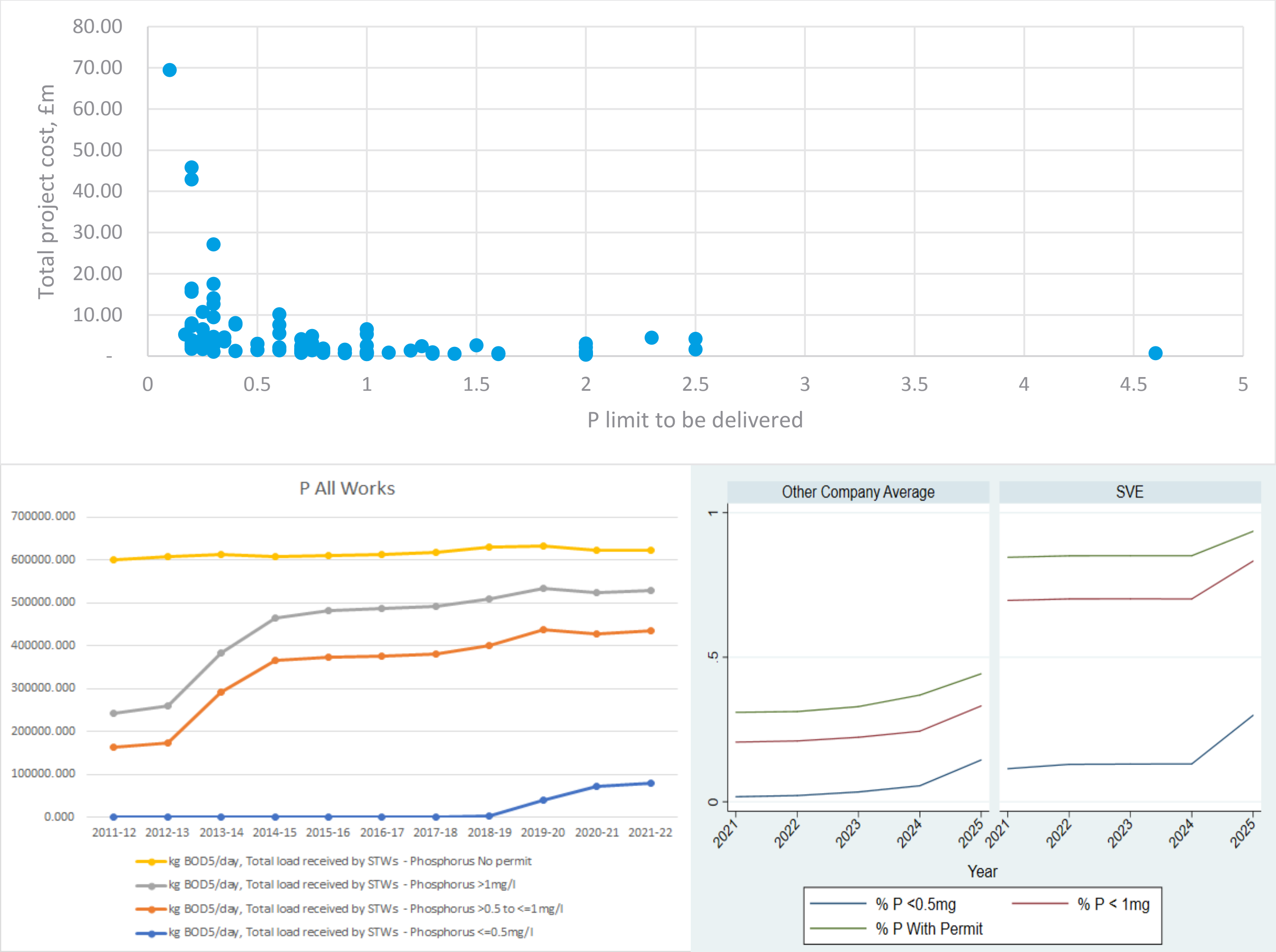
Constructing, operating and maintaining STWs that need to operate within tight P consents drive costs significantly. Figure 16, shows that this is a material and growing issue.

With external support from *Jacobs*, we have sought to understand the basis of how operating to tight P consents incurs increased cost. This review has concluded that tight P consents incur increased chemical costs and associated sludge management costs. This is particularly acute in lower bands, where we would expect process controls, mixing and consistency of flow to be poorer. It is also more acute for fixed-film processes. However, sites with pre-existing biological P removal should have lower chemical usage than other sites for the same consent. Tight P consents also require increased mixing requirements, through larger and more complex tanks, as well as the addition of tertiary treatment processes.

There is no one point at which tightened P consents result in a step change in cost, but it is likely that costs will accelerate at around 1 mg/l TP due to the increased likelihood of requiring tertiary solids removal, which necessitates additional plant, chemical and labour costs; the increased likelihood for multi-point chemical dosing; and the increased chemical demand to meet low consents.

Currently, Ammonia consents <3mg/l alone are used to describe complex sewage treatment processes. The evidence suggests this is too simplistic. Additional treatment complexity drivers could be introduced or a composite driver could be used (APH, P, UV, BOD).

Figure 16: A collection of charts showing - Forecast project cost (£m) against p limit to be delivered (top) which shows tighter P consents incur significantly more cost; P consents rising across the industry (bottom left); and P Consents at Severn Trent against other companies, showing this is more of an issue for certain (inland) companies.



Developing composite drivers to provide greater richness to sewage treatment complexity explanatory variables

We have developed five different weighted average complexity measures of the form:

$$ln\ (a_1\left(Prop.\ \ load\ with\ NH_3 \le 3\frac{mg}{l}\right) + a_2\left(Prop.\ \ load\ with\ P \le 0.5\frac{mg}{l}\right) + a_3(Prop.\ \ Load\ treated\ with\ UV))$$

We called our measures WAC (weighted average complexity) 1 to 5.

For WAC1-3, we iterated through 27,000*8 models using data from 2012-2021

- One set of the 27,000 iterations considered SWT1 with $\left(Prop.\ \ load\ with\ NH_3 \le 3\frac{mg}{l}\right)$ replaced with the variable above, another set with SWT2, then 6 corresponding sets were run swapping the $(Prop.\ \ Load\ treated\ with\ UV)$ and $\left(Prop.\ \ load\ with\ P \le 0.5\frac{mg}{l}\right)$ with $\left(Prop.\ \ Load\ treated\ with\ UV \ge \frac{\frac{30mW}{cm^2}}{s}\right)$ and $\left(Prop.\ \ load\ with\ P \le 1\frac{mg}{l}\right)$ respectively, but the specification above provided the best results.

- For each set, we allowed $a_{1,2,3}$ to iterate through 1-30 and selected the best weightings on the basis of AIC and R^2.

WAC5 uses a similar process and selects on the basis of AIC, but instead of iterating through models a gradient descent algorithm was used.

We recognise that this approach may be fitting inefficiency to some extent. However, we consider it pragmatic in the absence of granular industry-wide cost data.

Models with these variables included also provide a better fit to the PR24 data than individual complexity terms, as well as simple averages.

WAC4 is based on our interpretation of Thames' weighted average complexity driver based on industry-wide intensity.

We have also considered a weighted average scale driver, lnwas2, which is the log of load treated in bands 1-6 and weighted by the industry unit costs of each band. Our weightings are shown in table 7.

Table 7: Table showing our selected weightings for sewerage treatment complexity and why they were selected.

Variable	Basis	a1 (NH3)	a2 (P)	a3 (UV)
WAC1	Optimal weightings based on AIC in SWT1 and SWT2	6	30	1
WAC2	Optimal weightings based on R^2 in SWT2	10	30	1
WAC3	Optimal weightings based on R^2 in SWT1	30	30	1
WAC4	Industry intensity weightings change year on year – refer to SVE_FM1_WWW1			
WAC5	Optimal weightings from a gradient descent algorithm	1.35	1.06	0.21
avgNH3P05	Average of proportion of load with NH3 consents less than 3mg/l and P consents less than 0.5mg/l	0.5	0.5	0
avgNH3P05UV	Average of proportion of load with NH3 consents less than 3mg/l, P consents less than 0.5mg/l, and load treated with UV	$0.3\dot{3}$	$0.3\dot{3}$	$0.3\dot{3}$

3.3.6 SWC EE3: Network Complexity

The sewerage networks are typically much less interconnected and disparate than water networks. This is evidenced by the fact that we have nearly 10 times as many sewage works as we do water treatment works. Sewerage networks are also much more gravity focused rather than pressurised. This is because it is much more complex and costly to pump and transport sewage long distances due to issues of ragging and septicity. Therefore, where rising mains are present, additional costs are anticipated due to the operation and maintenance of the increased assets required (sewage pumping stations), and the likely performance considerations of managing these more complex systems.

The configuration of the sewerage network into combined and separated systems also drives differing cost pressures. Separated systems will increase the size of the asset base with associated maintenance effects. However, combined systems are typically larger, older and of increased criticality. Combined systems also require careful management of the surface water entering the sewers. This can be through the provision of network storage, and monitoring / managing discharges to the environment from CSOs during bad weather.

At PR19, Ofwat used sewage pumping capacity (kw) as the network complexity driver. Whilst this has logical appeal, we consider that this data has had much less attention than the equivalent water APH values. Our analysis suggests that this data may be of reduced confidence and comparability.

Therefore, was believe that care needs to be taken when using sewage pumping capacity as an explanatory driver.

The % of rising mains is a logical alternative however, we have also struggled to find coherent results when we have tested it as an explanatory factor. Similar to sewage pumping capacity, rising mains does not describe the pumping 'work' being done. Further consideration of how to derive some more insightful metrics in this area should be considered for further analysis.

The complexities associated with managing combined systems are likely to require separate explanatory drivers. The % of combined sewers is the most appropriate metric for this. However, as discussed in section 3.1 we have calculated this as: length of combined legacy sewers / total legacy sewers.

In the absence of more direct cost drivers, population density is likely to provide a high level proxy for sewage network complexity drivers.

3.4 Weather Engineering Expectations

3.4.1 WRP EE7, TWD EE5 & SWC EE4: Weather as a Cost Driver

Water

There is a strong correlation between high water demand and persistent high temperatures.

When demand increases substantially, marginal costs also increase with WTWs operating at maximum rather than optimum capacities, an inability to schedule pumping to maximise efficiency, and increased operational stress of assets.

Scale drivers do not account for periods of high demand, therefore, if a weather driver is not included these costs incurred during exceptional demand will contribute to model noise. We have considered number of days above 25°C as an appropriate explanatory variable.

We also consider that there is a choice for companies around whether to accommodate or attempt to reduce peak demand. Using peak demand directly rather than the weather proxy would favour the former (providing more supply), despite the latter (managing demand) also incurring cost. Companies are also expected to reduce per capita consumption, so using peak demand directly is likely to produce perverse incentives.

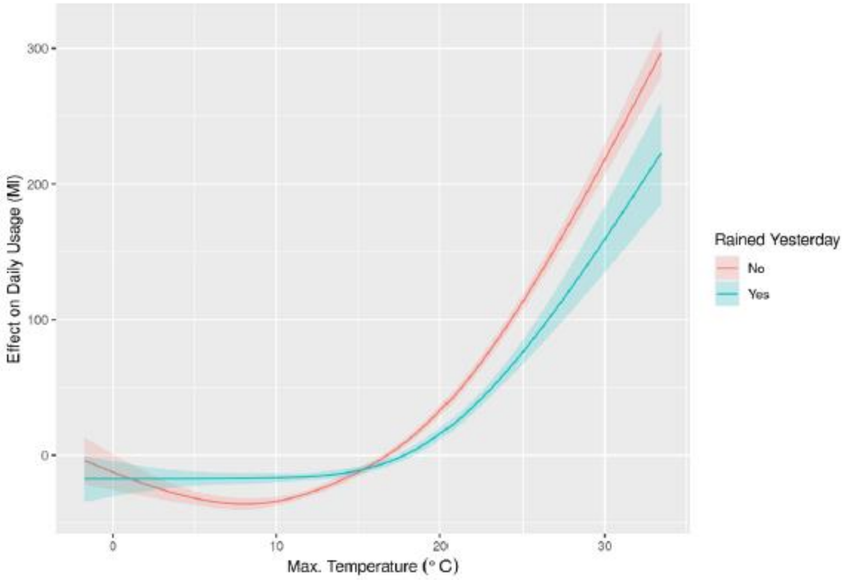
Waste

Intense urban rainfall events drive wastewater costs because of increased network pumping, treatment volumes (captured in storm tanks), and increased costs associated with CSOs (operation and response). Scale drivers do not account for intense rainfall, therefore, these costs will contribute to model noise.

3.4.2 Reason for Choosing Days Over 25^{o}C

We have commissioned the Met Office to assess the impact weather on water demand. This has told us that for Severn Trent the additional effect on water usage at 25^{o}C is just over 100Ml/d (figure 17). This roughly corresponds to the industry average difference between peak demand and average demand over the course of the modelling dataset of 108.7Ml/d. Hence we have decided to use proportion of days over 25^{o}C as our weather variable.

Figure 17: Graph produced by the Met Office showing the additional demand as a result of temperature.



3.4.3 Developing a weather dataset

We have downloaded maximum daily temperature data from for each 12 km OS grid square from the Met Office Hadley Centre website[1] for each year from 2011/12 to 2021/22. In total this amounts to more than 4.2 million observations. Figure 18 shows this graphically for a given day in the timeseries.

We have then fitted the OS 12 km grid to water company boundaries using GIS software. When a company boundary interacts with the 12km grid (either with a neighbouring company, with the coast or with the Scottish border), we have identified the proportion of each grid square that relates to each company.

We have calculated a weighted average maximum daily temperature for each company:

$$MaxTemp_{it} = \frac{\sum(MaxTemp_{jt} \times GridArea_j)}{CompanyArea_i}$$

$$where\ Company\ Area_i\ is\ made\ up\ of\ the\ unique\ combination\ of\ GridArea_j\ which\ form\ the\ relevant\ company\ area.$$

We have then counted the number of days per year that the weighted average company maximum temperature is greater than 25 degrees. This then becomes the explanatory variable used in our model development.

We consider that this dataset has significant potential to be a valuable explanatory variable. Variables could be constructed in different ways, therefore we have provided both the raw data that we have collected, and the transformed data that we have included in our submitted models.

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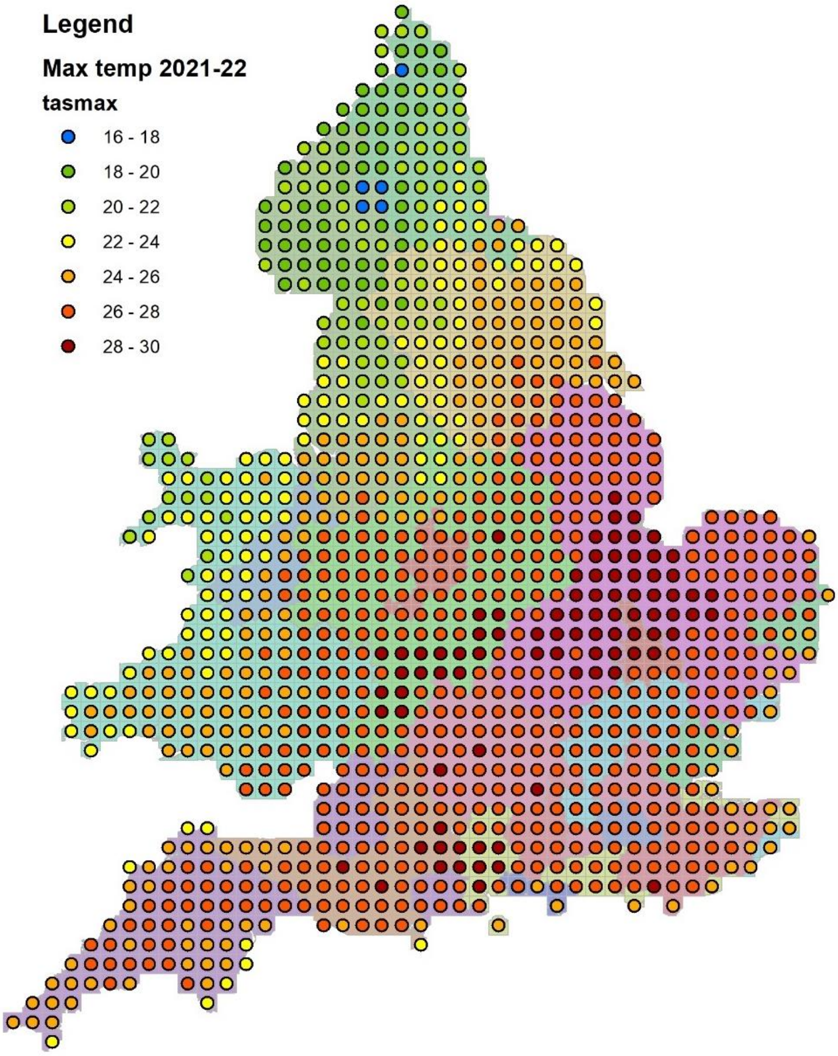
[1] https://catalogue.ceda.ac.uk/uuid/4dc8450d889a491ebb20e724debe2dfb

Figure 18: Map showing daily maximum temperature by OS 12km grid and water company boundary. Data shows values for 6 September 2021 as an example. (note that we are using days above 25°C as our proposed variable).



3.5 AMP Effect Expectations

3.5.1 WRP EE8, TWD EE6, SWT EE5 & SWC EE5: AMP Cycle Effects

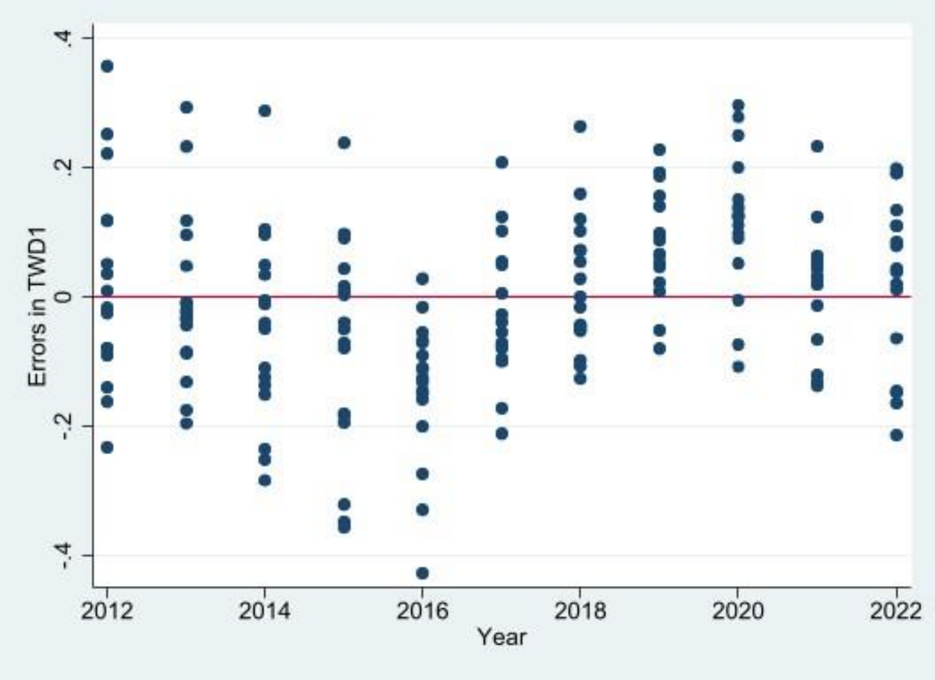
Where AMP effects are not accounted for, we encounter autocorrelation in the model's residuals. This means that companies are systematically incurring more or less costs in a given year (see figure 19). Asset related cost drivers will not be able to account for this pattern given they are relatively inflexible over time. Therefore, the model will interpret the residuals as inefficiency. This would infer that all companies move together and are inefficient in one year and efficient the next. This is not plausible.

Therefore, our expectation is that the distribution of residuals is the function of some omitted variables that are able to explain this variation in costs but are unaccounted for.

This is primarily due to cyclical capex expenditure. The variables to explain the variation above are not present in the dataset, and there is likely to be some cyclical aspect with companies making similar investment timing decisions over the course of an AMP as allowances are finalised. When viewed across the entire regulatory period since 1989 (figure 20), this becomes very apparent.

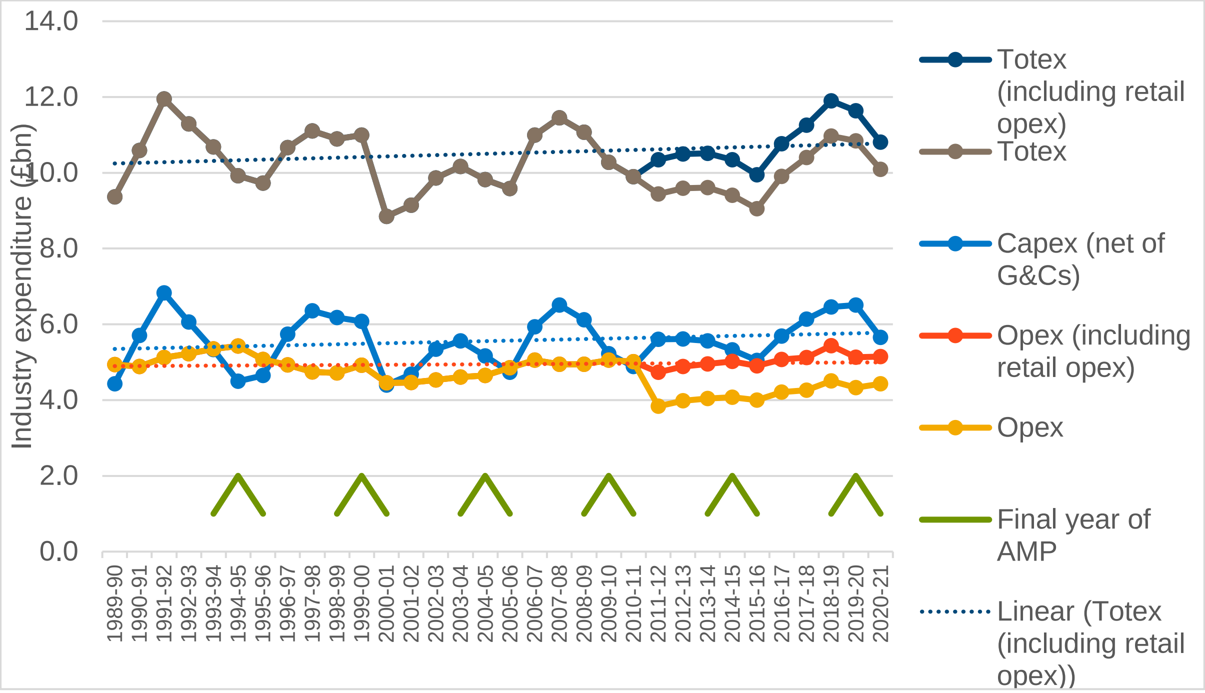
Companies make varying spending decisions across years within an AMP cycle due to procurement reasons and the need to meet allowance guidance. These fluctuating spending decisions within an AMP are likely to degrade model accuracy as every estimated coefficient picks up on the volatility, lowering the reliability of the models. This cannot be considered inefficiency if we assume that a regulatory AMP cycle creates a short business cycle for the regulated companies. Investment patterns in competitive industries are also cyclical, in general just over a longer term.

Figure 19: Chart showing the pattern of residuals in Ofwat's PR19 TWD Model.



Longer term data shows a clear cyclical pattern in expenditure throughout the AMP periods. This appears to be driven by Capex rather than Opex. This cycle is not explained by current explanatory factors. Therefore, this a major contributor of modelling noise. Dummy values or a pre modelling adjustment would help to control for this effect and allow the true explanatory drivers to differentiate between companies. Ideally, it would be more desirable to have more observations per AMP year for a dummy approach to be used. However, as seen in Figure 20, there is clear evidence of a consistent cycle across each AMP justifying a case to proceed with such an approach.

Figure 20: Expenditure over time showing AMP cycles mainly driven by Capex expenditure.



3.6 Merging the engineering logic at a subservice level to water wholesale and waste network plus

We have focused on identifying and modelling the engineering expectations in the four wholesale sub-services (WRP, TWD, SWC and SWT). This is because we consider these provide the clearest demonstration of cost : cost driver relationships for the data available and avoid the need to account for differing interpretations of cost drivers between the subservices.

However, provided we can set out whether the expectations relate only to once subservice, operate consistently across the subservices or interact across them, combined models can also be generated with an appropriate level of confidence. We set out our expectations for water wholesale and wastewater network plus models in the tables 8 and 9 below.

Table 8: Applicability of WRP and TWD engineering expectations at a wholesale (WW) level

Area	WRP (Water resources and Treatment)	TWD (Water distribution)
Scale	**WRP EE1.** Clear basis for properties being a scale driver in both WRP and TWD	**TWD EE1.** Clear basis for properties being a scale driver in both WRP and TWD. Length is less applicable to WRP costs but is highly correlated with properties (0.971).
Economies of Scale (population density)	**WRP EE2.** The need to account for the differences between GW and SW economies of scale in treatment remains appropriate for WRP costs but less material at a WW level as it is not directly relevant to TWD costs (but may influence the shape of the network). **WRP EE3.** Population density drives both WRP and TWD costs. However, there is a greater basis for non-linear density in TWD than in WRP. This means that the case for or against a non-linear term becomes more nuanced.	**TWD EE2.** Population density drives both WRP and TWD costs. However, there is a greater basis for non-linear density in TWD than in WRP. This means that the case for or against a non-linear term becomes more nuanced. Given that TWD costs are larger than WRP costs, it feels appropriate to prioritise TWD (i.e. including density2).
Complexity (driven by Geography / Geology)	**WRP EE4.** Ofwat's treatment complexity bands remain poor explanatory variables for WRP costs but less sensitive as less relevant to TWD costs.	**TWD EE3.** Booster/length drive TWD costs but will be less sensitive at a WW level as it is not relevant to WRP costs.

	WRP EE5. Water treatment APH remains an appropriate proxy for treatment complexity but will be less sensitive as it is not relevant to TWD costs. **WRP EE6.** Raw water APH remains an appropriate differentiator of water resource opportunities but will be less sensitive as it is less relevant to TWD costs (there is likely to be a trade-off between raw water and treated water pumping).	**TWD EE4.** TWD APH drive TWD costs but will be less sensitive at a WW level as it is less relevant to WRP costs (there is likely to be a trade-off between raw water and treated water pumping).
Weather effects	**WRP EE7.** Weather is a complementary proxy for both WRP and TWD cost drivers.	**TWD EE5.** Weather is a complementary proxy for both WRP and TWD cost drivers.
AMP effects	**WRP EE8.** Capex costs vary materially according to the AMP cycle across both WRP and TWD.	**TWD EE6.** Capex costs vary materially according to the AMP cycle across both WRP and TWD.

Table 9: Applicability of SWT and SWC engineering expectations at a wastewater network plus (WWWNP) level

Area	SWT (Waste Treatment)	SWC (Waste Network)
Scale	**SWT EE1.** Load is more relevant in SWT than SWC. However, load and properties are highly correlated (0.997), and SWT costs are slightly larger than SWC costs.	**SWC EE1.** Load is less relevant in SWC than SWT. However, load and properties are highly correlated (0.997), and SWT costs are slightly larger than SWC costs.
Economies of Scale (population density)	**SWT EE2.** Opportunities for economies of scale and population density are interrelated. Opportunities for economies of scale are a clearer cost driver in SWT than population density and largest at smaller size bands. However, there will be a level of correlation with various population density metrics.	**SWC EE2.** Opportunities for economies of scale at treatment works is not directly relevant to network assets. However, there will be a level of correlation between various population density metrics and EOS proxies.
Complexity (driven by Geography / Geology)	**SWT EE3.** Composite complexity drivers will help to describe treatment costs but will be less sensitive in WWWNP models as they are not relevant to SWC costs.	**SWC EE3.** There are a range of network complexity drivers, some may have greater levels of data robustness than others. However, given that these do not relate to SWT cost, they will be less sensitive in WWWNP model configurations.
Weather effects	**SWT EE4.** Weather less likely to be a material driver of cost than with SWC.	**SWC EE4.** The effect of weather remains for SWC costs but will likely be less sensitive due to the less clear link to SWT.
AMP effects	**SWT EE5.** Capex costs vary materially according to the AMP cycle across both SWT and SWC, but overfitting risks remain.	**SWC EE5.** Capex costs vary materially according to the AMP cycle across both SWT and SWC, but overfitting risks remain.

3.7 Bioresources and Retail expectations

3.7.1 Bioresources

Following discussion with bioresources specialists we set out engineering expectations in table 10.

Table 10: Bioresources engineering expectations

Cost driver	Basis
Scale	• TDS (Tonnes of Dry Solids received) is an uncontentious scale driver. We have specified models on a unit cost basis therefore inclusion of a scale driver will convert to a description of (dis)economies of scale at a company level.
Economies of scale in sludge collection	• Sludge treatment requires the development of complex assets that are discrete from the sewage treatment flow path. It is not economic to construct sludge treatment assets at each sewage works. • Sludge treatment facilities have been constructed at the large sewage works as they have on onsite supply of sludge and can benefit from economies of scale of treatment assets. As the size of sewage treatment works get smaller so these economies of scale reduce and eventually to the point where onsite treatment is not economic. At this point treatment of sludge at a regional hub is required with associated intersiting costs. Intersiting costs are a function of both: ○ the need to treat at regional hubs (i.e. sewage treatment works size) ○ the transport requirements to the sludge treatment hub (i.e. the distance travelled and the method of transport)

	• Economies of scale could be directly accounted for using information about the size of sewage works and intersiting 'work' done. • Population Density can be considered as a proxy for opportunities for economies of scale. However, it will not be able to distinguish between the various cost drivers related to economies of scale.
Sewage treatment complexity	• The characteristics of the sludge being treated will drive costs. Sludges generated from sewage treatment works with tight ammonia will have a higher % of secondary sludge which is more complex to treat. Tight phosphorus consents will have more inert sludge because of the dosing requirements of treatment. Inert sludge has lower renewable energy potential.
Disposal complexity	• The way in which sludge is disposed of will drive costs. Disposal to land (either farmland or land reclamation) is significantly more economic that alternative thermal processes (pyrolysis, gasification, incineration). This is because it is highly inefficient to combust material with elevated water content. • The opportunities to dispose to land are impacted by the availability of land (i.e. rurality of surrounding areas and sludge to land regulations) and the challenges of transporting it to the disposal site. • Disposal complexity can be directly accounted for, or population density may form a weak proxy.
Sludge treatment complexity	• Sludge treatment processes impact on the quality of the treated product and the opportunities for renewable energy. They are an important component in managing landbank risk. • Advanced anaerobic digestion (ADD) requires significantly more complex assets which in turn have more stringent maintenance requirements. This generates an improved product (reduced pathogens and % dry solids) which is more attractive to landowners and cheaper to transport. It also leads to increased renewable energy yields. In summary, both cost pressures and opportunities are elevated. This leads to a complex overall cost driver picture.

3.7.2 Retail

We set out high-level expectations of retail cost drivers in table 11.

Table 11: Retail prior expectations

Cost driver	Basis
Scale	• Households served is an uncontentious scale driver. We have specified models on a unit cost basis therefore inclusion of a scale driver will convert to a description of (dis)economies of scale at a company level. • As the number of households served by a company increases, we would expect increasing economies of scale as the size of assets and purchasing power increases. • We would anticipate that the cost to bill a given customer and respond to routine queries should be covered by the scale driver.
Ability to pay / Deprivation	• Customers who are struggling to pay are more likely make contact to query billing and seek support. This is also likely to be a major driver of bad debt costs. • The size of the water bill is a strong and direct driver of retail traffic (more queries, more requirements for support, greater likelihood of debt costs) • There are a wide range of external potential deprivation metrics that can be used which will for a proxy for ability to pay. • Population density is also likely to form a wider proxy, as more urban areas typically have more deprivation issues.
Meter reading	• The volume of meters to read will drive cost. However, this will be complicated by the metering technology installed (AMI technologies and ability to remotely read) and the attributes of the supply area / metered population (traffic congestion, proximity of houses to the road). • Population density is also likely to form a wider proxy, for metering costs but is likely to be non-linear (costs at extremes of density and rurality).
Population transience	• Where there are significant changes in the population served, account changes increase and there is a higher likelihood of debt management / bad debt as customers leave without closing accounts. • Population density may form a wider proxy, there is likely to be larger transience in more urban areas, particularly in student populations.

4. Running and Selecting Models

4.1 Our model development approach

From setting out our prior engineering expectations (section 3), our model development approach (figure 21) identified plausible explanatory drivers (table 12) and iterated through model possibilities. We refined this long list down through a number of statistical metrics and Ofwat’s tests before making final selections that satisfied engineering expectations and improved upon the PR19 model predictive capability (see sections 4.2 – 4.6).

Fig 21: Our model development approach

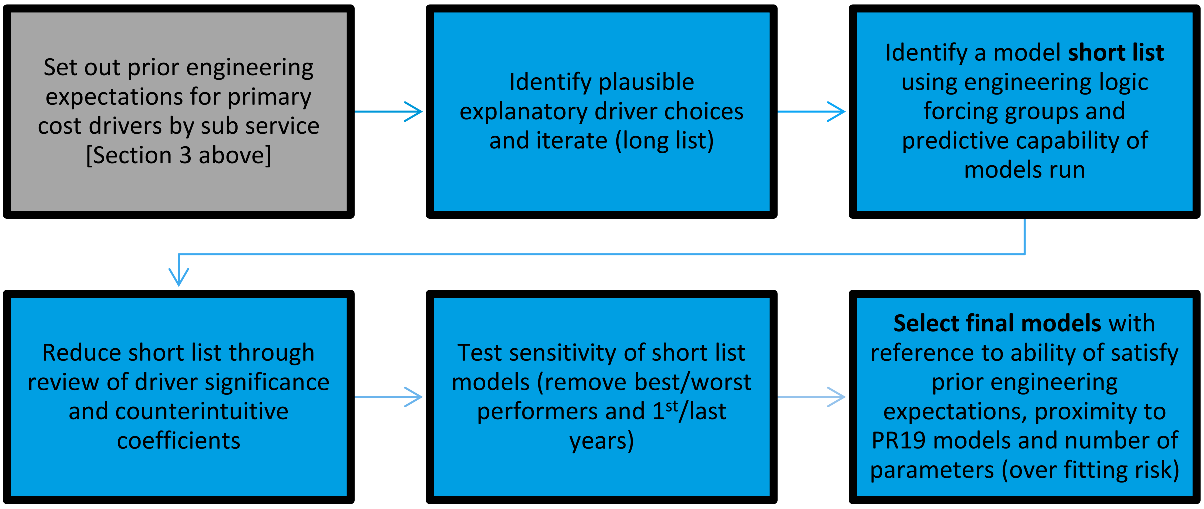


Table 12: Plausible variable that we iterated through in developing our model long list.

