Wastewater Botex Modelling for PR19: Developing a Robust Model for Regulatory Cost Assessment from an Appropriate Conceptual Model of How Cost Interactions Drive Integrated Expenditures

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Background and Motivation

- Our development of conceptual understanding of what drives costs in sewage (Japanese and Anglian Water operational managers), as well as our previous research experience in other network industries.
- Focus exclusively on modelling Wholesale Wastewater costs and are driven by interaction between Treatment and Network transportation costs.

Wastewater Systems are Complex Multiple Output Networks

- **Economies of Size determined by complex cost interactions between:** Volume of output (treatment load), connections served (connected property), transportation (length of main- standard proxy), operating characteristics

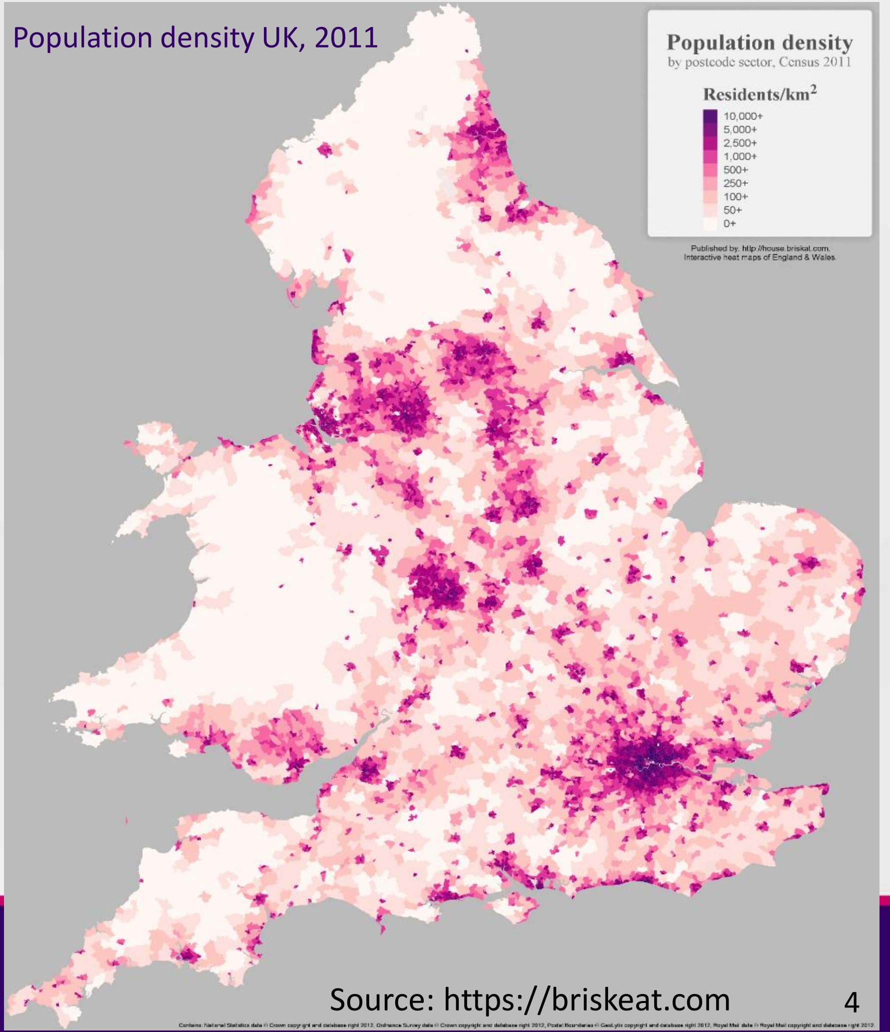
- **Each Wastewater System's Configuration involves a complex trade-off between:**
  1. The Potential benefits of plant size cost economies in production
     - Wastewater Treatment Centres (WWTCs)
     - Sludge Treatment Centres (STCs)
  2. Transportation Costs
     - The costs of Network Transportation required to achieve a given WWTC scale
     - The costs of sludge transport and dewatering required to achieve a given STC scale
  3. Geographic, environmental and planning considerations that influence
     - demand for,
     - siting and
     - potential scale of WWTC and STC facilities

We know population density influences costs at firm level in most network industries

- Well known that density has a nonlinear impact on costs of service (See Thames Water Consultation Response)
- Academic models of network industries typically include connections, network length and squared terms and interactions with other variables to capture this impact on overall size economies
- Ofwat developed measures of the proportion of served population in dense and sparse areas, but they were not been used by CEPA in its modelling

