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# Urban infrastructure: Density matters, not just size.

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**Abstract**

The cumulative investment in urban infrastructure is enormous yet its role in urban economics has been little emphasized. In this paper, the case of water supply is taken to illustrate some general points which, it is suggested, may be applicable to infrastructure more generally. Although there is good evidence for economies of scale in water treatment, this can be more than offset by diseconomies in distribution as the scale of settlement increases; on the other hand, higher density tends to reduce unit distribution costs whatever the size of settlement.

The tension between scale (and other) economies associated with geographic concentration of industry within a city, and diseconomies, such as commuting costs, is a long-established theme in urban economics. The key implication of this paper is to suggest that density may be as important as size *per se* in the economics of urban systems. It is their higher density that enables cities to overcome the cost of distance and so exploit economies of scale.

## Economic characteristics of infrastructure

While there is probably no "right" definition of infrastructure, much depending on the context, there is some advantage in reserving the term for structures and facilities that are the result of human intervention, creating something physical that was not there before. This definition can still embrace the movement of soil to create embankments or cuttings as well as the erection of buildings and the laying of lines. This is similar to the position taken by Biehl (1986, p. 87): "The difference between infrastructure and other potentiality factors, such as the location of the region or its natural resource endowment, is that the service bundles inherent in infrastructure have been 'artificially' created through investment, whereas location and natural resources are 'naturally' given."

There are various ways in which infrastructure so defined can be categorized. The simplest is descriptive: Buildings, roads and related items, utilities, etc. However, this is not particularly helpful from an analytical point of view. A more economic approach is to consider supply characteristics, particularly economies of scale, and demand characteristics, particularly the "publicness" of the goods or services provided, and to develop a categorization on this basis.

For present purposes, however, we adopt a categorization based on just two characteristics, which highlight access to the service. We see much of the man-made urban infrastructure as belonging to one or other of two broad types:

- Area Type: Provides services within a defined area (e.g. utilities, transport systems). In such cases, getting the service to users involves distribution costs;
- Point Type: Provides services at a specific point (e.g. hospitals, schools, offices, shops, museums, theatres, etc). In such cases, the equivalent consideration is the cost to users of accessing the facility.

In the urban economics literature, the provision of infrastructure services tends to be viewed as naturally monopolistic because of scale economies. It seems self-evident that setting up rival systems to compete with each other to supply a community would mean duplication and waste. And the more people who can be connected to a system, the lower average costs must be. However, this view overlooks the effect of distribution or access costs. The purpose of this paper is to explore the implications of taking such costs into account. What they introduce is a trade-off between economies of scale in production of services and diseconomies of scale in distribution.

For concreteness, the analysis focuses on water supply. This sector has the advantages of a relatively straightforward technology, which does not vary much from place to place and evolves only slowly; there is only one (free) raw material and the costs of distribution are significant – all of which should help to bring to light the effects of interest. A further advantage, in England & Wales, is the public availability of most of the data submitted annually to the Office of the Water Regulator (Ofwat), the "June Returns" – 43 tables in all, covering both financial and non-financial information, which, since it is all compiled using the same guide-lines, should be consistent across companies. At the same time, the conclusions would appear to be applicable with very little modification to other Area Type infrastructure (sewerage, electricity, telecomms, transport[1], etc) and, if distribution costs are replaced by access costs, to Point Type infrastructure also.

[1] Application to the transport sector may not be immediately evident but consider the functional analogy between water distribution systems and roads or railway lines (whether over or under ground); and between treatment works and stations or bus termini. Transport does however raise additional complications, such as that transport itself is part of distribution costs; and that traffic flow consists of units that can exercise some choice about routing.

**<u>The components of water supply</u>**

Broadly, there are three main elements in any urban water supply system: water acquisition, water treatment and water distribution, each with its own distinctive economic characteristics. These characteristics can be summarised as:

***Water acquisition***

This is highly dependent on the geography and geology of local water resources but typically involves some or all of:

- Impounding dams and reservoirs;
- River abstractions; and
- Boreholes to tap underground water.

The economics of water acquisition reflect these technologies. Dams are clearly large, indivisible items; and an increase in the height of a dam will generally result in a more than proportionate increase in water stored. River abstractions may also enjoy some scale economies due to pumping technology and the volume benefits of larger pipes (the volume of a pipe varies with radius squared, surface area with radius). With boreholes, however, abstraction tends to be optimised with several small ones rather than a few large ones. Nevertheless, overall water acquisition is likely to be characterized by significant scale economies. But there is an important qualification: water has a high weight to value ratio so it quickly becomes uneconomic to deliver water over long distances. This is particularly the case where pumping is required because there is insufficient difference in levels to allow gravity feed. There is thus a trade-off between scale economies in water acquisition and transmission costs. Distance introduces diseconomies, a point that will re-appear more strongly when water distribution is considered.