Variable Category	WRP	TWD	SWT	SWC
Dependent	• Botex+ • Smoothed Botex+	• Botex+ • Smoothed Botex+	• Botex+ • Smoothed Botex+	• Botex+ • Smoothed Botex+
Scale	• Properties	• Lengths of Main • Properties	• Load	• Legacy Sewer Length • Properties
Density	• LAD • MSOA • Population per Area	• LAD • MSOA • Population per Area	• -	• LAD • MSOA • Properties per Legacy Sewer Length
Additional Density	• Squared Densities • Groundwater Interaction	• Squared Densities	• -	• Squared Densities
Network Complexity/ Pumping	• Water Resources Plus APH • Water Resources APH • Water Treatment APH	• Boosters per Lengths of Main • Treated Water Distribution APH	• -	• Pumping Capacity per Sewer Legacy Length • Combined Sewers per Legacy Sewer Length • Rising Mains per Legacy Sewer Length

Treatment Complexity	• Percentage Water Treated in bands 3-6 • Weighted Average Complexity (Various Options) • APH_WT	• -	• NH3 <= 3mg/l • P <= 0.5mg/l • UV >30mW/s/cm2 • Composite Complexity (9 options)	• -
Assets Economies of Scale	• Weighted Average Size of Works	• -	• Pct load treated in size bands 6+ • Pct load treated in size bands 1-3 • Weighted EoS (2 options)	• -
Weather	• Proportion of Days Over 25^{o}C	• Proportion of Days Over 25^{o}C	• Urban Rainfall per Sewer Length (LAD and MSOA) • Rainfall (mm) Over Urban Areas	• -
Time	• AMP Year Effects • AMP Effects • Trend (for smoothed models only)	• AMP Year Effects • AMP Effects • Trend (for smoothed models only)	• AMP Year Effects • AMP Effects • Trend (for smoothed models only)	• AMP Year Effects • AMP Effects • Trend (for smoothed models only)
Spatial	• Considered	• Considered	• Considered	• Considered

4.2 Appropriate use of endogenous explanatory variables

We understand the premise that cost models which are seeking to identify efficiency should be driven by exogenous cost drivers (i.e., drivers that are outside of company control).

However, exogenous dependent variables are typically not direct drivers of cost. Instead, exogenous dependent variables usually act as a proxy for the true cost driver, for example population density acting as a proxy for treatment economies of scale. There is usually a trade-off between independence and the ability of the variable to accurately describe the cost driver

Where this disparity is material such that the proxy does not capture the complexity of the cost driver, we consider that endogenous cost drivers should be preferred in tandem with complementary safeguards where needed.

As also suggested by Ofwat, we consider that it is not appropriate to reject the use of endogenous cost drivers that improve the predictive capability of models where there is no short to medium term management control. This is typically the case for the size and location of large assets which have very large sunk costs. Fundamental decisions may have been taken decades, and in some cases over a century, ago – for example the last major reservoir, Carsington, started construction in 1989.

4.3 Reviewing performance in the round to ensure a robust set of models are selected

It is uncontentious that the most important metric of model predictive capability is R^2. However, it is important not to focus on this without consideration of other diagnostic information. Considering other indicators provides a fuller picture of model performance and allows us to more confidently select a model that accurately describes costs.

Therefore, when reviewing and selecting models, we have taken account of a range of metrics. In addition to R^2, we have placed particular significance on a review of:

- the R^2 of the equivalent unit cost configuration of the model being considered;
- consideration of the distribution of the model error residuals; and
- the relative performance against an information criterion.

Explanatory variables need to provide an appropriate level of statistical significance. We support Ofwat's view that there should be some flexibility on the 10% significance criterion but consider 30% is not sufficient to provide appropriate confidence. Consequently we have decided to use 20% as the cut-off point in our assessment of statistical significance for variables in the potential models.

The exception to our 20% rule is in the AMP year indicators, where we have allowed them to be insignificant so they call all be interpreted relative to a reference year (the first year of the AMP). We have excluded models where the majority of AMP year indicators are insignificant.

When looking at these statistics, we have considered them relative to the PR19 set of models (with the obvious exception of NPWWW where no models were used) to ensure improvement in the explanatory and predictive capability of the models.

4.3.1 Considering Unit cost R^2

The R^2 of a model will be strongly influenced by the performance of the model scale driver. Given the predictive capability that scale drivers offer, this is clearly important. However, as all models with a sensible scale driver will have a high R^2, such values can give false confidence that variations beyond scale are adequately accounted for. It is these secondary explanatory variables that add the depth to models and are likely to make legitimate differentiations between companies (i.e. whether they are operating under favourable or unfavourable conditions).

Converting to a unit cost model – by subtracting the logged scale driver from the logged dependent variable – and calculating the R^2 will reveal the extent to which the non-scale drivers are explaining the distribution of costs seen.

We have used unit cost R^2 primarily to decide between two competing models that are equivalent in terms of engineering logic and have with the same total cost R^2. In this scenario, we consider that the additional fit provided by the non-scale drivers mean the model with the higher unit cost R^2 can be considered preferable.

4.3.2 Appropriate use of random effect and correctly interpreting error terms: σ_μ (Sigma Mu) and σ_ε (Sigma Epsilon)

Where possible we consider that Random Effect (RE) model estimation should be used in preference to OLS. RE provides much greater opportunity for identifying true efficiency. It should be noted that Ofwat have suggested a test should be used for this. In practice that test often suggests random effects should be used in any case.

RE modelling allows the error term to split into σ_μ and σ_ε. σ_ε (Sigma Epsilon) describes the traditional random error term. The 'time variant error term' reflects costs which vary from year to year due to natural fluctuation that is not sufficient to be accounted for by an explanatory driver. This should not be considered as inefficiency. Given the natural complexity of companies, and the fact and our asset base or customers do not operate in perfectly predictable ways, time variant error is never likely to be zero in any given year, but should average to roughly 0 over the course of the panel. While we do have concerns with autocorrelation in this error term (as discussed in section 3.5.1), and do not believe it can be attributed to inefficiency, we have proposed remedies in section 4.9.1.

σ_μ (Sigma Mu) describes the standard deviation of the company-specific error term which is constant across time. The 'time invariant error' should account for two things:

- **Omitted variables**. These are legitimate material cost drivers that are not appropriately accounted for and therefore show companies to be more or less expensive to each other.
- **'True' inefficiency**. This is where all the legitimate material cost drivers have been accounted for (and separate consideration is given to natural variation in the time variant error term), but companies continue to incur different levels of expenditure relative to each other. Since company circumstances are not changing substantially over time, e.g. we have the same topography now as we did in 2011, omitted variables that do not substantially change will lie in this error term.

If we add variables that can be legitimately justified based on engineering expectation, σ_μ is likely to reduce as omitted variables become increasingly accounted for. Therefore, we have sought to identify models with a lower σ_μ - those with higher values are likely to be wrongly attributing legitimate drivers of cost to inefficiency.

Accepting that all companies are not perfectly efficient, there is a limit to minimising σ_μ. This is particularly so where engineering expectation is not clear (i.e. the selected variables do not account for legitimate external cost drivers) or variables are added unnecessarily increasing overfitting risk. When $\sigma_\mu = 0$ the model estimator reverts to OLS and the opportunity to interpret the error terms is reduced. However, where the engineering expectations remain sound, we have considered it to be appropriate to accept such models particularly where other RE models are available for triangulation. Accepting the potential overfitting risk, we have made sure to make such assessments in conjunction with other indicators of model performance, particularly AIC (as described below).

We note that Ofwat are proposing the use of a normality test. We agree that the time-varying error component (ε_{it}) of a model should be normal. As above, we do not consider that it is appropriate to consider this as inefficiency. However, we do consider that the distribution of what is considered to be inefficiency should be skewed – most companies should exist close to the frontier level of efficiency while some laggards will be present. The inverse distribution (i.e. with outlier super efficient companies) is likely to lead to unstable efficiency challenges or may require careful consideration of how benchmark companies are selected.

4.3.3 Using AIC as a measure of model quality

Information Criterion statistics seek to test whether the additional predictive capability derived from adding extra parameters outweigh the associated disadvantages of the additional variables – namely overfitting risk.

AIC (Akaike Information Criterion) can be calculated as:

$$2k - 2\,ln(\hat{L})$$

$\boldsymbol{ln(\hat{L})}$ is the log-likelihood of a model estimated by the maximum likelihood estimator, which in stata fits a random-effects model with the maximum likelihood estimator rather than GMM (General Method of Moments). This estimator selects the $\boldsymbol{\beta}$ values in our model such that the likelihood of the independent variables producing the dependent variable is maximised. In practice for our purposes the coefficients estimated by maximum likelihood and by GMM are almost identical. $\boldsymbol{k}$ is the number of parameters being estimated in the model.

The minimum AIC is the optimal model, and clearly there is a penalty of 2 with each additional independent variable. As a result, where R^2 will almost always increase with additional significant independent variables, AIC can prefer a model with fewer variables even where an additional variable might be significant. This helps us to ensure models are kept suitably simplistic.

An alternative Information Criterion that is often used is BIC (Bayesian Information Criterion), given as:

$$kln(n) - 2\,ln(\hat{L})$$

Here, $\boldsymbol{n}$ is the number of observations, so where we have more than 8 observations in a model, BIC provides a tougher penalty for additional explanatory variables.

For our purposes, we prefer AIC over BIC. BIC is designed to attempt to find the ‘true’ model from a candidate set, whereas AIC accepts that the true data generating process is not present within the candidate set. Ofwat accepts the latter to be the case here, hence why Ofwat does not set the efficiency challenge at the frontier and allow for cost adjustment claims.

As a rule of thumb, where $\boldsymbol{AIC_1 \leq AIC_2 - 4}$ we prefer the model that gives $\boldsymbol{AIC_1}$. Where $\boldsymbol{AIC_2 - 4 \leq AIC_1 \leq AIC_2 + 4}$ we can consider the models to have equal support. Note that only models with the same dependent variable should be compared with AIC.

4.3.4 Alternative VIF statistic

We have abided by the rule of thumb that suggests models with a Variance Inflation Factor (VIF) of greater than 10 should be removed.

However, where we have a variable that we expect to cause issues with the variance inflation factor as defined we have removed it and reported the maximum VIF value without the inclusion of that variable. For example, where we have a density and its square, we expect VIF to be high. This is not an issue in itself, but we are concerned that this might mask some multicollinearity issues in the other variables, so we have reported the maximum VIF without the problematic variable to show that the remaining variables we have considered are robust.

Therefore, we have reported an alternative VIF statistic in addition to the one defined in Ofwat’s do files.

4.4 Calculating efficiency performance across an entire AMP period

We have shown the efficiency performance of each company in the required model proforma. This has been calculated as per Ofwat’s published .do files. However, these use the last four years of data for SVE and HDD whilst the efficiency for each of other companies is calculated on the last five years. Using five years feels more desirable as it encompasses a full AMP cycle.

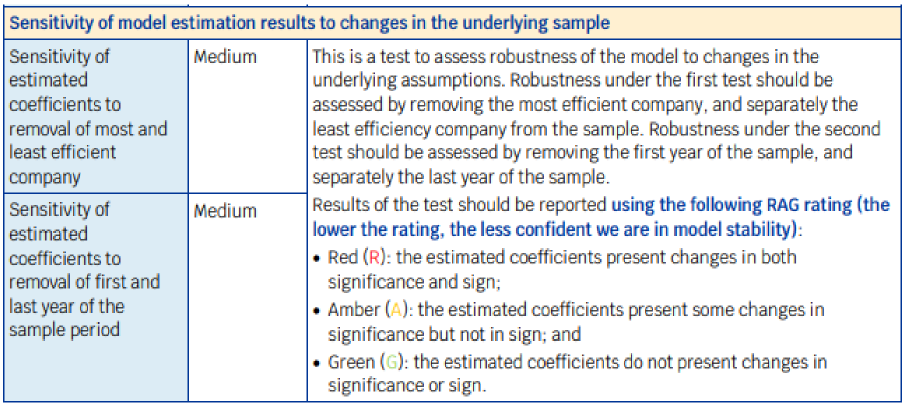
Whilst we have reported efficiency in line with Ofwat’s .do file calculations, we consider that adding the SVT 2017/18 value to the four years of SVE (and similar for DVW and HDD) would be preferable for the purposes of assessing models. This would then mean that all companies would then be compared across an entire AMP period. Comparing efficiency on different timescales could be problematic given the cyclical nature of expenditure across AMPs and might erroneously highlight sensitivity concerns if HDD or SVE appear as the most or least efficient company.

We are aware that this is not likely to be a long-term issue; the availability of 2022/23 data for the calculation of models that will be used to set the final allowances are produced will mean that 5 years of comparable information will be available. We also note that, for the purposes of deriving models, we agree that 2017/18 should always remain a SVT observation.

4.5 Assessing sensitivity

4.5.1 Determining the sensitivity of variables

Figure 22: Ofwat's criteria for assessing sensitivity.



Sensitivity of model estimation results to changes in the underlying sample		
Sensitivity of estimated coefficients to removal of most and least efficient company	Medium	This is a test to assess robustness of the model to changes in the underlying assumptions. Robustness under the first test should be assessed by removing the most efficient company, and separately the least efficiency company from the sample. Robustness under the second test should be assessed by removing the first year of the sample, and separately the last year of the sample.
Sensitivity of estimated coefficients to removal of first and last year of the sample period	Medium	Results of the test should be reported **using the following RAG rating (the lower the rating, the less confident we are in model stability)**: • Red (R): the estimated coefficients present changes in both significance and sign; • Amber (A): the estimated coefficients present some changes in significance but not in sign; and • Green (G): the estimated coefficients do not present changes in significance or sign.

To address Ofwat's sensitivity analysis suggestions (figure 22), we re-ran our shortlist of models with the most efficient company removed and separately the least efficient company removed. The same approach was applied with the removal of the first and last years of data from the panel.

The following sections outline our approach to this.

*We applied an only-as-good-as-your-worst approach. For example, if a significant variable remains significant when the best company is removed, but becomes insignificant when the worst company is removed, then the coefficient is granted **orange**.*

Our rules for colour coding **the variables** in the sensitivity analysis of the shortlist are as follows:

- Green
    - No major change in significance and no change in sign of coefficient.
    - Any moves across the 10%, 5% and 1% significance levels remain green.
    - In a limited number of cases, any coefficient that began insignificant and remained insignificant also stays green.
        - *For example, when the best company is removed, the p-value of a variable coefficient moves from 0.3 to 0.4. No change in sign of the coefficient.*
- Yellow
    - Change in significance but not beyond 15% and no change in sign of coefficient.
    - This ensures that any coefficient that is originally significant within 10%, especially those close to 10%, are not removed if their significance levels change minimally.
        - *For example, when the worst company is removed, the p-value of a variable coefficient moves from 0.09 to 0.13 (or vice versa). There is no change in sign of the coefficient*
- Amber
    - Either a substantial change in significance, or a coefficient that was originally significant between 15-20% moves beyond 20%.

    - *For example, when the first year is removed, the p-value of a variable coefficient moves from 0.07 to 0.23. There is no change in sign of the coefficient.*
- Red
  - Sign of coefficient changes (and significance)
    - *For example, when the last year is removed, a previously positive coefficient turns negative.*

4.5.2 Determining the sensitivity of models

Our rules for colour coding the overall model in the sensitivity analysis of the shortlist are as follows:

- Green
  - All variables remain green after sensitivity check.
  - For models with AMP effects included, a maximum of 3 ambers across the AMP year/dummy variables were permitted.
    - *This prevents discrimination against AMP effects during the year sensitivity check.*
  - Variables that turned yellow were permitted.
- Amber
  - At least one variable (non-AMP effect) turned amber.
- Red
  - More than one variable (non-AMP effect) turned amber.
  - At least one variable (non-AMP effect) turned red.

Given the sample size, we expect that some variables will show a change in significance when removing a company or year from the model. Therefore, we consider that models with 'Amber' sensitivity are acceptable, but models with 'Red' sensitivities are not.

4.6 Selecting a final set of models

Our primary considerations when selecting a final set of models were as follows:

- Number of prior engineering logic expectations satisfied
- Journey from PR19 (number of changes from PR19 models)
- Number of model parameters used (to consider over-fitting risk)

We then undertook predictive performance checks to ensure that statistical robustness remained.

Balancing engineering logic with model simplicity:

Selected models are presented in sequence as increasing engineering expectations are added to PR19 models. Models with the same number of prior engineering expectations met are then ordered using predictive capability (R^2).

The models we are presenting show that there is a broad continuum between:

- increasing engineering coherence and improving/maintaining predictive capability (satisfying increasing engineering expectations); and

- increasing model complexity where supplementary variables are required (number of parameters) and/or increasing the number of incremental changes away from the PR19 models.

Consequently, we have presented a range of models across this continuum. Those on the left-hand side of our tables of models prioritise simplicity, whereas those on the right-hand side of the tables represent greater engineering coherence.

- It is our view that models should seek to increase the amount of engineering logic accounted for (i.e. moving to the right) until the additional model complexity creates complications which counteract the benefits of adding increasing engineering logic.
- We acknowledge that there is an element of judgement when selecting from this continuum. However, AIC is a useful measure that's shows where additional engineering logic may be outweighed by the risks of model complexity (i.e. overfitting).

4.7 Considering simpler and more sophisticated models separately

As we account for more engineering expectations, models are likely to get more complicated. Therefore, there is likely to be a trade-off between adding additional parameters to account for them and running into econometric problems such as overfitting or deriving models that are overly complex and therefore difficult to interpret or challenge.

Identifying 'simple' models

We have initially presented a series of 'simple' models across this continuum which take the same form as PR19 models. These are limited to a:

- Scale driver;
- Measure(s) of economies of scale in assets/density;
- one or more complexity variables;
- potentially a weather variable.

All the variables can be explained and interpreted from an engineering perspective. As model parameters increase we have sought to test that additional parameters are being justified with a corresponding predictive improvement using the Akaike Information Criterion.

Presentation of more sophisticated but complex models

Models with AMP years, AMPs and spatial variables have been presented after the 'simpler' models. This is to acknowledge that these models are more complex than PR19 models. They conform to expectation and improve predictive capability of the models. However, we acknowledge that the additional parameters also increase the risk the models are over fitted, particularly in waste where there are fewer companies. We have excluded models or have been clear where we think this may be a problem.

4.7.1 AMP cycle remedies

Including AMP year and AMP indicators goes some way to correcting for the issue of model residuals varying over time (see figure 23). AMP year indicators explaining the cyclical pattern, and AMP indicators allow for structural changes between AMPs.

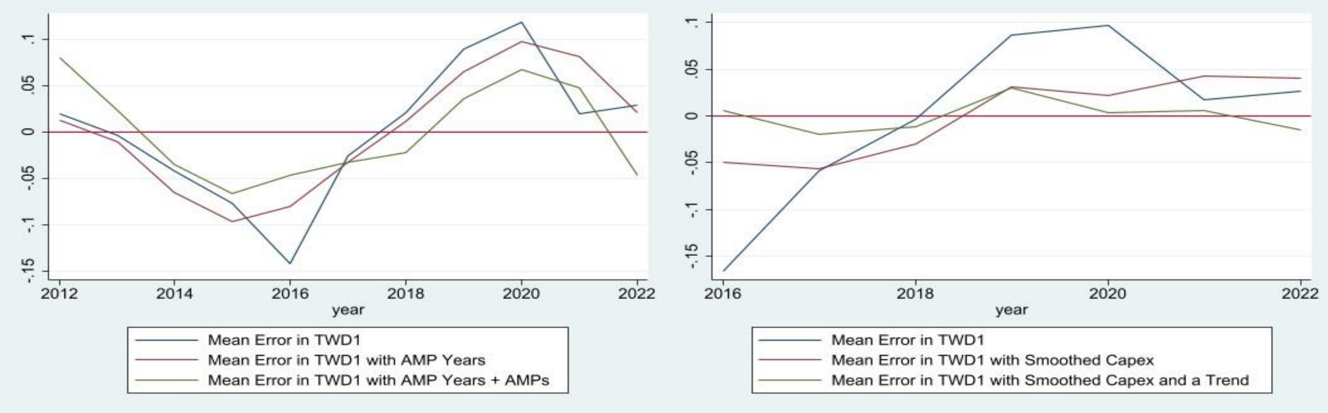
Correcting for this pattern also allows for the ‘true’ effects of the explanatory variables to be identified. Without this, we may wrongly attribute some variable as having an association with costs when in reality, over the course of the short historical panel, there is an association with the AMP year which may or may not itself be spurious.

We also considered smoothed capex as an alternative and see that with the inclusion of a trend this has a similar effect (see figure 23). The smoothed models we report use a 5-year rolling average (4 historical years plus the current year) to smooth capex, hence the smaller sample size, but alternatives could be considered, such as 2 previous years, the current year, and 2 future years. The latter may align with Ofwat’s desire to give some consideration to the future in its modelling.

Whilst a time trend is not likely to be appropriate in an unsmoothed model because of the short time series and potential structural break between AMPs, this becomes much less concerning in a smoothed model where the underlying trend is much clearer.

While the logic holds for all subservices, the additional variables – or in the case of smoothed capex the loss of observations – lead to a danger of overfitting. While we contest that this is less of a problem in water as shown by AIC (described in 4.5.3), we accept that this is a problem in waste, due to the smaller initial set of observations.

Figure 23: Correcting for AMP cycle effects using AMP years and AMP dummies (left).Correcting for AMP cycle effects using smoothed capex and time trend (right).



4.7.2 Allowing for spatial dependencies through inclusion of spatially weighted cost drivers

Spatial dependencies exist in regulated utilities, especially if companies operate and monopolise separate regions. This implies that certain characteristics across neighbouring companies may be spatially correlated which violates the fundamental assumption of independent observations/entities. Not accounting for spatial autocorrelation can therefore result in unreliable and unstable regression estimates.

Spatial lags of variables can be produced through a spatial weights matrix and the observations of neighbouring companies. For example, SVE’s spatial lag of density can be calculated as:

$$W.Density_{SVE} = W_{SVE,HDD} \times Density_{HDD} + W_{SVE,WSH} \times Density_{WSH} + W_{SVE,TMS} \times Density_{TMS} + \cdots$$

Where $W_{i,j}$ is the spatial weight between companies i and j. These spatial weights are based on border length data between companies. Companies that share a longer border are more susceptible to spill-over effects and are also likely to be more consistent with the characteristics of that bordering company.

An important aspect of spatial econometrics is the specification of the spatial weights matrices. We have considered and applied two different specifications to determine the spatial weights due to differing theoretical justifications:

Specification 1 – Maximum Eigenvalue

Weights are normalised to the longest shared border in the whole sector – the border between SVE and SSC is given a weighting of 1 ($W_{SVE,SSC} = 1$) as this is the longest border (from 2019 onwards). Every border is therefore weighted according to its relative length to this border between SVE and SSC.

This allows spill-over effects between companies to stay relative (the effect of spill-over between the ANH and NES border would not be as strong as the one between SVE and SSC) as proportions between companies are preserved.

However, it is noted that much smaller companies may receive underestimated spatial lags due to their weights with other companies being almost negligible.

This specification appears to inflate VIF statistics because of correlation with the scale driver. This feels acceptable because larger companies with longer borders are likely to absorb more of an effect from their neighbours.

Specification 2 – Row Normalisation

Specification 2 uses weights normalised to each company's total border length (each weight is the proportion of the border to the company's total border length).

Spill-over effects onto small companies have the same potential as that of large companies. This is potentially useful if the purpose of the spatial lags is to form weighted average observations of a company's neighbours.

However, it also indicates that proportions between companies are lost, and asymmetries are introduced where $W_{SVE,SSC} \neq W_{SSC,SVE}$. This may produce counter-intuitive applications as a small border length on a small company may hold more importance than a longer border length but on a much larger company. This could only be plausible if the spill-over effect of a big company onto a small company is thought to be more substantive than the other way.

Nevertheless, total exposure to spatial effects is likely to vary from company to company[2]. Since this specification does not have a uniform normalisation factor (each row has a different scale factor), this approach tends to lead to misspecification unless strong theory grants its justification.

Spatial driver rationale

Including the spatial lags of variables in our models may not only account for unobserved heterogeneity between companies, but also provide flexibility across company characteristics.

For example, we are consistently finding the spatial lag of density and treatment complexity to be significant across our models.

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[2] Neumayer, E. & Plümper, T., (2015), W. Political Science Research and Methods. Pp. 1-19.

Density

The spatial lag of density can be thought of as providing a more complete picture of density rather than a uniform value across a company’s region. For example, Thames is seen to be an incredibly urban region given its high population density. The non-spatial models therefore assume the region has a uniform high-density level, failing to account for the vast areas of Thames which are very rural (e.g. Cotswolds). Therefore, the spatial lag provides an extra layer of density which proxies for the more rural regions close to the borders.

Treatment Complexity

The spatial lag of treatment complexity is thought to proxy for either unobserved or omitted geographical/regional variables, possibly topography/topology. Areas close to and across company borders are more likely to be similar in terms of such characteristics.

The current variables only capture the average of that characteristic for the company region. Using a spatial lag of such variables provides another layer of topography/topology built up as the weighted average of the company’s neighbours, providing information about the areas especially close to the borders.

5. Summary of models submitted

Our final selection of models is as follows (table 13).

Table 13: Number of models submitted buy scope

	WRP	TWD	SWC	SWT	WW	WWWNP	BR	Retail	Total
Simple models*	16	8	6	10	16	15	4	4	79
More novel models**	5	9	10	7					31
Total	21	17	16	17	16	15	4	4	110

**Models with primary cost drivers only*

***Models with additional time and special effects and smoothed capex*

The following tables in this section set out the models by scope. Simple models are presented first (on the left-hand side) followed by the more novel specifications (on the right-hand side).

We have grouped and categorised the explanatory variables according to engineering expectation. Cells are coloured green when the expectation has been met. Each table has then been ordered by the number of expectations met. This means that the models to the right of each table contain the most inherent engineering logic.

We have then set out the headline statistical tests that we have used to assess model performance and select models (R^2, AIC, Unit R^2 and σ_μ). These have been coloured to reflect their performance relative to the relative PR19 model(s) unless otherwise specified (WWWNP). Finally, we have set out the number of changes form PR19 models and the number of parameters estimated and highlighted where this may become a problem.

The colouring in the tables can be interpreted as follows:

- Model groupings (in header column): Ofwat model PR19 model (grey); Simple models (blue); models with AMP year dummies (pink); models with smoothed capex (turquoise); and models with spatial drivers (yellow).
- EE = Engineering expectation. Cells coloured green where satisfied. In Wholesale water and Network plus waste models, cells coloured light green when satisfied for one of TWD/WRP or SWC/SWT. Cells also coloured light green where the engineering expectation is partially satisfied (in these cases, the expectation has not been classified as met).
- R^2: The text is green where greater than Ofwat PR19;
- R^2 Unit considers Botex per unit, the text is green when greater than Ofwat PR19; σ_μ text is green when lower than Ofwat.
- AIC: Models are colour coded relative to the best performing model overall in the non-novel set and Ofwat's best performing model. Blue: AIC lower than best performing model, but model is in the novel set; Green: less than 4 greater than the best performing model; Yellow: More than 4 greater than the best performing model, but less than 4 lower than Ofwat's best performing model; Red: More than 4 greater than Ofwat's best performing model.
- Changes and number of parameters: The text is coloured amber where starting to be material.

5.1 Simple Water resources plus models

Key findings:

- We have been able to create a series of robust models that include an increased amount of engineering logic (from left to right in the table).
- Model performance remains high as additional engineering logic is added.
- Treatment pumping is a strong proxy for treatment complexity. Previous complexity bands didn't differentiate sufficiently. This can account for complexity by itself or add differentiation between the processes in bands 3-6.
- Economies of scale are desirable but aren't seen due to the interaction between GW and SW. However, the required GW and SW data is not available. Using density with a GW driver increases coherence.
- Economies of scale should always increase with density, therefore $density^2$ variables are not appropriate here. This is in line with the SWT models where data to allow for economies of scale is possible.
- APH_WR is insignificant in both models that use it. However, we have retained due to engineering logic.

Table 14: Final WRP models (simple)

Model	Ofwat PR19 WRP1	Ofwat PR19 WRP2	SVE-WRP1	SVE-WRP2	SVE-WRP3	SVE-WRP4	SVE-WRP5	SVE-WRP6	SVE-WRP7	SVE-WRP8
Scale (EE1)	Props	Props	Props	Props	Props	Props	Props	Props	Props	Props
Density	LAD	LAD	LAD	LAD	LAD	pop/km	LAD	LAD	LAD	LAD
GW effects (EE2)								%		
Density 2 (EE3)	Yes	Yes	Yes	🟩	Yes	🟩	🟩	Yes	🟩	🟩
Complexity bands (EE4)	Bands 3-6	Weighted	Bands 3-6	Bands 3-6	🟩	🟩	🟩	🟩	Bands 3-6	🟩
Treatment Pumping (EE5)			Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Raw water pumping (EE6)					Yes (WR)					
Weather (EE7)									Yes	yes
AMP years (EE8)										
AMPs										
Time Trend										
EEs met (of 8)	1	1	2	3	4	4	4	4	4	5
R^2	0.917	0.907	0.933	0.931	0.918	0.92	0.921	0.929	0.930	0.919
AIC	-23	-20	-26	-26	-21	-21	-23	-24	-26	-23
Unit $R^2_{properties}$	0.389	0.305	0.507	0.494	0.390	0.419	0.417	0.476	0.483	0.399
σ_μ	0.221	0.241	0.190	0.190	0.223	0.213	0.212	0.203	0.188	0.198
Changes from PR19			1	2	3	4	3	3	3	4
No. of parameters	5	5	6	5	5	4	4	6	6	5

Table 14: Final WRP models (simple), continued

Model	Ofwat PR19 WRP1	Ofwat PR19 WRP2	SVE-WRP9	SVE-WRP10	SVE-WRP11	SVE-WRP12	SVE-WRP13	SVE-WRP14	SVE-WRP15	SVE-WRP16
Scale (EE1)	Props	Props	Props	Props	Props	Props	Props	Props	Props	Props
Density	LAD	LAD	pop/km	pop/km	LAD	LAD	pop/km	pop/km	LAD	LAD
GW effects (EE2)			%	Interaction	%	Interaction	%	%	%	%
Density 2 (EE3)	Yes	Yes								
Complexity bands (EE4)	Bands 3-6	Weighted								
Treatment Pumping (EE5)			Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Raw water pumping (EE6)							Yes (WR)			Yes (WRP)
Weather (EE7)								yes	yes	yes
AMP years (EE8)										
AMPs										
Time Trend										
EEs met (of 8)	1	1	5	5	5	5	6	6	6	7
R^2	0.917	0.907	0.927	0.928	0.93	0.931	0.925	0.927	0.929	0.928
AIC	-23	-20	-23	-23	-25	-25	-22	-24	-25	-23
Unit $R^2_{properties}$	0.389	0.305	0.468	0.475	0.483	0.495	0.445	0.466	0.480	0.465
σ_μ	0.221	0.241	0.2	0.198	0.197	0.191	0.204	0.206	0.202	0.204
Changes from PR19			5	5	4	4	6	6	5	6
No. of parameters	5	5	5	5	5	5	6	6	6	7

5.1.1 More Novel WRP modelling

Key findings:

AMP years / AMPs

- Accounting for AMP years provides better specified models. This allows the company characteristic variable coefficients to be more reliable.
- AIC justifies the additional variables.
- Allowing for AMPs, does the same as above, but acknowledges structural changes between price reviews.

Smoothed capex in dependent variable.

- Accounting for AMP years can also be done by smoothing capex. This sacrifices observations for a more parsimonious model.
- R^2 remains high providing confidence that these models are accurately describing costs.

Table 15: Final WRP models (novel)

Model	Ofwat PR19 WRP1	Ofwat PR19 WRP2	SVE-WRP17	SVE-WRP18	SVE-WRP19	SVE-WRP20	SVE-WRP21
Scale (EE1)	Props	Props	Props	Props	Props	Props	Props
Density	LAD	LAD	LAD	Pop/km	LAD	LAD	LAD
GW effects (EE2)				%	%	%	%
Density 2 (EE3)	Yes	Yes	Yes				
Complexity bands (EE4)	Bands 3-6	Weighted	Bands 3-6				
Treatment Pumping (EE5)			Yes	Yes	Yes	Yes	Yes
Raw water pumping (EE6)			Yes (WRP)				
Weather (EE7)							
AMP years (EE8)			yes	yes	yes	Yes (smooth)	Yes (smooth)
AMPs				yes	yes		
Time Trend							Yes
EEs met (of 8)	1	1	4	6	6	6	6
R^2	0.917	0.907	0.92	0.933	0.935	0.938	0.939
AIC	-23	-20	-20	-31	-33	N/A	N/A
Unit $R^2_{properties}$	0.389	0.305	0.410	0.502	0.519	0.533	0.547
σ_μ	0.221	0.241	0.236	0.208	0.201	0.224	0.224
Changes from PR19			2	7	6	6	5
No. of parameters	5	5	10	11	11	5	6

5.2 Simple Treated Water Distribution models

Key findings:

- We have been able to create a series of robust models that include an increasing amount of engineering logic (from left to right in the table).
- Length of mains and properties both provide appropriate explanatory power as scale drivers.
- TWD had rurality and urbanity cost drivers.
  - Given this, density is best specified as properties / area, which doesn't weight to urban as LAD does.
  - In combination with a squared term, this allows for greater consideration of rurality cost drivers than other metrics (with the inflection point greater than low-density companies).
- APH and boosters/length both provide material explanatory power and can sit in models happily (remain significant and improve performance)
- Weather can be shown to have a small but significant impact on costs.
- Variables are available to improve model performance. AIC suggests adding these variables is justified.

Table 16: Final TWD models (simple)

Model	Ofwat PR19 TWD	SVE-TWD1	SVE-TWD2	SVE-TWD3	SVE-TWD4	SVE-TWD5	SVE-TWD6	SVE-TWD7	SVE-TWD8
Scale (EE1)	Length	Length	Props	Props	Length	Props	Props	Length	Props
Density (EE2)	LAD	LAD	LAD	MSOA	Pop/ km2	LAD	Pop/ km2	Pop/ km2	Pop/ km2
Density 2	yes	yes	yes	yes	yes	yes	yes	yes	yes
Boosters/ length (EE3)	yes	yes	yes	yes	yes	yes	yes	yes	yes
TWD pumping (EE4)		yes	yes	yes	yes	yes	yes	yes	yes
Weather (EE5)						yes		yes	yes
AMP years (EE6)									
AMPs									
Spatial drivers									
Time trend									
EEs met (of 6)	2	3	3	3	4	4	4	5	5
R^2	0.957	0.964	0.968	0.968	0.967	0.967	0.97	0.969	0.971
AIC	-128	-135	-142	-142	-142	-149	-147	-149	-153
Unit $R^2_{properties}$	0.433	0.584	0.581	0.580	0.606	0.605	0.601	0.626	0.621
Unit R^2_{length}	0.620	0.685	0.692	0.719	0.706	0.715	0.716	0.722	0.733
σ_μ	0.165	0.143	0.128	0.129	0.133	0.133	0.116	0.133	0.117
Changes from PR19		1	2	3	2	3	3	3	4
No. of parameters	5	6	6	6	6	7	6	7	7

5.2.1 More novel TWD modelling

AMP years / AMPs

- Accounting for AMP years provides better specified models. This allows the company characteristic variable coefficients to be more reliable.
- AIC justifies the additional variables.
- Allowing for AMPs, does the same as above, but acknowledges structural changes between price reviews.

Smoothed capex in dependent variable

- Accounting for AMP years can also be done by smoothing capex. This sacrifices observations for a more parsimonious model.
- R^2 remains high providing confidence that these models are accurately describing costs.

Spatial drivers

- The attributes of neighbouring companies can account for spatial autocorrelation. Some omitted variables relate to companies' regional circumstances (e.g. topography).
- For example, the spatial lag of density can be thought of as providing a more complete picture of density across a company's region.