- **But accounting for population density is not enough to explain how the multiple optimal wastewater system designs that have been chosen by managers and engineers as the least cost solution to a given population settlement pattern resulting from demographic, economic, planning, and geographic factors influences costs.**

Population density UK, 2011



Source: https://briskeat.com

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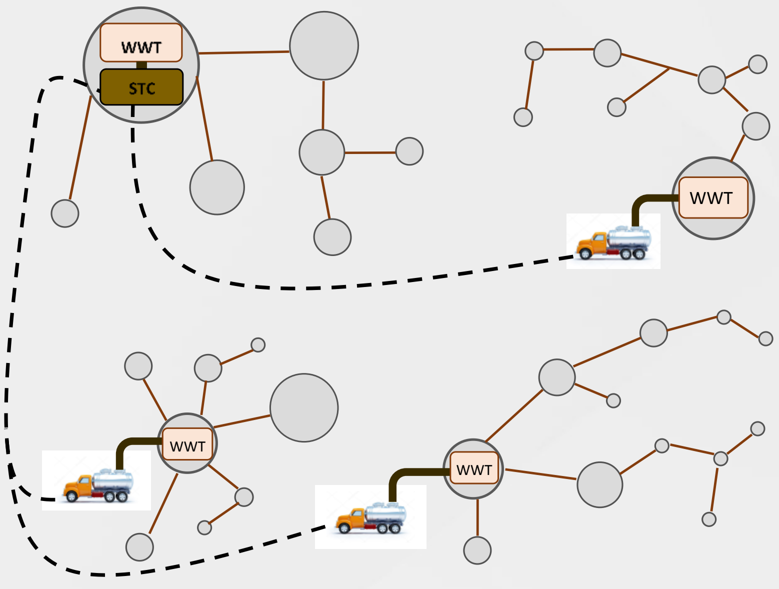
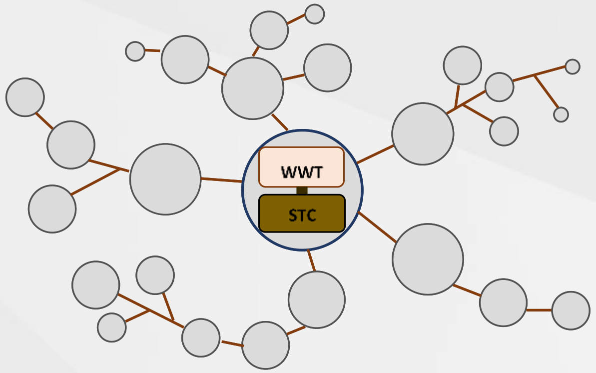
Two Service Areas with alternative system configurations

Area A



4 distinct WW collection and WW treatment systems

Area B



1 Fully integrated WW collection and WW and Sludge treatment system

Configuration details of Service Areas A and B

- The size of each circle represents population.
- By construction, the sum of the areas of the circles is identical in both pictures, i.e. the population and sewage treatment load is the same in both Service areas .
- Same served area (represented by the two identical big squares) and thus same population density (population/ km^2).
- Both Service Areas generate the same volume of sludge, and each one has a single STC of equal size.
- The configuration of Service Area A:
  - Four disconnected wastewater collection and treatment systems (four WWTCs)
  - More dispersed population than Service Area B
- The configuration of Service Area B:
  - A single connected wastewater colection and treatment system (a single and larger WWTC)
  - Population is more concentrated

Key implications:

- **In Service Area A most sludge is non-indigenously treated** (60% by construction in picture A, 0% picture B)
- **Higher transportation costs** resulting from:
  - Wastewater collection **(network transportation)**
  - Non-indigenous sludge transport , dewatering, etc. **(tankers and trucks)**
- Suboptimal size of the smaller WWTCs in Service Area A, suggesting higher average costs of wastewater treatment (note scale economies are not fully represented in these Figures)