***Water treatment***

This is a relatively straightforward semi-industrial process involving filtration and chemical treatment. As such it shows the kind of scale economies typical of industrial processes. However, Nick Curtis of Strategic Management Consultants (2002) reports that the Minimum Efficient Scale (MES) of water treatment plant is relatively low at about the size required to serve some 50,000 properties (about 20 Ml/day). Unit cost curves estimated by both Curtis and Deloitte, Haskins & Sells (1990) indicate that a doubling of output secures a 20% reduction in costs although it is not clear whether such savings continue much beyond 100,000 properties served. Curtis further reports (p.30) that "the average size of surface water treatment plant of the five largest water industry companies [in UK] in 1993 … was 44,500 properties." This may be because in practice the size of treatment works is determined less by the cost-minimising scale of plant than by distribution costs, which we consider next.

***Water distribution***

The water distribution system of any settlement tends to be a reflection of history and local geography rather than technical or economic optimisation, making generalisation difficult. However, simple modelling indicates that unit water distribution costs are unlikely in general to decline with size of population served. Rather, like average commuting costs, and for much the same reasons, they tend (for a given population density) to increase with size of community served. This is essentially because as the size of the community increases, the average distance over which water must be delivered increases more than proportionately, as does the amount of pipework. However, modelling also indicates that higher population densities should be associated with lower unit distribution costs, *ceteris paribus*. As a result, the higher costs of

distributing to a larger population may be offset to the extent that larger populations are more densely settled.

## Water treatment: cost analysis

It is generally accepted in the engineering literature[2] that the costs of water treatment at plant level can reasonably be represented by a function of the form[3]:

$$CT = \beta(QT)^{\alpha} \qquad \ldots\ldots\ldots\ldots. \qquad (1)$$

where $CT$ is total treatment costs and $QT$ is volume of water treated, with $\alpha<1$, reflecting scale economies in both the capital and operating costs of water treatment plant[4]. In unit cost form, this becomes:

$$UCT = \beta.(QT)^{\alpha-1} \qquad \ldots\ldots\ldots\ldots. \qquad (2)$$

where $UCT$ is the unit cost of treatment (i.e. $CT/QT$).

In applying this formulation to water company data, account needs to be taken of the point that it relates strictly to individual treatment plants whereas water companies in England & Wales generally operate large numbers of plants (ranging from 2 in the case of Tendring Hundred Water to 173 in the case of Severn Trent). A simplistic solution to this problem would be to apply (2) to the average plant:

$$UCT = \beta(AVQT)^{\alpha-1} \qquad \ldots\ldots\ldots. \qquad (3)$$

where $AVQT = QT/TNO$ and $TNO$ is number of treatment plants. However, this formulation does not take account of the mix of plants of different sizes.

A more sophisticated solution is also possible making use of the information in the Ofwat June Returns on the number of treatment plants operated by each company in 9 size bands, and the proportion of output from each size band. A modified version of (2) to exploit the availability of this information is:

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[2] See for example Clark & Stevie (1981), p.20 or Grigg (1986), p.67. The latter includes the following table (last column calculated from Grigg's data):

| **Size of treatment plant** | **Population served** | **Total project cost ($m, 1978)** | **Annual capital cost per person served ($, 1978)** |
|---|---|---|---|
| 700 gpm package | 4,500 | 0.710 | 27.6 |
| 5 mgd conventional | 20,000 | 2.364 | 19.8 |
| 40 mgd conventional | 125,000 | 10.334 | 14.8 |
| 130 mgd conventional | 575,000 | 26.050 | 7.7 |

[3] The economist's starting point, on the other hand, is usually the notion of a production function expressing output as a function of inputs. More specifically, in this case, the output of the water treatment stage of water supply (*QT*) might be taken to be the result of applying two kinds of input, water treatment assets (*TASS*) and water treatment operating costs (*VCT*). Various specifications of the production function are available, including the flexible forms now extensively used in the utility regulation literature. The author has explored this approach but the results so far are disappointing, probably because company data is at too aggregate a level to expose plant level affects. Similar problems were encountered in trying to estimate a production function for water distribution.

[4] Some authors mention a saving of about 20% in costs with each doubling of output (i.e. $\alpha \approx 0.8$) - see Strategic Management Consultants (2002).

$$UCT = \beta\left\lfloor \sum_{i=1}^{9} p_i \left(q_i\right)^{\alpha-1} \right\rfloor \qquad \ldots\ldots\ldots\ldots\ldots \qquad (4)$$

where $p$ is the proportion of output and $q$ the average production of a plant in the $i$th size band.

In addition, it is recognised that treatment costs may be affected both by variations in the quality of the source water (in particular, surface water is generally more costly to treat than groundwater) and by the water quality standards required of water suppliers. Water quality standards will generally be the same for all suppliers within one jurisdiction but there can be significant variation in the sources of water between suppliers.