Table 17: Final TWD models (novel)

Model	Ofwat PR19 (TWD)	SVE-TWD9	SVE-TWD10	SVE-TWD11	SVE-TWD12	SVE-TWD13	SVE-TWD14	SVE-TWD15	SVE-TWD16	SVE-TWD17
Scale (EE1)	Length	Props	Length	Props	Props	Props	Props	Props	Props	Props
Density (EE2)	LAD	Pop/ km2	Pop/ km2	Pop/ km2	Pop/ km2	Pop/ km2	Pop/ km2	Pop/ km2	Pop/ km2	Pop/ km2
Density 2	yes	yes	yes	yes	yes	yes				
Boosters/ length (EE3)	yes	yes	yes	yes	yes	yes	Yes	yes	yes	yes
TWD pumping (EE4)		yes	yes	yes	yes	yes	Yes	yes	yes	yes
Weather (EE5)			yes	yes	yes	yes				
AMP years (EE6)		yes	yes	yes	Yes (smooth)	Yes (smooth)		yes		yes
AMPs			yes	yes						
Spatial drivers							Yes (spec1)	Yes (spec1)	Yes (spec2)	Yes (spec2)
Time trend						Yes				
EEs met (of 6)	2	5	6	6	6	6	4	5	4	5
R^2	0.957	0.971	0.970	0.973	0.970	0.971	0.961	0.962	0.956	0.957
AIC	-128	-148	-152	-155	N/A	N/A	-134	-138	-127	-130
Unit $R^2_{properties}$	0.433	0.613	0.646	0.641	0.589	0.607	0.472	0.492	0.418	0.431
Unit R^2_{length}	0.620	0.725	0.736	0.785	0.791	0.794	0.622	0.635	0.561	0.567
σ_{μ}	0.165	0.122	0.137	0.121	0.150	0.150	0.184	0.175	0.198	0.192
Changes from PR19		4	5	6	5	6	5	6	5	6
No. of parameters	5	10	13	13	7	8	8	12	7	11

5.3 Simple Sewerage collection models

Key findings

Properties was selected over sewer length as the scale driver. This removes some of the data issues associated with PDAS data.

Choice of density measure doesn't seem to substantially affect the performance of models. Although our alternative density measure (altLAD) may not prove to be as strong on a performance basis, its engineering rationale means we have retained it.

Using more than one complexity driver improves model performance substantially.

The proportion of combined sewers is a strong complexity driver as it is included in all improved models.

Pumping capacity per length remains in the majority of models but we have concerns over the veracity of the data.

Weather provides a small but significant improvement to the models in terms of unit R^2.

Table 18: Final SWC models (simple)

Model	Ofwat PR19 (SWC)	CMA PR19 (SWC)	SVE - SWC1	SVE – SWC2	SVE – SWC3	SVE – SWC4	SVE – SWC5	SVE – SWC6
Scale (EE1)	Sewer length	Sewer length	Props	Props	Props	Props	Props	Props
Economies of Scale (population density) (EE2)	Pop/ length	LAD	LAD	altLAD	LAD	altLAD	Props / legacy length	Props / legacy length
Density 2		Yes	Yes	Only	Yes	Only	Yes	Yes
Complexity (EE3)	Pumping capacity	Pumping capacity	Pumping capacity / legacy length and combined sewers / legacy length	Pumping capacity / legacy length and combined sewers / legacy length	Pumping capacity / legacy length and combined sewers / legacy length	Pumping capacity / legacy length and combined sewers / legacy length	combined sewers / legacy length	combined sewers / legacy length
Weather (EE4)					Yes	Yes		Yes
AMP years (EE5)								
AMPs								
Spatial								
EEs met (of 5)	1	0	1	1	2	2	3	4
R^2	0.917	0.895	0.941	0.937	0.941	0.937	0.93	0.93
AIC	-120	-114	-139	-133	-137	-132	-124	-125
Unit $R^2_{properties}$	0.549	0.593	0.681	0.656	0.681	0.655	0.62	0.621
Unit $R^2_{sewerlength}$	0.621	0.532	0.641	0.633	0.655	0.651	0.664	0.652
σ_μ	0.093	0.144	0.025	0.048	0.034	0.057	0.067	0.078
Changes from PR19			3	5	4	6	3	4
No. of parameters	4	5	6	6	7	6	5	6

5.3.1 More novel SWC models

AMP years / AMPs

- Accounting for AMP years provides better specified models. This allows the company characteristic variable coefficients to be more reliable.
- Allowing for AMPs, does the same as above, but acknowledges structural changes between price reviews.
- AIC suggests we shouldn't use AMP or AMP Year variables in waste however. Given the lower sample size relative to water, the additional fit does not give a better model than those without the AMP (year) effects.

Smoothed capex in dependent variable

- Accounting for AMP years can also be done by smoothing capex. This sacrifices observations for a more parsimonious model.
- R^2 remains high providing confidence that these models are accurately describing costs.

Spatial drivers

- The attributes of neighbouring companies can account for spatial autocorrelation. Some omitted variables relate to companies' regional circumstances (e.g. topography).

Table 19: Final SWC models (novel)

Model	Ofwat PR19 (SWC)	CMA PR19 (SWC)	SVE – SWC7	SVE – SWC8	SVE – SWC9	SVE – SWC10
Scale (EE1)	Sewer length	Sewer length	Props	Props	Props	Props
Economies of Scale (population density) (EE2)	Pop/ length	LAD	LAD	LAD	Props / legacy length	Props / legacy length
Density 2		Yes	Yes	Yes	Yes	Yes
Complexity (EE3)	Pumping capacity	Pumping capacity	Pumping capacity / legacy length and combined sewers / legacy length	Pumping capacity / legacy length and combined sewers / legacy length	combined sewers / legacy length	combined sewers / legacy length
Weather (EE4)						
AMP years (EE5)			Yes	Yes	Yes	Yes
AMPs				Yes		Yes
Spatial						
EEs met (of 5)	1	0	2	2	4	4
R^2	0.917	0.895	0.944	0.948	0.933	0.937
AIC	-120	-114	-135	-141	-121	-125
Unit $R^2_{properties}$	0.549	0.593	0.694	0.719	0.633	0.656
Unit $R^2_{sewerlength}$	0.621	0.532	0.651	0.675	0.676	0.695
σ_μ	0.093	0.144	0.025	0.029	0.067	0.068
Changes from PR19			4	4	4	4
No. of parameters	4	5	10	12	9	11

Table 19: Final SWC models (novel), continued

Model	Ofwat PR19 (SWC)	CMA PR19 (SWC)	SVE – SWC11	SVE – SWC12	SVE – SWC13	SVE – SWC14	SVE – SWC15	SVE – SWC16
Scale (EE1)	Sewer length	Sewer length	Props	Props	Props	Props	Props	Props
Economies of Scale (population density) (EE2)	Pop/ length	LAD	LAD	altLAD	altLAD	altLAD	LAD	LAD
Density 2		Yes	Yes	Only	Only	Only	Yes	Yes
Complexity (EE3)	Pumping capacity	Pumping capacity	Pumping capacity / legacy length and combined sewers / legacy length	Pumping capacity / legacy length and combined sewers / legacy length	Pumping capacity / legacy length and combined sewers / legacy length	c Pumping capacity / legacy length and combined sewers / legacy length	Pumping capacity / legacy length and combined sewers / legacy length	Pumping capacity / legacy length and combined sewers / legacy length
Weather (EE4)						Yes		
AMP years (EE5)								Yes
AMPs								Yes
Spatial					Yes (spec1)	Yes (spec1)	Yes (spec2)	Yes (spec2)
EEs met (of 5)	1	0	1	1	1	2	1	1
R^2	0.917	0.895	0.974	0.967	0.941	0.945	0.944	0.952
AIC	-120	-114	-148	-144	-136	-142	-138	-142
Unit $R^2_{properties}$	0.549	0.593	0.826	0.781	0.68	0.7	0.697	0.736
Unit $R^2_{sewerlength}$	0.621	0.532	0.738	0.722	0.635	0.675	0.719	0.753
σ_{μ}	0.093	0.144	0.066	0.081	0.04	0.033	0 (OLS)	0.011
Changes from PR19			3	5	6	7	4	5
No. of parameters	4	5	6	5	7	8	9	15

5.4 Simple sewage treatment models

Table 20: Final SWT models (simple)

Model	Ofwat PR19 (SWT1)	Ofwat PR19 (SWT2)	SVE-SWT1	SVE-SWT2	SVE-SWT3	SVE-SWT4	SVE-SWT5	SVE-SWT6	SVE-SWT7	SVE-SWT8	SVE-SWT9	SVE-SWT10
Scale (EE1)	Load	Load	Load	Load	Load	Load	Load	Load	Load	Load	Load	Load
Economies of Scale (population density) (EE2)	Size band 1-3	Size band 6	Size band 1-3	Weighted bands	Size band 1-3	Weighted bands	Size band 1-3	Weighted bands	Size band 1-3	Weighted bands	Weighted bands	Size band 1-3
Complexity (EE3)	Ammonia <3	Ammonia <3	Composite (ave P, NH,UV)	Composite (ave P, NH,UV)	Composite (WAC5)	Composite (WAC4)	Composite (WAC1)	Composite (WAC1)	Composite (WAC2)	Composite (WAC2)	Composite (WAC3)	Composite (WAC3)
AMP years (EE5)												
AMPs												
EE met (of 4)	2	1	3	3	3	3	3	3	3	3	3	3
R2	0.854	0.855	0.824	0.831	0.861	0.865	0.868	0.87	0.872	0.873	0.878	0.88
AIC	-105	-107	-103	-104	-106	-105	-110	-111	-110	-111	-108	-109
Unit R^2_{load}	0.362	0.365	0.265	0.281	0.403	0.410	0.431	0.439	0.446	0.448	0.466	0.477
σ_μ	0.180	0.187	0.172	0.177	0.178	0.181	0.178	0.179	0.175	0.176	0.170	0.167
Changes from PR19			1	2	1	2	1	2	1	2	2	1
No. of parameters	4	4	4	4	4	4	4	4	4	4	4	4

Key findings:

- A composite complexity driver appears to improve the performance of models.
- This shows that treating P to tight consent levels drives incremental costs over and above just treating to tight ammonia consents.
- There are various options of how to implement this interaction.
- But they all show that UV has very little impact on costs
- Weighted size bands best describe the average cost curve, therefore provide greatest theoretical coverage.
- Size bands 1-3 have the greatest change in costs and therefore explain most of the gradient of the average cost curve. Consequently, a threshold metric is pragmatic but lacks flexibility.

5.4.1 Novel sewage treatment models

AMP years / AMPs

- Accounting for AMP years provides better specified models. This allows the company characteristic variable coefficients to be more reliable.
- Allowing for AMPs, does the same as above, but acknowledges structural changes between price reviews.
- AIC suggests we shouldn't use AMP or AMP Year variables in waste however. Given the lower sample size relative to water, the additional fit does not give a better model than those without the AMP (year) effects.

Smoothed capex in dependent variable

- Accounting for AMP years can also be done by smoothing capex. This sacrifices observations for a more parsimonious model.
- R^2 remains high providing confidence that these models are accurately describing costs.

Table 21: Final SWT models (novel)

Model	Ofwat PR19 (SWT1)	Ofwat PR19 (SWT2)	SVE-SWT11	SVE-SWT12	SVE-SWT13	SVE-SWT14	SVE-SWT15	SVE-SWT16	SVE-SWT17
Scale (EE1)	Load	Load	Load	Load	Load	Load	Load	Load	Load
Economies of Scale (population density) (EE2)	Size band 1-3	Size band 6	Weighted bands	Size band 1-3	Size band 1-3	Weighted bands	Size band 1-3	Size band 1-3	Weighted bands
Complexity (EE3)	Ammonia <3	Ammonia <3	Composite (ave P, NH,UV)	Composite (ave P, NH)	Composite (WAC3)	Composite (WAC3)	Composite (WAC3)	Composite (WAC3)	Composite (WAC3)
AMP years (EE5)			yes	yes	Yes	yes	yes	Yes (smoothed)	Yes (smoothed)
AMPs			yes	yes		yes	yes		
EE met (of 4)	2	1	4	4	4	4	4	4	4
R^2	0.854	0.855	0.854	0.868	0.881	0.884	0.886	0.905	0.898
AIC	-105	-107	-107	-108	-105	-106	-106	N/A	N/A
Unit R^2_{load}	0.362	0.365	0.380	0.431	0.482	0.489	0.499	0.451	0.414
σ_μ	0.180	0.187	0.177	0.180	0.167	0.171	0.168	0.165	0.172
Changes from PR19			4	3	2	4	3	2	3
No. of parameters	4	4	10	10	8	10	10	4	4

5.5 Wholesale Water models

Key findings:

- We have been able to create a series of robust models that include an increased amount of engineering logic (from left to right in the table).
- Inclusion of Density2 is preferred suggesting the dominance of the TWD form
- Models select different complexity metrics however treatment pumping is shown in all models suggesting it is providing material predictive capability
- Water treatment pumping remains significant throughout
- Raw water and network typically provide additional model improvements.
- Weather is present in the majority of models,
- Model performance seems to be optimised where 6-9 engineering expectations are met, LAD density is used, and the model doesn't change substantially from those used at PR19.

Table 22: Final WW models (simple)

Model	Ofwat PR19 (WW1)	Ofwat PR19 (WW2)	SVE-WW1	SVE-WW2	SVE-WW3	SVE-WW4	SVE-WW5	SVE-WW6
Scale (WRPEE1/TWDEE1)	Props	Props	Props	Props	Props	Props	Props	Props
Density	LAD	LAD	LAD	LAD	LAD	LAD	LAD	LAD
GW effects (WRPEE2)								Yes
Density 2 (WRPEE3/TWDEE2)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Complexity bands (WRPEE4)	Bands 3-6	Weighted	Bands 3-6	Weighted	Bands 3-6	Weighted	Bands 3-6	
Boosters/length (TWDEE3)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Treatment Pumping (WRPEE5)			Yes	Yes	Yes	Yes	Yes	Yes
Raw water pumping (WRPEE6)					Yes	Yes		
TWD pumping (TWDEE4)			Yes	Yes	Yes	Yes	Yes	Yes
Weather (WRPEE7/TWDEE5)							Yes	
EEs met (of 14)	3	3	6	6	7	7	7	8
R^2	0.970	0.971	0.975	0.976	0.974	0.974	0.975	0.972
AIC	-161	-162	-171	-173	-170	-171	-173	-165
Unit R^2	0.531	0.547	0.614	0.623	0.591	0.591	0.617	0.567
σ_μ	0.111	0.097	0.096	0.085	0.105	0.096	0.1	0.122
Changes from PR19	0	0	2	2	2	2	3	3
No. of parameters	6	6	8	8	8	8	9	7

Table 22: Final WW models (simple) ,continued

Model	Ofwat PR19 (WW1)	Ofwat PR19 (WW2)	SVE-WW7	SVE-WW8	SVE-WW9	SVE-WW10	SVE-WW11	SVE-WW12	SVE-WW13	SVE-WW14	SVE-WW15	SVE-WW16
Scale (WRPEE1/TWDEE1)	Props	Props	Props	Props	Props	Props	Props	Props	Props	Props	Props	Props
Density	LAD	LAD	LAD	Pop/km2	LAD	LAD	LAD	LAD	LAD	Pop/km2	Pop/km2	LAD
GW effects (WRPEE2)					Yes				Yes	Yes	Yes	Yes
Density 2 (WRPEE3/TWDEE2)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Complexity bands (WRPEE4)	Bands 3-6	Weighted	Weighted			Weighted	Weighted					
Boosters/length (TWDEE3)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Treatment Pumping (WRPEE5)			Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Raw water pumping (WRPEE6)				Yes	Yes	Yes	Yes	Yes		Yes	Yes	Yes
TWD pumping (TWDEE4)			Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather (WRPEE7/TWDEE5)			Yes			Yes	Yes	Yes	Yes	Yes	Yes	Yes
EEs met (of 14)	3	3	8	9	9	9	9	10	10	11	11	11
R^2	0.970	0.971	0.976	0.967	0.97	0.973	0.973	0.968	0.973	0.968	0.969	0.97
AIC	-161	-162	-174	-168	-165	-172	-172	-167	-169	-167	-170	-168
Unit R^2	0.531	0.547	0.621	0.49	0.536	0.576	0.588	0.507	0.579	0.51	0.516	0.545
σ_μ	0.111	0.097	0.090	0.136	0.141	0.1	0.1	0.127	0.127	0.153	0.143	0.147
Changes from PR19	0	0	3	5	4	2	3	3	5	7	6	5
No. of parameters	6	6	9	7	8	8	9	8	9	9	8	9

5.6 Wastewater Network Plus models

Key Findings:

- We have generated to wide range of plausible models.
- Load dominates scale.
- Density and economies of scale iterate between models without significant preference.
- Composite complexity drivers are preferred. We considered a simple average complexity measure here, but the weighted average complexity variables we constructed remain significant at this level of aggregation.
- Pumping capacity per legacy length is included in all models.
- Weather provides better models in general, as do measures of density, as long as sewage works size is also accounted for.
- Given the lack of clear preferences within engineering groups and between SWC and SWT focused variables there is a strong case for triangulation.

Table 23: Final WWWNP models (simple)

Models	SVE-WWWNP1	SVE-WWWNP2	SVE-WWWNP3	SVE-WWWNP4	SVE-WWWNP5
Scale (SWCEE1/SWTEE1)	Load	Load	Load	Load	Load
Density (SWCEE2/SWTEE2)	LAD	Props / Legacy length	LAD& % Bands 1-3	LAD & Weighted Bands	Weighted Bands
Density 2			Yes	Yes	
Treatment Complexity (SWTEE3)	Ammonia <3mg/l	Ammonia <3mg/l	Composite (ave P, NH,UV)	Composite (ave P, NH,UV)	Composite (ave P, NH,UV)
Network Complexity (SWCEE3)	Pumping Capacity per Length	Pumping Capacity per Length & Prop Combined	Pumping Capacity per Length & Prop Combined	Pumping Capacity per Length & Prop Combined	Pumping Capacity per Length & Prop Combined
Weather (SWCEE4)			Yes	Yes	Yes
EEs met (of 7)	1	2	3	3	3
R^2	0.951	0.96	0.966	0.966	0.965
AIC	-172	-181	-192	-191	-194
Unit R^2	0.734	0.782	0.813	0.813	0.81
σ_μ	0.069	0.035	0	0	0
Changes from PR19	NA	NA	NA	NA	NA
No. of parameters	5	6	9	9	7

Note: Since we do not have PR19 models to compare to, AIC is coloured relative to the best performing of our models. Less than 4 away is green, less than 10 but more than 4 is amber, and more than 10 is red.

Table 23: Final WWWNP models (simple), continued

Models	SVE-WWWNP6	SVE-WWWNP7	SVE-WWWNP8	SVE-WWWNP9	SVE-WWWNP10	SVE-WWWNP11	SVE-WWWNP12	SVE-WWWNP13	SVE-WWWNP14	SVE-WWWNP15
Scale (SWCEE1/SWTEE1)	Load	Load	Load	Load	Load	Load	Load	Load	Load	Load
Density (SWCEE2/SWTEE2)	LAD & % Bands 1-3	% Bands 1-3	Weighted Bands	% Bands 1-3	LAD & Weighted Bands	Weighted Bands	% Bands 1-3	Weighted Bands	% Bands 1-3	Props / Legacy length & % Bands 1-3
Density 2	Yes									
Treatment Complexity (SWTEE3)	Composite (ave P, NH,UV)	Composite (ave P, NH,UV)	Composite (ave P, NH,UV)	Composite (ave P, NH,UV)	Composite (ave P, NH,UV)	Composite (ave P, NH,UV)	Composite (ave P, NH,UV)	Composite (ave P, NH,UV)	Composite (ave P, NH,UV)	Composite (ave P, NH,UV)
Network Complexity (SWCEE3)	Pumping Capacity per Length	Pumping Capacity per Length & Prop Combined	Pumping Capacity per Length & Prop Combined	Pumping Capacity per Length & Prop Combined	Pumping Capacity per Length	Pumping Capacity per Length	Pumping Capacity per Length	Pumping Capacity per Length	Pumping Capacity per Length	Pumping Capacity per Length
Weather (SWCEE4)	Yes	Yes			Yes	Yes	Yes			Yes
EEs met (of 7)	3	3	3	3	3	3	3	3	3	4
R^2	0.965	0.964	0.964	0.963	0.963	0.962	0.96	0.954	0.954	0.962
AIC	-191	-190	-193	-191	-188	-187	-183	-177	-177	-186
Unit R^2	0.808	0.803	0.805	0.801	0.8	0.794	0.78	0.751	0.747	0.794
σ_μ	0.035	0.011	0	0	0.03	0.036	0.054	0.066	0.067	0.036
Changes from PR19	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
No. of parameters	8	7	6	6	7	6	6	5	5	7

5.7 Bioresources models

Key Findings:

- Modelling in Bioresources appears difficult because proportional complexity variables are largely bunched at 0 or 1.
- Models suggest a diseconomy of scale is present
- Economies of scale in sludge collection can be accounted for in difference ways. Direct cost drivers include metrics using the size of sewage treatment works and a measure of intersiting ‘work’.
- Sewage treatment complexity has strong engineering rationale but is insignificant in models. This is likely due to the lack of tight P consents currently in the industry. Therefore, is feels like a strong candidate for a model adjustment claim.
- Disposal routes materially effects costs and perform well in models
- Cost pressures and opportunities from sludge treatment complexity are challenging to unpick however, % of AD and AAD are shown to be a legitimate cost driver.
- Density appears to proxy for several of the engineering expectations and performs well in models.

Table 24: Final BR models (simple)

Unit cost model	Ofwat PR19 (WW1)	Ofwat PR19 (WW1)	SVE-BR1	SVE-BR2	SVE-BR3	SVE-BR4
Scale	Sludge Prod.	Sludge Prod.	Sludge Prod.		Sludge Prod.	Sludge Prod.
Economies of Scale	PctBands13	STWs / Prop	PctBands13	Weighted Average Scale		
Density	Prop / Length					LAD
Density 2						Yes
Sludge treatment complexity					% AD or AAD	% AD or AAD
Intersiting			% truck or tanker	% truck or tanker	% truck or tanker and intersiting work per unit of sludge	% truck or tanker
Disposal route			% to farm	% to farm	% to farm	% to farm
AMP Years						
AMPs						
EEs met (of 5)	1	1	1	1	2	3
R^2	0.203	0.110	0.366	0.301	0.473	0.507
AIC	34	35	28	29	3	7
σ_μ	0.182	0.228	0.123	0.159	0.173	0.122
Changes from PR19	-	-	2	4	5	6
No. of parameters			5	5	4	5

5.8 Retail models

Key Findings:

- Economies of scale appear to be present in all models.
- Deprivation drivers appear to be interchangeable however bill size appears to be a more consistent explanatory variable.
- Meter penetration may provide some limited explanatory power, it may be proxied through other variables.
- Population transience is a poor variable and is always insignificant
- Density appears in all specifications, this is likely to be proxying for multiple expectations (e.g. deprivation, meter reading costs, and population transience such as student populations).

Table 25: Final RTC models (simple)

Unit cost model	Ofwat PR19 (re1)	Ofwat PR19 (re4320)	Ofwat PR19 (Re4332)	SVE- RTC1	SVE – RTC2	SVE- RTC3	SVE- RTC4
Scale		Households	Households	Households	Households	Households	Households
Meter penetration	Yes	Yes	Yes	Yes			
Dual service households							
Density				LAD	LAD	LAD	LAD
Density 2				Yes	Yes	Yes	
Deprivation	% Default	% Default	% Default & Income Score (u)	% Default	Council Tax, Credit Risk & Income Score (u)		
Bill Size	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Transience			Yes				
EEs met (of 6)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
R^2	0.613	0.636	0.636	0.695	0.673	0.675	0.661
AIC	-153	-156	-153	-160	-159	-161	-161
σ_μ	0.144	0.126	0.126	0.115	0.129	0.124	0.126
Changes from PR19				2	6	4	3
No. of parameters	5	6	8	7	8	5	4

ST Classification: UNMARKED

1. Treated Water Distribution

1.1. Econometric Models

Model Number	Model
SVE-TWD1	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Lengths\ of\ Main_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 (Ln(WADLADwater_{it}))^2 + \beta_4 Ln(Booster\ per\ Length_{it}) + \beta_5 Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$
SVE-TWD2	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 (Ln(WADLADwater_{it}))^2 + \beta_4 Ln(Booster\ per\ Length_{it}) + \beta_5 Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$
SVE-TWD3	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADMSOAwaterpopulation_{it}) + \beta_3 (Ln(WADMSOAwaterpopulation_{it}))^2 + \beta_4 Ln(Booster\ per\ Length_{it}) + \beta_5 Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$
SVE-TWD4	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Lengths\ of\ Main_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 (Ln(Populationperareawater_{it}))^2 + \beta_4 Ln(Booster\ per\ Length_{it}) + \beta_5 Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$
SVE-TWD5	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 (Ln(WADLADwater_{it}))^2 + \beta_4 Ln(Booster\ per\ Length_{it}) + \beta_5 Ln(APH\_TWD_{it}) + \beta_6 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$
SVE-TWD6	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 (Ln(Populationperareawater_{it}))^2 + \beta_4 Ln(Booster\ per\ Length_{it}) + \beta_5 Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$
SVE-TWD7	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Lengths\ of\ Main_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 (Ln(Populationperareawater_{it}))^2 + \beta_4 Ln(Booster\ per\ Length_{it}) + \beta_5 Ln(APH\_TWD_{it}) + \beta_6 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$
SVE-TWD8	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 (Ln(Populationperareawater_{it}))^2 + \beta_4 Ln(Booster\ per\ Length_{it}) + \beta_5 Ln(APH\_TWD_{it}) + \beta_6 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$
SVE-TWD9	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 (Ln(Populationperareawater_{it}))^2 + \beta_4 Ln(Booster\ per\ Length_{it}) + \beta_5 Ln(APH\_TWD_{it}) + \beta_6 AMPY2_t + \beta_7 AMPY3_t + \beta_8 AMPY4_t + \beta_9 AMPY5_t + \mu_i + \varepsilon_{it}$

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SVE-TWD10	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Lengths\ of\ Main_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 (Ln(Populationperareawater_{it}))^2 + \beta_4 Ln(Booster\ per\ Length_{it}) + \beta_5 Ln(APH\_TWD_{it}) + \beta_6 PropDaysOver25_{it} + \beta_7 AMPY2_t + \beta_8 AMPY3_t + \beta_9 AMPY4_t + \beta_{10} AMPY5_t + \beta_{11} AMP5_t + \beta_{12} AMP6_t + \mu_i + \varepsilon_{it}$
SVE-TWD11	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 (Ln(Populationperareawater_{it}))^2 + \beta_4 Ln(Booster\ per\ Length_{it}) + \beta_5 Ln(APH\_TWD_{it}) + \beta_6 PropDaysOver25_{it} + \beta_7 AMPY2_t + \beta_8 AMPY3_t + \beta_9 AMPY4_t + \beta_{10} AMPY5_t + \beta_{11} AMP5_t + \beta_{12} AMP6_t + \mu_i + \varepsilon_{it}$
SVE-TWD12	$Ln(BotexNR\_TWD\_sm_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 (Ln(Populationperareawater_{it}))^2 + \beta_4 Ln(Booster\ per\ Length_{it}) + \beta_5 Ln(APH\_TWD_{it}) + \beta_6 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$
SVE-TWD13	$Ln(BotexNR\_TWD\_sm_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Populatioperareawater_{it}) + \beta_3 (Ln(Populationperareawater_{it}))^2 + \beta_4 Ln(Booster\ per\ Length_{it}) + \beta_5 Ln\left(APH_{TWD_{it}}\right) + \beta_6 PropDaysOver25_{it} + \beta_7 t + \mu_i + \varepsilon_{it}$
SVE-TWD14	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 Ln(Booster\ per\ Length_{it}) + \beta_4 Ln(APH\_TWD_{it}) + \beta_5 W1_{it} Ln(Populationperareawater_{it}) + \beta_6 W1_{it} Ln(Booster\ per\ Length_{it}) + \beta_7 W1_{it} Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$
SVE-TWD15	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 Ln(Booster\ per\ Length_{it}) + \beta_4 Ln(APH\_TWD_{it}) + \beta_5 AMPY2_t + \beta_6 AMPY3_t + \beta_7 AMPY4_t + \beta_8 AMPY5_t + \beta_9 W1_{it} Ln(Populationperareawater_{it}) + \beta_{10} W1_{it} Ln(Booster\ per\ Length_{it}) + \beta_{11} W1_{it} Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$
SVE-TWD16	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 Ln(Booster\ per\ Length_{it}) + \beta_4 Ln(APH\_TWD_{it}) + \beta_5 W2_{it} Ln(Populationperareawater_{it}) + \beta_6 W2_{it} Ln(Booster\ per\ Length_{it}) + \beta_7 W2_{it} Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$

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SVE-TWD17	$Ln(BotexNR\_TWD_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 Ln(Booster\ per\ Length_{it}) + \beta_4 Ln(APH\_TWD_{it}) + \beta_5 AMPY2_t + \beta_6 AMPY3_t + \beta_7 AMPY4_t + \beta_8 AMPY5_t + \beta_9 W2_{it} Ln(Populationperareawater_{it}) + \beta_{10} W2_{it} Ln(Booster\ per\ Length_{it}) + \beta_{11} W2_{it} Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$

1.2. Variable List

Dependent Variable:	Variable name in model	Description
Treated Water Distribution (TWD) Botex including network reinforcement.	BotexNR_TWD	Treated Water Distribution Botex including network reinforcement as reported in the published PR24 wholesale dataset. Code: Botex+NR_TWD in Interface_real.
Smoothed Capex Treated Water Distribution Botex including network reinforcement	BotexNR_TWD_sm	Treated Water Distribution Botex with smoothed capex including network reinforcement. A 5-year rolling average (year t down to t-4) was used to smooth capex to form this botex measure.
Independent Variable:		
Total length of mains	Lengths of Main	Total mains length in km as reported in the published wholesale dataset. Code: lengthsofmain in Interface_real
Total properties	Properties	Total properties as reported in the published wholesale dataset. Code: properties in Interface_real
Population density	WADLADwater (WADLADwater2)	Weighted average population density using Local Authority Districts (LAD) as reported in the published wholesale dataset. WADLADwater2 is the squared density term for WADLADwater. Code: WAD-LAD-Water in Interface_real
Population density	WADMSOAwater population (WADMSOAwaterpopulation2)	Weighted average population density using Middle Layer Super Output Areas (MSOA) as reported in the published wholesale dataset. WADMSOAwaterpopulation2 is the squared density term for WADMSOAwaterpopulation. Code: WAD-MSOA-water-population in Interface_real
Population density	Populationperarea water (Populationperarea water2)	Population per area (km2) as reported in the published wholesale dataset. Populationperareawater2 is the squared density term for populationperareawater.

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		Code: Population per area – water in Interface_real
Network Complexity (boosters per length)	Booster per Length	Number of boosters per length of main as reported in the published wholesale dataset. Code: boosterperlength in Interface_real
Network Complexity (Average pumping head)	APH_TWD	Average Pumping Head (APH) – Distribution as reported in the published wholesale dataset (Stata dataset). Code: BN4870 in Stata dataset
Weather (days above a 25 degree celsius threshold)	PropDaysOver25	% of days in a year which experienced temperatures over 25 degrees Celsius. Calculated as the weighted average using 12km Hadley centre grids. See propDaysOver25 in Interface_real of SVE_FM_WW1.
AMP year	AMPY***X***	Dummy variable =1 if year is the $\boldsymbol{X^{th}}$ year of the AMP, =0 if year is the 1st year of the AMP.
AMP	AMP5 AMP6	Dummy variable =1 if year is in AMP5, 0 otherwise. Dummy variable =1 if year is in AMP6, 0 otherwise.
Spatial Lag of X	W1.*Variable* W2.*Variable*	The spatial lag of the respective independent variable using the maximum eigenvalue normalised spatial weights matrix (Specification 1). The spatial lag of the respective independent variable using the row normalised spatial weights matrix (Specification 2). Refer to section 4.7.2 'Improving Ofwat's cost models for use at PR24' for more information. Full derivation of spatial variables and subsequent data can be provided on request.
Time Trend	t	Time trend applied on the smoothed capex models only.

1.3. Brief Model Description

Model Number	Description
SVE-TWD1	As per Ofwat's PR19 model, with the addition of Average Pumping Head (Distribution) to improve engineering expectation within network complexity. The addition of APH clearly indicates a small but rather significant improvement in robustness in terms of R^2, RESET and AIC.
SVE-TWD2	As per SVE-TWD1, with the scale driver (length of mains) substituted for properties. The substitution produces a small but noteworthy improvement in robustness through R^2 and AIC.
SVE-TWD3	As per SVE-TWD2, with the population density measure (LAD) substituted for MSOA.
SVE-TWD4	As per SVE-TWD1, with the population density measure (LAD) substituted for population per area.
SVE-TWD5	As per SVE-TWD2, with weather (PropDaysOver25) included. The inclusion of weather is to proxy for atypical intensive asset use and peak demand.
SVE-TWD6	As per SVE-TWD2, with the population density measure (LAD) substituted for population per area. Slight improvement is shown through the AIC and Sigma u measures.
SVE-TWD7	As per SVE-TWD4, with weather (PropDaysOver25) included.
SVE-TWD8	As per SVE-TWD6, with weather (PropDaysOver25) included.

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SVE-TWD9	As per SVE-TWD6 with AMP year dummies included. The inclusion of AMP years allows for the fluctuation of capex cost across an AMP cycle to be accounted for in the models, despite the lack of improvement in robustness over SVE-TWD6.
SVE-TWD10	As per SVE-TWD7 with AMP year and AMP dummies included.
SVE-TWD11	As per SVE-TWD8 with AMP year and AMP dummies included.
SVE-TWD12	As per SVE-TWD8 with smoothed capex botex as the dependent variable.
SVE-TWD13	As per SVE-TWD12 with a time trend.
SVE-TWD14	As per SVE-TWD6 with spatial lags included and squared population density term excluded. The inclusion of spatial lags not only proxies for potential unobserved heterogeneity across companies, but also provides flexibility within company characteristics by providing a first-order gradient.
SVE-TWD15	As per SVE-TWD12 with AMP year dummies included.
SVE-TWD16	As per SVE-TWD12 with row-normalised spatial matrix as opposed to maximum eigenvalue normalisation. The spatial lag of APH_TWD was dropped in this model as it was insignificant.
SVE-TWD17	As per SVE-TWD14 with AMP year dummies included.

1.4. Brief Comment on the Models

We have included Ofwat's updated PR19 TWD model for comparative purposes (model number Ofwat PR19 TWD).

Models SVE-TWD1 to SVE-TWD11, and SVE-TWD14 to SVE-TWD17, use a panel spanning from 2011-12 to 2021-22, a total of 11 years.

Models SVE-TWD12 to SVE-TWD13 use a panel spanning from 2014-15 to 2021-2022, a total 7 years.

Alternative VIFs have been reported where squared population density terms have been included in the models. This is calculated without the problematic squared density term in the model as it is not a concern that this specific variable inflates the VIF.

Any insignificant variable that has remained in the models are due to their strength in engineering expectation and rationale.

Variables included in the following models are also relevant in other levels of aggregations and are included as such.

All variables are expressed in logs apart from the following: PropDaysOver25_10yrf, AMPY2, AMPY3, AMPY4, AMPY5, AMP5, AMP6.