Differences between Service Areas A and B

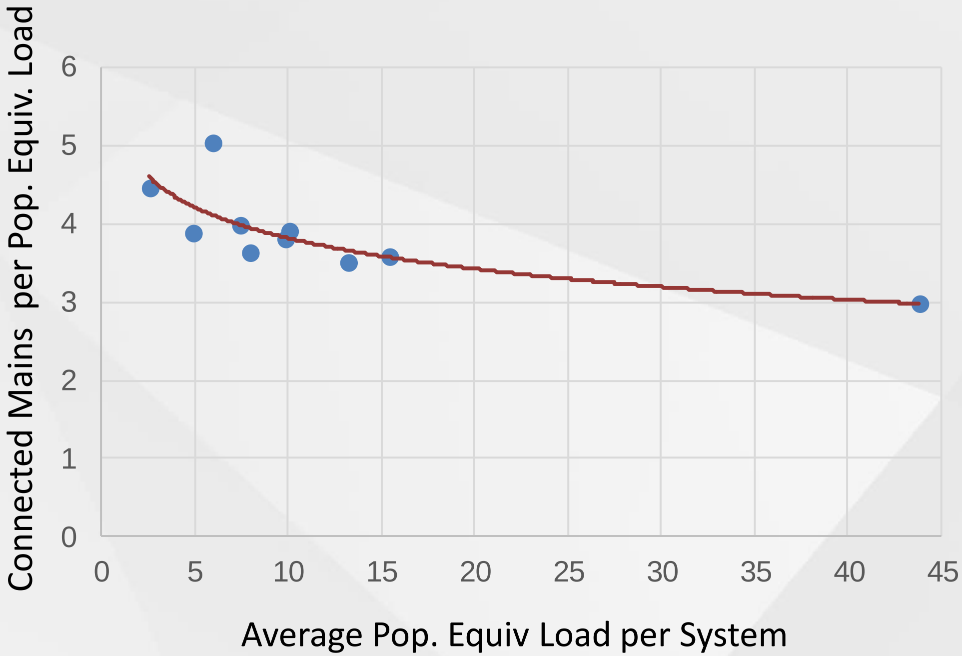
- The Service Areas face different **spatial** characteristics (e.g. geographic and demographic conditions). How should cost drivers properly model?
- Costs differences between A and B are driven by differences in the **population dispersion** and the **origin of the sludge** to be treated at STCs.
- By considering a single output (e.g. total population served) **spatially-driven cost differences** between A and B are not properly taken into account: We would naively conclude that Service Area A is just more inefficient than Service Area B.
- **Each WaSC actually operates hundreds of distinct systems with appropriate configuration so company level costs are really the summation of hundreds of system level optimisation decisions**

Implications for cost modelling

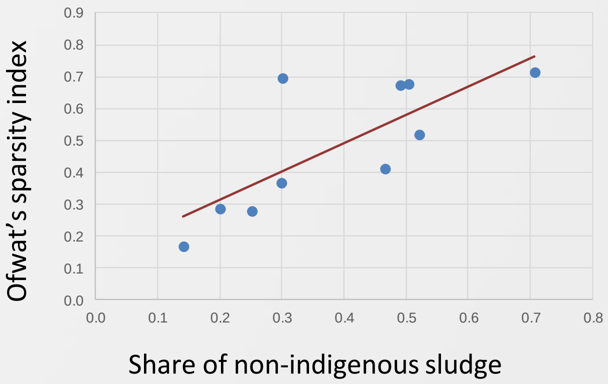
- The indigenous versus non-indigenous treatment decision, is the **result of rational cost minimizing managers' decisions** with regard to
  - Population size
  - Population dispersion (Sparsity)
  - Population density
  - Sewage Collection and Sludge Transportation Costs
- **Need for a modelling approach** capturing cost interactions between network and sewage and sludge treatment activities.
- Our modelling approach is based on using indigenous and non-indigenous treatment of sludge as an **effective proxy to capture key differences in systems configurations**.

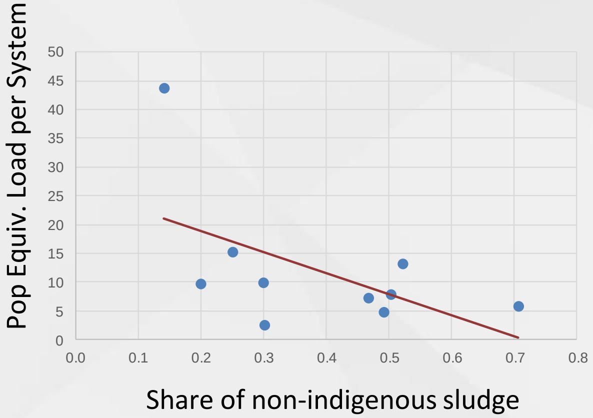
We cannot directly observe system level data, but is average Wastewater Collection and Treatment works data consistent with this conceptual model?

