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# Exploring urban mines: Pipe Length and Material Stocks in Urban Water and Wastewater Networks

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# Exploring Urban Mines: Estimating Pipe Length and Material Stocks in Urban Water and Wastewater Networks

ABSTRACT:

Underground pipe networks for water distribution and wastewater transport represent large capital assets and material stocks. Understanding how the material content of these networks scales with the population and the size of a given catchment or city may show how one can design networks with lower resource demand and lower construction and maintenance costs. In this paper, we develop a fractal model of water/wastewater networks where the different levels represent the pipe hierarchy from the private connections to the main trunk lines. The model is calibrated and the total network length and mass for the wastewater networks of 25 cities of varying sizes (population, surface area) is estimated. The results show that most of the network mass is concentrated in the trunk lines. For a catchment of given size, both total network length and mass grow slower than population, thus demonstrating efficiency of scale in the network.

KEYWORDS: water pipeline network; wastewater pipeline network; asset management; material flow analysis; material stocks; fractal network model;

WORD COUNT:

Total, including references, title, tables: 5800. Main text only: 4000.

## 1. Introduction

Cities are major consumers of materials and energy. Since 2007, more than 50% of the world’s population has been living in cities (United Nations 2011). Global urban population is expected to double within the next 40-50 years (UN Department of Economic and Social Affairs 2011), which will consequentially boost demand for buildings and infrastructure networks. This expansion requires large capital investments and entails a demand for construction materials and associated upstream impacts and carbon emissions. There has been a long discussion on the optimal size and density of human settlements regarding resource and carbon footprint (Handy 1992, Alberti 1999, Clifton *et al.* 2008). As can be seen from the reviews, most of the research in this area has been dedicated towards the relationship between transportation demand and urban density. But it is not only the *use* of automobiles and other modes of transportation that contributes to energy use and emissions, but also the construction and material *supply* for the underlying infrastructure networks: Rapidly-growing urban structures will increase the competition for inexpensive construction materials (Deilmann 2009) and boost emissions associated with bulk construction materials, especially concrete and steel (Allwood *et al.* 2010, Hu *et al.* 2010). In the light of climate change, solutions for decoupling the carbon footprint associated with building up and maintaining the material stocks in products, buildings, and infrastructure from the service these stocks provide are urgently required (Milford *et al.*, Allwood *et al.* 2012).

Amongst the many infrastructure services a city provides to its inhabitants, water distribution and wastewater transport pipeline networks represent large underground assets and material stocks, especially of concrete and cast iron. Beyond the provision of services (the social imperative), questions of economic and environmental sustainability of water and wastewater networks are also gaining importance (Abbott and Cohen 2010). Underground pipeline and tunnel networks are difficult to maintain and even more difficult to replace once the urban structure is mature. A growing maintenance backlog has been identified for ageing pipeline networks that do not experience an appropriate amount of rehabilitation (Ugarelli *et al.* 2008, Venkatesh *et al.* 2009). Understanding which parts of the network contribute most to material demand and construction or maintenance costs allows for anticipation of future maintenance hotspots, rehabilitation needs and material recovery opportunities. To a large extent, these are directly related to the quality and degradation processes of pipe materials.

Unlike road or rail networks, water and wastewater networks are characterized by a small number of centres (treatment plants), to which all clients are connected. They show a clear hierarchy in both diameter and function with a wide range of levels reaching from connections to individual houses or street inlets to large underground tunnels that form the backbone of the network. From a planner's perspective, it is important to understand the development of the different levels of the network when a city expands and the relevance of these levels to material consumption and future maintenance. Material stocks in pipe networks are diverse and widely scattered - ranging from thin plastic pipes with a specific mass of less than 200 g/m (Venkatesh *et al.* 2009) to large concrete underground tunnels with masses up to many tonnes per metre (APWA 2006, Loganathan *et al.* 2008). The mass per metre covers five orders of magnitude. In order to assess the mass, the environmental footprint, and the potential recyclability of this stock, it is imperative to understand how the total length of the different diameter classes in the network and their material content scale with changing city size and population.

Venkatesh and Brattebø (Ugarelli *et al.* 2008, Venkatesh *et al.* 2009) analyse the temporal development of material stocks and length of water and wastewater networks in the Norwegian municipalities of Trondheim and Oslo. They find that both network length and mass per capita have saturated or are slightly falling. The dominating material for wastewater networks is concrete, which contribute approximately 85 % to the total mass. Venkatesh (2011) shows that for Oslo, the total length of pipes in all diameter classes has saturated, and that the per-capita length is falling due to the growing population.

Several scholars have worked on optimal network topology and pipe diameter as well as minimizing the total flow through all treatment plants in the network (Lavric *et al.* 2007, Castro *et al.* 2009, Azoumah *et al.* 2012).

Venkatesh and Brattebø (2011) tested a detailed dataset on pipe lengths of 30 Norwegian municipalities for a power law between length of pipes and number of pipes by length in the network. They found a strong relationship between the two with a coefficient of determination $R^2$ of more than 0.9 for most municipalities. Most of the pipes in the networks analyzed have a length below 100 m.