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1.5. Model Results (SVE-TWD1 to SVE-TWD8)

	Ofwat PR19 TWD	SVE-TWD1	SVE-TWD2	SVE-TWD3	SVE-TWD4	SVE-TWD5	SVE-TWD6	SVE-TWD7	SVE-TWD8
Dependent Variable	BotexNR_ TWD	BotexNR_ TWD	BotexNR_ TWD	BotexNR_ TWD	BotexNR_ TWD	BotexNR_ TWD	BotexNR_ TWD	BotexNR_ TWD	BotexNR_ TWD
Lengthsofmain	1.077*** {0.000}	1.069*** {0.000}			1.132*** {0.000}			1.133*** {0.000}	
Properties			1.088*** {0.000}	1.059*** {0.000}		1.091*** {0.000}	1.094*** {0.000}		1.094*** {0.000}
WADLADwater	-2.946*** {0.000}	-2.879*** {0.000}	-2.494*** {0.000}			-2.393*** {0.000}			
WADLADwater2	0.235*** {0.000}	0.228*** {0.000}	0.180*** {0.000}			0.172*** {0.000}			
Boosterperlength	0.437*** {0.002}	0.334*** {0.008}	0.409*** {0.009}	0.509*** {0.000}	0.525*** {0.000}	0.419*** {0.003}	0.501*** {0.001}	0.522*** {0.000}	0.500*** {0.000}
APH_TWD		0.275*** {0.000}	0.333*** {0.000}	0.382*** {0.000}	0.222*** {0.002}	0.298*** {0.000}	0.303*** {0.000}	0.188** {0.012}	0.271*** {0.000}
WADMSOAwaterpopulation				-5.803*** {0.000}					
WADMSOAwaterpopulation2				0.378*** {0.000}					
Populationperareawater					-2.968*** {0.000}		-3.062*** {0.000}	-2.874*** {0.000}	-2.972*** {0.000}
Populationperareawater2					0.294*** {0.000}		0.269*** {0.000}	0.284*** {0.000}	0.260*** {0.000}
PropDaysOver25						0.017*** {0.000}		0.018*** {0.000}	0.017*** {0.000}
AMPY2									

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AMPY3									
AMPY4									
AMPY5									
AMP5									
AMP6									
t (trend)									
W1.Populationperareawater									
W1.Boosterperlength									
W1.APH_TWD									
W2.Populationperareawater									
W2.Boosterperlength									
Constant	4.722*** {0.002}	3.026** {0.032}	-2.021 {0.127}	12.272*** {0.007}	1.822 {0.268}	-2.215 {0.104}	-1.498 {0.243}	1.699 {0.336}	-1.616 {0.233}
Estimation Method	RE	RE	RE	RE	RE	RE	RE	RE	RE
N (Sample Size)	187	187	187	187	187	187	187	187	187
Model Robustness Tests									
R2 overall	0.957	0.964	0.968	0.968	0.967	0.97	0.97	0.969	0.971

RESET test		0.101	0.474	0.562	0.721	0.103	0.653	0.413	0.265	0.62
VIF (max)		2.108	211.424	208.531	504.846	255.653	212.331	256.119	259.365	259.865
Pooling / Chow test		0.814	1	0.96	0.889	1	0.999	0.999	1	1
Normality of model residuals		0.521	0.83	0.313	0.538	0.021	0.039	0.094	0.001	0.011
Heteroskedasticity of model residuals		0.248	0.883	0.73	0.27	0.977	0.399	0.83	0.628	0.43
Test of pooled OLS versus Random Effects (LM test)		0	0	0	0	0	0	0	0	0
Efficiency Score Distribution	Minimum	0.77	0.73	0.88	0.85	0.87	0.88	0.85	0.86	0.86
	Maximum	1.38	1.36	1.43	1.46	1.36	1.35	1.44	1.29	1.37
Sensitivity of estimated coefficients to removal of most and least efficient company			G	G	G	G	G	G	G	G
Sensitivity of estimated coefficients to removal of first and last year of the sample			G	G	G	G	G	G	G	G
Additional Diagnostic Checks										
AIC		-128	-135	-142	-142	-142	-149	-147	-149	-153
Sigma u		0.165	0.143	0.128	0.129	0.133	0.126	0.116	0.133	0.117
Alternative VIF		2.108	2.163	2.214	1.735	2.18	2.312	2.173	2.236	2.173

1.6. Model Results (SVE-TWD9 to SVE-TWD17)

	SVE-TWD9	SVE-TWD10	SVE-TWD11	SVE-TWD12	SVE-TWD13	SVE-TWD14	SVE-TWD15	SVE-TWD16	SVE-TWD17
Dependent Variable	BotexNR_TWD	BotexNR_TWD	BotexNR_TWD	BotexNR_TWD_sm	BotexNR_TWD_sm	BotexNR_TWD	BotexNR_TWD	BotexNR_TWD	BotexNR_TWD
Lengthsofmain		1.127*** {0.000}							
Properties	1.097*** {0.000}		1.090*** {0.000}	1.109*** {0.000}	1.090*** {0.000}	1.003*** {0.000}	1.008*** {0.000}	1.074*** {0.000}	1.081*** {0.000}

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WADLADwater									
WADLADwater2									
Boosterperlength	0.516*** {0.000}	0.496*** {0.000}	0.481*** {0.000}	0.567*** {0.001}	0.551*** {0.003}	0.630*** {0.000}	0.656*** {0.000}	0.788*** {0.000}	0.833*** {0.000}
APH_TWD	0.301*** {0.000}	0.196*** {0.009}	0.274*** {0.000}	0.206* {0.096}	0.188 {0.155}	0.230** {0.011}	0.227** {0.015}	0.267*** {0.002}	0.259*** {0.009}
WADMSOAwaterpopulation									
WADMSOAwaterpopulation2									
Populationperareawater	-3.125*** {0.000}	-2.751*** {0.001}	-2.873*** {0.000}	-2.415** {0.011}	-2.265** {0.031}	0.130 {0.144}	0.141* {0.097}	0.169 {0.123}	0.185* {0.089}
Populationperareawater2	0.275*** {0.000}	0.272*** {0.000}	0.250*** {0.000}	0.218*** {0.006}	0.202** {0.020}				
PropDaysOver25		0.018* {0.056}	0.017** {0.049}	0.009** {0.042}	0.005 {0.116}				
AMPY2	0.074*** {0.000}	0.092*** {0.000}	0.090*** {0.000}				0.084*** {0.000}		0.079*** {0.000}
AMPY3	0.085*** {0.009}	0.116*** {0.003}	0.116*** {0.004}				0.094*** {0.004}		0.092*** {0.004}
AMPY4	0.088*** {0.003}	0.065 {0.319}	0.065 {0.314}				0.098*** {0.001}		0.097*** {0.001}
AMPY5	0.082* {0.050}	0.120** {0.017}	0.118** {0.020}				0.093** {0.029}		0.090** {0.032}
AMP5		-0.073 {0.125}	-0.068 {0.163}						
AMP6		-0.03	-0.03						

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			{0.352}	{0.349}						
t (trend)						0.012* {0.096}				
W1.Populationperareawater							0.246** {0.044}	0.296** {0.018}		
W1.Boosterperlength							0.475*** {0.008}	0.556*** {0.002}		
W1.APH_TWD							0.142*** {0.005}	0.152*** {0.004}		
W2.Populationperareawater									0.378* {0.099}	0.477** {0.036}
W2.Boosterperlength									0.785** {0.038}	0.984** {0.010}
Constant		-1.382 {0.274}	1.27 {0.501}	-1.940 {0.167}	-3.047 {0.317}	-3.19 {0.321}	-8.868*** {0.000}	-8.943*** {0.000}	-8.385*** {0.000}	-8.180*** {0.000}
Estimation Method		RE	RE	RE	RE	RE	RE	RE	RE	RE
N (Sample Size)		187	187	187	112	112	187	187	187	187
Model Robustness Tests										
R2 overall		0.971	0.97	0.973	0.97	0.971	0.961	0.962	0.956	0.957
RESET test		0.298	0.528	0.743	0.18	0.322	0.935	0.895	0.65	0.579
VIF (max)		257.26	263.932	264.474	421.882	422.057	451.546	452.631	4.312	4.324
Pooling / Chow test		1	1	1	1	1	0.995	1	0.986	1
Normality of model residuals		0.111	0	0.003	0.579	0.854	0.065	0.087	0.007	0.009
Heteroskedasticity of model residuals		0.94	0.609	0.371	0.841	0.604	0.974	0.973	0.237	0.189
Test of pooled OLS versus Random Effects (LM test)		0	0	0	0	0	0	0	0	0
Efficiency Score Distribution	Minimum	0.86	0.85	0.83	0.82	0.79	0.81	0.80	0.83	0.83
	Maximum	1.45	1.29	1.33	1.36	1.33	1.45	1.40	1.62	1.57

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Sensitivity of estimated coefficients to removal of most and least efficient company	G	G	G	G	A	A	G	A	A
Sensitivity of estimated coefficients to removal of first and last year of the sample	G	A	A	G	A	A	G	G	G
Additional Diagnostic Checks									
AIC	-148	-152	-155	-181*	-188*	-134	-138	-127	-130
Sigma u	0.122	0.137	0.121	0.15	0.15	0.184	0.175	0.198	0.192
Alternative VIF	1.103	3.643	3.639	1.841	1.843	451.546	452.631	4.312	4.324
*AIC incomparable as different dependent variable is used.									

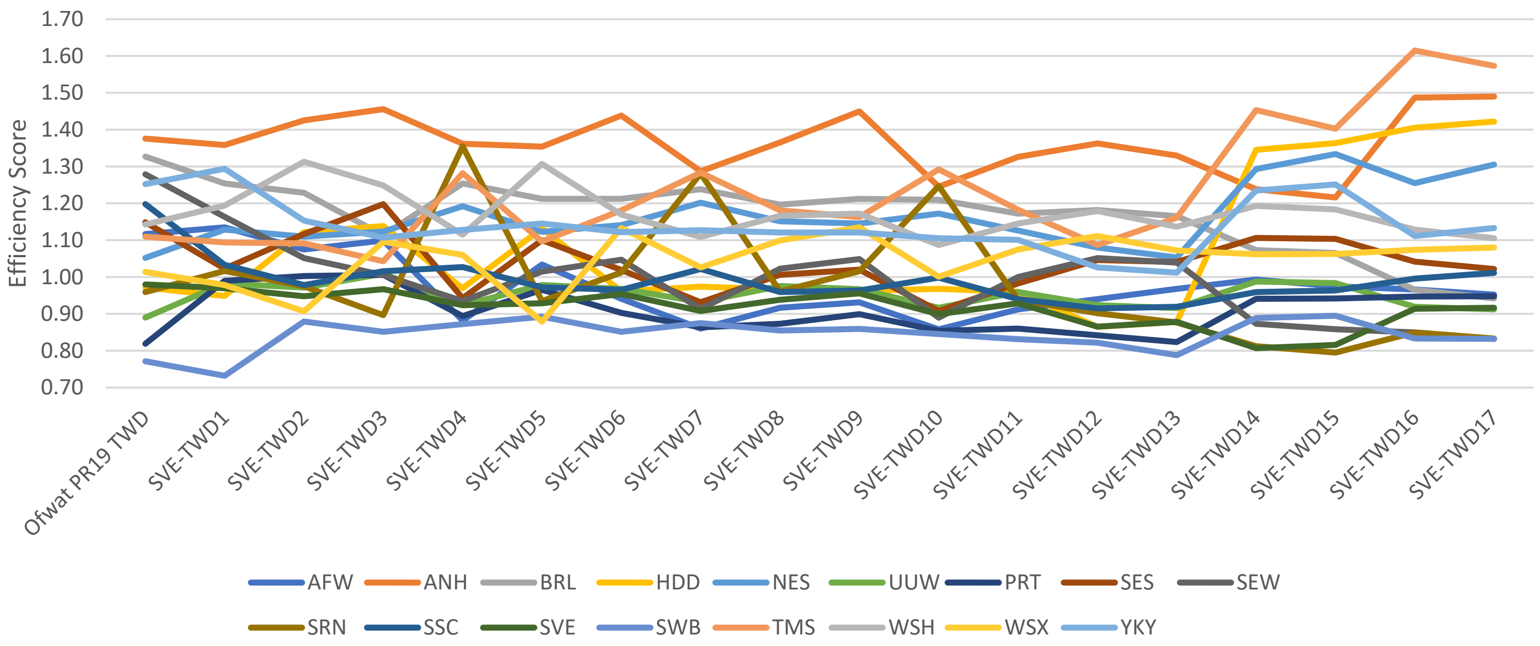
Figure 1.1. SVE-TWD Model Efficiency Score Distributions

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1.7. Efficiency Score Distribution & Rankings – Treated Water Distribution (SVE-TWD1 to SVE-TWD8)

Ranking	Ofwat PR19 TWD		SVE-TWD1		SVE-TWD2		SVE-TWD3		SVE-TWD4		SVE-TWD5		SVE-TWD6		SVE-TWD7		SVE-TWD8	
1	SWB	0.77	SWB	0.73	SWB	0.88	SWB	0.85	SWB	0.87	WSX	0.88	SWB	0.85	AFW	0.86	SWB	0.86
2	PRT	0.82	HDD	0.95	WSX	0.91	SRN	0.90	AFW	0.88	SWB	0.89	PRT	0.90	PRT	0.86	PRT	0.87
3	UUW	0.89	SVE	0.97	SVE	0.95	SVE	0.97	PRT	0.89	SVE	0.93	AFW	0.94	SWB	0.88	AFW	0.92
4	SRN	0.96	WSX	0.98	UUW	0.97	SEW	1.01	UUW	0.92	SRN	0.94	SVE	0.95	SVE	0.91	SVE	0.94
5	HDD	0.97	UUW	0.98	SRN	0.98	PRT	1.01	SVE	0.92	PRT	0.97	HDD	0.96	SEW	0.91	SSC	0.96
6	SVE	0.98	PRT	0.99	SSC	0.98	UUW	1.01	SEW	0.94	SSC	0.97	SSC	0.97	SES	0.93	SRN	0.96
7	WSX	1.01	SRN	1.02	PRT	1.00	SSC	1.02	SES	0.94	UUW	0.98	UUW	0.97	UUW	0.93	HDD	0.97
8	NES	1.05	SES	1.02	SEW	1.05	TMS	1.04	HDD	0.97	SEW	1.02	SRN	1.01	HDD	0.97	UUW	0.98
9	TMS	1.11	SSC	1.03	AFW	1.08	WSX	1.10	SSC	1.03	AFW	1.03	SES	1.02	SSC	1.02	SES	1.01
10	AFW	1.12	TMS	1.09	TMS	1.09	AFW	1.10	WSX	1.06	TMS	1.10	SEW	1.05	WSX	1.03	SEW	1.02
11	WSH	1.14	NES	1.13	NES	1.11	YKY	1.11	WSH	1.12	SES	1.10	YKY	1.12	WSH	1.11	WSX	1.10
12	SES	1.15	AFW	1.14	SES	1.12	BRL	1.11	YKY	1.13	NES	1.12	WSX	1.13	YKY	1.13	YKY	1.12
13	SSC	1.20	SEW	1.16	HDD	1.12	NES	1.12	NES	1.19	HDD	1.13	NES	1.14	NES	1.20	NES	1.15
14	YKY	1.25	WSH	1.19	YKY	1.15	HDD	1.14	BRL	1.25	YKY	1.15	WSH	1.17	BRL	1.24	WSH	1.17
15	SEW	1.28	BRL	1.25	BRL	1.23	SES	1.20	TMS	1.28	BRL	1.21	TMS	1.18	SRN	1.28	TMS	1.18
16	BRL	1.33	YKY	1.29	WSH	1.31	WSH	1.25	SRN	1.36	WSH	1.31	BRL	1.21	TMS	1.28	BRL	1.20
17	ANH	1.38	ANH	1.36	ANH	1.43	ANH	1.46	ANH	1.36	ANH	1.35	ANH	1.44	ANH	1.29	ANH	1.37

1.8. Efficiency Score Distribution & Rankings – Treated Water Distribution (SVE-TWD9 to SVE-TWD17)

Ranking	SVE-TWD9		SVE-TWD10		SVE-TWD11		SVE-TWD12		SVE-TWD13		SVE-TWD14		SVE-TWD15		SVE-TWD16		SVE-TWD17	
1	SWB	0.86	SWB	0.85	SWB	0.83	SWB	0.82	SWB	0.79	SVE	0.81	SRN	0.80	SWB	0.83	SEW	0.83
2	PRT	0.90	PRT	0.85	PRT	0.86	PRT	0.84	PRT	0.82	SRN	0.81	SVE	0.82	SEW	0.85	SWB	0.83
3	AFW	0.93	AFW	0.86	AFW	0.91	HDD	0.87	SRN	0.88	SEW	0.87	SEW	0.86	SRN	0.85	SRN	0.83
4	SVE	0.96	SEW	0.89	SVE	0.93	SVE	0.87	HDD	0.88	SWB	0.89	SWB	0.90	SVE	0.91	UUW	0.91
5	HDD	0.96	SVE	0.90	SRN	0.94	SRN	0.90	SVE	0.88	PRT	0.94	PRT	0.94	UUW	0.92	SVE	0.92

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6	SSC	0.96	SES	0.91	SSC	0.94	SSC	0.92	UUW	0.92	SSC	0.96	SSC	0.96	PRT	0.95	BRL	0.94
7	UUW	0.97	UUW	0.92	UUW	0.96	UUW	0.92	SSC	0.92	UUW	0.99	AFW	0.98	BRL	0.97	PRT	0.95
8	SRN	1.02	HDD	0.97	HDD	0.96	AFW	0.94	AFW	0.97	AFW	0.99	UUW	0.98	AFW	0.97	AFW	0.95
9	SES	1.02	SSC	1.00	SES	0.98	YKY	1.03	YKY	1.01	WSX	1.06	WSX	1.06	SSC	1.00	SSC	1.01
10	SEW	1.05	WSX	1.00	SEW	1.00	SES	1.05	SEW	1.04	BRL	1.07	BRL	1.07	SES	1.04	SES	1.02
11	YKY	1.12	WSH	1.09	WSX	1.08	SEW	1.05	SES	1.04	SES	1.11	SES	1.10	WSX	1.07	WSX	1.08
12	WSX	1.14	YKY	1.11	YKY	1.10	NES	1.08	NES	1.05	WSH	1.19	WSH	1.18	YKY	1.11	WSH	1.11
13	NES	1.15	NES	1.17	NES	1.13	TMS	1.09	WSX	1.07	YKY	1.24	ANH	1.22	WSH	1.13	YKY	1.13
14	TMS	1.16	BRL	1.21	WSH	1.15	WSX	1.11	WSH	1.14	ANH	1.24	YKY	1.25	NES	1.26	NES	1.31
15	WSH	1.17	ANH	1.25	BRL	1.17	WSH	1.18	TMS	1.16	NES	1.29	NES	1.33	HDD	1.41	HDD	1.42
16	BRL	1.21	SRN	1.25	TMS	1.18	BRL	1.18	BRL	1.17	HDD	1.35	HDD	1.36	ANH	1.49	ANH	1.49
17	ANH	1.45	TMS	1.29	ANH	1.33	ANH	1.36	ANH	1.33	TMS	1.45	TMS	1.40	TMS	1.62	TMS	1.57

2. Water Resources Plus

2.1. Econometric Models

Model Number	Model
SVE-WRP1	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(pctwatertreated36_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 Ln(APH\_WT_{it}) + \mu_i + \varepsilon_{it}$
SVE-WRP2	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(pctwatertreated36_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 Ln(APH\_WT_{it}) + \mu_i + \varepsilon_{it}$
SVE-WRP3	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 (Ln(WADLADwater_{it}))^2 + \beta_4 Ln(APH\_WT_{it}) + \beta_5 Ln(APH\_WR_{it}) + \mu_i + \varepsilon_{it}$
SVE-WRP4	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(APH\_WT_{it}) + \beta_3 Ln(Populationperareawater_{it}) + \mu_i + \varepsilon_{it}$
SVE-WRP5	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 Ln(APH\_WT_{it}) + \mu_i + \varepsilon_{it}$
SVE-WRP6	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 (Ln(WADLADwater_{it}))^2 + \beta_4 Ln(APH\_WT_{it}) + \beta_5 PropGW_{it} + \mu_i + \varepsilon_{it}$
SVE-WRP7	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(pctwatertreated36_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 Ln(APH\_WT_{it}) + \beta_5 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$
SVE-WRP8	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 Ln(APH\_WT_{it}) + \beta_4 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$
SVE-WRP9	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(APH\_WT_{it}) + \beta_3 Ln(Populationperareawater_{it}) + \beta_4 PropGW_{it} + \mu_i + \varepsilon_{it}$
SVE-WRP10	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(APH\_WT_{it}) + \beta_3 Ln(Populationperareawater_{it}) + \beta_4 Ln(PopulationperareawaterGW_{it}) + \mu_i + \varepsilon_{it}$
SVE-WRP11	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 Ln(APH\_WT_{it}) + \beta_4 PropGW_{it} + \mu_i + \varepsilon_{it}$
SVE-WRP12	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 Ln(APH\_WT_{it}) + \beta_4 Ln(WADLADwaterGW_{it}) + \mu_i + \varepsilon_{it}$
SVE-WRP13	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(APH\_WT_{it}) + \beta_3 Ln(APH\_WR_{it}) + \beta_4 PropGW_{it} + \beta_5 Ln(Populationperareawater_{it}) + \mu_i + \varepsilon_{it}$

SVE-WRP14	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 Ln(APH\_WT_{it}) + \beta_4 PropDaysOver25_{it} + \beta_5 PropGW_{it} + \mu_i + \varepsilon_{it}$
SVE-WRP15	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 Ln(APH\_WT_{it}) + \beta_4 PropGW_{it} + \beta_5 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$
SVE-WRP16	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 Ln(APH\_WT_{it}) + \beta_4 PropGW_{it} + \beta_5 PropDaysOver25_{it} + \beta_6 Ln(APH\_WR_{it}) + \mu_i + \varepsilon_{it}$
SVE-WRP17	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(pctwatertreated36_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 Ln(APH\_WRP_{it}) + \beta_6 AMPY2_t + \beta_7 AMPY3_t + \beta_8 AMPY4_t + \beta_9 AMPY5_t + \mu_i + \varepsilon_{it}$
SVE-WRP18	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Populationperareawater_{it}) + \beta_3 Ln(APH\_WT_{it}) + \beta_4 PropGW_{it} + \beta_5 AMPY2_t + \beta_6 AMPY3_t + \beta_7 AMPY4_t + \beta_8 AMPY5_t + \beta_9 AMP5_t + \beta_{10} AMP6_t + \mu_i + \varepsilon_{it}$
SVE-WRP19	$Ln(BotexNR\_WRP_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 Ln(APH\_WT_{it}) + \beta_4 PropGW_{it} + \beta_5 AMPY2_t + \beta_6 AMPY3_t + \beta_7 AMPY4_t + \beta_8 AMPY5_t + \beta_9 AMP5_t + \beta_{10} AMP6_t + \mu_i + \varepsilon_{it}$
SVE-WRP20	$Ln(BotexNR\_WRP\_sm_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 Ln(APH\_WT_{it}) + \beta_4 PropGW_{it} + \mu_i + \varepsilon_{it}$
SVE-WRP21	$Ln(BotexNR\_WRP\_sm_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WADLADwater_{it}) + \beta_3 Ln(APH\_WT_{it}) + \beta_4 PropGW_{it} + \beta_5 t + \mu_i + \varepsilon_{it}$

2.2. Variable List

Dependent Variable:	Variable name in model	Description
Water Resources Plus botex including network reinforcement.	BotexNR_WRP	Water Resources Plus botex including network reinforcement as reported in the published PR24 wholesale dataset. Code: Botex+NR_WRP in Interface_real.
Smoothed Capex Water Resources Plus Botex including network reinforcement	BotexNR_WRP_sm	Water Resources Plus Botex with smoothed capex including network reinforcement. A 5-year rolling average (year t down to t-4) was used to smooth capex to form this botex measure.
Independent Variable:		
Total properties	Properties	Total properties as reported in the published wholesale dataset.

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		Code: properties in Interface_real
Population density	WADLADwater (WADLADwater2)	Weighted average population density using Local Authority Districts (LAD) as reported in the published wholesale dataset. WADLADwater2 is the squared density term for WADLADwater. Code: WAD-LAD-Water in Interface_real
Population density	WADMSOAwater-population (WADMSOAwater-population2)	Weighted average population density using Middle Layer Super Output Areas (MSOA) as reported in the published wholesale dataset. WADMSOAwaterpopulation2 is the squared density term for WADMSOAwaterpopulation. Code: WAD-MSOA-water-population in Interface_real
Population density	Populationperarea-water (Populationperarea-water2)	Population per area (km2) as reported in the published wholesale dataset. Populationperareawater2 is the squared density term for populationperareawater. Code: Population per area – water in Interface_real
Population density	PropGW	Proportion of water treatment works that serve Ground Water (GW). See propGW in Interface_real of SVE_FM_WW1
Population density×PropGW	WADLADwaterGW	Interaction term between population density (LAD) and Ground Water %.
Population density× PopulationperareawaterGW	Populationperarea-waterGW	Interaction term between population density (Population per area) and Ground Water %.
Treatment Complexity	Pctwatertreated36	Proportion of volume of water treated in complexity bands 3 to 6 as reported in the published wholesale dataset. Code: Pctwatertreated36 in Interface_real
Network Complexity (Average pumping head – treatment)	APH_WT	Average Pumping Head (APH) – Treatment as reported in the published wholesale dataset (Stata dataset). Code: BN10902 in Stata dataset
Network Complexity (Average pumping head - resources)	APH_WR	Average Pumping Head (APH) – Resources as reported in the published wholesale dataset (Stata dataset). Code: BN4861 in Stata dataset
Network Complexity	APH_WRP	Average Pumping Head (APH) – Water Resources Plus calculated as the sum of APH – Resources, Raw water transport & Treatment

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		as reported in the published wholesale dataset (Stata dataset). Code: BN4861 + BN4862 + BN10902 in Stata dataset (real)
Weather (days above a 25 degree celsius threshold)	PropDaysOver25	% of days in a year which experienced temperatures over 25 degrees Celsius. Calculated as the weighted average using 12km Hadley centre grids. See propDaysOver25 in Interface_real of SVE_FM_WW1
AMP year	AMPYX	Dummy variable =1 if year is the X^{th} year of the AMP, =0 if year is the 1st year of the AMP.
AMP	AMP5 AMP6	Dummy variable =1 if year is in AMP5, 0 otherwise. Dummy variable =1 if year is in AMP6, 0 otherwise.
Time Trend	t	Time trend applied on the smoothed capex models only.

2.3. Brief Model Description

Model Number	Description
SVE-WRP1	As per Ofwat PR19 WRP1, with the addition of Average Pumping Head (Treatment) to improve engineering expectations in network complexity. The addition of APH_WT to the Ofwat PR19 WRP1 model significantly improves model robustness as indicated by R2, significant reduction in efficiency score range and AIC.
SVE-WRP2	As per SVE-WRP1, without the inclusion of the squared population density term (WADLADwater2). Given the robustness results, it may be the squared density term is unnecessary and the engineering rationale behind it is questionable.
SVE-WRP3	As per SVE-WRP1, with the inclusion of Average Pumping Head (Resources) APH_WR to improve engineering expectations in network complexity. Pctwatertreated36 is also withdrawn.
SVE-WRP4	As per SVE-WRP2, without Pctwatertreated36, and population per area used as the population density measure instead of Local Authority Districts (LAD).
SVE-WRP5	As per SVE-WRP4, with LADs used as the population density measure instead of population per area.
SVE-WRP6	As per SVE-WRP5, with the inclusion of a squared population density term and PropGW. The inclusion of PropGW allows for the population density term to have a level of proxy for the cost differences exhibited between ground water and surface water.
SVE-WRP7	As per SVE-WRP2, with the inclusion of a weather variable (PropDaysOver25). The inclusion of weather is to proxy for atypical intensive asset use and peak demand.
SVE-WRP8	As per SVE-WRP7, without Pctwatertreated36.
SVE-WRP9	As per SVE-WRP4, with the inclusion of PropGW.
SVE-WRP10	As per SVE-WRP9, with PopulationperareawaterGW in place of PropGW.
SVE-WRP11	As per SVE-WRP5, with the inclusion of PropGW.

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SVE-WRP12	As per SVE-WRP11, with WADLADwaterGW in place of PropGW.
SVE-WRP13	As per SVE-WRP9, with the inclusion of APH_WR.
SVE-WRP14	As per SVE-WRP9, with the inclusion of weather (PropDaysOver25).
SVE-WRP15	As per SVE-WRP11, with the inclusion of weather (PropDaysOver25).
SVE-WRP16	As per SVE-WRP15, with the inclusion of APH_WR.
SVE-WRP17	As per Ofwat PR19 WRP1, with the inclusion of APH_WRP and AMP year dummies.
SVE-WRP18	As per SVE-WRP9, with the inclusion of AMP year and AMP dummies.
SVE-WRP19	As per SVE-WRP11, with the inclusion of AMP year and AMP dummies.
SVE-WRP20	As per SVE-WRP11, with smoothed capex WRP botex as the dependent variable.
SVE-WRP21	As per SVE-WRP20, with a trend.

2.4. Brief Comment on the Models

We have included Ofwat's updated PR19 WRP models for comparative purposes (model numbers Ofwat PR19 WRP1 and WRP2).

Models SVE-WRP1 to SVE-WRP19 use a panel spannning from 2011-12 to 2021-22, a total of 11 years.

Models SVE-WRP20 to SVE-WRP21 use a panel spanning from 2014-15 to 2021-2022, a total 7 years.

Alternative VIFs have been reported where squared population density terms have been included in the models. This is calculated without the problematic squared density term in the model as it is not a concern that this specific variable inflates the VIF.

Any insignificant variable that has remained in the models are due to their strength in engineering expectation and rationale.

Variables included in the following models are also relevant in other levels of aggregations and are included as such.

All variables are expressed in logs apart from the following: Pctwatertreated36, PropGW, PropDaysOver25, AMPY2, AMPY3, AMPY4, AMPY5, AMP5, AMP6.

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2.5. Model Results (SVE-WRP1 to SVE-WRP10)

	Ofwat PR19 WRP1	Ofwat PR19 WRP2	SVE-WRP1	SVE-WRP2	SVE-WRP3	SVE-WRP4	SVE-WRP5	SVE-WRP6	SVE-WRP7	SVE-WRP8	SVE-WRP9	SVE-WRP10
Dependent Variable	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP
Properties	1.074*** {0.000}	1.069*** {0.000}	1.066*** {0.000}	1.044*** {0.000}	1.097*** {0.000}	1.016*** {0.000}	1.056*** {0.000}	1.033*** {0.000}	1.047*** {0.000}	1.058*** {0.000}	0.980*** {0.000}	0.975*** {0.000}
Pctwatertreated36	0.006*** {0.000}		0.005*** {0.007}	0.005*** {0.007}					0.005** {0.012}			
WADLADwater	-1.614*** {0.000}	-1.412*** {0.005}	-1.228*** {0.001}	-0.180*** {0.005}	-1.487*** {0.006}		-0.176** {0.018}	-1.045*** {0.004}	-0.190*** {0.004}	-0.188** {0.012}		
WADLADwater2	0.101*** {0.000}	0.087*** {0.009}	0.075*** {0.004}		0.095** {0.011}			0.064*** {0.006}				
Wac (Ofwat models only)		0.377 {0.123}										
APH_WT			0.115* {0.057}	0.128** {0.024}	0.126** {0.038}	0.142** {0.014}	0.150*** {0.008}	0.141** {0.030}	0.127** {0.025}	0.154*** {0.006}	0.144** {0.018}	0.145** {0.018}
APH_WR					0.109 {0.138}							
APH_WRP												
Populationperareawater						-0.179** {0.037}					-0.136* {0.073}	-0.109 {0.134}
PopulationperareawaterGW												-0.059** {0.024}
WADLADwaterGW												
PropGW								-0.337**			-0.338**	

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								{0.035}			{0.023}	
PropDaysOver25									0.01 {0.204}	0.011 {0.123}		
AMPY2												
AMPY3												
AMPY4												
AMPY5												
AMP5												
AMP6												
t (trend)												
Constant	-5.093*** {0.000}	-5.805*** {0.000}	-6.554*** {0.000}	-9.877*** {0.000}	-6.164*** {0.000}	-9.332*** {0.000}	-9.701*** {0.000}	-6.355*** {0.000}	-9.862*** {0.000}	-9.690*** {0.000}	-8.961*** {0.000}	-9.041*** {0.000}
Estimation Method	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE
N (Sample Size)	187	187	187	187	187	187	187	187	187	187	187	187
Model Robustness Tests												
R2 overall	0.917	0.907	0.933	0.931	0.918	0.92	0.921	0.929	0.93	0.919	0.927	0.928
RESET test	0.438	0.324	0.571	0.852	0.482	0.75	0.884	0.694	0.922	0.953	0.923	0.906
VIF (max)	1.174	1.22	230.965	1.221	329.757	1.075	1.157	208.03	1.288	1.267	1.309	1.499
Pooling / Chow test	0.995	0.999	0.984	0.94	0.999	0.978	0.994	0.988	0.8	0.487	0.95	0.948
Normality of model residuals	0.128	0.574	0.956	0.353	0.024	0.353	0.005	0.888	0.377	0.014	0.256	0.373

Heteroskedasticity of model residuals		0	0	0.002	0.034	0.008	0.004	0.021	0	0.025	0.01	0	0
Test of pooled OLS versus Random Effects (LM test)		0	0	0	0	0	0	0	0	0	0	0	0
Efficiency Score Distribution	Minimum	0.53	0.50	0.60	0.60	0.58	0.58	0.59	0.61	0.59	0.59	0.59	0.59
	Maximum	2.02	1.98	1.71	1.63	1.60	1.50	1.57	1.79	1.60	1.54	1.61	1.63
Sensitivity of estimated coefficients to removal of most and least efficient company				A	A	A	G	G	A	A	A	G	G
Sensitivity of estimated coefficients to removal of first and last year of the sample				G	G	A	G	G	G	G	A	G	G
Additional Diagnostic Checks													
AIC		-23	-20	-26	-26	-21	-21	-23	-24	-26	-23	-23	-23
Sigma u		0.221	0.241	0.19	0.19	0.223	0.213	0.212	0.203	0.188	0.198	0.2	0.198
Alternative VIF		1.174	1.22	1.221	1.221	1.498	1.075	1.157	1.41	1.288	1.267	1.309	1.499

2.6. Model Results (SVE-WRP11 to SVE-WRP21)

	SVE-WRP11	SVE-WRP12	SVE-WRP13	SVE-WRP14	SVE-WRP15	SVE-WRP16	SVE-WRP17	SVE-WRP18	SVE-WRP19	SVE-WRP20	SVE-WRP21
Dependent Variable	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP	BotexNR_WRP_sm	BotexNR_WRP_sm
Properties	1.014*** {0.000}	1.003*** {0.000}	0.993*** {0.000}	0.979*** {0.000}	1.014*** {0.000}	1.021*** {0.000}	1.104*** {0.000}	0.979*** {0.000}	1.012*** {0.000}	1.040*** {0.000}	1.014*** {0.000}
Pctwatertreated36							0.005*** {0.008}				
WADLADwater	-0.142**	-0.114*			-0.153**	-0.147*	-1.992***		-0.153**	-0.152**	-0.164***

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	{0.037}	{0.077}			{0.030}	{0.055}	{0.000}		{0.020}	{0.022}	{0.010}
WADLADwater2							0.130*** {0.000}				
Wac (Ofwat models only)											
APH_WT	0.152** {0.012}	0.155*** {0.010}	0.137** {0.026}	0.137** {0.024}	0.145** {0.016}	0.141** {0.019}		0.157*** {0.005}	0.167*** {0.004}	0.131** {0.027}	0.134** {0.025}
APH_WR			0.074 {0.245}			0.049 {0.456}					
APH_WRP							0.159 {0.186}				
Populationperareawater			-0.130 {0.121}	-0.151* {0.058}				-0.162** {0.031}			
PopulationperareawaterGW											
WADLADwaterGW		-0.051** {0.020}									
PropGW	-0.335** {0.025}		-0.326** {0.033}	-0.365** {0.013}	-0.365** {0.013}	-0.356** {0.018}		-0.285* {0.066}	-0.296* {0.053}	-0.256 {0.108}	-0.277** {0.035}
PropDaysOver25				0.013* {0.064}	0.013* {0.069}	0.012* {0.077}					
AMPY2							0.026 {0.273}	0.077** {0.033}	0.076** {0.034}		
AMPY3							0.092** {0.047}	0.172*** {0.001}	0.171*** {0.001}		
AMPY4							0.027 {0.494}	0.115** {0.014}	0.114** {0.015}		
AMPY5							0.017 {0.619}	0.102** {0.025}	0.100** {0.029}		

AMP5									-0.190** {0.032}	-0.184** {0.037}		
AMP6									-0.087* {0.081}	-0.082* {0.096}		
t (trend)												0.013 {0.192}
Constant		-9.231*** {0.000}	-9.276*** {0.000}	-9.444*** {0.000}	-8.869*** {0.000}	-9.172*** {0.000}	-9.491*** {0.000}	-4.863*** {0.000}	-8.824*** {0.000}	-9.171*** {0.000}	-9.573*** {0.000}	-9.225*** {0.000}
Estimation Method		RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE
N (Sample Size)		187	187	187	187	187	187	187	187	187	112	112
Model Robustness Tests												
R2 overall		0.93	0.931	0.925	0.927	0.929	0.928	0.92	0.933	0.935	0.938	0.939
RESET test		0.976	0.967	0.904	0.939	0.991	0.987	0.802	0.958	1	0.939	0.669
VIF (max)		1.41	1.506	1.505	1.595	1.564	1.612	227.928	2.815	2.813	1.712	1.713
Pooling / Chow test		0.936	0.915	0.977	0.948	0.919	0.99	1	1	1	1	1
Normality of model residuals		0.768	0.817	0.292	0.259	0.809	0.685	0.406	0.485	0.576	0.368	0.513
Heteroskedasticity of model residuals		0	0	0	0	0	0	0	0	0	0.038	0.047
Test of pooled OLS versus Random Effects (LM test)		0	0	0	0	0	0	0	0	0	0	0
Efficiency Score Distribution	Minimum	0.61	0.61	0.57	0.57	0.59	0.58	0.53	0.57	0.58	0.61	0.60
	Maximum	1.71	1.72	1.59	1.60	1.70	1.67	1.84	1.50	1.58	1.57	1.51
Sensitivity of estimated coefficients to removal of most and least efficient company		G	G	A	G	G	A	A	G	G	G	A
Sensitivity of estimated coefficients to removal of		G	G	A	G	G	G	A	G	G	G	A

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first and last year of the sample											
Additional Diagnostic Checks											
AIC	-25	-25	-22	-24	-25	-23	-20	-31	-33	-124*	-129*
Sigma u	0.197	0.191	0.204	0.206	0.202	0.204	0.236	0.208	0.201	0.224	0.224
Alternative VIF	1.41	1.506	1.505	1.595	1.564	1.612	1.82	2.815	2.813	1.712	1.713
*AIC incomparable as different dependent variable is used.											