Therefore, in using either (3) or (4), controls for surface water proportion (*SP*) are likely to be helpful. A further control for resource pumping head (for which Ofwat data is available) should also help. There are various possible specifications for such controls. In this case it was decided to use (1 + *SP*) and (1 + *PHR/APHR*), where *PHR* is resource pumping head and *APHR* is average resource pumping head. In this way the control does not affect the relationship should *SP* or *PHR* be zero. This leads to an expanded version of (3):

$$\ln(UCT) = \beta_0 + \beta_1 \ln(1+SP) + \beta_2 \ln\left(1+\frac{PHR}{APHR}\right) + (\alpha-1)\ln(AVQT) \quad \ldots\ldots\ldots \qquad (5)$$

The specification of (4) with controls for surface water proportion and resource pumping head is:

$$UCT = \beta_0 (1+SP)^{\beta_1} \left(1+\frac{PHR}{APHR}\right)^{\beta_2} \sum p_i (q_i)^{\alpha-1} \qquad \ldots\ldots\ldots\ldots\ldots \qquad (6)$$

The *a priori* expectation using either (5) or (6) is to find $\alpha < 1$, confirming economies of scale in water treatment while the $\beta$ coefficients will be positive.

## <u>Water distribution: Measurement and modeling</u>

### *a. Interpretation of scale (dis)economies in the context of distribution*

As Duncombe & Yinger (1993) have pointed out, the notion of scale in public production has more than one dimension. In their study of fire protection services, they identify three fundamental aspects: the quality of the services provided, the level of activity by the government agency and the number of people served. With multiple products, they observe, a fourth dimension, economies of scope, must also be considered. These ideas can be adapted to apply to water distribution as follows:

- *Quality of service*: In water distribution this includes reliability, adequate pressure, etc as well as meeting specified water quality standards. In the UK all companies meet substantially the same (high) standards so that differences in standards play little part in our analysis. However, it remains the case that the cost of achieving these standards may vary from company to company because of environmental factors, such as soil conditions, softness or hardness of water supplies and hilliness of the terrain.
- *Level of activity*: This is here taken to be the volume of water put into distribution, with the economies of scale in water treatment discussed above being equivalent to the 'first stage' or 'technical returns to scale' identified by Duncombe & Yinger.
- *Number of people served*: Here we see a need to extend Duncombe & Yinger's framework to recognize that the size of the area served as well as the number of people in the area affects distribution costs. The costs of serving a dense population will be different from the costs of serving the same population spread less densely over a larger

area. In fact, we use water consumed (equal to number of properties times average consumption) and settlement density as the key variables.

- *Economies of scope*: Although some authors have portrayed water supply as a multi-product activity, by distinguishing between residential and non-residential supply (Kim & Clark (1988)), or between water delivered to customers and water lost through leakage (Garcia & Thomas (2001)), we see this as an unnecessary complication in the present context (on the other hand, distinguishing between the water supply and sewerage activities of companies that do both would seem entirely justified).

### b. Unit cost of distribution

The cost of distribution recorded in the Ofwat returns has two main components: Distribution operating costs (*VCD*), which includes items such as power (for pumping), labour costs, maintenance materials, etc; and Capital maintenance costs (*CMD*) related to the assets used for distribution (the main asset here is the network of pipes through which the water is delivered to users; other distribution assets include pumping stations and service reservoirs). However, there is an additional cost which needs to be taken into account - distribution losses, here referred to as leakage (*LKG*), which can be valued for each company at the cost of treated water indicated by the water treatment model. The total cost of distribution including leakage (*TCDL*) is then the sum of *VCD*, *CMD* and *LKG.* The unit cost of distribution, *UCDL*, can then be defined as *TCDL/QC*, where *QC* is the total volume of water reaching consumers (i.e. *QC = QT – LKG*).

One approach to the analysis of distribution economics is to investigate how *TCDL* or *UCDL* vary with *QC*, which is similar in spirit to the approach to water treatment costs described above. As can be seen from the results reported further below, this approach seems to work quite well. A simple specification for this purpose is:

$$TCDL = \beta.QC^{\alpha} \quad \text{……………..} \quad (7)$$

or in unit cost form:

$$UCDL = \beta.QC^{\alpha-1} \quad \text{…………….} \quad (8)$$

However, a typical company will serve many settlements through systems which are largely independent of each other. A better representation would therefore be:

$$UCDL = \beta.(AVQC)^{\alpha-1} \quad \text{……………..} \quad (9)$$

where *AVQC* is *QC* divided by the number of settlements in a company's area. In addition, we wish to assess the effect of density and to introduce a control for distribution pumping head, leading to the expanded version of (9) restated in log form as:

$$\ln(UCDL) = \beta_0 + \beta_1 \ln(DENS) + \beta_2 \ln\left(1 + \frac{PHD}{APHD}\right) + (\alpha - 1)\ln(AVQC) \quad \text{……} \quad (10)$$

where *DENS* is a measure of population density, *PHD* is distribution pumping head and *APHD* is average distribution pumping head.