Maurer *et al.* (2012) provide a generic model of length, diameter distribution, and replacement costs for the sewer network in a given catchment area. They consider three levels within the catchment: private connection pipes, secondary sewer lines, and the sewer main trunk that connects the settlement to the rest of the network. Assuming a uniform settlement density, an intuitive geometry, and the Manning-Strickler-approach to determine the pipe capacities, the authors determine the diameter depending on the flow of wastewater through each pipe and calculate the construction or replacement costs dependent on pipe diameter and trench depth. Regional statistics on rainfall and the amount of wastewater generated specify the required service of the network.

The previous work indicated that the bulk of the material in a water or wastewater network is concentrated in the largest pipes (Venkatesh *et al.* 2009), and we therefore need a model that provides more details on large pipes and tunnels in the catchment area than the one given by Maurer *et al.* (2012) and that unlike Venkatesh and Brattebø (2011) uses pipe diameter rather than pipe length as explanatory variable.

This is especially important for very large cities, where large diameter pipelines probably represent a larger share of the total mass. We are interested in how the total network length and mass scales with the city's size, population, and population density, and we hence need a model that covers the entire network rather than a section of it. The following two research questions specify our scope:

1. How does length and mass of the pipelines in the water/wastewater network of a city relate to population and city size, and how does it scale with changing population and population density?
2. Which diameter classes contribute most to network length and mass and what are the consequences for asset management, material consumption, and urban planning?

We provide a first, calibrated estimate of the total length, mass, and the diameter distribution in cases where very little is known about the settlement. These "rules of thumb" shall help city planners to estimate the total length, diameter distribution, and total network mass as central characteristics of the pipeline stock that will be important inputs to asset management and the future urban sustainable infrastructure policies.

## 2. Methodology

We have collected data on the water and wastewater networks of settlements and cities ranging from 500 to 23,000,000 inhabitants to test for an empirical scaling law for the network length, which is presented in section 2.1. We subsequently develop a hierarchical network model to estimate the contribution of different diameter classes to both length and mass, and provide a first estimate of the network mass in a catchment with given population and size using the same empirical data (section 2.2.).

### *2.1. Network length and empirical data:*

We use the empirical data to identify how the total network length L scales with population P and size $L_0$ by estimating the coefficient α, β, and γ in the following simple relationship

$$L = \alpha \cdot P^{\beta} \cdot L_0^{\gamma} + \varepsilon \tag{0.1}$$

In Equation 1.1, all lengths are in km and $\varepsilon$ is the residual. The parameters are estimated by transforming Equation 1.1 to a logarithmic scale and applying the robust linear regression tool provided by Matlab (Holland and Welsch 1977).

We collected city-level data on population served P, and total network length L for the water and wastewater networks of 35 cities from 5 countries in 3 continents (Table 1). For the Brazilian cities, we obtained a time series for the years 1995-2008 (which is not shown in Table 1). In total, we have approximately 100 data points for both water and wastewater networks. We assumed the area supplied by the network as a rectangle with width a, length b, and diagonal $L_0$ in order to facilitate the subsequent application of the network model. These parameters were estimated from network maps where available and from city maps otherwise.

[Table 1 about here]

Table 1: Primary data on networks (W: Water, WW: Wastewater). The columns $n_0$ and δ are network characteristics defined in section 2.2. The other columns contain the primary data. Data sources: Brazil: (Ministério das Cidades 2012), Germany: (S & P Consult Bochum 2009), Maldives: (Mujthaba 2012). The data on Norway and Switzerland have been obtained by G. Venkatesh from the individual municipalities in connection with Venkatesh *et al.* (2009).