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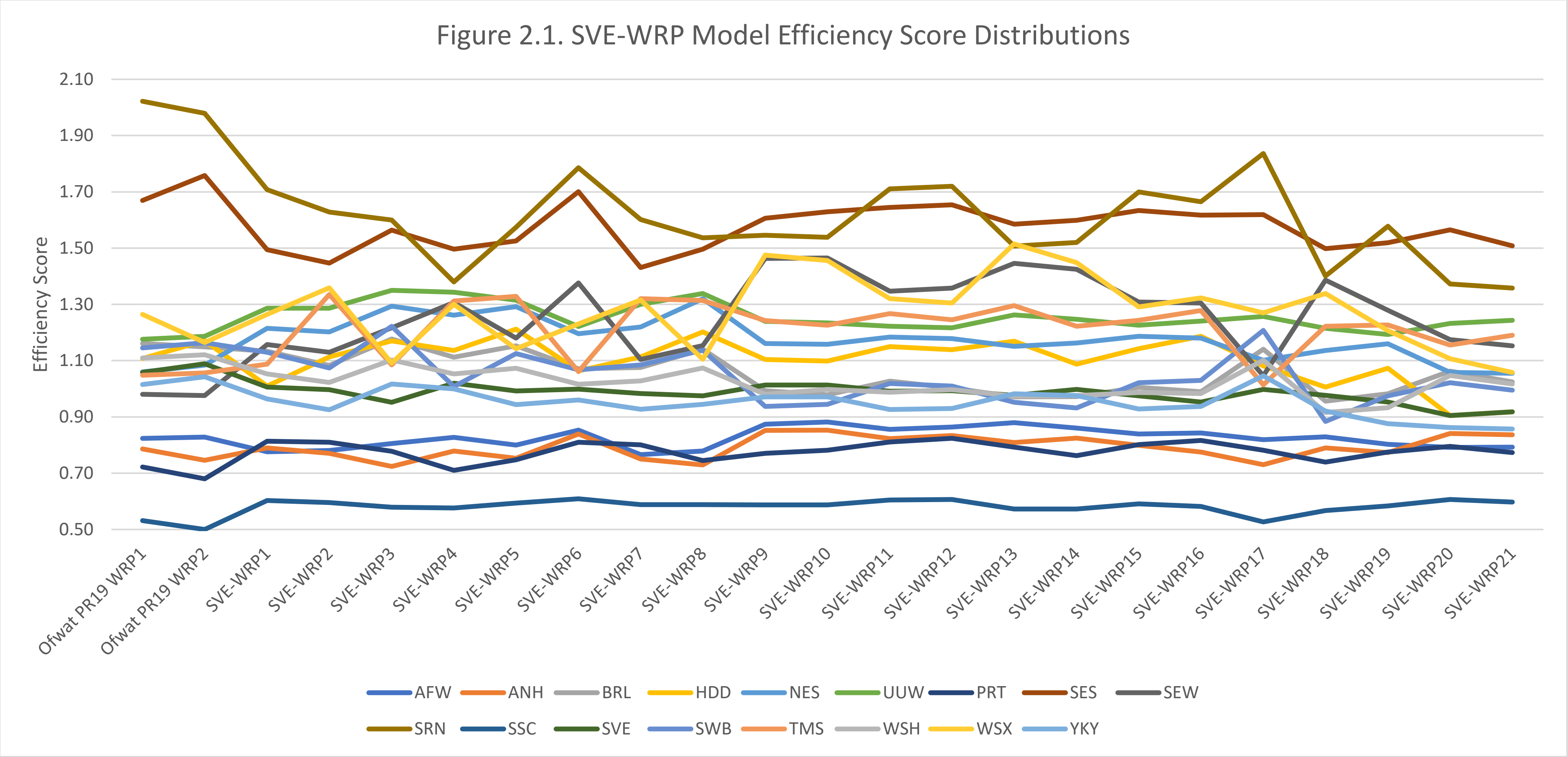

Figure 2.1. SVE-WRP Model Efficiency Score Distributions

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2.7. Efficiency Score Distributions and Rankings – Water Resources Plus (Models SVE-WRP1 to SVE-WRP10)

Ranking	Ofwat PR19 WRP1		Ofwat PR19 WRP2		SVE-WRP1		SVE-WRP2		SVE-WRP3		SVE-WRP4		SVE-WRP5		SVE-WRP6		SVE-WRP7		SVE-WRP8		SVE-WRP9		SVE-WRP10	
1	SSC	0.53	SSC	0.50	SSC	0.60	SSC	0.60	SSC	0.58	SSC	0.58	SSC	0.59	SSC	0.61	SSC	0.59	SSC	0.59	SSC	0.59	SSC	0.59
2	PRT	0.72	PRT	0.68	AFW	0.78	ANH	0.77	ANH	0.72	PRT	0.71	PRT	0.75	PRT	0.81	ANH	0.75	ANH	0.73	PRT	0.77	PRT	0.78
3	ANH	0.79	ANH	0.75	ANH	0.79	AFW	0.78	PRT	0.78	ANH	0.78	ANH	0.75	ANH	0.84	AFW	0.77	PRT	0.75	ANH	0.85	ANH	0.85
4	AFW	0.82	AFW	0.83	PRT	0.81	PRT	0.81	AFW	0.81	AFW	0.83	AFW	0.80	AFW	0.85	PRT	0.80	AFW	0.78	AFW	0.87	AFW	0.88
5	SEW	0.98	SEW	0.98	YKY	0.96	YKY	0.93	SVE	0.95	YKY	1.00	YKY	0.94	YKY	0.96	YKY	0.93	YKY	0.95	SWB	0.94	SWB	0.95
6	YKY	1.02	YKY	1.04	SVE	1.01	SVE	1.00	YKY	1.02	SWB	1.01	SVE	0.99	SVE	1.00	SVE	0.98	SVE	0.98	YKY	0.97	YKY	0.97
7	TMS	1.05	TMS	1.06	HDD	1.01	WSH	1.02	TMS	1.09	SVE	1.02	WSH	1.07	WSH	1.02	WSH	1.03	WSH	1.07	WSH	0.98	BRL	0.98
8	SVE	1.06	NES	1.08	WSH	1.05	SWB	1.07	WSX	1.09	WSH	1.05	SWB	1.13	TMS	1.06	BRL	1.08	WSX	1.11	BRL	0.99	WSH	1.00
9	NES	1.06	SVE	1.09	TMS	1.09	BRL	1.08	WSH	1.10	BRL	1.11	WSX	1.14	HDD	1.06	SWB	1.09	SWB	1.14	SVE	1.01	SVE	1.01
10	HDD	1.11	WSH	1.12	SWB	1.13	HDD	1.11	HDD	1.17	HDD	1.14	BRL	1.15	SWB	1.07	SEW	1.10	BRL	1.14	HDD	1.10	HDD	1.10
11	WSH	1.11	BRL	1.15	BRL	1.13	SEW	1.13	BRL	1.18	NES	1.26	SEW	1.18	BRL	1.07	HDD	1.11	SEW	1.15	NES	1.16	NES	1.16
12	SWB	1.15	SWB	1.16	SEW	1.16	NES	1.20	SEW	1.22	WSX	1.30	HDD	1.21	NES	1.20	NES	1.22	HDD	1.20	UUW	1.24	TMS	1.23
13	BRL	1.16	WSX	1.17	NES	1.22	UUW	1.29	SWB	1.22	SEW	1.31	NES	1.29	UUW	1.22	UUW	1.30	TMS	1.31	TMS	1.24	UUW	1.23
14	UUW	1.18	HDD	1.17	WSX	1.26	TMS	1.34	NES	1.29	TMS	1.31	UUW	1.32	WSX	1.23	WSX	1.32	NES	1.32	SEW	1.46	WSX	1.46
15	WSX	1.26	UUW	1.19	UUW	1.29	WSX	1.36	UUW	1.35	UUW	1.34	TMS	1.33	SEW	1.38	TMS	1.32	UUW	1.34	WSX	1.48	SEW	1.47
16	SES	1.67	SES	1.76	SES	1.49	SES	1.45	SES	1.56	SRN	1.38	SES	1.53	SES	1.70	SES	1.43	SES	1.50	SRN	1.55	SRN	1.54
17	SRN	2.02	SRN	1.98	SRN	1.71	SRN	1.63	SRN	1.60	SES	1.50	SRN	1.57	SRN	1.79	SRN	1.60	SRN	1.54	SES	1.61	SES	1.63

ST Classification: UNMARKED

2.8. Efficiency Score Distributions and Rankings – Water Resources Plus (Models SVE-WRP11 to SVE-WRP21)

Ranking	SVE-WRP11		SVE-WRP12		SVE-WRP13		SVE-WRP14		SVE-WRP15		SVE-WRP16		SVE-WRP17		SVE-WRP18		SVE-WRP19		SVE-WRP20		SVE-WRP21	
1	SSC	0.61	SSC	0.61	SSC	0.57	SSC	0.57	SSC	0.59	SSC	0.58	SSC	0.53	SSC	0.57	SSC	0.58	SSC	0.61	SSC	0.60
2	PRT	0.81	PRT	0.82	PRT	0.79	PRT	0.76	ANH	0.80	ANH	0.78	ANH	0.73	PRT	0.74	ANH	0.77	AFW	0.79	PRT	0.77
3	ANH	0.82	ANH	0.83	ANH	0.81	ANH	0.83	PRT	0.80	PRT	0.82	PRT	0.78	ANH	0.79	PRT	0.78	PRT	0.80	AFW	0.79
4	AFW	0.86	AFW	0.86	AFW	0.88	AFW	0.86	AFW	0.84	AFW	0.84	AFW	0.82	AFW	0.83	AFW	0.80	ANH	0.84	ANH	0.84
5	YKY	0.93	YKY	0.93	SWB	0.95	SWB	0.93	YKY	0.93	YKY	0.94	SVE	1.00	SWB	0.88	YKY	0.88	YKY	0.86	YKY	0.86
6	WSH	0.99	SVE	0.99	BRL	0.97	BRL	0.97	SVE	0.98	SVE	0.95	TMS	1.01	WSH	0.92	WSH	0.93	HDD	0.91	HDD	0.92
7	SVE	0.99	WSH	1.00	WSH	0.97	WSH	0.98	WSH	0.99	WSH	0.98	SEW	1.05	YKY	0.92	SVE	0.95	SVE	0.91	SVE	0.92
8	SWB	1.02	BRL	1.00	SVE	0.98	YKY	0.98	BRL	1.01	BRL	0.99	YKY	1.05	BRL	0.96	SWB	0.98	SWB	1.02	SWB	1.00
9	BRL	1.03	SWB	1.01	YKY	0.98	SVE	1.00	SWB	1.02	SWB	1.03	HDD	1.08	SVE	0.98	BRL	0.98	WSH	1.05	WSH	1.02
10	HDD	1.15	HDD	1.14	NES	1.15	HDD	1.09	HDD	1.14	NES	1.18	NES	1.10	HDD	1.01	HDD	1.07	NES	1.06	BRL	1.02
11	NES	1.18	NES	1.18	HDD	1.17	NES	1.16	NES	1.19	HDD	1.19	WSH	1.10	NES	1.14	NES	1.16	BRL	1.06	NES	1.06
12	UUW	1.22	UUW	1.22	UUW	1.26	TMS	1.22	UUW	1.23	UUW	1.24	BRL	1.14	UUW	1.22	UUW	1.19	WSX	1.11	WSX	1.06
13	TMS	1.27	TMS	1.25	TMS	1.30	UUW	1.25	TMS	1.24	TMS	1.28	SWB	1.21	TMS	1.22	WSX	1.21	TMS	1.16	SEW	1.15
14	WSX	1.32	WSX	1.31	SEW	1.45	SEW	1.43	WSX	1.29	SEW	1.31	UUW	1.26	WSX	1.34	TMS	1.23	SEW	1.18	TMS	1.19
15	SEW	1.35	SEW	1.36	SRN	1.51	WSX	1.45	SEW	1.31	WSX	1.32	WSX	1.27	SEW	1.39	SEW	1.28	UUW	1.23	UUW	1.24
16	SES	1.65	SES	1.65	WSX	1.52	SRN	1.52	SES	1.63	SES	1.62	SES	1.62	SRN	1.40	SES	1.52	SRN	1.37	SRN	1.36
17	SRN	1.71	SRN	1.72	SES	1.59	SES	1.60	SRN	1.70	SRN	1.67	SRN	1.84	SES	1.50	SRN	1.58	SES	1.57	SES	1.51

ST Classification: UNMARKED

3. Wholesale Water

3.1. Econometric Models

Model Number	Model
SVE-WW1	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 Pctwatertreated36_{it} + \beta_6 Ln(APH\_WT_{it}) + \beta_7 Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$
SVE-WW2	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 Ln(Wac_{it}) + \beta_6 Ln(APH\_WT_{it}) + \beta_7 Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$
SVE-WW3	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 Pctwatertreated36_{it} + \beta_6 Ln(APH\_TWD_{it}) + \beta_7 Ln(APH\_WRP_{it}) + \mu_i + \varepsilon_{it}$
SVE-WW4	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 Ln(Wac_{it}) + \beta_6 Ln(APH\_TWD_{it}) + \beta_7 Ln(APH\_WRP_{it}) + \mu_i + \varepsilon_{it}$
SVE-WW5	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 Pctwatertreated36_{it} + \beta_6 Ln(APH\_WT_{it}) + \beta_7 Ln(APH\_TWD_{it}) + \beta_8 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$
SVE-WW6	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 PropGW_{it} + \beta_6 Ln(APH\_WT_{it}) + \beta_7 Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$

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SVE-WW7	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 Ln(Wac_{it}) + \beta_6 Ln(APH\_WT_{it}) + \beta_7 Ln(APH\_TWD_{it}) + \beta_8 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$
SVE-WW8	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(Populationperareawater_{it}) + \beta_4 (Ln(Populationperareawater_{it}))^2 + \beta_5 Ln(APH\_WW_{it}) + \mu_i + \varepsilon_{it}$
SVE-WW9	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 PropGW_{it} + \beta_6 Ln(APH\_WRP_{it}) + \beta_7 Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$
SVE-WW10	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 Ln(Wac_{it}) + \beta_6 Ln(APH\_WW_{it}) + \beta_7 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$
SVE-WW11	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 Ln(Wac_{it}) + \beta_6 Ln(APH\_TWD_{it}) + \beta_7 Ln(APH\_WRP_{it}) + \beta_8 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$
SVE-WW12	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 PropDaysOver25_{it} + \beta_6 Ln(APH\_WRP_{it}) + \beta_7 Ln(APH\_TWD_{it}) + \mu_i + \varepsilon_{it}$
SVE-WW13	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 PropGW_{it} + \beta_6 Ln(APH\_WT_{it}) + \beta_7 Ln(APH\_TWD_{it}) + \beta_8 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$

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SVE-WW14	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(Populationperareawater_{it}) + \beta_4 (Ln(Populationperareawater_{it}))^2 + \beta_5 PropGW_{it} + \beta_6 Ln(APH\_WRP_{it}) + \beta_7 Ln(APH\_TWD_{it}) + \beta_8 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$
SVE-WW15	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(Populationperareawater_{it}) + \beta_4 (Ln(Populationperareawater_{it}))^2 + \beta_5 PropGW_{it} + \beta_6 Ln(APH\_WW_{it}) + \beta_7 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$
SVE-WW16	$Ln(BotexNR\_WW_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Boosterperlength_{it}) + \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2 + \beta_5 PropGW_{it} + \beta_6 Ln(APH\_WRP_{it}) + \beta_7 Ln(APH\_TWD_{it}) + \beta_8 PropDaysOver25_{it} + \mu_i + \varepsilon_{it}$

3.2. Variable List

Dependent Variable:	Variable name in model	Description
Wholesale Water Botex including network reinforcement.	BotexNR_WW	Wholesale Water Botex including network reinforcement as reported in the published PR24 wholesale dataset. Code: Botex+NR_WW in Interface_real.
Independent Variable:		
Total properties	Properties	Total properties as reported in the published wholesale dataset. Code: properties in Interface_real
Population density	WADLADwater (WADLADwater2)	Weighted average population density using Local Authority Districts (LAD) as reported in the published wholesale dataset. WADLADwater2 is the squared density term for WADLADwater. Code: WAD-LAD-Water in Interface_real
Population density	Populationperarea-water (Populationperarea-water2)	Population per area (km2) as reported in the published wholesale dataset. Populationperareawater2 is the squared density term for populationperareawater.

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		Code: Population per area – water in Interface_real
Population density	PropGW	Proportion of water treatment works that serve Ground Water (GW). See propGW in Interface_real of SVE_FM_WW1
Treatment Complexity	Pctwatertreated36	Proportion of volume of water treated in complexity bands 3 to 6 as reported in the published wholesale dataset. Code: Pctwatertreated36 in Interface_real
Treatment Complexity	Wac	Weighted average treatment complexity as reported in the published wholesale dataset. Code: wac in Interface_real
Network Complexity (boosters per length)	Booster per Length	Number of boosters per length of main as reported in the published wholesale dataset. Code: boosterperlength in Interface_real
Network Complexity (Average pumping head – treatment)	APH_WT	Average Pumping Head (APH) – Treatment as reported in the published wholesale dataset. Code: BN10902 in Stata dataset (real)
Network Complexity	APH_WW	Average Pumping Head (APH) – Wholesale Water calculated as the sum of APH – Resources, Raw water transport, Treatment & Distribution as reported in the published wholesale dataset (Stata dataset). Code: BN4861 + BN4862 + BN10902 + BN4870 in Stata dataset (real)
Network Complexity	APH_WRP	Average Pumping Head (APH) – Water Resources Plus calculated as the sum of APH – Resources, Raw water transport & Treatment as reported in the published wholesale dataset (Stata dataset). Code: BN4861 + BN4862 + BN10902 in Stata dataset (real)
Network Complexity (Average pumping head – distribution)	APH_TWD	Average Pumping Head (APH) – Distribution as reported in the published wholesale dataset. Code: BN4870 in Stata dataset (real)
Weather (days above a 25 degree celsius threshold)	PropDaysOver25	% of days in a year which experienced temperatures over 25 degrees Celsius. Calculated as the weighted average using 12km Hadley centre grids. See propDaysOver25 in Interface_real of SVE_FM_WW1

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3.3. Brief Model Description

Model Number	Model Description
SVE-WW1	As per Ofwat’s PR19 WW1 model with the addition of APH_WT and APH_TWD.
SVE-WW2	As per Ofwat’s PR19 WW2 model with the addition of network complexity drivers in APH_WT and APH_TWD.
SVE-WW3	As per SVE-WW1, but with APH_WRP instead of APH_WT.
SVE-WW4	As per SVE-WW2, but with APH_WRP instead of APH_WT.
SVE-WW5	As per SVE-WW1 with the addition of PropDaysOver25.
SVE-WW6	As per SVE-WW2, with the addition of PropGW and removal of wac.
SVE-WW7	As per SVE-WW2 with the addition of a weather variable (PropDaysOver25).
SVE-WW8	As per Ofwat’s PR19 WW1 model, with the removal of Pctwatertreated36, and addition of APH_WW. The density measure (WAD_LAD) is also substituted for Populationperareawater.
SVE-WW9	As per SVE-WW4, with the addition of PropGW and removal of wac.
SVE-WW10	As per SVE-WW7, but with APH_WW instead of APH_TWD and APH_WT.
SVE-WW11	As per SVE-WW4 with the addition of PropDaysOver25.
SVE-WW12	As per SVE-WW11, but with Wac removed.
SVE-WW13	As per SVE-WW6, with the addition of PropDaysOver25.
SVE-WW14	As per SVE-WW13, with APH_WT substituted for APH_WRP. The population density measure (LADs) is also replaced by Populationperareawater.
SVE-WW15	As per SVE-WW14, with APH_WW replacing APH_TWD and APH_WRP.
SVE-WW16	As per SVE-WW9, with the addition of PropDaysOver25.

3.4. Brief Comment on the Models

We have included Ofwat’s updated PR19 WW models for comparative purposes (model numbers Ofwat PR19 WW1 and WW2).

The panel data used to produce the following models span from 2011-12 to 2021-22, a total of 11 years.

All variables are expressed in logs apart from the following: Pctwatertreated36, PropGW, PropDaysOver25.

Alternative VIFs have been reported where squared population density terms have been included in the models. This is calculated without the problematic squared density term in the model as it is not a concern that this specific variable inflates the VIF.

Any insignificant variable that has remained in the models are due to their strength in engineering expectation and rationale.

Variables included in the following models are also relevant in other levels of aggregations.

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3.5. Model Results – Wholesale Water (SVE-WW1 to SVE-WW8)

	Ofwat PR19 WW1	Ofwat PR19 WW2	SVE-WW1	SVE-WW2	SVE-WW3	SVE-WW4	SVE-WW5	SVE-WW6	SVE-WW7	SVE-WW8
Dependent Variable	BotexNR_WW	BotexNR_WW	BotexNR_WW	BotexNR_WW	BotexNR_WW	BotexNR_WW	BotexNR_WW	BotexNR_WW	BotexNR_WW	BotexNR_WW
Properties	1.071*** {0.000}	1.059*** {0.000}	1.065*** {0.000}	1.055*** {0.000}	1.085*** {0.000}	1.076*** {0.000}	1.068*** {0.000}	1.049*** {0.000}	1.059*** {0.000}	1.107*** {0.000}
WADLADwater	-2.094*** {0.000}	-1.832*** {0.000}	-1.968*** {0.000}	-1.749*** {0.000}	-2.293*** {0.000}	-2.088*** {0.000}	-1.906*** {0.000}	-1.845*** {0.000}	-1.704*** {0.000}	
WADLADwater2	0.147*** {0.000}	0.128*** {0.000}	0.137*** {0.000}	0.121*** {0.000}	0.161*** {0.000}	0.146*** {0.000}	0.131*** {0.000}	0.129*** {0.000}	0.117*** {0.000}	
Boosterperlength	0.335** {0.032}	0.334** {0.018}	0.213** {0.042}	0.213** {0.030}	0.272** {0.019}	0.278** {0.015}	0.225** {0.032}	0.21 {0.123}	0.224** {0.028}	0.375** {0.010}
Pctwatertreated36	0.004*** {0.000}		0.003*** {0.007}		0.003** {0.017}		0.003** {0.012}			
APH_WT			0.048 {0.118}	0.053* {0.076}			0.046 {0.134}	0.066* {0.094}	0.052* {0.094}	
APH_TWD			0.240*** {0.005}	0.221** {0.012}	0.219** {0.022}	0.208** {0.042}	0.220** {0.012}	0.295*** {0.001}	0.206** {0.023}	
Wac		0.430*** {0.001}		0.350** {0.024}		0.320** {0.039}			0.327** {0.034}	
APH_WRP					0.105* {0.054}	0.098** {0.049}				
PropDaysOver25							0.012*** {0.001}		0.011*** {0.001}	
PropGW								-0.169** {0.033}		
Populationperareawater										-2.817***

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											{0.000}
Populationperareawater2											0.243*** {0.000}
APH_WW											0.423*** {0.000}
Constant		-1.566* {0.074}	-2.590*** {0.001}	-3.441*** {0.000}	-4.229*** {0.000}	-2.651*** {0.009}	-3.337*** {0.001}	-3.551*** {0.000}	-3.657*** {0.000}	-4.291*** {0.000}	-2.906** {0.016}
Estimation Method		RE	RE	RE	RE	RE	RE	RE	RE	RE	RE
N (Sample Size)		187	187	187	187	187	187	187	187	187	187
Model Robustness Tests											
R2 overall		0.97	0.971	0.975	0.976	0.974	0.974	0.975	0.972	0.976	0.967
RESET test		0.223	0.122	0.594	0.493	0.623	0.583	0.593	0.551	0.488	0.899
VIF (max)		2.211	2.214	234.693	214.262	236.451	238.75	235.516	213.539	217.169	269.872
Pooling / Chow test		0.869	0.724	0.931	0.609	0.851	0.632	0.995	0.947	0.873	1
Normality of model residuals		0.224	0.836	0.534	0.81	0.776	0.969	0.274	0.818	0.784	0.316
Heteroskedasticity of model residuals		0	0	0.001	0	0	0	0	0.005	0	0.004
Test of pooled OLS versus Random Effects (LM test)		0	0	0	0	0	0	0	0	0	0
Efficiency Score Distribution	Minimum	0.78	0.77	0.83	0.81	0.80	0.77	0.83	0.81	0.80	0.75
	Maximum	1.38	1.41	1.29	1.26	1.28	1.28	1.26	1.32	1.23	1.25
Sensitivity of estimated coefficients to removal of most and least efficient company				A	A	A	A	A	A	A	G
Sensitivity of estimated coefficients to removal of first and last year of the sample				A	A	G	G	A	A	A	G
Additional Diagnostic Checks											

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AIC	-161	-162	-171	-173	-170	-171	-173	-165	-174	-168
Sigma u	0.111	0.097	0.096	0.085	0.105	0.096	0.1	0.122	0.09	0.136
Alternative VIF	2.211	2.214	2.355	2.353	2.427	2.43	2.373	2.364	2.092	2.322

3.6. Model Results – Wholesale Water (SVE-WW9 to SVE-WW16)

	SVE-WW9	SVE-WW10	SVE-WW11	SVE-WW12	SVE-WW13	SVE-WW14	SVE-WW15	SVE-WW16
Dependent Variable	BotexNR_WW	BotexNR_WW	BotexNR_WW	BotexNR_WW	BotexNR_WW	BotexNR_WW	BotexNR_WW	BotexNR_WW
Properties	1.080*** {0.000}	1.085*** {0.000}	1.078*** {0.000}	1.100*** {0.000}	1.048*** {0.000}	1.073*** {0.000}	1.085*** {0.000}	1.076*** {0.000}
WADLADwater	-2.323*** {0.000}	-1.982*** {0.000}	-2.016*** {0.000}	-2.240*** {0.000}	-1.781*** {0.000}			-2.210*** {0.000}
WADLADwater2	0.166*** {0.000}	0.139*** {0.000}	0.141*** {0.000}	0.158*** {0.000}	0.124*** {0.000}			0.157*** {0.000}
Boosterperlength	0.290* {0.057}	0.323** {0.011}	0.284** {0.016}	0.313** {0.025}	0.222 {0.112}	0.384** {0.021}	0.377** {0.018}	0.294* {0.062}
Pctwatertreated36								
APH_WT					0.062 {0.114}			
APH_TWD	0.257** {0.013}		0.195* {0.058}	0.220** {0.042}	0.272*** {0.003}	0.211** {0.045}		0.240** {0.018}
Wac		0.293* {0.059}	0.301** {0.049}					
APH_WRP	0.152*** {0.010}		0.088* {0.080}	0.142*** {0.007}		0.158*** {0.003}		0.132** {0.017}

PropDaysOver25			0.011*** {0.001}	0.011*** {0.002}	0.012*** {0.001}	0.014*** {0.000}	0.012*** {0.001}	0.013*** {0.001}	0.013*** {0.001}
PropGW		-0.158* {0.069}				-0.202*** {0.010}	-0.208** {0.031}	-0.182* {0.065}	-0.187** {0.029}
Populationperareawater							-2.562*** {0.000}	-2.685*** {0.000}	
Populationperareawater2							0.222*** {0.000}	0.232*** {0.000}	
APH_WW			0.252** {0.029}					0.386*** {0.000}	
Constant		-2.516** {0.042}	-3.572*** {0.000}	-3.448*** {0.001}	-2.795** {0.046}	-3.703*** {0.000}	-2.610* {0.090}	-2.778** {0.017}	-2.661** {0.026}
Estimation Method		RE	RE	RE	RE	RE	RE	RE	RE
N (Sample Size)		187	187	187	187	187	187	187	187
Model Robustness Tests									
R2 overall		0.97	0.973	0.973	0.968	0.973	0.968	0.969	0.97
RESET test		0.549	0.449	0.475	0.407	0.578	0.73	0.794	0.476
VIF (max)		234.626	221.034	249.16	242.732	216.092	312.076	280.732	244.081
Pooling / Chow test		0.973	0.98	0.851	0.955	0.98	1	1	0.987
Normality of model residuals		0.522	0.756	0.986	0.486	0.996	0.038	0.075	0.866
Heteroskedasticity of model residuals		0	0	0	0	0.001	0.002	0.001	0
Test of pooled OLS versus Random Effects (LM test)		0	0	0	0	0	0	0	0
Efficiency Score Distribution	Minimum	0.77	0.78	0.76	0.76	0.80	0.75	0.75	0.76
	Maximum	1.34	1.31	1.27	1.29	1.30	1.31	1.30	1.34
Sensitivity of estimated coefficients to removal of		G	G	A	G	A	G	G	G

ST Classification: UNMARKED

most and least efficient company								
Sensitivity of estimated coefficients to removal of first and last year of the sample	G	G	G	G	A	G	G	G
Additional Diagnostic Checks								
AIC	-161	-162	-171	-173	-170	-171	-173	-165
Sigma u	0.111	0.097	0.096	0.085	0.105	0.096	0.1	0.122
Alternative VIF	2.4	2.488	2.578	2.502	2.332	2.504	2.244	2.502

ST Classification: UNMARKED

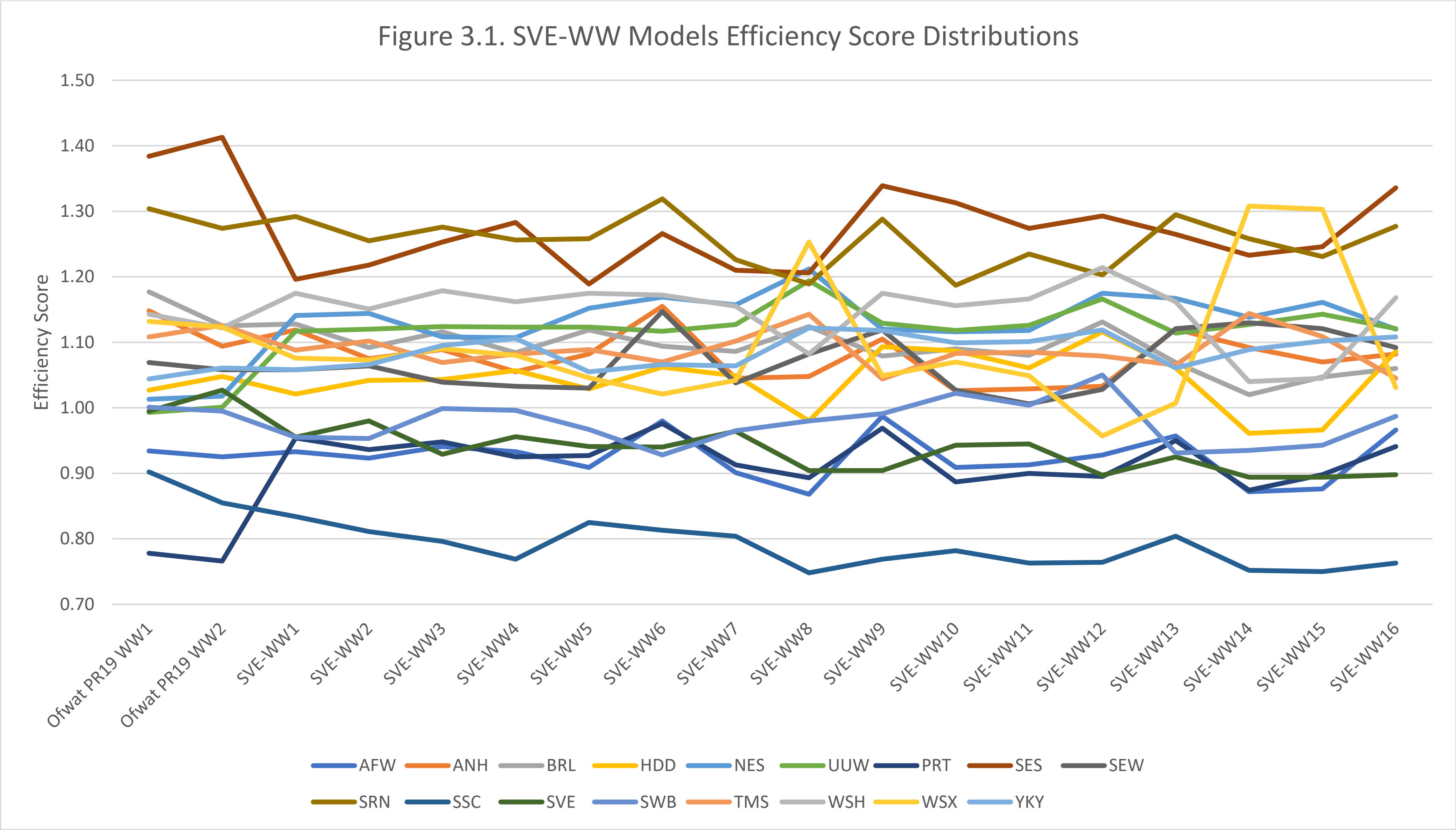
Figure 3.1. SVE-WW Models Efficiency Score Distributions