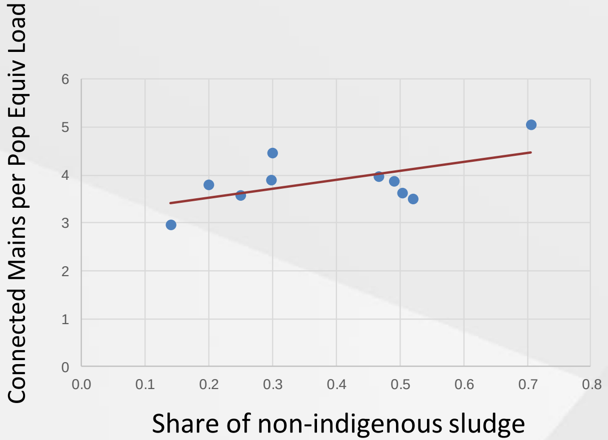
Company	Number of Systems (WWTCs)	Avg Pop Equiv Load per System	Connected Mains/ Pop Equiv Load	Share of Non Indig. Treated Sludge
ANH	1138	5.93	5.05	0.71
NES	412	7.35	3.98	0.47
NWT	567	15.34	3.59	0.25
SRN	365	13.17	3.50	0.52
SVT	1013	10.07	3.91	0.30
SWT	648	2.52	4.46	0.30
TMS	351	43.76	2.97	0.14
WSH	835	4.82	3.89	0.49
WSX	406	7.93	3.63	0.50
YKY	619	9.84	3.81	0.20
E. & W.	6354	12.07	3.88	0.39



Indigenous treatment of sludge is a strong proxy of underlying demographic, geographic, planning, and economic conditions that inform decision making with regard to system design







Indigenous sludge treatment and Ofwat's sparsity threshold measures are positively correlated

Smaller systems with more non-indigenous treatment reflect the prohibitive cost of the networking needed to allow sufficient network scale to treat sludge indigenously

The higher the non-indigenous treatment, the larger the network length per population equivalent, reflecting the higher household passing distance required to connect households in sparsely populated areas.

The Average System Model (ASM)

- Models conceptually average systems of a company and breaks out indigenous and non-indigenous treatment
- Average cost per system and average length and average population equivalent load for indigenous and non-indigenous treatment
- Implies that companies’ costs are actually the aggregation of the optimal system designs chosen for many systems
- Chosen model is a rigorously tested down specific restriction of a more general “translog” model in which only statistically significant interactions are retained

ASM: Results

Model Estimates- Ordinary Least Squares				
Dependent Variable Ln (Botex/Works)	base model	general model	restricted model	restricted model with no time dummies
Population Equivalent Load Output Variables				
ln (PopEquiv/Works)	0.190			
ln (IndgPopEquiv/Works)		0.313	0.114*	0.126*
ln (NotIndgPopEquiv/Works)		0.186	0.233***	0.255***
Network Length Output Variable				
ln (L/Works)	0.419**	0.259	0.520***	0.499***
Output Interaction Variables				
ln (IndgPopEquiv/Works)* ln (L/Works)		0.958		
ln (NotIndgPopEquiv/Works) * ln (L/Works)		2.161	0.203***	0.216***
ln (IndgPopEquiv/Works)*ln (NotIndgPopEquiv/Works)		-1.005		
Squared System Output Variables				
$(\ln(\text{IndgPopEquiv/Works}))^2$		-0.979		
$(\ln \text{Not}(\text{IndgPopEquiv/Works}))^2$		-0.214		
$(\ln(\text{L/Works}))^2$		-2.616		
System Operating Characteristic Variables				
Not Indgenous Share	0.078			
Share of Combined Sewers in Connected Total Lenth	0.009***	0.008***	0.008***	0.008***
Pumping Capacity/Works	0.003***	0.003***	0.002***	0.002***