| Name | Type | Population served P | Length of network L (km) | Length a of catchment area (km) | Width b of catchment area (km) | Network diagonal $L_0$ (km) | Highest order in network $n_0$ | Average distance between two nodes (m) | Density of served population (1/km$^2$) |
|---|---|---|---|---|---|---|---|---|---|
| Belém (BR) 2008 | W | 1825450 | 5076 | 16 | 9 | 18 | 7.1 | 45 | 12677 |
| Brasília (BR) 2008 | W | 2543094 | 7507 | 37 | 18 | 41 | 6.5 | 152 | 3818 |
| Porto Alegre (BR) 2008 | W | 5892099 | 24148 | 26 | 12 | 29 | 8.7 | 23 | 18885 |
| Rio de Janeiro (BR) 2008 | W | 10544756 | 19732 | 52 | 13 | 54 | 7.5 | 89 | 15599 |
| Salvador (BR) 2008 | W | 8918739 | 27357 | 13 | 8 | 15 | 9.8 | 6 | 85757 |
| São Paulo (BR) 2008 | W | 23161850 | 62582 | 43 | 25 | 50 | 9.3 | 27 | 21546 |
| Geneve 2 (CH) | W | 412961 | 1254 | 5 | 4 | 6 | 6.6 | 23 | 20648 |
| Zurich (CH) | W | 360704 | 1566 | 10 | 10 | 14 | 5.8 | 91 | 3607 |
| Basel (CH) | W | 204913 | 517 | 8 | 6 | 10 | 4.7 | 138 | 4269 |
| Lausanne (CH) | W | 204242 | 845 | 10 | 8 | 13 | 5.0 | 139 | 2553 |
| Bern (CH) | W | 126752 | 705 | 7 | 4 | 8 | 5.4 | 64 | 4527 |
| Winterthur (CH) | W | 91243 | 571 | 8 | 4 | 9 | 5.0 | 95 | 2851 |
| St. Gallen (CH) | W | 69876 | 246 | 8 | 2 | 8 | 3.8 | 174 | 4367 |
| Luzern (CH) | W | 60291 | 164 | 4 | 3 | 5 | 4.0 | 110 | 5024 |
| Biel (CH) | W | 48942 | 280 | 12 | 4 | 13 | 3.4 | 378 | 1020 |
| Dietikon (CH) | W | 21275 | 77 | 3.5 | 3 | 5 | 3.0 | 207 | 2026 |
| Kloten (CH) | W | 17433 | 108 | 5 | 4 | 6 | 3.0 | 282 | 872 |
| Kreuzlingen (CH) | W | 19000 | 81 | 4 | 3 | 5 | 2.9 | 230 | 1583 |
| Male (MV) | W | 123400 | 157 | 2 | 3 | 4 | 4.4 | 59 | 20567 |
| Åseral(Kyrkjebygd) (NO) | WW | 500 | 61 | 5 | 0.7 | 5 | 2.5 | 255 | 143 |
| Alta (NO) | WW | 14000 | 215 | 7 | 1 | 7 | 3.9 | 136 | 2000 |
| Steinkjer (NO) | WW | 16000 | 542 | 5 | 4 | 6 | 5.4 | 54 | 800 |
| Stjørdal (NO) | WW | 15000 | 187 | 4.5 | 2 | 5 | 4.2 | 88 | 1667 |
| Tromsø (NO) | WW | 53000 | 436 | 8 | 4 | 9 | 4.6 | 126 | 1656 |
| Egersund (NO) | WW | 14170 | 109 | 3.5 | 1.5 | 4 | 3.8 | 90 | 2699 |
| Bodø (NO) | WW | 47282 | 663 | 12 | 2 | 12 | 4.7 | 131 | 1970 |
| Larvik (NO) | WW | 42412 | 641 | 6 | 4 | 7 | 5.5 | 57 | 1767 |
| Hamar (NO) | WW | 28344 | 407 | 4 | 3 | 5 | 5.3 | 44 | 2362 |
| Svelvik (NO) | WW | 6466 | 92 | 3 | 1 | 3 | 3.8 | 71 | 2155 |
| Sandefjord (NO) | WW | 43785 | 419 | 6 | 4 | 7 | 4.8 | 88 | 1824 |
| Tønsberg (NO) | WW | 39367 | 294 | 5 | 3 | 6 | 4.6 | 81 | 2624 |
| Ålesund (NO) | WW | 20000 | 199 | 8 | 1 | 8 | 3.6 | 190 | 2500 |
| Moss (NO) | WW | 30030 | 207 | 3.5 | 3.5 | 5 | 4.3 | 86 | 2451 |
| Trondheim (NO) | WW | 150000 | 1100 | 12.5 | 5 | 13 | 5.3 | 108 | 2400 |
| Oslo (NO) | WW | 586860 | 1975 | 11 | 6 | 13 | 6.3 | 54 | 8892 |
| Stavanger (NO) | WW | 110000 | 1120 | 14 | 5 | 15 | 5.2 | 128 | 1571 |
| Belém (BR) 2008 | WW | 85312 | 558 | 13 | 7 | 15 | 4.2 | 272 | 937 |
| Brasília (BR) 2008 | WW | 2347080 | 4935 | 25 | 15 | 29 | 6.4 | 119 | 6259 |
| Porto Alegre (BR) 2008 | WW | 621611 | 1869 | 17 | 8 | 19 | 5.6 | 127 | 4571 |
| Rio de Janeiro (BR) 2008 | WW | 5114361 | 5252 | 25 | 15 | 29 | 6.5 | 112 | 13638 |
| Salvador (BR) 2008 | WW | 3058544 | 5808 | 10 | 8 | 13 | 7.8 | 20 | 38232 |
| São Paulo (BR) 2008 | WW | 19198397 | 41242 | 43 | 25 | 50 | 8.7 | 41 | 17859 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Hamburg (DE) | WW | 1800000 | 5400 | 25 | 30 | 39 | 6.1 | 200 | 2400 |
| Billerbeck (DE) | WW | 11500 | 75 | 3 | 3 | 4 | 3.1 | 180 | 1278 |
| Male (MV) | WW | 123400 | 161 | 2 | 3 | 4 | 4.4 | 57 | 20567 |

### *2.2. The network model and network mass*

In order to represent a generic city water and wastewater network, we apply a simple, rectangular, fractal, hierarchical model if a network with a centre. At level 0 - the city-level - four main backbone pipes branch off the centre to reach out to the respective centres of the four equally-sized quadrants (Fig. 1). From one level to the next, the cell size halves and 2x2 copies of the original X-shaped network are added. This procedure continues until the level of the final connection (house or block) is reached. We assume that the network clients are evenly distributed over the whole catchment. From each level to the next the length $L_n$ doubles and for $n = 0$ the length equals the network diagonal $L_0$, where L is the total length of the network, N is the total number of network clients (the number of pipes on the highest level $n_0$), and $\delta$ is the average distance between two clients on the highest level (cf. Table 1). From the third line in Equation 1.2 the highest network order $n_0$ can be determined for cases where the length L is given (cf. Table 1).