ST Classification: UNMARKED

3.7. Efficiency Score Distributions and Rankings – Sewage Collection (Models SVE-WW1 to SVE-WW8)

Ranking	Ofwat PR19 WW1		Ofwat PR19 WW2		SVE-WW1		SVE-WW2		SVE-WW3		SVE-WW4		SVE-WW5		SVE-WW6		SVE-WW7		SVE-WW8	
1	PRT	0.78	PRT	0.77	SSC	0.83	SSC	0.81	SSC	0.80	SSC	0.77	SSC	0.83	SSC	0.81	SSC	0.80	SSC	0.75
2	SSC	0.90	SSC	0.86	AFW	0.93	AFW	0.92	SVE	0.93	PRT	0.93	AFW	0.91	SWB	0.93	AFW	0.90	AFW	0.87
3	AFW	0.93	AFW	0.93	PRT	0.95	PRT	0.94	AFW	0.94	AFW	0.93	PRT	0.93	SVE	0.94	PRT	0.91	PRT	0.89
4	UUW	0.99	SWB	1.00	SVE	0.96	SWB	0.95	PRT	0.95	SVE	0.96	SVE	0.94	PRT	0.98	SVE	0.96	SVE	0.90
5	SVE	1.00	UUW	1.00	SWB	0.96	SVE	0.98	SWB	1.00	SWB	1.00	SWB	0.97	AFW	0.98	SWB	0.97	HDD	0.98
6	SWB	1.00	NES	1.02	HDD	1.02	HDD	1.04	SEW	1.04	SEW	1.03	HDD	1.03	WSX	1.02	SEW	1.04	SWB	0.98
7	NES	1.01	SVE	1.03	SEW	1.06	SEW	1.06	HDD	1.04	ANH	1.06	SEW	1.03	HDD	1.06	WSX	1.04	ANH	1.05
8	HDD	1.03	HDD	1.05	YKY	1.06	YKY	1.07	TMS	1.07	HDD	1.06	WSX	1.05	YKY	1.07	ANH	1.05	SEW	1.08
9	YKY	1.04	SEW	1.06	WSX	1.08	WSX	1.07	ANH	1.09	WSX	1.08	YKY	1.06	TMS	1.07	HDD	1.05	WSH	1.08
10	SEW	1.07	YKY	1.06	TMS	1.09	ANH	1.08	WSX	1.09	TMS	1.08	ANH	1.08	BRL	1.09	YKY	1.06	YKY	1.12
11	TMS	1.11	ANH	1.09	UUW	1.12	BRL	1.09	YKY	1.10	BRL	1.08	TMS	1.09	UUW	1.12	BRL	1.09	BRL	1.12
12	WSX	1.13	WSH	1.12	ANH	1.12	TMS	1.10	NES	1.11	YKY	1.11	BRL	1.12	SEW	1.15	TMS	1.10	TMS	1.14
13	WSH	1.14	WSX	1.12	BRL	1.13	UUW	1.12	BRL	1.12	NES	1.11	UUW	1.12	ANH	1.16	UUW	1.13	SRN	1.19
14	ANH	1.15	BRL	1.13	NES	1.14	NES	1.14	UUW	1.12	UUW	1.12	NES	1.15	NES	1.17	WSH	1.16	UUW	1.19
15	BRL	1.18	TMS	1.13	WSH	1.18	WSH	1.15	WSH	1.18	WSH	1.16	WSH	1.18	WSH	1.17	NES	1.16	SES	1.21
16	SRN	1.30	SRN	1.27	SES	1.20	SES	1.22	SES	1.25	SRN	1.26	SES	1.19	SES	1.27	SES	1.21	NES	1.21
17	SES	1.38	SES	1.41	SRN	1.29	SRN	1.26	SRN	1.28	SES	1.28	SRN	1.26	SRN	1.32	SRN	1.23	WSX	1.25

3.8. Efficiency Score Distributions and Rankings – Sewage Collection (Models SVE-WW9 to SVE-WW16)

Ranking	SVE-WW9		SVE-WW10		SVE-WW11		SVE-WW12		SVE-WW13		SVE-WW14		SVE-WW15		SVE-WW16	
1	SSC	0.77	SSC	0.78	SSC	0.76	SSC	0.76	SSC	0.80	SSC	0.75	SSC	0.75	SSC	0.76
2	SVE	0.90	PRT	0.89	PRT	0.90	PRT	0.90	SVE	0.93	AFW	0.87	AFW	0.88	SVE	0.90
3	PRT	0.97	AFW	0.91	AFW	0.91	SVE	0.90	SWB	0.93	PRT	0.87	SVE	0.89	PRT	0.94
4	AFW	0.99	SVE	0.94	SVE	0.95	AFW	0.93	PRT	0.95	SVE	0.89	PRT	0.90	AFW	0.97
5	SWB	0.99	SWB	1.02	SWB	1.00	WSX	0.96	AFW	0.96	SWB	0.94	SWB	0.94	SWB	0.99
6	TMS	1.04	ANH	1.03	SEW	1.01	SEW	1.03	WSX	1.01	HDD	0.96	HDD	0.97	WSX	1.03

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7	WSX	1.05	SEW	1.03	ANH	1.03	ANH	1.03	HDD	1.06	BRL	1.02	WSH	1.05	TMS	1.05	
8	BRL	1.08	WSX	1.07	WSX	1.05	SWB	1.05	YKY	1.06	WSH	1.04	BRL	1.05	BRL	1.06	
9	HDD	1.09	TMS	1.08	HDD	1.06	TMS	1.08	TMS	1.07	YKY	1.09	ANH	1.07	ANH	1.08	
10	ANH	1.11	HDD	1.09	BRL	1.08	HDD	1.12	BRL	1.07	ANH	1.09	YKY	1.10	HDD	1.09	
11	YKY	1.12	BRL	1.09	TMS	1.09	YKY	1.12	UUW	1.11	UUW	1.13	TMS	1.11	SEW	1.09	
12	SEW	1.12	YKY	1.10	YKY	1.10	BRL	1.13	ANH	1.12	SEW	1.13	SEW	1.12	YKY	1.11	
13	NES	1.12	NES	1.12	NES	1.12	UUW	1.17	SEW	1.12	NES	1.14	UUW	1.14	NES	1.12	
14	UUW	1.13	UUW	1.12	UUW	1.13	NES	1.18	WSH	1.16	TMS	1.14	NES	1.16	UUW	1.12	
15	WSH	1.18	WSH	1.16	WSH	1.17	SRN	1.20	NES	1.17	SES	1.23	SRN	1.23	WSH	1.17	
16	SRN	1.29	SRN	1.19	SRN	1.24	WSH	1.21	SES	1.27	SRN	1.26	SES	1.25	SRN	1.28	
17	SES	1.34	SES	1.31	SES	1.27	SES	1.29	SRN	1.30	WSX	1.31	WSX	1.30	SES	1.34	

ST Classification: UNMARKED

4. Sewage Collection

4.1. Econometric Models

Model Number	Model
SVE-SWC1	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WAD\_LAD_{it}) + \beta_3 (Ln(WAD\_LAD_{it}))^2 + \beta_4 Ln(Pumpingcapperknownlength_{it}) + \beta_5 Propcombined_{it} + \mu_i + \varepsilon_{it}$
SVE-SWC2	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Altlad2_{it}) + \beta_3 Ln(Pumpingcapperknownlength_{it}) + \beta_4 Propcombined_{it} + \mu_i + \varepsilon_{it}$
SVE-SWC3	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WAD\_LAD_{it}) + \beta_3 (Ln(WAD\_LAD_{it}))^2 + \beta_4 Ln(Pumpingcapperknownlength_{it}) + \beta_5 Propcombined_{it} + \beta_6 Ln(Urbanrainfallperknownlength_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWC4	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Altlad2_{it}) + \beta_3 Ln(Pumpingcapperknownlength_{it}) + \beta_4 Propcombined_{it} + \beta_5 Ln(Urbanrainfallperknownlength_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWC5	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Density\_knownlength_{it}) + \beta_3 (Ln(Density\_knownlength_{it}))^2 + \beta_4 Propcombined_{it} + \mu_i + \varepsilon_{it}$
SVE-SWC6	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Density\_knownlength_{it}) + \beta_3 (Ln(Density\_knownlength_{it}))^2 + \beta_4 Propcombined_{it} + \beta_5 Ln(Urbanrainfallperknownlength_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWC7	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WAD\_LAD_{it}) + \beta_3 (Ln(WAD\_LAD_{it}))^2 + \beta_4 Ln(Pumpingcapperknownlength_{it}) + \beta_5 Propcombined_{it} + \beta_6 AMPY2_t + \beta_7 AMPY3_t + \beta_8 AMPY4_t + \beta_9 AMPY5_t + \mu_i + \varepsilon_{it}$
SVE-SWC8	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WAD\_LAD_{it}) + \beta_3 (Ln(WAD\_LAD_{it}))^2 + \beta_4 Ln(Pumpingcapperknownlength_{it}) + \beta_5 Propcombined_{it} + \beta_6 AMPY2_t + \beta_7 AMPY3_t + \beta_8 AMPY4_t + \beta_9 AMPY5_t + \beta_{10} AMP5_t + \beta_{11} AMP6_t + \mu_i + \varepsilon_{it}$

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SVE-SWC9	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Density\_knownlength_{it}) + \beta_3 (Ln(Density\_knownlength_{it}))^2 + \beta_4 Propcombined_{it} + \beta_5 AMPY2_t + \beta_6 AMPY3_t + \beta_7 AMPY4_t + \beta_8 AMPY5_t + \mu_i + \varepsilon_{it}$
SVE-SWC10	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(Density\_knownlength_{it}) + \beta_3 (Ln(Density\_knownlength_{it}))^2 + \beta_4 Propcombined_{it} + \beta_5 AMPY2_t + \beta_6 AMPY3_t + \beta_7 AMPY4_t + \beta_8 AMPY5_t + \beta_9 AMP5_t + \beta_{10} AMP6_t + \mu_i + \varepsilon_{it}$
SVE-SWC11	$Ln(Botex\_SC\_SFR\_sm_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WAD\_LAD_{it}) + \beta_3 (Ln(WAD\_LAD_{it}))^2 + \beta_4 Ln(Pumpingcapperknownlength_{it}) + \beta_5 Propcombined_{it} + \mu_i + \varepsilon_{it}$
SVE-SWC12	$Ln(Botex\_SC\_SFR\_sm_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(altlad2_{it}) + \beta_3 Ln(Pumpingcapperknownlength_{it}) + \beta_4 Propcombined_{it} + \mu_i + \varepsilon_{it}$
SVE-SWC13	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(altlad2_{it}) + \beta_3 Ln(Pumpingcapperknownlength_{it}) + \beta_4 Propcombined_{it} + W1_{it} \beta_5 Ln(altlad2_{it}) + W1_{it} \beta_6 Ln(Pumpingcapperknownlength_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWC14	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(altlad2_{it}) + \beta_3 Ln(Pumpingcapperknownlength_{it}) + \beta_4 Propcombined_{it} + \beta_5 Ln(Urbanrainfallperknownlength_{it}) + W1_{it} \beta_6 Ln(altlad2_{it}) + W1_{it} \beta_7 Ln(Pumpingcapperknownlength_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWC15	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WAD\_LAD_{it}) + \beta_3 (Ln(WAD\_LAD_{it}))^2 + \beta_4 Ln(Pumpingcapperknownlength_{it}) + \beta_5 Propcombined_{it} + W2_{it} \beta_6 Ln(WAD\_LAD_{it}) + W2_{it} \beta_7 (Ln(WAD\_LAD_{it}))^2 + W2_{it} \beta_8 Propcombined_{it} + \mu_i + \varepsilon_{it}$
SVE-SWC16	$Ln(Botex\_SC\_SFR_{it}) = \beta_0 + \beta_1 Ln(Properties_{it}) + \beta_2 Ln(WAD\_LAD_{it}) + \beta_3 (Ln(WAD\_LAD_{it}))^2 + \beta_4 Ln(Pumpingcapperknownlength_{it}) + \beta_5 Propcombined_{it} + W2_{it} \beta_6 Ln(WAD\_LAD_{it}) + W2_{it} \beta_7 (Ln(WAD\_LAD_{it}))^2 + W2_{it} \beta_8 Propcombined_{it} + \beta_9 AMPY2_t + \beta_{10} AMPY3_t + \beta_{11} AMPY4_t + \beta_{12} AMPY5_t + \beta_{13} AMP5_t + \beta_{14} AMP6_t + \mu_i + \varepsilon_{it}$

ST Classification: UNMARKED

4.2. Variable List

Dependent Variable:	Variable name in model	Description
Sewage Collection Botex including sewer flooding and network reinforcement.	Botex_SC_SFR	Sewage Collection Botex including sewer flooding and network reinforcement as reported in the published PR24 wholesale dataset. Code: botex_sc_sewerflood_rein in Interface_real.
Smoothed Capex Sewage Collection Botex including sewer flooding and network reinforcement	Botex_SC_SFR_sm	Sewage Collection Botex with smoothed capex including sewer flooding and network reinforcement. A 5-year rolling average (year t down to t-4) was used to smooth capex to form this botex measure.
Independent Variable:		
Total properties	Properties	Total properties as reported in the published wholesale dataset. Code: properties in Interface_real
Population Density	WAD_LAD (WAD_LAD2)	Weighted average population density using Local Authority Districts (LAD) as reported in the published wholesale dataset. WAD_LAD2 is the squared density term for WAD_LAD. Code: WAD_LAD in Interface_real
Population Density	WAD_MSOA (WAD_MSOA2)	Weighted average population density using Middle Layer Super Output Areas (MSOA) as reported in the published wholesale dataset. WAD_MSOA2 is the squared density term for WAD_MSOA. Code: WAD_MSOA in Interface_real
Population Density	Altlad2	Alternative measure of population density. See ‘Improving Ofwat’s cost models for use at PR24’ for more information.
Population Density	Density_knownlength (Density_knownlength2)	Population density measure calculated as $properties/knownlength$. Knownlength is the legacy sewer length (Code: BN13535_21 in Stata dataset (real)). Density_knownlength2 is the squared density term for Density_knownlength.

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		Code: density_knownlength in Interface_real of SVE_FM_WWW1.
Network Complexity	Pumpingcapperknownlength	Alternative Pumpingcapperlength measure calculated as: $Pumping\ capacity/knownlength$ Code: Pumping capacity in Interface_real. Knownlength is the legacy sewer length (Code: BN13535_21 in Stata dataset (real)).
Network Complexity	Propcombined	Proportion of combined legacy sewers over total legacy sewers. Code: propcombined in Interface_real of SVE_FM_WWW1.
Weather	Urbanrainfallperknownlength	Alternative urbanrainfallperlength calculated as $urbanrainfall/knownlength$. Code: urbanrainfall in Interface_real Knownlength is the legacy sewer length (Code: BN13535_21 in Stata dataset (real)).
AMP year	AMPY***X***	Dummy variable =1 if year is the $\boldsymbol{X^{th}}$ year of the AMP, =0 if year is the 1st year of the AMP.
AMP	AMP5 AMP6	Dummy variable =1 if year is in AMP5, 0 otherwise. Dummy variable =1 if year is in AMP6, 0 otherwise.
Spatial Lag of X	W1.*Variable* W2.*Variable*	The spatial lag of the respective independent variable using the maximum eigenvalue normalised spatial weights matrix (Specification 1). The spatial lag of the respective independent variable using the row normalised spatial weights matrix (Specification 2). Refer to section 4.7.2 ‘Improving Ofwat’s cost models for use at PR24’ for more information. Full derivation of spatial variables and subsequent data can be provided on request.

4.3. Brief Model Description

Model Number	Model Description
SVE-SWC1	As per CMA PR19 SWC2, with properties replacing sewer length, and with the addition of Propcombined. Pumpingcapperlength is substituted for Pumpingcapperknownlength. The addition of Propcombined provides an alternative legitimate network complexity driver.
SVE-SWC2	As per SVE-SWC1, with altlad2 replacing WAD_LAD and WAD_LAD2.
SVE-SWC3	As per SVE-SWC1, with the addition of Urbanrainfallperknownlength. This allows for the effect of intense rainfall on sewage costs to be reflected.
SVE-SWC4	As per SVE-SWC2, with the addition of Urbanrainfallperknownlength.
SVE-SWC5	As per SVE-SWC1, with density_known length replacing LADs as the population density measure. Pumpingcapperknownlength is also removed.
SVE-SWC6	As per SVE-SWC5, with the addition of Urbanrainfallperknownlength.
SVE-SWC7	As per SVE-SWC1, with the addition of AMP year dummies. The inclusion of AMP years allows for the fluctuation of capex cost across an AMP cycle to be accounted for in the models.
SVE-SWC8	As per SVE-SWC7, with the addition of AMP dummies.
SVE-SWC9	As per SVE-SWC5, with the addition of AMP year dummies.
SVE-SWC10	As per SVE-SWC9, with the addition of AMP dummies.
SVE-SWC11	As per SVE-SWC1, but with the smoothed capex measure (Botex_SC_SFR_sm) as the dependent variable.
SVE-SWC12	As per SVE-SWC2, but with Botex_SC_SFR_sm as the dependent variable.
SVE-SWC13	As per SVE-SWC2, with the addition of spatial lags of pumpingcapperknownlength and altlad2.
SVE-SWC14	As per SVE-SWC13, with the addition of Urbanrainfallperknownlength.
SVE-SWC15	As per SVE-SWC1, with the addition of spatial lags of WAD_LAD, WAD_LAD2 and Propcombined.
SVE-SWC16	As per SVE-SWC15, with the addition of AMP year and AMP dummies.

4.4. Brief Comment on the Models

We have included Ofwat's updated PR19 SWC1 and CMA's PR19 SWC2 model for comparative purposes (model numbers Ofwat PR19 SWC1 and CMA PR19 SWC2).

Models SVE-SWC1 to SVE-SWC10 and SVE-SWC13 to SVE-SWC16 use a panel spanning from 2011-12 to 2021-22, a total of 11 years.

Models SVE-SWC11 to SVE-SWC12 use a panel spanning from 2014-15 to 2021-2022, a total 7 years.

Alternative VIFs have been reported where squared population density terms have been included in the models. This is calculated without the problematic squared density term in the model as it is not a concern that this specific variable inflates the VIF.

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Any insignificant variable that has remained in the models are due to their strength in engineering expectation and rationale.

Variables included in the following models are also relevant in other levels of aggregations and are included as such.

All variables are expressed in logs apart from the following: Propcombined, W2Propcombined, AMPY2, AMPY3, AMPY4, AMPY5, AMP5, AMP6.

ST Classification: UNMARKED

4.5. Model Results – Sewage Collection (SVE-SWC1 to SVE-SWC6)

	Ofwat PR19 SWC1	CMA PR19 SWC2	SVE-SWC1	SVE-SWC2	SVE-SWC3	SVE-SWC4	SVE-SWC5	SVE-SWC6
Dependent Variable	Botex_SC_SFR	Botex_SC_SFR	Botex_SC_SFR	Botex_SC_SFR	Botex_SC_SFR	Botex_SC_SFR	Botex_SC_SFR	Botex_SC_SFR
Properties			0.891*** {0.000}	0.883*** {0.000}	0.884*** {0.000}	0.872*** {0.000}	0.751*** {0.000}	0.771*** {0.000}
Sewer Length (Ofwat/CMA models only)	0.804*** {0.000}	0.860*** {0.000}						
WAD_LAD		-2.476** {0.021}	-1.964*** {0.000}		-1.948*** {0.000}			
WAD_LAD2		0.181*** {0.010}	0.140*** {0.000}		0.139*** {0.000}			
Pumpingcapperlength (Ofwat/CMA models only)	0.345** {0.012}	0.605*** {0.000}						
Pumpingcapperknownlength			0.487*** {0.000}	0.491*** {0.000}	0.462*** {0.000}	0.454*** {0.000}		
Propcombined			0.004*** {0.000}	0.005*** {0.000}	0.004*** {0.000}	0.004** {0.019}	0.003** {0.015}	0.002 {0.170}
Altlad2				0.069*** {0.000}		0.072*** {0.002}		
Urbanrainfallperknownlength					0.047** {0.048}	0.077** {0.041}		0.104*** {0.002}
Density (Ofwat/CMA models only)	1.043*** {0.000}							
Density_knownlength							-51.795*** {0.000}	-53.031*** {0.000}
Density_knownlength2							6.114*** {0.000}	6.238*** {0.000}

ST Classification: UNMARKED

AMPY2								
AMPY3								
AMPY4								
AMPY5								
AMP5								
AMP6								
W1.Pumpingcapperknownlength								
W1.Altlad2								
W2.WAD_LAD								
W2.WAD_LAD2								
W2.Propcombined								
Constant	-7.957*** {0.000}	3.592 {0.396}	-1.979*** {0.003}	-8.787*** {0.000}	-1.774* {0.057}	-8.352*** {0.000}	103.338*** {0.000}	106.374*** {0.000}
Estimation Method	RE	RE	RE	RE	RE	RE	RE	RE
N (Sample Size)	110	110	110	110	110	110	110	110
Model Robustness Tests								
R2 overall	0.917	0.895	0.941	0.937	0.941	0.937	0.93	0.93
RESET test	0.356	0.268	0.655	0.535	0.743	0.525	0.72	0.543

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VIF (max)		2.337	1.93	415.968	2.753	417.871	2.861	6146.271	6177.566
Pooling / Chow test		0.72	0.988	0.443	0.623	0.707	0.849	0.879	0.967
Normality of model residuals		0.393	0.267	0.004	0.016	0.002	0.01	0.114	0.044
Heteroskedasticity of model residuals		0.299	0.051	0.443	0.439	0.389	0.422	0.377	0.365
Test of pooled OLS versus Random Effects (LM test)		0	0	0.184	0.242	0.251	0.172	0.016	0.008
Efficiency Score Distribution	Minimum	0.91	0.87	0.94	0.92	0.94	0.91	0.87	0.90
	Maximum	1.13	1.21	1.04	1.05	1.04	1.08	1.10	1.13
Sensitivity of estimated coefficients to removal of most and least efficient company				G	A	A	G	G	A
Sensitivity of estimated coefficients to removal of first and last year of the sample				G	G	A	A	G	A
Additional Diagnostic Checks									
AIC		-120	-114	-139	-133	-137	-132	-124	-125
Sigma u		0.093	0.144	0.025	0.048	0.034	0.057	0.067	0.078
Alternative VIF		2.337	1.93	2.762	2.753	2.894	2.861	1.345	2

4.6. Model Results – Sewage Collection (SVE-SWC7 to SVE-SWC16)

	SVE-SWC7	SVE-SWC8	SVE-SWC9	SVE-SWC10	SVE-SWC11	SVE-SWC12	SVE-SWC13	SVE-SWC14	SVE-SWC15	SVE-SWC16
Dependent Variable	Botex_SC_SFR	Botex_SC_SFR	Botex_SC_SFR	Botex_SC_SFR	Botex_SC_SFR_sm	Botex_SC_SFR_sm	Botex_SC_SFR	Botex_SC_SFR	Botex_SC_SFR	Botex_SC_SFR
Properties	0.893*** {0.000}	0.892*** {0.000}	0.751*** {0.000}	0.751*** {0.000}	0.884*** {0.000}	0.872*** {0.000}	0.640*** {0.000}	0.520*** {0.000}	0.763*** {0.000}	0.762*** {0.000}
Sewer Length (Ofwat/CMA models only)										

ST Classification: UNMARKED

WAD_LAD	-1.965*** {0.000}	-1.984*** {0.000}			-2.123*** {0.000}				-4.888*** {0.000}	-4.937*** {0.000}
WAD_LAD2	0.140*** {0.000}	0.141*** {0.000}			0.148*** {0.000}				0.343*** {0.000}	0.346*** {0.000}
Pumpingcapperlength (Ofwat/CMA models only)										
Pumpingcapperknownlength	0.490*** {0.000}	0.494*** {0.000}			0.469*** {0.000}	0.474*** {0.000}	0.443*** {0.000}	0.327*** {0.000}	0.369** {0.014}	0.371** {0.010}
Propcombined	0.004*** {0.000}	0.004*** {0.000}	0.003** {0.012}	0.003** {0.017}	0.004*** {0.000}	0.004*** {0.009}	0.011*** {0.000}	0.012*** {0.000}	0.009*** {0.006}	0.009*** {0.004}
Altlad2						0.060*** {0.008}	0.172*** {0.000}	0.225*** {0.000}		
Urbanrainfallperknownlength								0.114*** {0.000}		
Density (Ofwat/CMA models only)										
Density_knownlength			-52.74*** {0.000}	-52.45*** {0.000}						
Density_knownlength2			6.225*** {0.000}	6.189*** {0.000}						
AMPY2	0.004 {0.825}	0.004 {0.857}	0.006 {0.754}	0.008 {0.778}						0.007 {0.777}
AMPY3	0.034 {0.247}	0.057** {0.045}	0.038 {0.168}	0.063* {0.056}						0.060** {0.036}
AMPY4	0.059** {0.039}	0.083** {0.036}	0.061** {0.042}	0.086* {0.054}						0.085** {0.034}
AMPY5	0.053* {0.084}	0.077*** {0.002}	0.055* {0.082}	0.080*** {0.002}						0.079*** {0.001}
AMP5		-0.048		-0.052						-0.054

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			{0.434}		{0.435}						{0.367}
AMP6			-0.096 {0.102}		-0.094 {0.127}						-0.100* {0.091}
W1.Pumpingcapperknownlength								0.067* {0.062}	0.075*** {0.004}		
W1.Altlad2								0.110*** {0.000}	0.160*** {0.000}		
W2.WAD_LAD										-6.845** {0.036}	-6.917** {0.026}
W2.WAD_LAD2										0.461** {0.040}	0.466** {0.029}
W2.Propcombined										0.002*** {0.010}	0.002** {0.011}
Constant		-2.028*** {0.002}	-1.919** {0.011}	105.3*** {0.000}	104.8*** {0.000}	-1.148 {0.171}	-8.594*** {0.000}	-5.827*** {0.000}	-3.842*** {0.000}	35.495** {0.041}	35.969** {0.030}
Estimation Method		RE	RE	RE	RE	RE	RE	RE	RE	POLS	RE
N (Sample Size)		110	110	110	110	70	70	110	110	110	110
Model Robustness Tests											
R2 overall		0.944	0.948	0.933	0.937	0.974	0.967	0.941	0.945	0.944	0.952
RESET test		0.646	0.708	0.787	0.769	0.443	0.608	0.732	0.951	0.67	0.792
VIF (max)		415.971	415.973	6148.366	6148.922	412.723	2.667	22.318	28.259	15144.27	15247.69
Pooling / Chow test		0.958	0.991	1	1	1	1	0.964	0.968	0.214	0.392
Normality of model residuals		0.009	0.016	0.256	0.262	0.039	0.294	0.011	0.002	0.002	0.008
Heteroskedasticity of model residuals		0.368	0.782	0.342	0.611	0.029	0.088	0.388	0.333	0.497	0.918
Test of pooled OLS versus Random Effects (LM test)		0.201	0.243	0.011	0.004	0.001	0	0.226	0.08	1	0.023
Efficiency Score Distribution	Minimum	0.94	0.94	0.87	0.86	0.94	0.94	0.91	0.93	0.91	0.90
	Maximum	1.04	1.03	1.10	1.09	1.06	1.09	1.03	1.04	1.11	1.10

ST Classification: UNMARKED

Sensitivity of estimated coefficients to removal of most and least efficient company	G	G	G	G	G	G	A	G	A	A
Sensitivity of estimated coefficients to removal of first and last year of the sample	G	G	G	G	G	G	G	G	G	G
Additional Diagnostic Checks										
AIC	-135	-141	-121	-125	-148*	-144*	-136	-142	-138	-142
Sigma u	0.025	0.029	0.067	0.068	0.066	0.081	0.04	0.033	0	0.011
Alternative VIF	2.763	2.84	1.819	2.852	2.662	2.185	22.318	28.259	6.555	6.594
*AIC incomparable as different dependent variable is used.										

ST Classification: UNMARKED

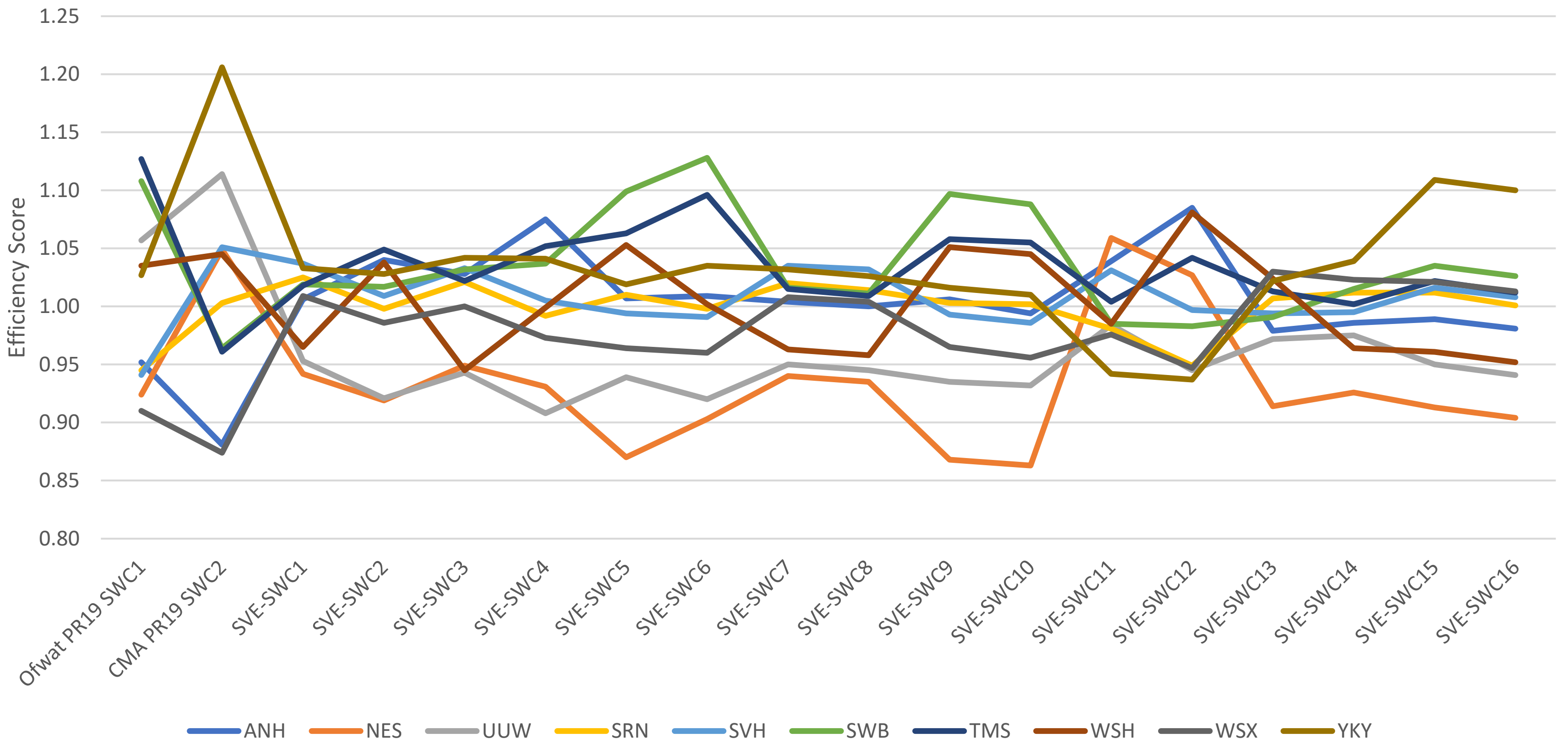

Figure 4.1. SVE-SWC Model Efficiency Score Distributions

ST Classification: UNMARKED

4.7. Efficiency Score Distributions and Rankings – Sewage Collection (Models SVE-SWC1 to SVE-SWC7)

Ranking	Ofwat PR19 SWC1		CMA PR19 SWC2		SVE-SWC1		SVE-SWC2		SVE-SWC3		SVE-SWC4		SVE-SWC5		SVE-SWC6		SVE-SWC7	
1	WSX	0.91	WSX	0.87	NES	0.94	NES	0.92	UUW	0.94	UUW	0.91	NES	0.87	NES	0.90	NES	0.94
2	NES	0.92	ANH	0.88	UUW	0.95	UUW	0.92	WSH	0.95	NES	0.93	UUW	0.94	UUW	0.92	UUW	0.95
3	SVH	0.94	TMS	0.96	WSH	0.97	WSX	0.99	NES	0.95	WSX	0.97	WSX	0.96	WSX	0.96	WSH	0.96
4	SRN	0.95	SWB	0.96	ANH	1.01	SRN	1.00	WSX	1.00	SRN	0.99	SVH	0.99	SVH	0.99	ANH	1.00
5	ANH	0.95	SRN	1.00	WSX	1.01	SVH	1.01	SRN	1.02	WSH	1.00	ANH	1.01	SRN	1.00	WSX	1.01
6	YKY	1.03	WSH	1.05	TMS	1.02	SWB	1.02	TMS	1.02	SVH	1.01	SRN	1.01	WSH	1.00	TMS	1.02
7	WSH	1.04	NES	1.05	SWB	1.02	YKY	1.03	ANH	1.03	SWB	1.04	YKY	1.02	ANH	1.01	SWB	1.02
8	UUW	1.06	SVH	1.05	SRN	1.03	WSH	1.04	SWB	1.03	YKY	1.04	WSH	1.05	YKY	1.04	SRN	1.02
9	SWB	1.11	UUW	1.11	YKY	1.03	ANH	1.04	SVH	1.03	TMS	1.05	TMS	1.06	TMS	1.10	YKY	1.03
10	TMS	1.13	YKY	1.21	SVH	1.04	TMS	1.05	YKY	1.04	ANH	1.08	SWB	1.10	SWB	1.13	SVH	1.04