The averaging involved in (9) is not very satisfactory as settlements are likely to vary considerably in size. A specification which tries to address this problem by assuming that each treatment plant serves a settlement of a size proportionate to its capacity can be derived as:

$$UCDL = \beta\left[\sum_i p_i\{(1-l)q_i\}^{\alpha-1}\right] \quad \ldots\ldots\ldots\ldots \quad (11)$$

where $p_i$ is the proportion of output from plants in the $i$th size band, $q_i$ is the average output of a plant of that size and $l$ is the proportion of water put into distribution that is lost through leakage. To take into account the effect of density and distribution pumping head, this can be expanded to give:

$$UCDL = \beta_0.(DENS)^{\beta_1}\left(1+\frac{PHD}{APHD}\right)^{\beta_2}\left[\sum_i p_i\{(1-l)q_i\}^{\alpha_1-1}\right] \quad \ldots\ldots.. \quad (12)$$

Ideally, the measurement of density and pumping head would be settlement specific but data on these items is only available at company level and this is reflected in the specification of (12). The *a priori* expectation using either (11) or (12) is that $\alpha > 1$, confirming scale diseconomies in water distribution, while the coefficient on *DENS* is negative (density economies).

## Data for England & Wales

### *a. Organisation of the water industry (England & Wales)*

Water supply in England and Wales is currently the responsibility of 10 combined water and sewerage companies (WaSCs) and 12 water supply only companies (WoCs)[5]. In the areas where the latter supply water (See **Annex A**), sewerage is the responsibility of one of the combined water and sewerage companies. Whereas the WaSCs cover very large areas, based in principle (following a reorganization of the industry in 1973) on river basins, the WoCs cover generally much smaller areas, reflecting their origins as municipal water suppliers (although with the passage of time, many have come to serve several urban areas).

As the ultimate purpose of this research is to throw light on how infrastructure affects the economics of urban settlements, the ideal would be to test the relationships set out above using data from individual urban areas. Data disaggregated to urban area level on the water supply activities of the WaSCs is not publicly available. For the WoCs there is, at least in some cases, a closer match between responsibilities and particular urban areas (e.g. Bristol, Cambridge, Portsmouth). However even in these cases the correspondence with urban areas, as defined for other purposes, e.g. Census key statistics for urban areas (ONS (2004)), local authority administrative boundaries or the Functional Urban Regions favoured by some researchers, is not very good; and in other cases (e.g. Three Valleys, South East Water), the correspondence appeared to be quite remote.

[5] Omitting the Cholderton & District Water Co, for which Ofwat does not publish data because it is too small.

**Tables 1A** and **1B** below show the key water supply figures for companies included in the analysis:

| **Company** | **Area (sq km)** | **Properties served ('000)** | **Treatment plants (No)** | **Water supplied (Ml/day)** |
|---|---|---|---|---|
| Bournemouth & West Hampshire Water plc | 1,041 | 188 | 7 | 160 |
| Bristol Water plc | 2,391 | 483 | 23 | 292 |
| Cambridge Water plc | 1,175 | 120 | 14 | 73 |
| Dee Valley Water plc | 831 | 117 | 9 | 70 |
| Folkestone & Dover Water Services Ltd | 420 | 72 | 18 | 50 |
| Mid-Kent Water plc | 2,050 | 242 | 29 | 157 |
| Portsmouth Water Ltd | 868 | 290 | 20 | 177 |
| South East Water plc | 3,607 | 590 | 65 | 376 |
| South Staffordshire Water plc | 1,507 | 548 | 29 | 331 |
| Sutton & East Surrey Water plc | 833 | 270 | 11 | 160 |
| Tendring Hundred Water Services Ltd | 352 | 70 | 2 | 30 |
| Three Valleys Water plc | 3,727 | 1,224 | 99 | 864 |

**Table 1A: Water only companies (England & Wales, 2003)**

| **Company** | **Area (sq km)** | **Properties served ('000)** | **Treatment plants (No)** | **Water supplied (Ml/day)** |
|---|---|---|---|---|
| Anglian Water Services Ltd | 27,600 | 1,930 | 143 | 1,159 |
| Welsh Water (Dwr Cymru) | 21,300 | 1,317 | 105 | 883 |
| Yorkshire Water Services Ltd | 13,900 | 2,109 | 90 | 1,299 |
| Northumbrian Water (incl Essex & Suffolk Water) | 12,261 | 1,899 | 67 | 736 |
| South West Water Ltd | 10,800 | 726 | 40 | 447 |
| Severn Trent plc | 21,650 | 3,279 | 173 | 1,958 |
| Southern Water | 10,450 | 1,007 | 102 | 595 |
| Thames Water | 13,328 | 3,474 | 99 | 2,804 |
| United Utilities (NW Water) | 14,445 | 3,120 | 137 | 1,952 |
| Wessex Water Services Ltd | 10,650 | 537 | 119 | 368 |

**Table 1B: Water and Sewerage companies (England & Wales, 2003)**

In further research in this area it would be desirable to obtain more disaggregated data on the numbers and size of settlements in each company's service area, and on the distribution networks used to connect treatment works to consumers. However in the results reported below, company level data and the averaging procedures described earlier had to be adopted.