$$\begin{aligned}
L_0 &= \sqrt{a^2 + b^2} \\
L_n &= 2^n \cdot L_0 \\
L &= \sum_{n=0}^{n_0} L_n = \left(2^{n_0+1} - 1\right) L_0 \\
N &= 4^{n_0+1} \\
\delta &= \frac{a+b}{2^{n_0+2}}
\end{aligned} \tag{0.2}$$

[Figure 1 about here]

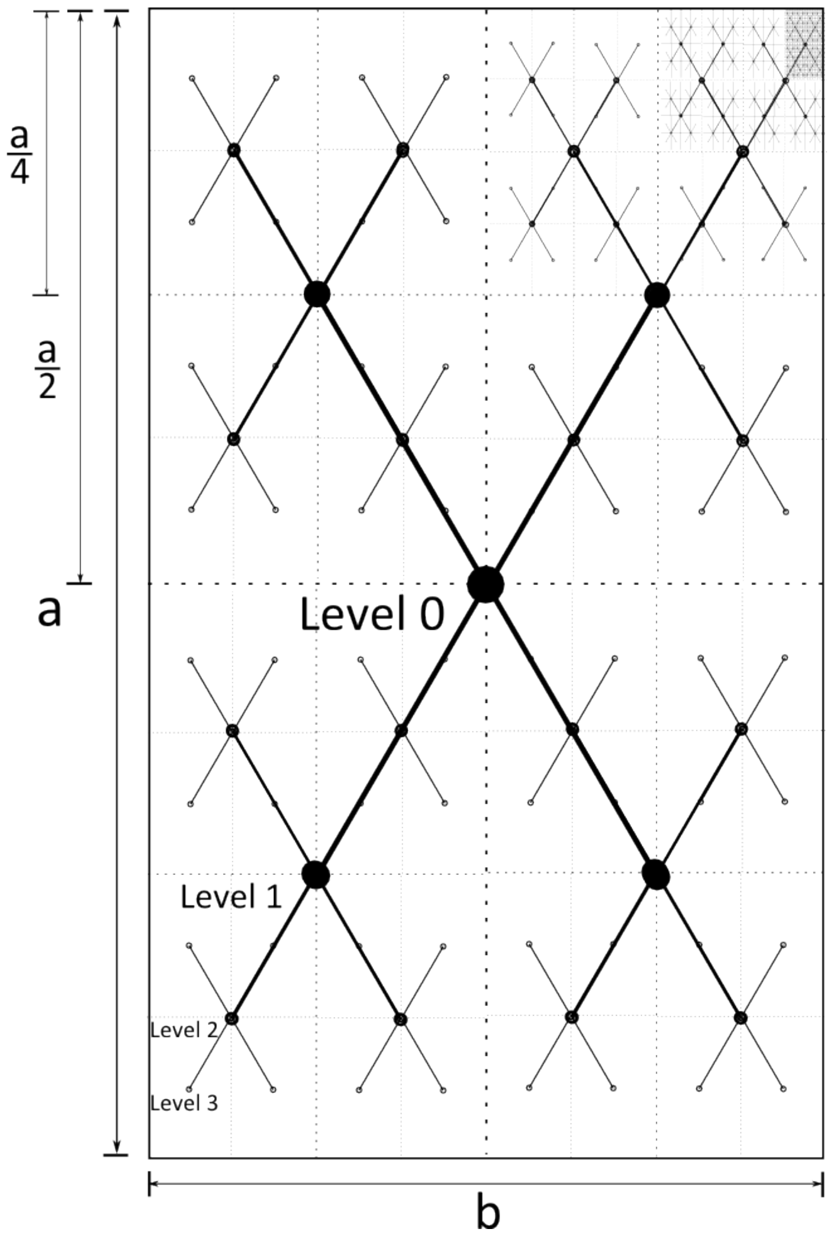

**Figure 1:** Outline of the network model.

The mass on each level, $M_n$, is given by the length $L_n$, the diameter $D_n$, the thickness $d_n(D_n)$, and the material density ρ:

$$M_n = \rho \cdot V_n = \rho \cdot A_n \cdot L_n \cong \rho \cdot \pi \cdot D_n \cdot d_n(D_n) \cdot L_n \qquad (0.3)$$

The total mass follows from integration of $M_n$ from n = 0 to the highest network order $n_0$. A central feature of the model is that the different levels are linked by a physical model. For the length, this is achieved by assuming that each pipe end is the start of a new sub-network that is a down-scaled copy of the existing one (self-similarity). In order to eventually determine the mass with Equation 1.3, we need to find a rule describing how the diameters scale between the different network levels. We obtain this scaling rule by assuming that the flow of water/wastewater in the pipes is turbulent and that the pipes are full of fluid and there exists no surface. While this assumption always holds for water networks which are under pressure, we assume that for mixed storm water and wastewater networks, the design process would consider a complete flooding with storm water as the case of maximum load. We further assume that the entire network is designed in a way that the head loss due to friction is the same on each level. For such cases the Darcy-Weissbach equation that relates head loss (or pressure drop) $h_f$ with velocity ν and diameter D applies:

$$h_f \propto \frac{v^2}{D} = \frac{\Phi^2}{D \cdot A^2} \propto \frac{\Phi^2}{D^5} \tag{0.4}$$