4.8. Efficiency Score Distributions and Rankings – Sewage Collection (Models SVE-SWC8 to SVE-SWC16)

Ranking	SVE-SWC8		SVE-SWC9		SVE-SWC10		SVE-SWC11		SVE-SWC12		SVE-SWC13		SVE-SWC14		SVE-SWC15		SVE-SWC16	
1	NES	0.94	NES	0.87	NES	0.86	YKY	0.94	YKY	0.94	NES	0.91	NES	0.93	NES	0.91	NES	0.90
2	UUW	0.95	UUW	0.94	UUW	0.93	WSX	0.98	UUW	0.95	UUW	0.97	WSH	0.96	UUW	0.95	UUW	0.94
3	WSH	0.96	WSX	0.97	WSX	0.96	SRN	0.98	WSX	0.95	ANH	0.98	UUW	0.98	WSH	0.96	WSH	0.95
4	ANH	1.00	SVH	0.99	SVH	0.99	UUW	0.98	SRN	0.95	SWB	0.99	ANH	0.99	ANH	0.99	ANH	0.98
5	WSX	1.00	SRN	1.00	ANH	0.99	SWB	0.99	SWB	0.98	SVH	0.99	SVH	1.00	SRN	1.01	SRN	1.00
6	TMS	1.01	ANH	1.01	SRN	1.00	WSH	0.99	SVH	1.00	SRN	1.01	TMS	1.00	SVH	1.02	SVH	1.01
7	SWB	1.01	YKY	1.02	YKY	1.01	TMS	1.00	NES	1.03	TMS	1.01	SRN	1.01	WSX	1.02	TMS	1.01
8	SRN	1.01	WSH	1.05	WSH	1.05	SVH	1.03	TMS	1.04	YKY	1.02	SWB	1.02	TMS	1.02	WSX	1.01
9	YKY	1.03	TMS	1.06	TMS	1.06	ANH	1.04	WSH	1.08	WSH	1.02	WSX	1.02	SWB	1.04	SWB	1.03
10	SVH	1.03	SWB	1.10	SWB	1.09	NES	1.06	ANH	1.09	WSX	1.03	YKY	1.04	YKY	1.11	YKY	1.10

ST Classification: UNMARKED

5. Sewage Treatment

5.1. Econometric Models

Model Number	Model
SVE-SWT1	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Pctbands13_{it} + \beta_3 avg\_p05nh33uv30_{it} + \mu_i + \varepsilon_{it}$
SVE-SWT2	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(was2_{it}) + \beta_3 avg\_p05nh33uv30_{it} + \mu_i + \varepsilon_{it}$
SVE-SWT3	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Pctbands13_{it} + \beta_3 Ln(wac_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWT4	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(was2_{it}) + \beta_3 Ln(wac4_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWT5	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Pctbands13_{it} + \beta_3 Ln(wac1_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWT6	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(was2_{it}) + \beta_3 Ln(wac1_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWT7	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Pctbands13_{it} + \beta_3 Ln(wac2_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWT8	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(was2_{it}) + \beta_3 Ln(wac2_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWT9	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(was2_{it}) + \beta_3 Ln(wac3_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWT10	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Pctbands13_{it} + \beta_3 Ln(wac3_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWT11	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(was2_{it}) + \beta_3 avg\_p05nh33uv30_{it} + \beta_4 AMPY2_t + \beta_5 AMPY3_t + \beta_6 AMPY4_t + \beta_7 AMPY5_t + \beta_8 AMP5_t + \beta_9 AMP6_t + \mu_i + \varepsilon_{it}$
SVE-SWT12	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Pctbands13_{it} + \beta_3 avg\_p05nh33_{it} + \beta_4 AMPY2_t + \beta_5 AMPY3_t + \beta_6 AMPY4_t + \beta_7 AMPY5_t + \beta_8 AMP5_t + \beta_9 AMP6_t + \mu_i + \varepsilon_{it}$
SVE-SWT13	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Pctbands13_{it} + \beta_3 Ln(wac3_{it}) + \beta_4 AMPY2_t + \beta_5 AMPY3_t + \beta_6 AMPY4_t + \beta_7 AMPY5_t + \mu_i + \varepsilon_{it}$
SVE-SWT14	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(was2_{it}) + \beta_3 Ln(wac3_{it}) + \beta_4 AMPY2_t + \beta_5 AMPY3_t + \beta_6 AMPY4_t + \beta_7 AMPY5_t + \beta_8 AMP5_t + \beta_9 AMP6_t + \mu_i + \varepsilon_{it}$

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SVE-SWT15	$Ln(Botex\_ST\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Pctbands13_{it} + \beta_3 Ln(wac3_{it}) + \beta_4 AMPY2_t + \beta_5 AMPY3_t + \beta_6 AMPY4_t + \beta_7 AMPY5_t + \beta_8 AMP5_t + \beta_9 AMP6_t + \mu_i + \varepsilon_{it}$
SVE-SWT16	$Ln(Botex\_ST\_SFR\_sm_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Pctbands13_{it} + \beta_3 Ln(wac3_{it}) + \mu_i + \varepsilon_{it}$
SVE-SWT17	$Ln(Botex\_ST\_SFR\_sm_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Pctbands13_{it} + \beta_3 Ln(was2_{it}) + \mu_i + \varepsilon_{it}$

5.2. Variable List

Dependent Variable:	Variable name in model	Description
Sewage Treatment Botex including sewer flooding.	Botex_ST_SFR	Sewage Treatment Botex including sewer flooding as reported in the published PR24 wholesale dataset. Code: botex_st_sewerflood in Interface_real.
Smoothed Capex Sewage Treatment Botex including sewer flooding.	Botex_ST_SFR_sm	Sewage Treatment Botex with smoothed capex including sewer flooding. A 5-year rolling average (year t down to t-4) was used to smooth capex to form this botex measure.
Independent Variable:		
Total Load	Load	Total load received by STWs (kg BOD5/day) as reported in the published PR24 wholesale dataset. Code: Load in Interface_real
Economies of Scale or Density	Pctbands13	Proportion of total load that is treated in bands 1 to 3 as reported in the published PR24 wholesale dataset. Code: pctbands13 in Interface_real
Economies of Scale or Density	Was2	Weighted average size of treatment works. Refer to section 3.2.8 ‘Improving Ofwat’s cost models for use at PR24’ for more information.
Treatment Complexity	Wac1 Wac2 Wac3 Wac4 Wac5	Weighted average treatment complexity using various weightings for each treatment band. Refer to section 3.3.5 ‘Improving Ofwat’s cost models for use at PR24’ for more information.
Treatment Complexity	Avg_p05nh33 Avg_p05nh33uv30	Composite complexity driver accounting for tight p-consents and ammonia (Avg_p05nh33), and UV (Avg_p05nh33uv30). Refer to section 3.3.5 ‘Improving Ofwat’s cost models for use at PR24’ for more information.

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AMP year	AMPY$\boldsymbol{X}$	Dummy variable =1 if year is the X^{th} year of the AMP, =0 if year is the 1st year of the AMP.
AMP	AMP5	Dummy variable =1 if year is in AMP5, 0 otherwise.
	AMP6	Dummy variable =1 if year is in AMP6, 0 otherwise.

5.3. Brief Model Description

Model Number	Model Description
SVE-SWT1	As per Ofwat PR19 SWT1, with Avg_p05nh33uv30 in place of Pctnh3below3mg.
SVE-SWT2	As per SVE-SWT1, with Was2 in place of Pctbands13.
SVE-SWT3	As per SVE-SWT1, with Wac5 in place of Avg_p05nh33uv30.
SVE-SWT4	As per SVE-SWT2, with Wac4 in place of Avg_p05nh33uv30.
SVE-SWT5	As per SVE-SWT1, with Wac1 in place of Avg_p05nh33uv30.
SVE-SWT6	As per SVE-SWT2, with Wac1 in place of Avg_p05nh33uv30.
SVE-SWT7	As per SVE-SWT1, with Wac2 in place of Avg_p05nh33uv30.
SVE-SWT8	As per SVE-SWT2, with Wac2 in place of Avg_p05nh33uv30.
SVE-SWT9	As per SVE-SWT2, with Wac3 in place of Avg_p05nh33uv30.
SVE-SWT10	As per SVE-SWT1, with Wac3 in place of Avg_p05nh33uv30.
SVE-SWT11	As per SVE-SWT2, with the addition of AMP year and AMP dummies.
SVE-SWT12	As per SVE-SWT1, with the addition of AMP year and AMP dummies, as well as Avg_p05nh33 in place of Avg_p05nh33uv30.
SVE-SWT13	As per SVE-SWT10, with the addition of AMP year dummies.
SVE-SWT14	As per SVE-SWT9, with the addition of AMP year and AMP dummies.
SVE-SWT15	As per SVE-SWT13, with the addition of AMP dummies.
SVE-SWT16	As per SVE-SWT10, with smoothed capex Botex_ST_SFR_sm as the dependent variable.
SVE-SWT17	As per SVE-SWT9, with smoothed capex Botex_ST_SFR_sm as the dependent variable.

5.4. Brief Comment on the Models

We have included Ofwat's updated PR19 SWT1 and SWT2 models for comparative purposes (model numbers Ofwat PR19 SWT1 and Ofwat PR19 SWT2 respectively).

Models SVE-SWT1 to SVE-SWT15 use a panel spanning from 2011-12 to 2021-22, a total of 11 years.

Models SVE-SWT16 to SVE-SWT17 use a panel spanning from 2014-15 to 2021-2022, a total 7 years.

Alternative VIFs have been reported where squared population density terms have been included in the models. This is calculated without the problematic squared density term in the model as it is not a concern that this specific variable inflates the VIF.

Any insignificant variable that has remained in the models are due to their strength in engineering expectation and rationale.

Variables included in the following models are also relevant in other levels of aggregations.

All variables are expressed in logs apart from the following: Pctbands13, Avg_p05nh33, Avg_p05nh33uv30, AMPY2, AMPY3, AMPY4, AMPY5, AMP5, AMP6.

5.5. Model Results – Sewage Treatment (SVE-SWT1 to SVE-SWT10)

	Ofwat PR19 SWT1	Ofwat PR19 SWT2	SVE-SWT1	SVE-SWT2	SVE-SWT3	SVE-SWT4	SVE-SWT5	SVE-SWT6	SVE-SWT7	SVE-SWT8	SVE-SWT9	SVE-SWT10
Dependent Variable	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR
Load	0.651*** (0.000)	0.682*** (0.000)	0.814*** (0.000)	0.841*** (0.000)	0.692*** (0.000)	0.641*** (0.000)	0.707*** (0.000)	0.727*** (0.000)	0.669*** (0.000)	0.682*** (0.000)	0.634*** (0.000)	0.634*** (0.000)
Pctbands13	0.028 (0.225)		0.046 (0.109)		0.042 (0.133)		0.042 (0.124)		0.044 (0.108)			0.047* (0.066)
Pctbands16 (Ofwat models only)		-0.011* (0.053)										
Was2				1.042 (0.136)		0.905 (0.136)		0.904* (0.092)		0.895* (0.095)	0.860 (0.108)	
Pctnh3below3mg (Ofwat models only)	0.006*** (0.000)	0.006*** (0.000)										
Wac1							0.158*** (0.000)	0.163*** (0.000)				
Wac2									0.168*** (0.000)	0.162*** (0.000)		
Wac3											0.163*** (0.002)	0.162*** (0.002)
Wac4						0.117*** (0.001)						
Wac5					0.184*** (0.000)							
Avg_p05nh33												
Avg_p05nh33uv30			0.015*** (0.000)	0.016*** (0.000)								
AMPY2												
AMPY3												
AMPY4												
AMPY5												

ST Classification: UNMARKED

AMP5												
AMP6												
Constant	-3.708*** (0.003)	-3.137*** (0.000)	-5.874*** (0.001)	-5.534*** (0.000)	-4.734*** (0.001)	-4.028*** (0.001)	-5.085*** (0.000)	-4.745*** (0.000)	-4.724*** (0.000)	-4.283*** (0.000)	-3.781*** (0.005)	-4.391*** (0.001)
Estimation Method	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE	RE
N (Sample Size)	110	110	110	110	110	110	110	110	110	110	110	110
Model Robustness Tests												
R2 overall	0.854	0.855	0.824	0.831	0.861	0.865	0.868	0.87	0.872	0.873	0.878	0.88
RESET test	0.059	0.157	0.14	0.145	0.073	0.092	0.035	0.059	0.052	0.081	0.088	0.06
VIF (max)	5.269	4.34	2.635	3.437	3.473	7.275	3.092	2.959	3.668	3.559	4.799	4.79
Pooling / Chow test	0.999	1	0.994	0.993	1	1	1	1	1	1	1	1
Normality of model residuals	0.028	0.042	0.039	0.044	0.046	0.029	0.124	0.071	0.103	0.06	0.042	0.059
Heteroskedasticity of model residuals	0.437	0.889	0.384	0.757	0.416	0.873	0.293	0.511	0.342	0.589	0.755	0.482
Test of pooled OLS versus Random Effects (LM test)	0	0	0	0	0	0	0	0	0	0	0	0
Efficiency Score Distribution — Minimum	0.81	0.85	0.82	0.85	0.87	0.88	0.86	0.85	0.87	0.86	0.88	0.87
Efficiency Score Distribution — Maximum	1.50	1.52	1.59	1.62	1.46	1.46	1.36	1.37	1.37	1.37	1.38	1.39
Sensitivity of estimated coefficients to removal of most and least efficient company			G	A	G	G	G	G	G	G	G	G
Sensitivity of estimated coefficients to removal of first and last year of the sample			G	G	G	G	G	G	G	G	G	G
Additional Diagnostic Checks												
AIC	-105	-107	-103	-104	-106	-105	-110	-111	-110	-111	-108	-109
Sigma u	0.180	0.187	0.172	0.177	0.178	0.181	0.178	0.179	0.175	0.176	0.170	0.167
Alternative VIF	5.269	4.34	2.635	3.437	3.473	7.275	3.092	2.959	3.668	3.559	4.799	4.79

ST Classification: UNMARKED

5.6. Model Results – Sewage Treatment (SVE-SWT11 to SVE-SWT17)

	SVE-SWT11	SVE-SWT12	SVE-SWT13	SVE-SWT14	SVE-SWT15	SVE-SWT16	SVE-SWT17
Dependent Variable	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR	Botex_ST_SFR_sm	Botex_ST_SFR_sm
Load	0.850*** (0.000)	0.708*** (0.000)	0.612*** (0.000)	0.727*** (0.000)	0.726*** (0.000)	0.549*** (0.000)	0.544*** (0.000)
Pctbands13		0.039 (0.145)	0.050** (0.036)		0.050* (0.056)	0.032* (0.055)	
Pctbands16 (Ofwat models only)							
Was2	1.070 (0.134)			0.889 (0.134)			0.548 (0.131)
Pctnh3below3mg (Ofwat models only)							
Wac1							
Wac2							
Wac3			0.182*** (0.001)	0.099 (0.136)	0.101 (0.128)	0.210* (0.014)	0.210** (0.013)
Wac4							
Wac5							
Avg_p05nh33		0.009*** (0.000)					
Avg_p05nh33uv30	0.011** (0.046)						
AMPY2	0.071** (0.032)	0.073** (0.031)	0.054* (0.050)	0.069** (0.042)	0.071** (0.038)		
AMPY3	0.089* (0.079)	0.091* (0.073)	0.046 (0.215)	0.082 (0.118)	0.084 (0.112)		
AMPY4	0.091 (0.120)	0.090 (0.109)	0.039 (0.322)	0.084 (0.173)	0.084 (0.163)		
AMPY5	0.054 (0.402)	0.05 (0.404)	-0.01 (0.819)	0.047 (0.474)	0.045 (0.480)		

AMP5		-0.136 (0.102)	-0.125* (0.087)		-0.118 (0.181)	-0.114 (0.179)		
AMP6		-0.059 (0.171)	-0.054 (0.191)		-0.053 (0.245)	-0.051 (0.259)		
Constant		-5.548*** (0.000)	-4.427*** (0.001)	-4.281*** (0.002)	-4.555*** (0.003)	-5.193*** (0.000)	-3.541** (0.012)	-3.083** (0.016)
Estimation Method		RE	RE	RE	RE	RE	RE	RE
N (Sample Size)		110	110	110	110	110	70	70
Model Robustness Tests								
R2 overall		0.854	0.868	0.881	0.884	0.886	0.905	0.898
RESET test		0.01	0.004	0.028	0.019	0.012	0.026	0.013
VIF (max)		2.263	5.539	4.848	5.26	5.242	5.253	5.314
Pooling / Chow test		1	1	1	1	1	1	1
Normality of model residuals		0.018	0.017	0.053	0.023	0.034	0.047	0.15
Heteroskedasticity of model residuals		0.774	0.399	0.511	0.708	0.425	0.582	0.824
Test of pooled OLS versus Random Effects (LM test)		0	0	0	0	0	0	0
Efficiency Score Distribution	Minimum	0.863	0.85	0.856	0.868	0.853	0.823	0.814
	Maximum	1.518	1.434	1.383	1.374	1.382	1.286	1.423
Sensitivity of estimated coefficients to removal of most and least efficient company		A	A	A	A	A	A	A
Sensitivity of estimated coefficients to removal of first and last year of the sample		A	A	G	A	A	G	G
Additional Diagnostic Checks								
AIC		-107	-108	-105	-106	-106	-127*	-127*
Sigma u		0.177	0.18	0.167	0.171	0.168	0.165	0.173
Alternative VIF		2.263	5.539	4.848	5.26	5.242	5.253	5.314
*AIC incomparable as different dependent variable is used.								

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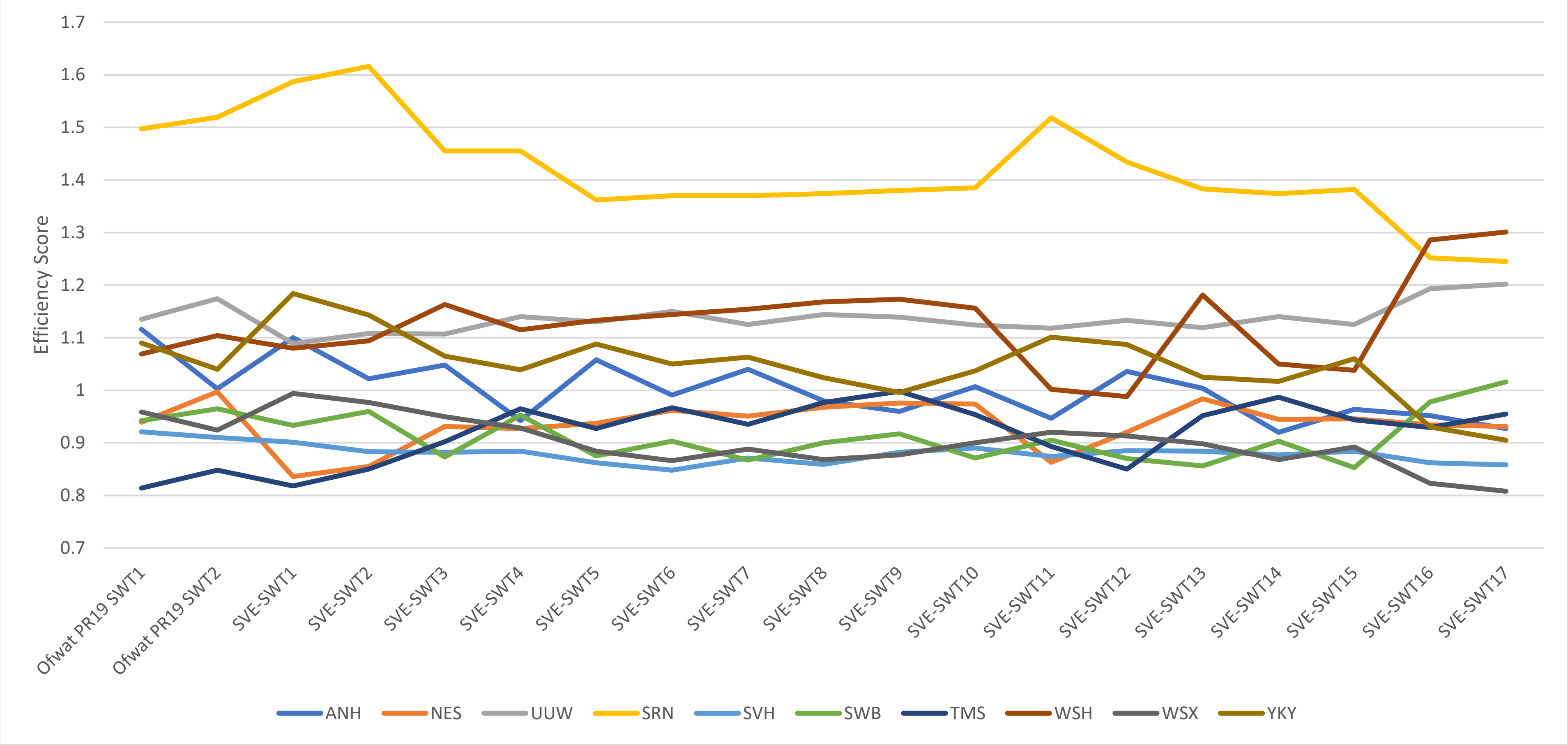

Figure 5.1. SVE-SWT Model Efficiency Score Distributions

ST Classification: UNMARKED

5.7. Efficiency Score Distributions and Rankings – Sewage Treatment (Models SVE-SWT1 to SVE-SWT10)

Ranking	Ofwat PR19 SWT1		Ofwat PR19 SWT2		SVE-SWT1		SVE-SWT2		SVE-SWT3		SVE-SWT4		SVE-SWT5		SVE-SWT6		SVE-SWT7		SVE-SWT8		SVE-SWT9		SVE-SWT10	
1	TMS	0.81	TMS	0.85	TMS	0.82	TMS	0.85	SWB	0.87	SVH	0.88	SVH	0.86	SVH	0.85	SWB	0.87	SVH	0.86	WSX	0.88	SWB	0.87
2	SVH	0.92	SVH	0.91	NES	0.84	NES	0.86	SVH	0.88	NES	0.93	SWB	0.88	WSX	0.87	SVH	0.87	WSX	0.87	SVH	0.88	SVH	0.89
3	NES	0.94	WSX	0.92	SVH	0.90	SVH	0.88	TMS	0.90	WSX	0.93	WSX	0.88	SWB	0.90	WSX	0.89	SWB	0.90	SWB	0.92	WSX	0.90
4	SWB	0.94	SWB	0.97	SWB	0.93	SWB	0.96	NES	0.93	ANH	0.94	TMS	0.93	NES	0.96	TMS	0.94	NES	0.97	ANH	0.96	TMS	0.95
5	WSX	0.96	NES	1.00	WSX	0.99	WSX	0.98	WSX	0.95	SWB	0.95	NES	0.94	TMS	0.97	NES	0.95	TMS	0.98	NES	0.98	NES	0.97
6	WSH	1.07	ANH	1.00	WSH	1.08	ANH	1.02	ANH	1.05	TMS	0.97	ANH	1.06	ANH	0.99	ANH	1.04	ANH	0.98	YKY	1.00	ANH	1.01
7	YKY	1.09	YKY	1.04	UUW	1.09	WSH	1.09	YKY	1.07	YKY	1.04	YKY	1.09	YKY	1.05	YKY	1.06	YKY	1.02	TMS	1.00	YKY	1.04
8	ANH	1.12	WSH	1.10	ANH	1.10	UUW	1.11	UUW	1.11	WSH	1.12	UUW	1.13	WSH	1.14	UUW	1.13	UUW	1.14	UUW	1.14	UUW	1.12
9	UUW	1.14	UUW	1.17	YKY	1.18	YKY	1.14	WSH	1.16	UUW	1.14	WSH	1.13	UUW	1.15	WSH	1.15	WSH	1.17	WSH	1.17	WSH	1.16
10	SRN	1.50	SRN	1.52	SRN	1.59	SRN	1.62	SRN	1.46	SRN	1.46	SRN	1.36	SRN	1.37	SRN	1.37	SRN	1.37	SRN	1.38	SRN	1.39

5.8. Efficiency Score Distributions and Rankings – Sewage Treatment (Models SVE-SWT11 to SVE-SWT17)

Ranking	SVE-SWT11		SVE-SWT12		SVE-SWT13		SVE-SWT14		SVE-SWT15		SVE-SWT16		SVE-SWT17	
1	NES	0.86	TMS	0.85	SWB	0.86	WSX	0.87	SWB	0.85	WSX	0.82	WSX	0.81
2	SVH	0.87	SWB	0.87	SVH	0.88	SVH	0.88	SVH	0.88	SVH	0.86	SVH	0.86
3	TMS	0.89	SVH	0.89	WSX	0.90	SWB	0.90	WSX	0.89	TMS	0.93	YKY	0.91
4	SWB	0.91	WSX	0.91	TMS	0.95	ANH	0.92	TMS	0.94	YKY	0.93	ANH	0.93
5	WSX	0.92	NES	0.92	NES	0.98	NES	0.95	NES	0.95	NES	0.93	NES	0.93
6	ANH	0.95	WSH	0.99	ANH	1.00	TMS	0.99	ANH	0.96	ANH	0.95	TMS	0.96
7	WSH	1.00	ANH	1.04	YKY	1.03	YKY	1.02	WSH	1.04	SWB	0.98	SWB	1.02
8	YKY	1.10	YKY	1.09	UUW	1.12	WSH	1.05	YKY	1.06	UUW	1.19	UUW	1.20
9	UUW	1.12	UUW	1.13	WSH	1.18	UUW	1.14	UUW	1.13	SRN	1.25	SRN	1.25
10	SRN	1.52	SRN	1.43	SRN	1.38	SRN	1.37	SRN	1.38	WSH	1.29	WSH	1.30

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6. Wastewater Network Plus

6.1. Econometric Models

Model Number	Model
SVE-WWWNP1	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Ln(WAD\_LAD_{it}) + \beta_4 Pctnh3below3mg_{it} + \mu_i + \varepsilon_{it}$
SVE-WWWNP2	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Ln(Density\_knownlength_{it}) + \beta_4 Pctnh3below3mg_{it} + \beta_5 Propcombined_{it} + \mu_i + \varepsilon_{it}$
SVE-WWWNP3	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Avg\_p05nh33uv30_{it} + \beta_4 Ln(Urbanrainfallperknownlength_{it}) + \beta_5 Pctbands13_{it} + \beta_6 Ln(WAD\_LAD_{it}) + \beta_7 \left(Ln(WAD_{LAD\,it})\right)^2 + \beta_8 Propcombined_{it} + \mu_i + \varepsilon_{it}$
SVE-WWWNP4	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Avg\_p05nh33uv30_{it} + \beta_4 Ln(Urbanrainfallperknownlength_{it}) + \beta_5 Ln(WAD\_LAD_{it}) + \beta_6 (Ln(WAD\_LAD_{it}))^2 + \beta_7 Ln(Was2_{it}) + \beta_8 Propcombined_{it} + \mu_i + \varepsilon_{it}$
SVE-WWWNP5	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Avg\_p05nh33uv30_{it} + \beta_4 Ln(Urbanrainfallperknownlength_{it}) + \beta_5 Ln(Was2_{it}) + \beta_6 Propcombined_{it} + \mu_i + \varepsilon_{it}$
SVE-WWWNP6	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Avg\_p05nh33uv30_{it} + \beta_4 Ln(Urbanrainfallperknownlength_{it}) + \beta_5 Pctbands13_{it} + \beta_6 Ln(WAD\_LAD_{it}) + \beta_7 \left(Ln(WAD_{LAD\,it})\right)^2 + \mu_i + \varepsilon_{it}$
SVE-WWWNP7	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Avg\_p05nh33uv30_{it} + \beta_4 Ln(Urbanrainfallperknownlength_{it}) + \beta_5 Pctbands13_{it} + \beta_6 Propcombined_{it} + \mu_i + \varepsilon_{it}$
SVE-WWWNP8	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Avg\_p05nh33uv30_{it} + \beta_4 Ln(Was2_{it}) + \beta_5 Propcombined_{it} + \mu_i + \varepsilon_{it}$
SVE-WWWNP9	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Avg\_p05nh33uv30_{it} + \beta_4 Pctbands13_{it} + \beta_5 Propcombined_{it} + \mu_i + \varepsilon_{it}$
SVE-WWWNP10	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Avg\_p05nh33uv30_{it} + \beta_4 Ln(Urbanrainfallperknownlength_{it}) + \beta_5 Ln(WAD\_LAD_{it}) + \beta_6 Ln(Was2_{it}) + \mu_i + \varepsilon_{it}$

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SVE-WWWNP11	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Avg\_p05nh33uv30_{it} + \beta_4 Ln(Urbanrainfallperknownlength_{it}) + \beta_5 Ln(Was2_{it}) + \mu_i + \varepsilon_{it}$
SVE-WWWNP12	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Avg\_p05nh33uv30_{it} + \beta_4 Ln(Urbanrainfallperknownlength_{it}) + \beta_5 Pctbands13_{it} + \mu_i + \varepsilon_{it}$
SVE-WWWNP13	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Avg\_p05nh33uv30_{it} + \beta_4 Ln(Was2_{it}) + \mu_i + \varepsilon_{it}$
SVE-WWWNP14	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Avg\_p05nh33uv30_{it} + \beta_4 Pctbands13_{it} + \mu_i + \varepsilon_{it}$
SVE-WWWNP15	$Ln(Botex\_NP\_SFR_{it}) = \beta_0 + \beta_1 Ln(Load_{it}) + \beta_2 Ln(Pumpingcapperknownlength_{it}) + \beta_3 Avg\_p05nh33uv30_{it} + \beta_4 Ln(Urbanrainfallperknownlength_{it}) + \beta_5 Pctbands13_{it} + \beta_6 Ln(Density\_knownlength_{it}) + \mu_i + \varepsilon_{it}$

6.2. Variable List

Dependent Variable:	Variable name in model	Description
Wastewater Network Plus Botex including sewer flooding and network reinforcement.	Botex_NP_SFR	Sewage Treatment Botex including sewer flooding as reported in the published PR24 wholesale dataset. Code: botex_network+_sewerflood_rein in Interface_real.
Independent Variable:		
Total Load	Load	Total load received by STWs (kg BOD5/day) as reported in the published PR24 wholesale dataset. Code: Load in Interface_real
Population Density	WAD_LAD (WAD_LAD2)	Weighted average population density using Local Authority Districts (LAD) as reported in the published wholesale dataset. WAD_LAD2 is the squared density term for WAD_LAD. Code: WAD_LAD in Interface_real
Population Density	Density_knownlength (Density_knownlength2)	Population density measure calculated as $properties/knownlength$. Knownlength is the legacy sewer length (Code: BN13535_21 in Stata dataset (real)). Density_knownlength2 is the squared density term for Density_knownlength.

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		Code: density_knownlength in Interface_real of SVE_FM_WWW1.
Network Complexity	Pumpingcapperknownlength	Alternative Pumpingcapperlength measure calculated as: $Pumping\ capacity/knownlength$ Code: Pumping capacity in Interface_real. Knownlength is the legacy sewer length (Code: BN13535_21 in Stata dataset (real)).
Network Complexity	Propcombined	Proportion of combined legacy sewers over total legacy sewers. Code: propcombined in Interface_real of SVE_FM_WWW1.
Weather	Urbanrainfallperknownlength	Alternative urbanrainfallperlength calculated as $urbanrainfall/knownlength$. Code: urbanrainfall in Interface_real Knownlength is the legacy sewer length (Code: BN13535_21 in Stata dataset (real)).
Economies of Scale or Density	Pctbands13	Proportion of total load that is treated in bands 1 to 3 as reported in the published PR24 wholesale dataset. Code: pctbands13 in Interface_real
Economies of Scale or Density	Was2	Weighted average size of treatment works. Refer to section 3.2.8 ‘Improving Ofwat’s cost models for use at PR24’ for more information.
Treatment Complexity	Avg_p05nh33 Avg_p05nh33uv30	Composite complexity driver accounting for tight p-consents and ammonia (Avg_p05nh33), and UV (Avg_p05nh33uv30). Refer to section 3.3.5 ‘Improving Ofwat’s cost models for use at PR24’ for more information.
Treatment Complexity	Pctnh3below3mg	Proportion of load treated to ammonia levels below 3mg/l as reported in the published PR24 wholesale dataset. Code: pctnh3below3mg in Interface_real

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6.3. Brief Model Description

Model Number	Model Description
SVE-NPWWW1	Model covering simple engineering expectations using the following variables Load, Pumpingcapperknownlength, WAD_LAD, Pctnh3below3mg.
SVE-NPWWW2	As per SVE-NPWWW1, with the addition of Density_knownlength and Propcombined, and with removal of WAD_LAD.
SVE-NPWWW3	As per SVE-NPWWW2, with the addition of Pctbands13, Avg_p05nh33uv30, Urbanrainfallperknownlength, WAD_LAD, WAD_LAD2, and with removal of Density_knownlength and Pctnh3below3mg
SVE-NPWWW4	As per SVE-NPWWW3, with Was2 replacing Pctbands13.
SVE-NPWWW5	As per SVE-NPWWW4, with the removal of WAD_LAD and WAD_LAD2.
SVE-NPWWW6	As per SVE-NPWWW3, with the removal of Propcombined
SVE-NPWWW7	As per SVE-NPWWW3, with the removal of WAD_LAD and WAD_LAD2.
SVE-NPWWW8	As per SVE-NPWWW5, with the removal of Urbanrainfallperknownlength.
SVE-NPWWW9	As per SVE-NPWWW8, with Pctbands13 replacing Was2.
SVE-NPWWW10	As per SVE-NPWWW5, with the addition of WAD_LAD, and removal of Propcombined.
SVE-NPWWW11	As per SVE-NPWWW10, with the addition of Pctbands13.
SVE-NPWWW12	As per SVE-NPWWW10, with the addition of Pctbands13, and removal of WAD_LAD and Was2.
SVE-NPWWW13	As per SVE-NPWWW11, with the removal of Urbanrainfallperknownlength.
SVE-NPWWW14	As per SVE-NPWWW9, with the removal of Propcombined.
SVE-NPWWW15	As per SVE-NPWWW12, with the addition of Density_knownlength.

6.4. Brief Comment on the Models

Models SVE-NPWWW1 to SVE-NPWWW15 use a panel spanning from 2011-12 to 2021-22, a total of 11 years.

Alternative VIFs have been reported where squared population density terms have been included in the models. This is calculated without the problematic squared density term in the model as it is not a concern that this specific variable inflates the VIF.

Any insignificant variable that has remained in the models are due to their strength in engineering expectation and rationale.

Variables included in the following models are also relevant in other levels of aggregations and are included as such.

All variables are expressed in logs apart from the following: Pctbands13, Avg_p05nh33, Avg_p05nh33uv30, AMPY2, AMPY3, AMPY4, AMPY5, AMP5, AMP6.