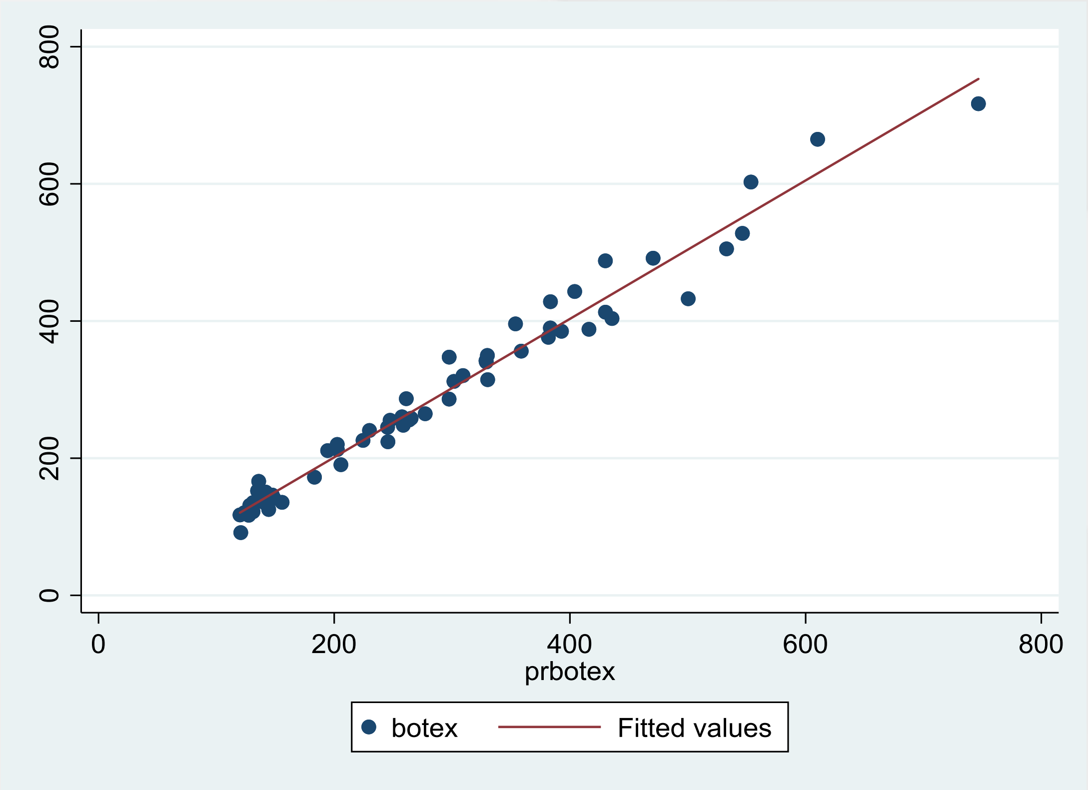
Time Dummies and Constant (2012 is base year represented by the constant)				
	base model	general model	restricted model	restricted model with no time dummies
constant	-0.101**	-0.059	-0.088***	-0.02
y2013	0.084*	0.100**	0.087**	
y2014	0.083*	0.084*	0.082**	
y2015	0.023	0.012	0.016	
y2016	0.088*	0.062	0.074*	
y2017	0.168***	0.144***	0.152***	

Joint Restriction Test Statistics				
	base model	general model	restricted model	restricted model with no time dummies
time dummies (5)	3.18	3.12	3.63	
significance	0.01	0.02	0.01	
variables removed in academic model (4)	NA	0.80		
significance	NA	0.53		
variables removed in regulatory model (5)	NA	0.82		
significance	NA	0.54		
removal of all squared terms (3)	NA	0.93		
significance	NA	0.44		
remval of all interactive terms (3)	NA	2.96		
significance	NA	0.04		
removal of network length interactive variables	NA			
significance	NA			
removal of two main exogs	70.64	26.66	34.73	27.88
significance	0.00	0.00	0.00	0.00

ASM: Model specification test

Model Test Statistics				
	base model	general model	restricted model	restricted model with no time dummies
R-Squared	0.976	0.984	0.982	0.976
Adjusted R-Squared	0.971	0.978	0.978	0.973
log likelihood	56.96	68.51	65.77	56.16
F-Test for the Overall Model	202.06	164.14	242.91	354.48
F-Test Significance	0.00	0.00	0.00	0.00
Ramsey Reset Test	1.65	0.35	0.17	1.16
Reset Test Signfiicance	0.1914	0.7875	0.9181	0.3359
Akaike information criterion	-91.91	-103.02	-107.55	-98.32
Bayesian information criterion	-68.88	-67.41	-82.42	-83.66
root mean squared error	0.104	0.0913	0.090	0.101
VIF Max	98.68	14,261.8	29.96	29.78
VIF Mean	20.69	2,294.9	8.05	13.22
Observations	60	60	60	60
Number of Parameters including Time Dummies	11	17	12	7
residual degrees of freedom	49	43	48	53
Breusch Pagan Test for Random Effects	0.42	0.00	1.57	0.00
significance	0.26	1.00	0.11	1.00