On the right side ν has been replaced by the flow rate Φ and the pipe cross section A. Under the assumption that $h_f$ does not change at a network node where four pipes merge, we obtain the following scaling rules for the pipe diameter $D_n$:

$$\frac{\Phi_{n+1}^2}{D_{n+1}^5} = \frac{\Phi_n^2}{D_n^5} \ , \ \Phi_{n+1} = \frac{1}{4}\Phi_n \ \rightarrow \ D_{n+1} = 2^{-0.8} \cdot D_n \tag{0.5}$$

To determine the mass according to Equation 1.3 a gauge diameter is required. Given that 25% of the population is served by a main collector pipe with diameter $D_0$ we can introduce the hypothetical diameter required to serve a single person $D_p$ as

$$D_0 = 2^{-0.8} \cdot P^{0.4} \cdot D_p \quad (0.6)$$

Once $D_0$ is known, the diameter of any other level can be obtained from Equation. 1.5.

In addition to the data on total network length shown in Table 1 we got access to a database containing length, material, and diameter of all individual pipes in the wastewater networks of the Norwegian cities of Oslo, Trondheim, and Stavanger. Together with an empirical relation between pipeline diameter and thickness (Fig. 5) we were able to estimate the total mass of these three wastewater networks. While doing so we also realized that assuming all pipes to be made from concrete or clay only slightly overestimates the mass but significantly simplifies the model calculations. For these three networks with known masses, we estimate first $D_0$ and then $D_p$ by applying the network model to those cities: We determine the model mass by summing up all individual mass given by Equation 1.3 and choose the gauge diameter so that model mass and empirical mass fit.

## 3. Results

### *3. 1. Length – entire sample*

To examine a potential dependency of total network length on the population served and the size of the associated catchment area, we plot the variables $L_0$, P, and L on a log-log scale (Fig. 2). The equation derived from the linear fit of the logarithms is shown for each case. The reported water network length shows a good dependency of population only. The goodness of fit measure $R^2$ is 0.90 and the mean estimation error is +40/-30% (1σ confidence). For water there is no significant dependency on network diameter or area. For wastewater both $L_0$ and P have similar influence on the network length but the variance of the residual is larger, leading to an $R^2$ of 0.74 and a mean error of +50/-35% (1σ confidence).

[Figure 2 about here]

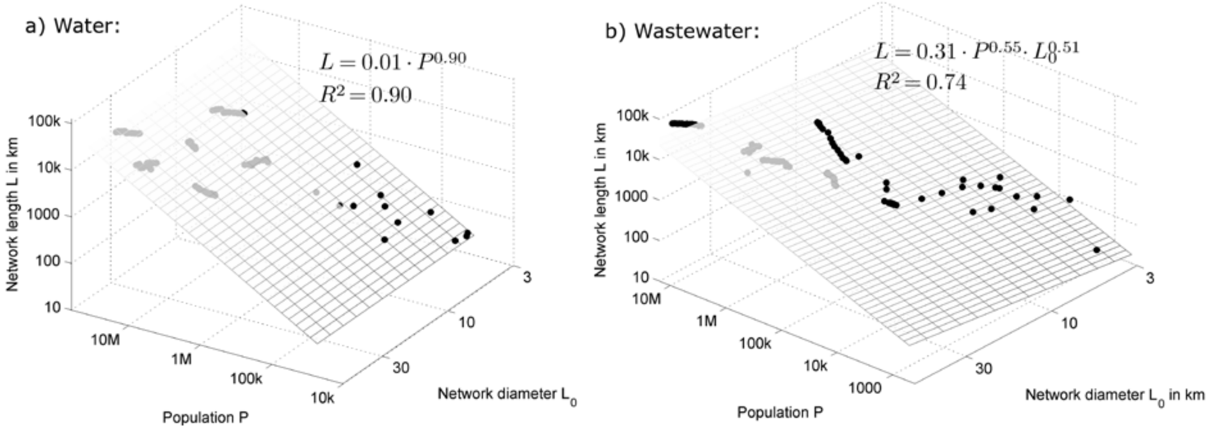

**Figure 2:** Regression of network length for Population and network diameter. Black dots lie above, grey dots below the meshed regression surface.

### *3.2. Testing the model*

We now identify how the different diameter classes contribute to the total network length. We therefore apply our network model to the cities of Oslo and Stavanger in Norway where detailed data on individual pipes are available. We group the diameters from the database into classes corresponding to the model hierarchy for both length (Fig. 3 left) and mass (Fig. 3 right). The model well represents how the different diameter classes contribute to the total network length and mass. Pipes of diameters below 25 cm dominate length and those with a diameter of 1m and beyond dominate mass. The difference between actual network length and mass and the model results is below 8%. The difference results from a mismatch between the model which only contains one diameter for each network level and the data where many different diameters occur. Given that the model correctly represents how contribution to length and mass changes with pipe diameter we decided to use it for the subsequent analysis.