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6.5. Model Results – Wastewater Network Plus (SVE-NPWWW1 to SVE-NPWWW8)

	SVE-NPWWW1	SVE-NPWWW2	SVE-NPWWW3	SVE-NPWWW4	SVE-NPWWW5	SVE-NPWWW6	SVE-NPWWW7	SVE-NPWWW8
Dependent Variable	Botex_NP_SFR	Botex_NP_SFR	Botex_NP_SFR	Botex_NP_SFR	Botex_NP_SFR	Botex_NP_SFR	Botex_NP_SFR	Botex_NP_SFR
Load	0.741*** {0.000}	0.824*** {0.000}	0.992*** {0.000}	0.990*** {0.000}	0.979*** {0.000}	0.980*** {0.000}	0.963*** {0.000}	0.979*** {0.000}
Pumpingcapperknownlength	0.333*** {0.000}	0.512*** {0.000}	0.464*** {0.000}	0.492*** {0.000}	0.496*** {0.000}	0.419*** {0.000}	0.471*** {0.000}	0.522*** {0.000}
Pctbands13			0.034*** {0.000}			0.036*** {0.000}	0.028*** {0.000}	
Avg_p05nh33uv30			0.012*** {0.000}	0.013*** {0.000}	0.013*** {0.000}	0.015*** {0.000}	0.009*** {0.000}	0.011*** {0.000}
Urbanrainfallperknownlength			0.043** {0.016}	0.061*** {0.000}	0.055*** {0.001}	0.074*** {0.000}	0.035* {0.067}	
WAD_LAD	-0.103*** {0.007}		0.728*** {0.003}	0.402** {0.010}		0.817** {0.044}		
WAD_LAD2			-0.053*** {0.002}	-0.027*** {0.008}		-0.061** {0.021}		
Was2				0.744*** {0.000}	0.692*** {0.000}			0.608*** {0.000}
Density_knownlength		-0.300*** {0.001}						
Pctnh3below3mg	0.005*** {0.000}	0.004*** {0.000}						
Propcombined		0.004*** {0.000}	0.002** {0.025}	0.002*** {0.000}	0.002*** {0.000}		0.003*** {0.000}	0.003*** {0.000}
Constant	-3.557***	-4.346***	-10.201***	-8.658***	-7.093***	-10.108***	-7.346***	-7.334***

ST Classification: UNMARKED

		{0.000}	{0.000}	{0.000}	{0.000}	{0.000}	{0.000}	{0.000}	{0.000}
Estimation Method		RE	RE	RE	RE	RE	RE	RE	RE
N (Sample Size)		110	110	110	110	110	110	110	110
Model Robustness Tests									
R2 overall		0.951	0.96	0.966	0.966	0.965	0.965	0.964	0.964
RESET test		0.931	0.757	0.904	0.956	0.767	0.725	0.185	0.858
VIF (max)		7.41	5.248	574.77	494.422	4.448	570.564	3.696	3.969
Pooling / Chow test		0.901	0.845	0.048	0.034	0.136	0.066	0.261	0.021
Normality of model residuals		0.001	0	0	0	0	0	0.001	0
Heteroskedasticity of model residuals		0.059	0.08	0.068	0.07	0.077	0.067	0.145	0.089
Test of pooled OLS versus Random Effects (LM test)		0	0.473	1	1	1	0.145	0.135	1
Efficiency Score Distribution	Minimum	0.94	0.95	0.94	0.94	0.95	0.95	0.95	0.94
	Maximum	1.07	1.06	1.05	1.06	1.06	1.06	1.06	1.06
Sensitivity of estimated coefficients to removal of most and least efficient company		G	G	G	A	G	A	G	G
Sensitivity of estimated coefficients to removal of first and last year of the sample		G	G	A	G	G	G	A	G
Additional Diagnostic Checks									
AIC		-172	-181	-192	-191	-194	-191	-190	-193
Sigma u		0.069	0.035	0	0	0	0.035	0.011	0
Alternative VIF		7.41	5.248	7.174	7.846	4.448	4.726	3.696	3.969

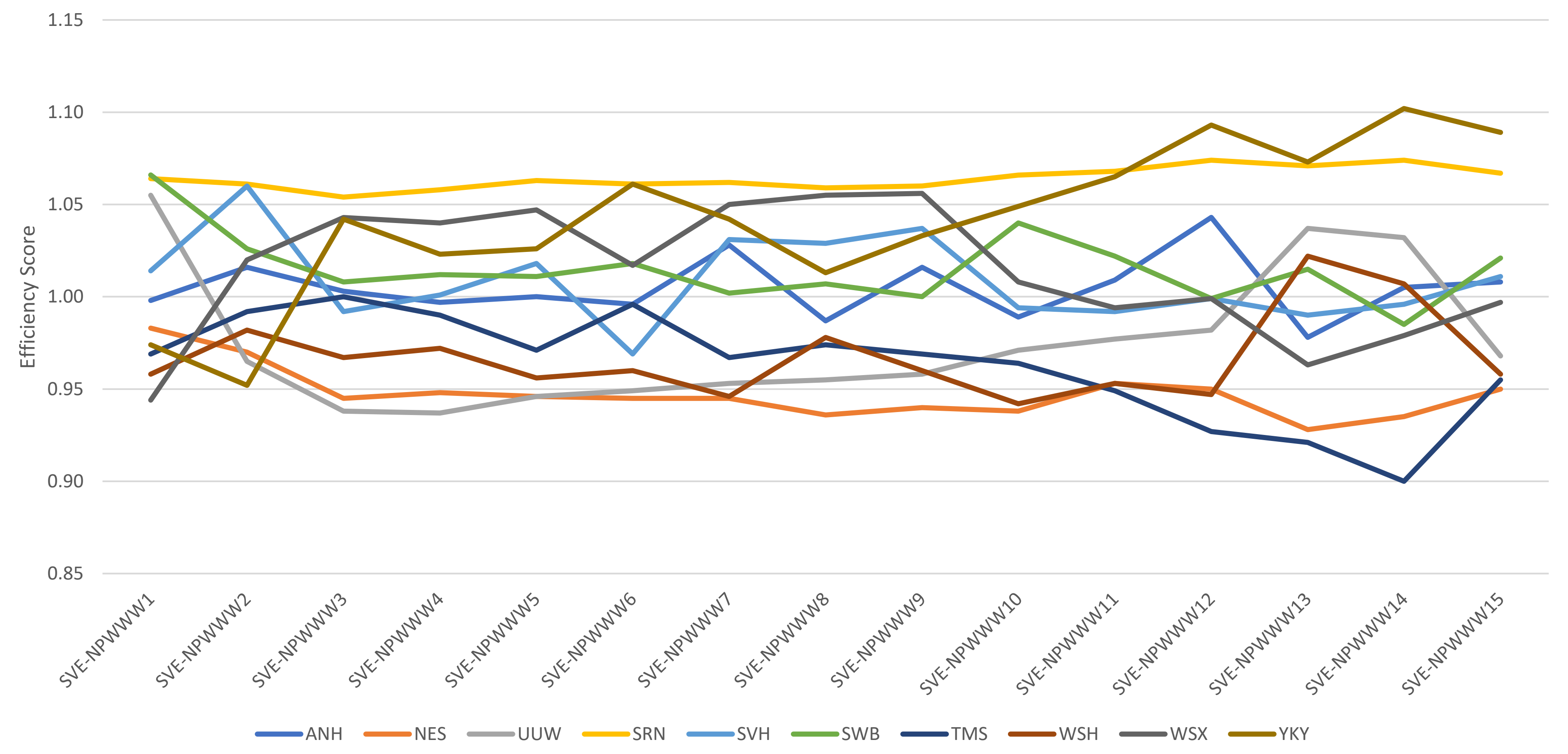
6.6. Model Results – Wastewater Network Plus (SVE-NPWWW9 to SVE-NPWWW15)

	SVE-NPWWW9	SVE-NPWWW10	SVE-NPWWW11	SVE-NPWWW12	SVE-NPWWW13	SVE-NPWWW14	SVE-NPWWW15
Dependent Variable	Botex_NP_SFR	Botex_NP_SFR	Botex_NP_SFR	Botex_NP_SFR	Botex_NP_SFR	Botex_NP_SFR	Botex_NP_SFR
Load	0.966*** {0.000}	0.950*** {0.000}	0.940*** {0.000}	0.923*** {0.000}	0.898*** {0.000}	0.901*** {0.000}	0.934*** {0.000}
Pumpingcapperknownlength	0.492*** {0.000}	0.434*** {0.000}	0.419*** {0.000}	0.393*** {0.000}	0.414*** {0.000}	0.405*** {0.000}	0.479*** {0.000}
Pctbands13	0.026*** {0.000}			0.034*** {0.000}		0.033*** {0.000}	0.025*** {0.000}
Avg_p05nh33uv30	0.009*** {0.000}	0.016*** {0.000}	0.014*** {0.000}	0.012*** {0.000}	0.013*** {0.000}	0.012*** {0.000}	0.013*** {0.000}
Urbanrainfallperknownlength		0.089*** {0.000}	0.106*** {0.000}	0.090*** {0.000}			0.113*** {0.000}
WAD_LAD		-0.061** {0.032}					
WAD_LAD2							
Was2		0.656*** {0.000}	0.745*** {0.000}		0.610*** {0.000}		
Density_knownlength							-0.369* {0.091}
Pctnh3below3mg							
Propcombined	0.003*** {0.000}						
Constant	-7.509*** {0.000}	-6.096*** {0.000}	-6.283*** {0.000}	-6.577*** {0.000}	-6.100*** {0.000}	-6.553*** {0.000}	-5.128*** {0.000}

ST Classification: UNMARKED

Estimation Method		RE	RE	RE	RE	RE	RE	RE
N (Sample Size)		110	110	110	110	110	110	110
Model Robustness Tests								
R2 overall		0.963	0.963	0.962	0.96	0.954	0.954	0.962
RESET test		0.275	0.468	0.132	0.008	0.492	0.058	0.111
VIF (max)		3.661	5.322	4.208	3.048	3.836	2.868	4.88
Pooling / Chow test		0.063	0.061	0.144	0.444	0.328	0.431	0.087
Normality of model residuals		0.001	0	0	0.001	0.005	0.009	0
Heteroskedasticity of model residuals		0.153	0.071	0.092	0.21	0.368	0.646	0.039
Test of pooled OLS versus Random Effects (LM test)		1	0.279	0.44	0.046	0	0	0.392
Efficiency Score Distribution	Minimum	0.94	0.94	0.95	0.93	0.92	0.90	0.95
	Maximum	1.06	1.07	1.07	1.09	1.07	1.10	1.09
Sensitivity of estimated coefficients to removal of most and least efficient company		G	A	A	G	G	G	G
Sensitivity of estimated coefficients to removal of first and last year of the sample		G	G	G	G	G	G	G
Additional Diagnostic Checks								
AIC		-191	-188	-187	-183	-177	-177	-186
Sigma u		0	0.03	0.036	0.054	0.066	0.067	0.036
Alternative VIF		3.661	5.322	4.208	3.048	3.836	2.868	4.88

Figure 6.1. SVE-NPWWW Model Efficiency Score Distribution



ST Classification: UNMARKED

6.7. Efficiency Score Distributions and Rankings – Wastewater Network Plus (Models SVE-NPWWW1 to SVE-NPWWW8)

Ranking	SVE-NPWWW1		SVE-NPWWW2		SVE-NPWWW3		SVE-NPWWW4		SVE-NPWWW5		SVE-NPWWW6		SVE-NPWWW7		SVE-NPWWW8	
1	WSX	0.94	YKY	0.95	UUW	0.94	UUW	0.94	NES	0.95	NES	0.95	NES	0.95	NES	0.94
2	WSH	0.96	UUW	0.97	NES	0.95	NES	0.95	UUW	0.95	UUW	0.95	WSH	0.95	UUW	0.96
3	TMS	0.97	NES	0.97	WSH	0.97	WSH	0.97	WSH	0.96	WSH	0.96	UUW	0.95	TMS	0.97
4	YKY	0.97	WSH	0.98	SVH	0.99	TMS	0.99	TMS	0.97	SVH	0.97	TMS	0.97	WSH	0.98
5	NES	0.98	TMS	0.99	TMS	1.00	ANH	1.00	ANH	1.00	ANH	1.00	SWB	1.00	ANH	0.99
6	ANH	1.00	ANH	1.02	ANH	1.00	SVH	1.00	SWB	1.01	TMS	1.00	ANH	1.03	SWB	1.01
7	SVH	1.01	WSX	1.02	SWB	1.01	SWB	1.01	SVH	1.02	WSX	1.02	SVH	1.03	YKY	1.01
8	UUW	1.06	SWB	1.03	YKY	1.04	YKY	1.02	YKY	1.03	SWB	1.02	YKY	1.04	SVH	1.03
9	SRN	1.06	SVH	1.06	WSX	1.04	WSX	1.04	WSX	1.05	YKY	1.06	WSX	1.05	WSX	1.06
10	SWB	1.07	SRN	1.06	SRN	1.05	SRN	1.06	SRN	1.06	SRN	1.06	SRN	1.06	SRN	1.06

6.8. Efficiency Score Distributions and Rankings – Wastewater Network Plus (Models SVE-NPWWW9 to SVE-NPWWW15)

Ranking	SVE-NPWWW9		SVE-NPWWW10		SVE-NPWWW11		SVE-NPWWW12		SVE-NPWWW13		SVE-NPWWW14		SVE-NPWWW15		
1	NES	0.94	NES	0.94	TMS	0.95	TMS	0.93	TMS	0.92	TMS	0.90	NES	0.95	
2	UUW	0.96	WSH	0.94	WSH	0.95	WSH	0.95	NES	0.93	NES	0.94	TMS	0.96	
3	WSH	0.96	TMS	0.96	NES	0.95	NES	0.95	WSX	0.96	WSX	0.98	WSH	0.96	
4	TMS	0.97	UUW	0.97	UUW	0.98	UUW	0.98	ANH	0.98	SWB	0.99	UUW	0.97	
5	SWB	1.00	ANH	0.99	SVH	0.99	SVH	1.00	SVH	0.99	SVH	1.00	WSX	1.00	
6	ANH	1.02	SVH	0.99	WSX	0.99	WSX	1.00	SWB	1.02	ANH	1.01	ANH	1.01	
7	YKY	1.03	WSX	1.01	ANH	1.01	SWB	1.00	WSH	1.02	WSH	1.01	SVH	1.01	
8	SVH	1.04	SWB	1.04	SWB	1.02	ANH	1.04	UUW	1.04	UUW	1.03	SWB	1.02	
9	WSX	1.06	YKY	1.05	YKY	1.07	SRN	1.07	SRN	1.07	SRN	1.07	SRN	1.07	
10	SRN	1.06	SRN	1.07	SRN	1.07	YKY	1.09	YKY	1.07	YKY	1.10	YKY	1.09	

ST Classification: UNMARKED

7. Bioresources

7.1. Econometric Models

Model Number	Model
SVE-BR1	$Ln(Botex\_Bio\_enh\_unit_{it}) = \beta_0 + \beta_1 Ln(Sludgeprod_{it}) + \beta_2 Pctbands13_{it} + \beta_3 Propdisposedtofarm_{it} + \beta_4 Propintersitingtt_{it} + \mu_i + \varepsilon_{it}$
SVE-BR2	$Ln(Botex\_Bio\_enh\_unit_{it}) = \beta_0 + \beta_1 Propdisposedtofarm_{it} + \beta_2 Propintersitingtt_{it} + \beta_3 Ln(Was2_{it}) + \mu_i + \varepsilon_{it}$
SVE-BR3	$Ln(Botex\_Bio\_enh\_unit_{it}) = \beta_0 + \beta_1 Propdisposedtofarm_{it} + \beta_2 Propintersitingtt_{it} + \beta_3 PropADplus_{it} + \beta_4 Ln(Intersitingworkpersludge_{it}) + \mu_i + \varepsilon_{it}$
SVE-BR4	$Ln(Botex\_Bio\_enh\_unit_{it}) = \beta_0 + \beta_1 Ln(Sludgeprod_{it}) + \beta_2 PropADplus_{it} + \beta_3 Propdisposedtofarm_{it} + \beta_4 Propintersitingtt_{it} + \beta_5 Ln(WAD\_LAD_{it}) + \beta_6 (Ln(WAD\_LAD_{it}))^2 + \mu_i + \varepsilon_{it}$

7.2. Variable List

Dependent Variable:	Variable name in model	Description
Bioresources botex including growth enhancement unit cost	Botex_Bio_enh_unit	Bioresources botex including growth enhancement at a unit cost level (per Sludgeprod). Code: realbotexbrenh in PR24 bioresources base cost do-file v1.0.
Independent Variable:		
Sludge Produced	Sludgeprod	Total sludge produced as reported in the published PR24 wholesale dataset. Code: sludgeprod in Interface_real
Population Density	WAD_LAD (WAD_LAD2)	Weighted average population density using Local Authority Districts (LAD) as reported in the published wholesale dataset. WAD_LAD2 is the squared density term for WAD_LAD. Code: WAD_LAD in Interface_real
Economies of Scale or Density	Pctbands13	Proportion of total load that is treated in bands 1 to 3 as reported in the published PR24 wholesale dataset. Code: pctbands13 in Interface_real
Economies of Scale or Density	Was2	Weighted average size of treatment works.

ST Classification: UNMARKED

		Refer to section 3.2.8 ‘Improving Ofwat’s cost models for use at PR24’ for more information.
Sludge Treatment Complexity	PropADPlus	Proportion of sludge treated by anaerobic digestion or advanced anaerobic digestion. Calculated as 100 times the sum of the following codes in Stata dataset (real) of SVE_FM_WWW1_BIO: BN5613INC + BN5614INC + BN5613TPS + BN5614TPS
Intersiting	Propintersitingtt	Proportion of total intersiting that is transported between sites via truck/tanker. Calculated using the following codes in Stata dataset (real) of SVE_FM_WWW1_BIO: (BN1641 + BN1642) / BN1643
Intersiting work per sludge	Intersitingworkpersludge	Sludge intersiting ‘work’ normalised by sludge produced volume. Log of Intersiting work over sludge produced. Intersiting work code: BN1643
Disposal Route	Propdisposedtofarm	Proportion of sludge disposed in farmland. Calculated as 100 times the sum of the following codes in Stata dataset)real) of SVE_FM_WWW1_BIO: BN5623INC + BN5623TPS

7.3. Brief Model Description

Model Number	Model Description
SVE-BR1	As per Ofwat Draft Methodology Proposal Option 2 (Ofwat DM BR1), with the addition of propdisposedtofarm and propintersitingtt.
SVE-BR2	As per SVE-BR1 with the addition of Was2, and removal of sludgeprod and pctbands13.
SVE-BR3	As per SVE-BR1, with PropADplus and Intersitingworkpersludge included and Pctbands13 removed.
SVE-BR4	As per SVE-BR3, with the addition of WAD_LAD and WAD_LAD2, and removal of Intersitingworkpersludge

ST Classification: UNMARKED

7.4. Brief Comment on the Models

Models SVE-BR1 to SVE-BR4 use a panel spanning from 2011-12 to 2021-22, a total of 11 years.

Alternative VIFs have been reported where squared population density terms have been included in the models. This is calculated without the problematic squared density term in the model as it is not a concern that this specific variable inflates the VIF.

Any insignificant variable that has remained in the models are due to their strength in engineering expectation and rationale.

Variables included in the following models are also relevant in other levels of aggregations and are included as such.

All variables are expressed in logs apart from the following: Pctbands13, Propintersitingtt, PropADplus.

7.5. Model Results – Bioresources (SVE-BR1 to SVE-BR4)

	Ofwat DM BR1	Ofwat DM BR2	SVE-BR1	SVE-BR2	SVE-BR3	SVE-BR4
Dependent Variable	Botex_Bio_enh_unit	Botex_Bio_enh_unit	Botex_Bio_enh_unit	Botex_Bio_enh_unit	Botex_Bio_enh_unit	Botex_Bio_enh_unit
Sludgeprod	0.157 {0.364}	0.169 {0.529}	0.169 {0.187}		0.209** {0.017}	0.191 {0.124}
Pctbands13	0.032 {0.231}		0.070*** {0.002}			
Propdisposedtofarm	-0.911 {0.159}		-0.011*** {0.004}	-0.011*** {0.008}	-0.006** {0.049}	-0.008*** {0.002}
Propintersitingtt			0.013*** {0.000}	0.010*** {0.001}	0.017*** {0.000}	0.012*** {0.000}
Was2				0.769* {0.054}		
PropADplus					-0.011*** {0.000}	-0.008*** {0.000}
Intersitingworkpersludge					0.205*** {0.001}	
WAD_LAD						-1.842*** {0.002}
WAD_LAD2						0.109*** {0.004}
Density (Ofwat models only)						
Swtwperpro (Ofwat models only)		0.290 {0.174}				
Constant	1.727 {0.352}	0.773 {0.357}	-2.008*** {0.008}	-0.383 {0.426}	-2.454*** {0.000}	6.158*** {0.006}
Estimation Method	RE	RE	RE	RE	RE	RE
Sample Size (N)	110	110	110	110	110	110

ST Classification: UNMARKED

Model Robustness Tests							
R2 overall		0.203	0.110	0.366	0.301	0.473	0.507
RESET test		0.110	0.317	0.359	0.721	0.108	0.309
VIF (max)		3.88	3.359	2.53	2.117	2.401	469.549
Pooling / Chow test		0.998	0.964	0.617	0.423	1	0.938
Normality of model residuals		0.296	0.089	0.021	0.004	0.004	0.028
Heteroskedasticity of model residuals		0.038	0.465	0.803	0.668	0.145	0.522
Test of pooled OLS versus Random Effects (LM test)		0	0	0.026	0	0	0.284
Efficiency Score Distribution	Minimum	0.66	0.60	0.68	0.60	0.69	0.74
	Maximum	1.61	1.46	1.54	1.53	1.70	1.49
Sensitivity of estimated coefficients to removal of most and least efficient company				A	G	G	A
Sensitivity of estimated coefficients to removal of first and last year of the sample				A	G	A	G
Additional Diagnostic Checks							
AIC		34	35	28	29	3	7
Sigma u		0.182	0.228	0.123	0.159	0.173	0.122
Alternative VIF		3.88	3.359	2.53	2.117	2.401	3.113

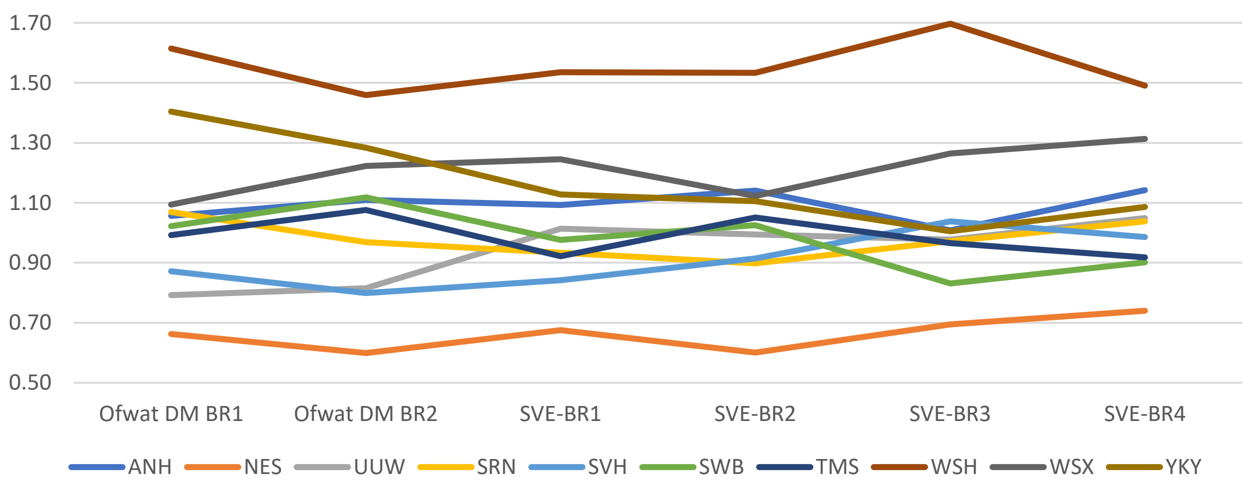


Figure 7.1. SVE-BR Model Efficiency Score Distributions

ST Classification: UNMARKED

7.6. Efficiency Score Distributions and Rankings – Bioresources (Models SVE-BR1 to SVE-BR4)

Ranking	Ofwat DM BR1		Ofwat DM BR2		SVE-BR1		SVE-BR2		SVE-BR3		SVE-BR4	
1	NES	0.71	NES	0.64	NES	0.68	NES	0.60	NES	0.69	NES	0.74
2	UUW	0.73	SVH	0.70	SVH	0.84	SRN	0.90	SWB	0.83	SWB	0.90
3	SVH	0.79	UUW	0.76	TMS	0.92	SVH	0.91	TMS	0.97	TMS	0.92
4	ANH	0.93	SRN	0.90	SRN	0.93	UUW	0.99	SRN	0.97	SVH	0.99
5	TMS	0.97	ANH	0.99	SWB	0.98	SWB	1.03	UUW	0.98	SRN	1.04
6	SRN	1.02	TMS	1.06	UUW	1.01	TMS	1.05	YKY	1.01	UUW	1.05
7	WSX	1.04	SWB	1.16	ANH	1.09	YKY	1.11	ANH	1.01	YKY	1.09
8	SWB	1.06	WSX	1.22	YKY	1.13	WSX	1.12	SVH	1.04	ANH	1.14
9	YKY	1.40	YKY	1.25	WSX	1.25	ANH	1.14	WSX	1.26	WSX	1.31
10	WSH	1.69	WSH	1.47	WSH	1.54	WSH	1.53	WSH	1.70	WSH	1.49

8. Retail

8.1. Econometric Models

Model Number	Model
SVE-RTC1	$Ln(sTC\_hh_{it}) = \beta_0 + \beta_1 Ln(hh\_t_{it}) + \beta_2 Ln(rev\_hh_{it}) + \beta_3 hhm\_hh_{it}$ $+ \beta_4 eq\_lpcf62_{it} + \beta_5 Ln(WADLADwater_{it})$ $+ \beta_6 (Ln(WADLADwater_{it}))^2 + \mu_i + \varepsilon_{it}$
SVE-RTC2	$Ln(sTC\_hh_{it}) = \beta_0 + \beta_1 Ln(hh\_t_{it}) + \beta_2 Ln(rev\_hh_{it}) + \beta_3 eq\_rgc102_{it}$ $+ \beta_4 counciltax_{it} + \beta_5 Ln(WADLADwater_{it})$ $+ \beta_6 (Ln(WADLADwater_{it}))^2$ $+ \beta_7 incomescore\_unadjusted_{it} + \mu_i + \varepsilon_{it}$
SVE-RTC3	$Ln(sTC\_hh_{it}) = \beta_0 + \beta_1 Ln(hh\_t_{it}) + \beta_2 Ln(rev\_hh_{it})$ $+ \beta_3 Ln(WADLADwater_{it}) + \beta_4 (Ln(WADLADwater_{it}))^2$ $+ \mu_i + \varepsilon_{it}$
SVE-RTC4	$Ln(sTC\_hh_{it}) = \beta_0 + \beta_1 Ln(hh\_t_{it}) + \beta_2 Ln(rev\_hh_{it})$ $+ \beta_3 Ln(WADLADwater_{it}) + \mu_i + \varepsilon_{it}$

8.2. Variable List

Dependent Variable:	Variable name in model	Description
Total cost per household with smoothed depreciation	sTC_hh	Total cost per household with smoothed depreciation as reported in published PR24 stata do-file. Code: sTC_hh in PR24 residential retail do-file v2.0.
Independent Variable:		
Total Households	hh_t	Total households connected as reported in published PR24 retail dataset. Code: hh_t in real statafile
Average Bill Size	rev_hh	Average bill size as reported in published PR24 retail dataset. Code: rev_hh in real statafile
Proportion of Metered Households	hhm_hh	Proportion of metered households as reported in published PR24 retail dataset. Code: hhm_hh in real statafile
Proportion of Households with Default	eq_lpfcf2	Proportion of households with default (Equifax variable) as reported in published PR24 retail dataset. Code: eq_lpcf62
Credit Risk Score	eq_rgc102	Credit risk score (Equifax variable) as reported in published PR24 retail dataset. Code: eq_rgc102
Council Tax collection rate	counciltax	Council tax collection rate as reported in published PR24 retail dataset. Code: counciltax

ST Classification: UNMARKED

Income Score (unadjusted)	incomescore_unadjusted	Combined income score for England Wales – unadjusted as reported in published PR24 retail dataset. Code: incomescore_unadjusted
Population Density	WAD_LAD (WAD_LAD2)	Weighted average population density using Local Authority Districts (LAD) as reported in the published wholesale dataset. WAD_LAD2 is the squared density term for WAD_LAD. Code: WAD_LAD in Interface_real

8.3. Brief Model Description

Model Number	Model Description
SVE-RTC1	Unit retail total cost model accounting for number of households, average bill size, metered households, defaulted households and population density.
SVE-RTC2	As per SVE-RTC1, with metered households and defaulted households replaced by council tax collection rate, credit risk score and unadjusted income score.
SVE-RTC3	As per SVE-RTC1, with defaulted households and metered households removed.
SVE-RTC4	As per SVE-RTC3, with the squared population density term (WAD_LAD2) removed.

8.4. Brief Comment on the Models

Models SVE-RTC1 to SVE-RTC4 use a panel spanning from 2013-14 to 2021-22, a total of 9 years.

Alternative VIFs have been reported where squared population density terms have been included in the models. This is calculated without the problematic squared density term in the model as it is not a concern that this specific variable inflates the VIF.

Any insignificant variable that has remained in the models are due to their strength in engineering expectation and rationale.

Variables included in the following models are also relevant in other levels of aggregations and are included as such.

All variables are expressed in logs apart from the following: hhm_hh, eq_lpcf62, counciltax, incomescore_unadjusted.

8.5. Model Results – Retail (SVE-RTC1 to SVE-RTC4)

		SVE-RTC1	SVE-RTC2	SVE-RTC3	SVE-RTC4
Dependent Variable		sTC_hh	sTC_hh	sTC_hh	sTC_hh
hh_t		-0.145*** (0.000)	-0.124*** (0.001)	-0.128*** (0.001)	-0.129*** (0.002)
rev_hh		0.775*** (0.000)	0.796*** (0.000)	0.789*** (0.000)	0.766*** (0.000)
hhm_hh		0.004 (0.189)			
eq_lpcf62		0.019 (0.132)			
WADLADwater		-0.653** (0.037)	-0.582 (0.137)	-0.559 (0.112)	0.111*** (0.003)
WADLADwater2		0.055** (0.011)	0.050* (0.063)	0.048** (0.042)	
counciltax			0.036** (0.013)		
incomescore_unadjusted			-0.018 (0.190)		
eq_rgc102			-0.016** (0.030)		
Constant		-5.724*** (0.000)	-6.558*** (0.000)	-5.594*** (0.000)	-7.733*** (0.000)
Estimation Method		RE	RE	RE	RE
Sample Size (N)		153	153	153	153
Model Robustness Tests					
R2 overall		0.695	0.673	0.675	0.661
RESET test		0.309	0.143	0.219	0.303
VIF (max)		204.719	200.381	193.995	3.02
Pooling / Chow test		0.964	0.997	0.987	0.94
Normality of model residuals		0.223	0.264	0.233	0.327
Heteroskedasticity of model residuals		0.023	0.016	0.028	0.051
Test of pooled OLS versus Random Effects (LM test)		0	0	0	0
Efficiency Score Distribution	Minimum	0.73	0.74	0.73	0.72
	Maximum	1.23	1.29	1.27	1.25
Sensitivity of estimated coefficients to removal of most and least efficient company		A	A	A	G
Sensitivity of estimated coefficients to removal of first and last year of the sample		A	A	G	G
Additional Diagnostic Checks					
AIC		-160	-159	-161	-161

Sigma u	0.115	0.129	0.124	0.126
Alternative VIF	3.579	11.533	3.02	3.02

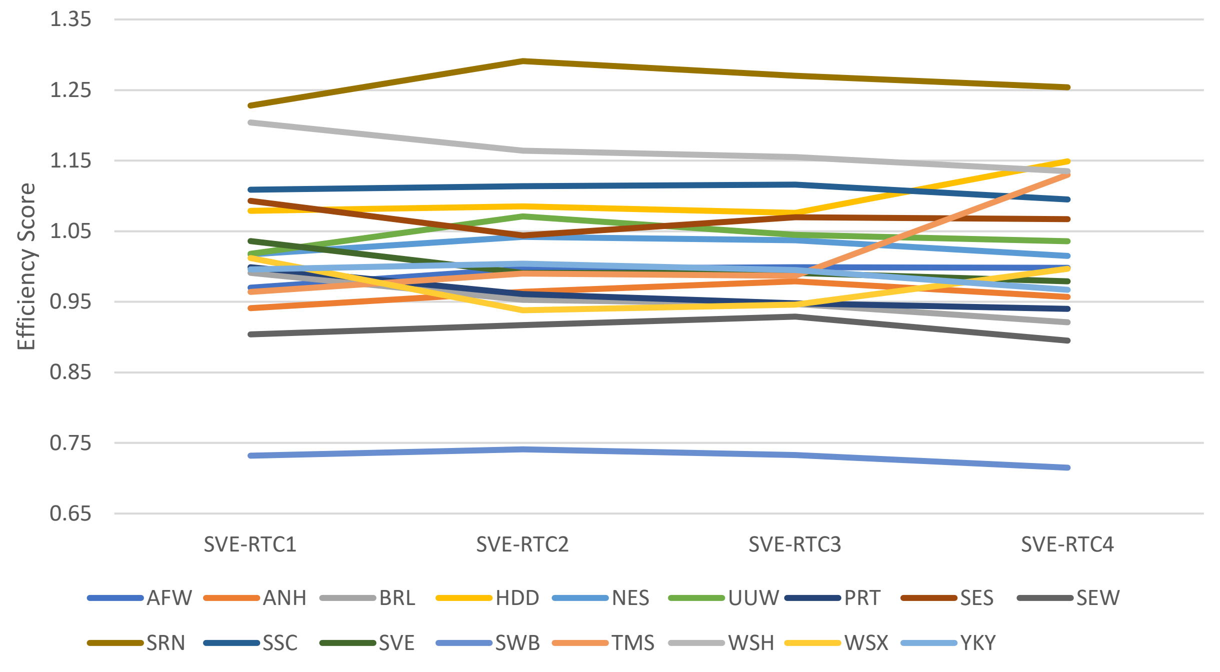


Figure 8.1. SVE-RTC Model Efficiency Score Distributions

8.6. Efficiency Score Distributions and Rankings – Retail (SVE-RTC1 to SVE-RTC4)

Ranking	SVE-RTC1		SVE-RTC2		SVE-RTC3		SVE-RTC4	
1	SWB	0.73	SWB	0.74	SWB	0.73	SWB	0.72
2	SEW	0.90	SEW	0.92	SEW	0.93	SEW	0.90
3	ANH	0.94	WSX	0.94	WSX	0.95	BRL	0.92
4	TMS	0.96	BRL	0.95	BRL	0.95	PRT	0.94
5	AFW	0.97	PRT	0.96	PRT	0.95	ANH	0.96
6	BRL	0.99	ANH	0.96	ANH	0.98	YKY	0.97
7	YKY	1.00	TMS	0.99	TMS	0.99	SVE	0.98
8	PRT	1.00	SVE	0.99	SVE	0.99	WSX	1.00
9	WSX	1.01	AFW	1.00	YKY	1.00	AFW	1.00
10	NES	1.02	YKY	1.00	AFW	1.00	NES	1.02
11	UUW	1.02	NES	1.04	NES	1.04	UUW	1.04
12	SVE	1.04	SES	1.04	UUW	1.05	SES	1.07
13	HDD	1.08	UUW	1.07	SES	1.07	SSC	1.10
14	SES	1.09	HDD	1.09	HDD	1.08	TMS	1.13
15	SSC	1.11	SSC	1.11	SSC	1.12	WSH	1.14
16	WSH	1.20	WSH	1.16	WSH	1.16	HDD	1.15
17	SRN	1.23	SRN	1.29	SRN	1.27	SRN	1.25