ASM also has very good predictive properties



Averages by Company

Comp	botex	prbotex	delta	deltashr
ANH	330.9	326.3	-4.6	-1.5%
NES	141.7	145.5	3.9	2.3%
NWT	437.4	427.2	-10.1	-2.4%
SRN	262.5	260.0	-2.5	-1.2%
SVT	388.0	374.8	-13.3	-3.8%
SWT	129.5	129.7	0.2	0.3%
TMS	575.0	581.7	6.7	1.4%
WSH	205.4	202.2	-3.3	-1.6%
WSX	126.2	130.2	4.1	3.5%
YKY	266.2	264.4	-1.8	-0.3%
Total	286.3	284.2	-2.1	-0.3%
			Range of Company Averages	7.4%

Averages by Time

Yearend	botex	prbotex	delta	deltashr
2012	253.8	256.7	2.9	-0.4%
2013	278.7	281.4	2.8	-0.2%
2014	283.5	282.7	-0.8	-0.2%
2015	280.0	269.4	-10.6	-0.6%
2016	297.7	290.3	-7.4	-0.3%
2017	324.1	324.8	0.7	-0.3%
Total	286.3	284.2	-2.1	-0.3%
			Range of Time Averages	0.4%

What prevented these models in the CEPA report?

- A priori restrictions
  - No more than six variables
  - No translog, i.e. no squared and cross terms of variables
  - VIF < 5, i.e. no variables that are correlated > 90%
  - A modelling approach that defines cost groups (output, density, system characteristic, quality, and “level of activity”(?)) and allows only a single variable form each group, thereby fundamentally excluding the potential to model the complex systems and cost interactions that exist in the water and sewerage industry.
- We did not impose those constraints but our models pass all the appropriate tests.

Reproducing the OWWW3 Model

Reproduction of Representative Ofwat model OWWW3 with Botex definition agreed with Anglian

- Is representative and typical of models presented by Ofwat in the cost assessment consultation
- Conceptually models a company
- Based on the a priori and highly restrictive modelling assumptions outlined in the CEPA's PR19's cost assessment report
- A priori assumptions include: 6 groups of cost drivers, only one output variable max 6 variables, VIF < 5, no translog terms etc.

Representative Ofwat Model OWWW3 reproduced with BOTEX

Model Estimates- Reproduction of OWWW3 with Botex		
Dependent Variable Ln (Botex)	Base	Add Time Dummies
Model Variables Employed in OWWW3		
ln (Load)	0.939***	0.937***
B1-B3 Works share in Load	0.059***	0.059***
ln (Density)=ln(Prop/Mains)	1.144***	1.130***
Trade Effluent Share in Load	0.038***	0.039***
Time Dummies and Constant (2012 is base year represented by the constant)		
constant	-3.763***	-3.843***
y2013		0.072
y2014		0.072
y2015		0.007
y2016		0.076
y2017		0.169***

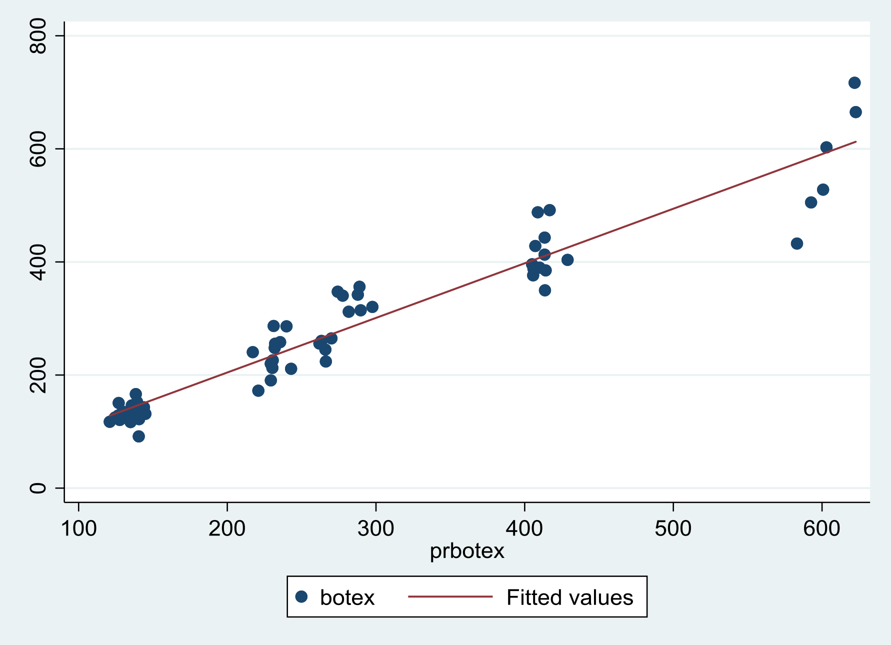
Model Test Statistics	Base	Add Time Dummies
R-Squared	0.934	0.945
Adjusted R-Squared	0.929	0.935
log likelihood	36.0	41.8
F-Test for the Overall Model	193.5	96.1
F-Test Significance	0	0
Ramsey Reset Test	4.18	2.76
Reset Test Signfiicance	0.01	0.05
Akaike information criterion	-61.984	-63.585
Bayesian information criterion	-51.513	-42.642
root mean squared error	0.139	0.132
VIF Max	2.59	2.59
VIF Mean	2.07	1.85
Observations	60	60
Number of parameters	5	10
residual degrees of freedom	55	50
Breusch Pagan Test for Random Effects	14.45	26.23
significance	0.0001	0.00