### *b. Data in the Ofwat "June Returns"*

Each year, all the water companies submit to Ofwat in a standard format (known as the "June Return") a large amount of data, both financial and non-financial, for regulatory purposes. This process has been in operation since 1992. Most of this data (omitting only a small amount judged to be commercially confidential) is publicly available on the Ofwat website or on CD-ROMs. The data is used by Ofwat to inform its regulatory activities; and analyses using appropriate parts of the data are included in Ofwat publications, notably (in the present context) an annual report on "Water and sewerage service unit costs and relative efficiency" (e.g. Ofwat (2004)). As noted earlier, a key difference between the Ofwat analyses and those reported here is that Ofwat's focus is on differences in the relative efficiency of companies, after allowing for differences in their operating environments, whereas our emphasis is precisely on how environmental factors (such as differences in population densities and the size of areas served) affect costs, at settlement rather than company level. Hence this paper looks at the data from a different perspective.

The source for nearly all the data used is the Ofwat June Returns for 2003 – Ofwat (2003). Figures for water company area (in sq. km) are from Water UK (2003).

**Results**

Using 2003 data for the 22 companies shown in **Tables 1A** and **1B** (12 WoCs and 10 WaSCs), the following relationship between unit cost of water treatment and average plant size was obtained using specification (7), with *t*-statistics in brackets:

$$\ln(UCT) = 4.843 + 0.657\ln(1+SP) + 0.697\ln\left(1+\frac{PHR}{APHR}\right) - 0.180\ln(AVQT) \quad \ldots\ldots\ldots \quad (13)$$

(1.89) (2.28) (-1.31) $R^2 = 0.3990$

where *UCT* is the unit cost of water treatment, *AVQT* is average treatment plant size, *SP* is proportion of surface water and *PHR* is resource pumping head. The relationship seems reasonably robust given the sample size. The coefficient on ln(*AVQT*) indicates quite strong economies of scale – 18% *reduction* in unit treatment cost with each doubling of plant size – while the coefficients on the *SP* and *PHR* terms indicate quite a strong positive effect on unit cost from these factors.

For a company with average surface water proportion (0.504) and average resource pumping head (52.5m), this yields:

$$UCT = 270(AVQT)^{-0.18} \quad \ldots\ldots\ldots\ldots \quad (14)$$

However, some caution is advisable regarding the economies of scale indicated by this relationship as when the alternative specification (6) was estimated (using non-linear least squares), the scale coefficient dropped to –0.081.

Using the same 22 company data set for 2003, the relationship between unit cost of distribution, average plant size and property density obtained using (10) was:

$$\ln(UCDL) = 5.693 - 0.160\ln(DENS1) - 0.087\ln\left(1+\frac{PHD}{APHD}\right) + 0.182\ln(AVQC) \quad \ldots.. \quad (15)$$

(-1.52) (-0.37) (1.67) $R^2 = 0.1630$

where *UCDL* is the unit cost of distribution (including the cost of leakage), *AVQCT* is average final consumption per plant size, *DENS1* is density measured as properties/hectare and *PHD* is distribution pumping head. This relationship is evidently not very robust, with a low $R^2$. Nevertheless, the coefficient on ln(*AVQC*) indicates quite strong diseconomies of scale in

distribution – an 18% *increase* in unit distribution cost with each doubling of settlement size, if it is supposed that each treatment plant serves a single settlement. The beneficial effect of higher density on distribution costs is also evident in the negative coefficient on ln(*DENS1*) while the negative coefficient on distribution pumping head, although not significantly different from zero, is somewhat puzzling.

This yields as the cost function for water distribution for a settlement of average density (*DENS1* = 17.98 properties/Ha), ignoring the effect of *PHD*, and letting *AVQC = 0.8AVQT* (i.e. assuming 20% leakage):

$$UCDL = 247.(17.98)^{-0.160}(AVQT)^{0.182} \quad \ldots\ldots\ldots \quad (16)$$

Again, some caution is in order in as regards the diseconomies of scale indicated by this relationship. Using the alternative specification (12), estimated using non-linear least squares, the estimate of scale diseconomies dropped to 0.096.

A sketch of the treatment and distribution cost functions – (14) and (16) above - is shown in **Figure 1** below:

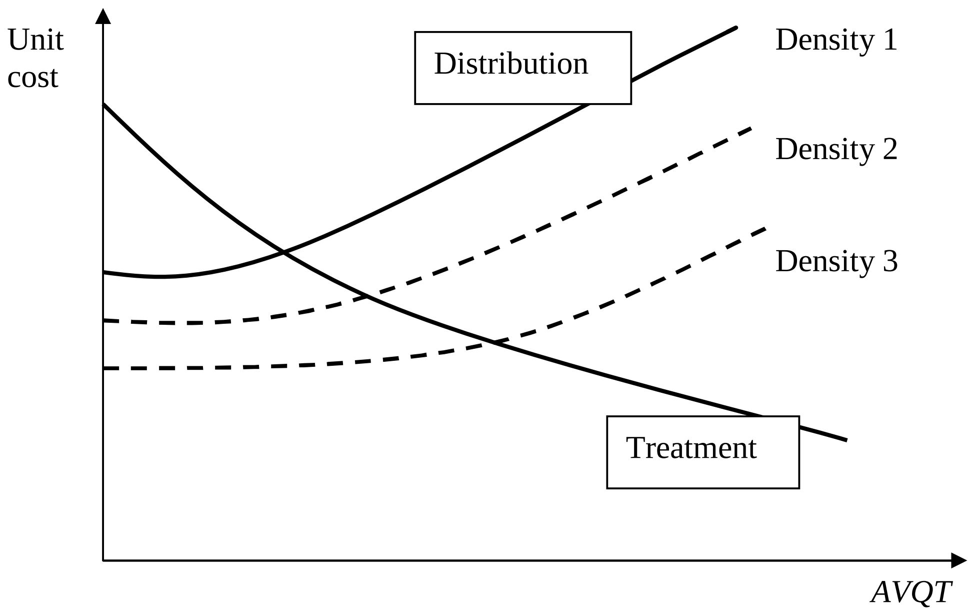


**Figure 1: Sketch of unit costs of water treatment and water distribution**

It is of course not correct to suppose that the combined costs are minimized where the lines cross. The optimum combination will depend on the relative slopes of the two curves, e.g. if there are strong economies of scale in treatment costs these might outweigh diseconomies in distribution costs well beyond the crossing point. However, it is evident that higher density will tend to push the cost minimizing point out to the right.

With the parameters estimated in (14) and (16) above, the cost minimizing combination can be computed to be a little under 3Ml/day. However, given the indications from the other regressions carried out that the scale coefficients on *AVQT* in (14) and (16) are too high, in what follows we explore the effect of assuming rather lower coefficients, as well as different densities.

Using the specifications:

$$UCT = \beta_T.(AVQT)^{\alpha_T} \quad \text{(for water treatment)}$$

and

$$UCDL = \beta_D.(DENS1)^{-0.15}(AVQT)^{\alpha_D} \quad \text{(for water distribution),}$$

unit costs were calculated for different plant/settlement sizes, and values of the α coefficients ranging from 0.05 to 0.20. **Figure 2** illustrates the results for $\alpha_T$ = -0.10 and $\alpha_D$ = 0.10. The data used are shown in the table in **Annex A** (with values for β and *DENS1* as indicated in the table).