[Figure 3 about here]

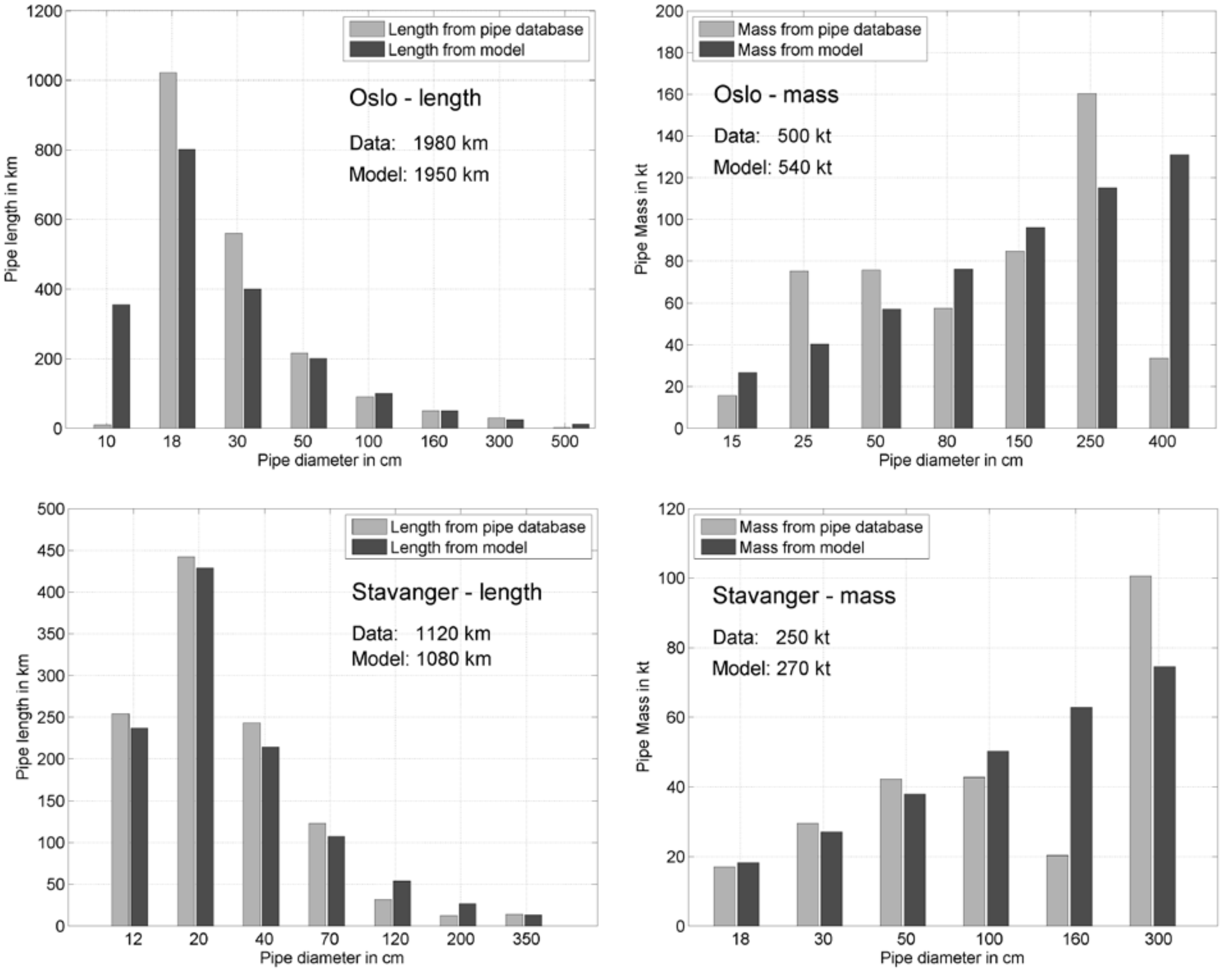

**Figure 3:** Comparison of model results with actual data on the wastewater networks of Oslo and Stavanger. The different diameters have been aggregated to the diameter classes shown.

The correlation between the highest network order $n_0$ and the city's population is strong (Fig. 4, right). We see that for cities with one million inhabitants or more there are between six and ten network levels from individual houses to the main backbone tunnel. With the hypothesis that the theoretical diameter at the level of the individual person is a constant (approximately. 2.6 cm, refer Table 2) the model forecasts a demand for gigantic backbone pipes in very large cities as between each level, the diameter increases by ca. 75%. Network size and density are only weakly correlated (Fig. 4 left): Cities of similar size can have very different highest orders of the network.

[Figure 4 about here]