Joint Restriction Test Statistics	Base	Add Time Dummies
time dummies (5)	NA	2.13
signficance	NA	0.08

"We considered alternative, more flexible, specification in light of the failure of the Reset test. **This search did not yield a better model and we consider that despite the low Reset tests the models are appropriate**"

Appendix 1 Modelling Results, page 69

OWWW3 model fails many specification tests and has very high range in delta share estimates (not resolved using RE and/or time dummies)



Averages by Company				
Comp	botex	prbotex	delta	deltashr
ANH	330.9	287.2	-43.7	-15.3%
NES	141.7	136.5	-5.2	-3.7%
NWT	437.4	415.9	-21.4	-5.2%
SRN	262.5	231.3	-31.2	-13.5%
SVT	388.0	407.9	19.9	4.8%
SWT	129.5	126.0	-3.4	-2.7%
TMS	575.0	604.0	29.0	5.1%
WSH	205.4	230.5	25.1	10.9%
WSX	126.2	140.7	14.5	10.4%
YKY	266.2	267.0	0.8	0.4%
Total	286.3	284.7	-1.6	-0.9%
			Range of Company Averages	26.2%

Averages by Time				
Yearend	botex	prbotex	delta	deltashr
2012	253.8	279.1	25.3	5.3%
2013	278.7	283.7	5.0	-1.0%
2014	283.5	283.7	0.2	-1.1%
2015	280.0	286.4	6.5	4.7%
2016	297.7	286.9	-10.7	-1.6%
2017	324.1	288.4	-35.7	-11.4%
Total	286.3	284.7	-1.6	-0.9%
			Range of Time Averages	16.7%

Conclusions

- We need **strong conceptual models** that allow for the complex cost interactions between different activities in the multiple output systems that we are modelling
- Our conceptual model and its empirical implementation illustrate that controlling for non-indigenous treatment of sludge appropriately provides a conceptually and statistically robust model for Wholesale Wastewater costs.

Appendix.

Alternative model: Extended Passing distance model (PDM)

- Developed with Anglian
- Models conceptually a company and breaks out indigenous and non-indigenous treatment thereby capturing differences in the combined botex elasticity and marginal costs of both overall wastewater and sludge treatment activities
- Captures system design / transportation cost interactions: an interaction between works size and network length on hypothesis that companies add plants to reduce required network transportation costs

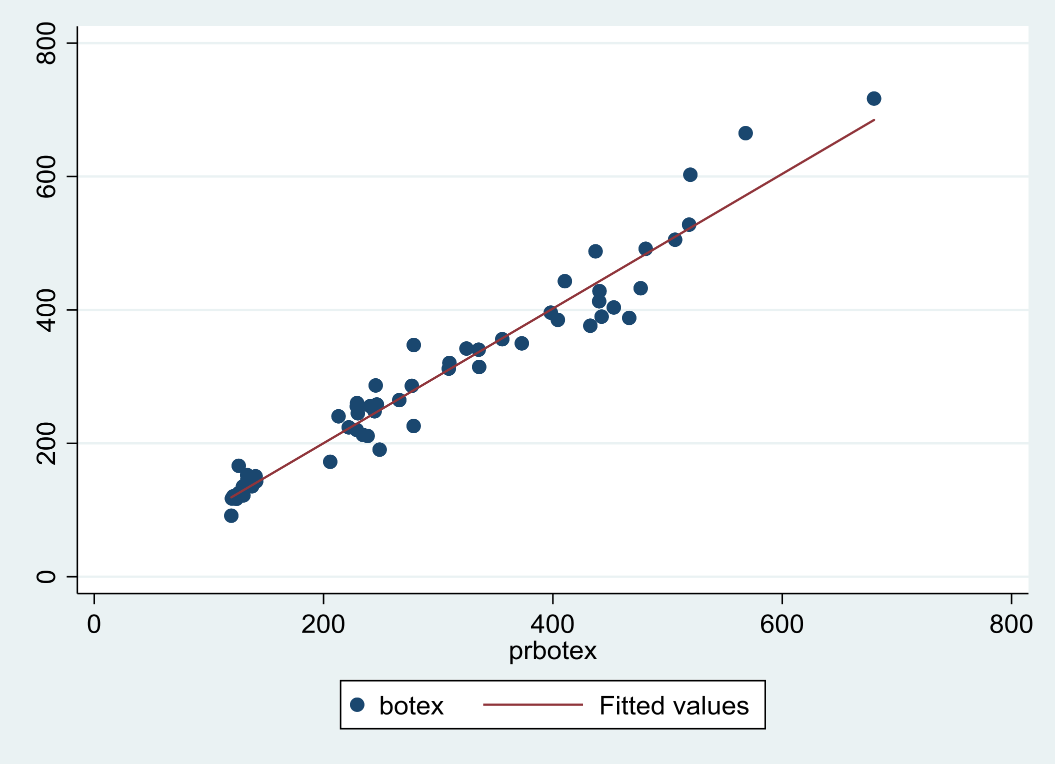
Alternative: Extended Passing Distance Model (PDM)