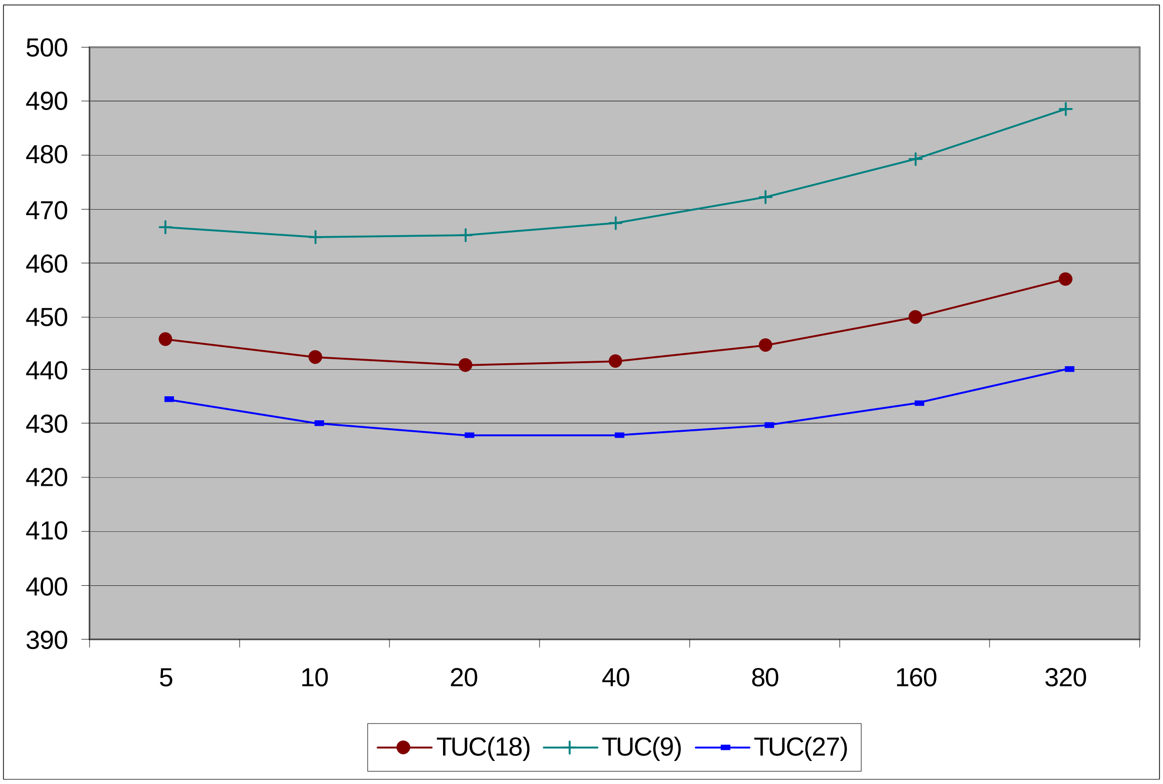


**Figure 2: Total unit cost of water supply for 3 settlement densities (data from Annex A)**

One way of viewing these results is to consider what scale of operations would minimize the total unit cost of water supply. Visual inspection of **Figure 2** indicates that with a density of 18 properties/hectare (middle line), unit cost is minimized at about 20 Ml/day. With a lower density of 9 properties/hectare (top line), this reduces to about 10 Ml/day; with a density of 27 properties/hectare, it rises to around 40 Ml/day. However, it is also evident that the lines are very flat so that the cost penalty from operating at above or below the optimum level is small. This can be seen in **Table 2** below which compares the cost of supplying a community taking 160 Ml/day using plants of different sizes[6].

| *No of plants* | *Size of plant* | *Unit Cost Treatment* | *Unit Cost Distribution* | *Total Unit Cost* |
|---|---|---|---|---|
| 1 | 160 Ml/d | 181 | 269 | 450 |
| 2 | 80 Ml/d | 194 | 251 | 445 |
| 4 | 40 Ml/d | 207 | 234 | 442 |
| 8 | 20 Ml/d | 222 | 219 | 441 |
| 16 | 10 Ml/d | 238 | 204 | 442 |

[6] Assuming a community with average density and pumping head.

**Table 2: Unit costs for supplying 160 Ml/day using different plant sizes**

The comparative costs in **Table 2** show how the lower unit costs of treatment using larger plant can get absorbed by the higher unit cost of distributing over a larger area (if settlement density does not vary). On these figures, the cost penalty of operating at half or double the optimum scale is less than 1%. The very small net effect is to some extent a consequence of using similar scale coefficients, given that the costs of water treatment and of water distribution are of similar magnitude. More striking results can be obtained by using scale coefficients which are markedly different as between water treatment and water distribution. But the picture presented here may not be unrealistic as regards the situation in practice. It is noticeable in the Ofwat data that there has been very little rationalization of plant numbers and sizes since privatization in England and Wales, despite strong pressure for cost savings under the price control regime. And in the case of the one company (Cambridge) that has made a big reduction in the number of its plants, from 23 to 14 between 1998 and 2003, it seems to have had little effect on unit costs.

The other notable feature of the figures in **Annex A** and **Figure 2** is the quite significant effect of differences in density on unit costs. At a scale of 40 Ml/day, the unit cost of distribution rises by £26 (11%) if density is halved from 18 properties/hectare to 9 properties/hectare; while the unit cost of distribution is reduced by £14 (6%) if density is increased by 50% from 18 properties/hectare to 27 properties/hectare. These calculations assume that properties are evenly spread over the service area. In the more realistic case where property densities are higher near the center of settlements and fall away around the margins, the savings associated with higher density settlements are likely to be greater. Moreover, bearing in mind that property densities can vary from less than 1 per hectare in rural areas to over 50 per hectare in the denser parts of large cities, the significance of density effects may be understated by these comparisons.

The results of this investigation of water supply costs can be summarized as:

- Confirmation of economies of scale in water treatment, perhaps in the range 10-20%, although the precise value of these remains unclear;
- Reasonable evidence for diseconomies of scale in water distribution, perhaps also in the range 10-20%, although again their precise value remains unclear;
- Combining these results indicates a U-shaped unit cost curve for water supply;
- However, it also appears that this cost curve is typically quite flat so that the cost penalty of operating above or below the optimum scale is small;
- Higher settlement density reduces unit distribution costs and this may be the most significant effect to emerge from this study.

## Implications for urban economics

The central facts to be explained by urban economics are, as Fujita *et al* (2001, p.1) express it:

> "The distribution of population and activity across the landscape is radically uneven; in advanced countries the majority of the population lives in large metropolitan areas, and these metropolises are themselves clustered into regions like the Boston-Washington corridor. Yet although agglomeration is clearly a powerful force, it is not all-powerful: London is big, but most Britons live elsewhere, in a system of cities with widely varying sizes and roles."

In seeking to explain these phenomena, the role of infrastructure has not been completely overlooked but it has been somewhat peripheral, ranking well behind such factors as economies of scale in manufacturing, technological spillovers and labour market effects.

The treatment of infrastructure in mainstream urban economics emphasizes economies of scale and the provision of (local) public goods. Fujita (1989, p.134-5) puts it as follows:

> "Perhaps the most fundamental reason for the existence of cities stems from *economies of scale* in production and consumption, which are, in turn due largely to the *indivisibility* of some commodities (such as persons, residences, plants, equipment and public facilities) … the provision of many *public services and facilities* (such as schools, hospitals, utilities, and highways) typically exhibits the characteristic of economies of scale."