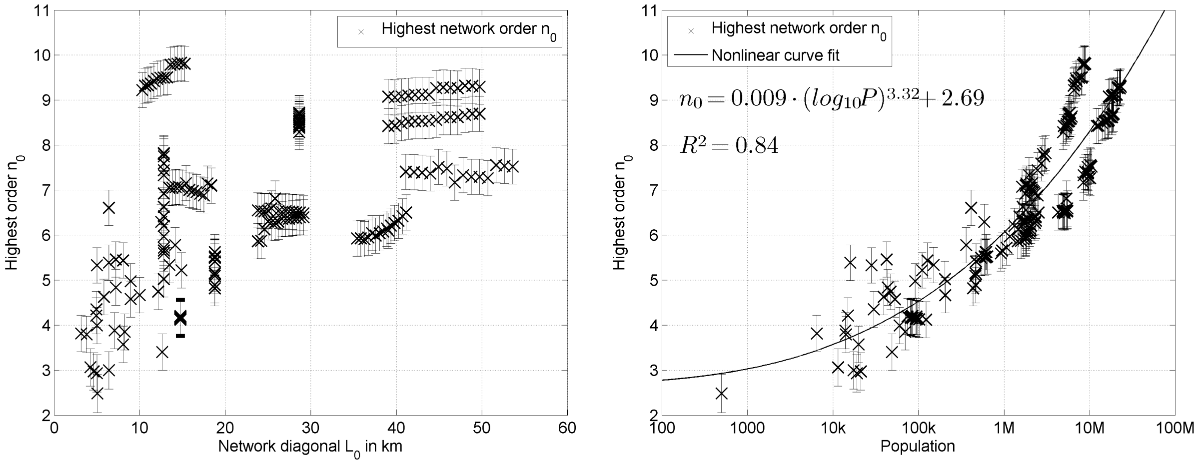

**Figure 4:** Highest network order $n_0$ over $L_0$ and P. n0 is calculated from the model data using Equation 2.

### *3.3. Mass of wastewater networks*

In our study we only have three networks with known mass, and hence no statistics can be run on our dataset. Instead, we make the highly-simplified assumption that the hypothetical diameter on the level of a single person, $D_p$, equals the mean of the empirical values in Table 2.

[Table 2 about here]

Table 2: Empirical mass M, highest order diameter $D_0$, hypothetical diameter for individual person $D_p$, population, and mass per capita for three Norwegian cities.

| | **M (tonnes)** | **D0 (m)** | **Dp (cm)** | **P (1000)** | **M/P (tonnes)** |
|---|---|---|---|---|---|
| **Oslo** | 503000 | 5.1 | 4.4 | 587 | 0.86 |
| **Trondheim** | 150000 | 3.4 | 5.4 | 150 | 1 |
| **Stavanger** | 250000 | 3.7 | 6.2 | 110 | 2.3 |

To estimate the total mass of the network according to Equation 3, we establish a relationship between pipe thickness and diameter. This is done by compiling and interpolating data sourced from various datasheets and technical reports (Fig. 5 left). For thin pipes, the thickness grows almost linearly with the diameter but for wastewater tunnels (> 3m) thickness and diameter decouple.

This information allows us to determine the mass on each network level and their summation yields the relationship depicted in Fig. 5 (right). The uncertainties of L and consequently that of $n_0$ play just a minor role as the highest network orders hardly contribute to mass. The main error source is $D_p$, for which we only could obtain three sample values. Yet, we believe that this estimation is quite reasonable, as the cities for which we know the pipeline masses, are of medium size. Urban wastewater networks cover a large range of masses from less than 1 million kilograms for villages to 10 million tonnes for megacities. The estimated per-capita stock of the wastewater networks plotted in Fig. 5 lies within the range of 0.4 to 1.8 tonnes with an average of 1.1 tonnes. Only the small settlement Kyrkjebygd (Norway) with 500 inhabitants is a significant outlier with an estimated per capita mass of 4 tonnes, respectively.

[Figure 5 about here]

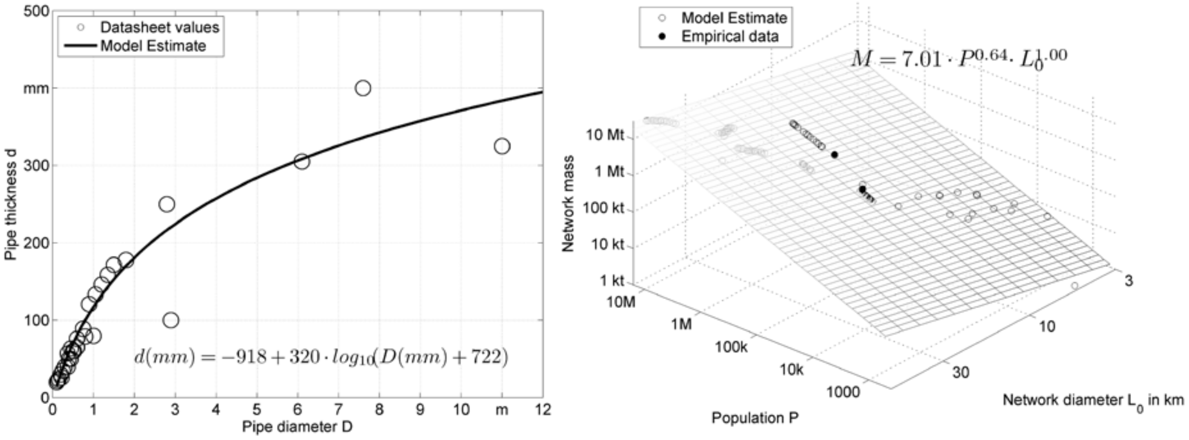

**Figure 5:** Obtained thickness-diameter relationship (left) and estimates network mass for wastewater (right). Diameter sources: (Bailey, Červenka Consulting, Sægrov 2012, Shows Dearman and Waits inc. 2012)