Dependent Variable Ln (Botex)	OLS	Random Effects
Population Equivalent Load Output Variables		
ln (IndgPopEquiv)	0.271***	0.373**
ln (NotIndgPopEquiv)	0.335***	0.509***
Network Length Output Variable		
ln (L)	0.522***	0.325
$(\ln (L))^2$	0.370***	0.542*
Network Length Works Interaction		
ln (L) ln (Total Works)	-0.370***	-0.45
System Operating Characteristic Variables		
Share of Combined Sewers in Legacy Network Length	0.008***	0.009**
Pumping Capacity/L	0.126***	0.118**
y2013	0.082	0.082**
y2014	0.077	0.073*
y2015	0.01	0.001
y2016	0.068	0.055
y2017	0.148***	0.134***
_cons	-0.017	-0.014

Model Test Statistics	OLS	Random Effects
R-Squared	0.962	
Adjusted R-Squared	0.952	
log likelihood	52.442	
F-Test for the Overall Model	98.25	
Akaike information criterion	-78.883	.
Bayesian information criterion	-51.657	.
root mean squared error	0.114	0.09
N	60	60
rank	13	13
df_r	47	
chi2		173.338
p		0
R-Squared -within		0.491
R-Squared -between		0.98
R-Squared -overall		0.958
sigma		0.163
sigma_u		0.135
sigma_e		0.091
rho		0.687
Ramsey Reset Test	1.65	
Reset Test Signfiicance	0.19	
VIF Max	28.07	
VIF Mean	6.15	
Breusch Pagan Test for Random Eff	10.64	
significance	0.0006	

Joint Restriction Test Statistics	OLS	Random Effects
joint sig. - Network variables	20.62	9.71
	0.00	0.02
joint sig of time dummies	2.22	15.67
	0.07	0.01
joint sig of popequiv variables	8.55	11.63
	0.00	0.00
joint sig of control variables	32.86	8.08
	0.00	0.02

PDM passes model specification tests, has relatively good fit, but has relatively high range in delta share estimates



Averages by Company				
Comp	botex	prbotex	delta	deltashr
ANH	330.9	328.4	-2.5	-0.8%
NES	141.7	132.1	-9.5	-7.4%
NWT	437.4	437.7	0.4	0.0%
SRN	262.5	242.6	-19.9	-8.5%
SVT	388.0	425.6	37.6	8.6%
SWT	129.5	128.2	-1.2	-0.8%
TMS	575.0	545.0	-30.0	-5.1%
WSH	205.4	239.2	33.7	13.9%
WSX	126.2	129.7	3.6	3.2%
YKY	266.2	244.4	-21.8	-8.6%
Total	286.3	285.3	-1.0	-0.6%
			Range of Company Averages	22.4%

Averages by Time				
Yearend	botex	prbotex	delta	deltashr
2012	253.8	258.2	4.4	-0.8%
2013	278.7	284.0	5.4	-0.3%
2014	283.5	284.8	1.3	-0.3%
2015	280.0	270.0	-9.9	-0.6%
2016	297.7	291.0	-6.7	-0.6%
2017	324.1	323.7	-0.4	-0.7%
Total	286.3	285.3	-1.0	-0.6%
			Range of Time Averages	0.5%