Fujita & Thisse (2002, p.133) add:

> " … the availability of local public goods remains a major ingredient of modern cities because the congregation of a large number of people facilitates the mutual provision of collective services that could not be obtained in isolation."

The 'New Economic Geography' literature picks up the public goods theme from a different perspective:

> "The mobile factor, entrepreneurs or *H* for short, naturally seek to locate in the region that can afford them the highest level of utility. In the basic FE model, this boils down to looking for the region with the highest real reward. However, once we allow for public goods, entrepreneurs will typically take into account the level of public goods available in each region when making their location decision. As we will see, this introduces an extra agglomeration force into the model, as shown by Andersson and Forslid (2003)." Baldwin *et al* (2003. p.384)

On the other hand, it also identifies congestion as a possible detriment to agglomeration:

> "In previous chapters … we have assumed that the agglomeration of workers into a single region does not involve any agglomeration costs. Yet, it is reasonable to believe that a growing settlement in a given region congests the use of local non-tradable resources. As pointed out by Helpman (1998), and Puga (1999), allowing for such phenomenon generates an additional dispersion force." Baldwin *et al* (2003, p.129)

When infrastructure is referred to explicitly, it seems generally to refer to transport infrastructure, with the analysis focusing on the consequences for economic geography of reductions in transport costs as a result of investment in such infrastructure – see Baldwin *et al* (2003), Ch 17.

Our findings on water supply costs, however, which may well generalize (*mutatis mutandis*) to other types of infrastructure, show that economies of scale and distribution costs tend to cancel each other out as the scale of settlements increases. Higher density on the other hand reduces costs whatever the scale of operation. The tension between scale (and other) economies associated with geographic concentration of industry within a city, and diseconomies, such as commuting costs, is a long-established theme in urban economics. The key implication of this paper is to suggest that density may be as important as size per se in the economics of urban systems. It is their higher density that enables cities to overcome the cost of distance and so exploit economies of scale.

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# ANNEX A

| AVQT | Beta-T | Alpha-T | UCT | Beta-D | DENS | Alpha-D | UCD | TUC |
|---|---|---|---|---|---|---|---|---|
| 5 | 300 | -0.1 | 255.402 | 250 | 18 | 0.1 | 190.347 | 445.749 |
| 10 | 300 | -0.1 | 238.2985 | 250 | 18 | 0.1 | 204.0089 | 442.3074 |
| 20 | 300 | -0.1 | 222.3403 | 250 | 18 | 0.1 | 218.6513 | 440.9917 |
| 40 | 300 | -0.1 | 207.4509 | 250 | 18 | 0.1 | 234.3447 | 441.7956 |
| 80 | 300 | -0.1 | 193.5585 | 250 | 18 | 0.1 | 251.1644 | 444.7229 |
| 160 | 300 | -0.1 | 180.5965 | 250 | 18 | 0.1 | 269.1914 | 449.7878 |
| 320 | 300 | -0.1 | 168.5025 | 250 | 18 | 0.1 | 288.5122 | 457.0146 |
| 5 | 300 | -0.1 | 255.402 | 250 | 9 | 0.1 | 211.2033 | 466.6052 |
| 10 | 300 | -0.1 | 238.2985 | 250 | 9 | 0.1 | 226.3621 | 464.6605 |
| 20 | 300 | -0.1 | 222.3403 | 250 | 9 | 0.1 | 242.6088 | 464.9492 |
| 40 | 300 | -0.1 | 207.4509 | 250 | 9 | 0.1 | 260.0217 | 467.4726 |
| 80 | 300 | -0.1 | 193.5585 | 250 | 9 | 0.1 | 278.6844 | 472.2429 |
| 160 | 300 | -0.1 | 180.5965 | 250 | 9 | 0.1 | 298.6865 | 479.283 |
| 320 | 300 | -0.1 | 168.5025 | 250 | 9 | 0.1 | 320.1243 | 488.6268 |
| 5 | 300 | -0.1 | 255.402 | 250 | 27 | 0.1 | 179.1152 | 434.5172 |
| 10 | 300 | -0.1 | 238.2985 | 250 | 27 | 0.1 | 191.9709 | 430.2694 |
| 20 | 300 | -0.1 | 222.3403 | 250 | 27 | 0.1 | 205.7493 | 428.0897 |
| 40 | 300 | -0.1 | 207.4509 | 250 | 27 | 0.1 | 220.5167 | 427.9675 |
| 80 | 300 | -0.1 | 193.5585 | 250 | 27 | 0.1 | 236.3439 | 429.9024 |
| 160 | 300 | -0.1 | 180.5965 | 250 | 27 | 0.1 | 253.3071 | 433.9036 |
| 320 | 300 | -0.1 | 168.5025 | 250 | 27 | 0.1 | 271.4879 | 439.9903 |

**Table 1: Calculated unit costs for water treatment (UCT), water distribution (UCD) and both together (TUC) for a range of plant sizes, densities and α values**