## 4. Discussion

The following relationships between demographic and geographic variables and length and mass of the network were obtained:

$$\begin{aligned} &\text{Water, empirical:} && L = 0.01 \cdot P^{0.9} \\ &\text{Wastewater, empirical:} && L = 0.3 \cdot P^{0.55} \cdot L_0^{0.51} \\ &\text{Wastewater, model:} && M = \;\; 7 \;\; \cdot P^{0.64} \cdot L_0, \end{aligned} \qquad (0.7)$$

where $L_0$ and L are in km, P in single inhabitants, and M in metric tonnes. Population has been identified as a major driver of both length and mass. For wastewater networks, the network diameter $L_0$ is relevant as well, and for mass, it has greater influence than population. The difference in scaling behaviour between water and wastewater network can be explained by the double function of the latter: as in many cases, both wastewater and storm-water are transported, the size of the catchment area will influence both length and mass. In all cases, the exponent of the population is smaller than unity, which means per-capita length and material stock is declining as the population in a given catchment increases. This effect is strongest for wastewater networks where size plays an important role, and weakest for water networks whose length is dominated by the population served. If a city is growing in population while the population density remains constant, e.g., by increasing urban sprawl, one can derive from Equation 1.1 that the per-capita length will slightly decrease as the network gets more scattered, but the per-capita mass will increase, because the trunk pipes have to be longer in such a case.

For wastewater networks, pipes of less than 25 cm diameter account for at least 50% of the network length, but in terms of mass, their contribution decreases as the city, and with it the network order $n_0$, grows. For cities with one million inhabitants or more, the mass of the narrow pipes will be less than 10% of the total mass of the network. For mega-cities like Tokyo with large tunnel systems for waste and storm water (Higuchi *et al.* 1994) we can expect the mass percentage share of the small pipes to be negligible. However, the maintenance and related costs of small pipes are crucial to the network operator. We hence identify a gap between maintenance and costs (proportional to length) and those related to mass of materials and their embodied life-cycle emissions and environmental impacts (depended mainly on city and population size):

Once the pipes are installed underground, it is difficult to access them, and maintenance or even replacement is difficult and expensive. Our model results show that the two realms - pipe maintenance and material stocks - can be separated in planning, as their respective domains lie at opposite ends of the network hierarchy. To facilitate maintenance, a sparser network with fewer, but thicker endpoint connections can drastically reduce network length and lower the need for maintenance of small diameter pipes. This can be achieved by focusing on apartment blocks rather than detached single family houses in city planning. Controlling and surveying the material stock, and with it the embodied emissions and mineral resources, can focus on the large diameter pipes which have a much shorter aggregated length than those pipes leading to the end-user. Although the entire network is spread over the whole catchment area, the largest masses are contained in the classes with the biggest pipes that contribute least to the overall network length. To obtain a sufficient understanding of these stocks and to allow for better material stock management it is therefore sufficient to track the material content of the trunk pipes with a diameter of more than 1m.

The mass model allows reflecting on an optimal city size seen from the perspective of networks with a centre. Given that urban planners have to decide whether to build one centralized network or to divide a new city or settlement into $n^2$ congruent rectangles, where n = 2,3,…, the total mass of the split network would be related to the mass of one single network according to:

$$M_{\text{split}} = n^2 \cdot \left( 7 \cdot \left( \frac{P}{n^2} \right)^{0.64} \cdot \frac{L_0}{n} \right) = \frac{1}{n^{0.28}} \cdot M_{\text{single}}, \quad n = 2, 3, ... \qquad (0.8)$$

This result can be understood from Fig. 1 where a division of the city into different catchments would mean that the highest network hierarchies are taken out of the system, resulting in a significant mass reduction. The overall length almost remains unchanged. From a mass perspective, decentralized systems are preferable as they may allow for significantly lower material stocks in pipelines. Contrary to that, a small number of large treatment plants may be cheaper to operate than many small ones and may show economies of scale regarding energy and material use (Maurer 2009). This fact counteracts the tendency towards smaller catchments driven by the material and capital intensity of large pipes and tunnels. We postulate that both from an economic and material point of view, there is an optimal catchment size that may require division of a mega-city onto several networks that may be only loosely connected.

Approximating the properties of such a sophisticated structure as urban networks just from some coarse data on the city implies large uncertainties. For wastewater, almost 25% of the sample variance cannot be related to the population or network size whereas for water, it is only about 10%. The assumption of uniform spatial distribution of network clients clearly represents a limit to accuracy, as in practice, cities are rather non-homogeneous structures with residential, commercial, industrial, and recreational areas, each requiring different network services. A network model that combines the service need and density of different settlement types as presented e.g. in Deilmann (2009) with a detailed map may help to identify how a more cost and material efficient network may look like. To determine the network mass with the given model, one has to rely on diameter estimates that enter the mass equation with a power greater than one. The assumption of a constant, hypothetical diameter on the level of the individual person, which is employed in this paper, can be replaced by carrying out a more detailed study on the diameter on different network levels.

The results enable one to estimate the number total length of the entire water and wastewater pipeline network of a city of any population and population density. A first estimate on how the total network mass scales with population and city size could be given. The proposed model allows urban planners to determine the direct impact of the shape of the city and structure of settlements on the network length and material stocks; and the indirect influence on pipeline network lengths and masses, such as future maintenance costs and emissions necessitated upstream to build up these stocks. This model could become a building block in the assessment of urban mines in existing cities and for assessing material demand and associated emissions for new urban structures.

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