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Article — Accepted Manuscript (Postprint) Cost and productivity effects of demographic changes on local water service

Utilities Policy

Provided in Cooperation with: German Institute for Economic Research (DIW Berlin)

Suggested Citation: Cullmann, Astrid; Stiel, Caroline (2022) : Cost and productivity effects of demographic changes on local water service, Utilities Policy, ISSN 1878-4356, Elsevier, Amsterdam, Vol. 79, pp. 1-35, https://doi.org/10.1016/j.jup.2022.101435

This Version is available at: https://hdl.handle.net/10419/307396

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This is the **postprint** of an article published in Utilities Policy 79 (2022), 101435, 17 S., available online at: https://doi.org/10.1016/j.jup.2022.101435

Cost and Productivity Effects of Demographic Changes on Local Water Service

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Abstract. We investigate the impact of demographic changes on local public services taking the case of water service. We apply a structural production function approach to a large panel of German water utilities between 2003 and 2014. Exploring variation of population density and the population age structure across service areas and over time, we provide evidence that demographics and their changes significantly affect the utilities' productivity and costs. We find that demographic changes cause significant cost increases in rapidly shrinking and ageing regions. Our results provide important policy implications regarding the prevention of growing regional disparities in public services.

JEL Classification: L95, R11, D24, L32

5 a.

Keywords: water service, demographic change, productivity growth, public service provision, costs structure

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1. Introduction

In many developed countries, demographic changes, like population decline, population ageing, and intra-country migration movements, profoundly alter the population structure (Hans et al., 2016; Martinez-Fernandez et al., 2012). When demographics are considered, the debate centres on macroeconomic trends, with extensive theoretical and empirical work documenting the implications of demographic change for macroeconomic performance.³ The microeconomic perspective of the demographic trends' implications for firms' supply is relatively neglected.

Utilities providing local public services, such as electricity, natural gas, and drinking water or wastewater disposal, are particularly vulnerable to demographic changes. These industries are characterised by a capital-intensive production process with large-scale infrastructure having service lives of up to 80 years. The lengthy lifecycle of the technical infrastructure, together with universal service obligations, preclude immediate adjustments to changing population patterns and demand changes. We take the drinking water sector as an example and empirically investigate whether and to what extent water utilities are affected by demographics. By means of a structural production function model, we quantify the impact of population density and age structure and their respective trends on water utilities' production, productivity growth, and costs.

The link between demographics and drinking water service has been studied in the literature. Empirical studies focusing on the link between population density and utilities' drinking water service show that population density affects utilities' productivity and costs (see, e.g., Guerrini et al., 2018; Filippini et al., 2008; Antonioli and Filippini, 2001, in the efficiency analysis context). Another stream in the literature studying the link between population age and water demand obtains inconclusive results (Nauges and Thomas, 2000; Martinez-Espiñeira, 2002; Arbués et al., 2010; Lyman, 1992; Mazzanti and Montini, 2006; Koegst et al., 2008). The empirical literature considers population density from a static perspective, analysing productivity and costs under the current demographic situation and ignoring dynamics in the demographic structure. Furthermore, the analyses remain limited to population density, and little attention has been paid to the influence of population age. This analysis aims to understand how both facets of demographics, population density and population age structure, affect utilities' supply, taking into account the dynamic implications of demographic changes. We specifically ask three questions:

1. To what extent is water service affected by the current population density and population age structure (*the demographic status quo*)?

2. Is firm-level productivity growth affected by changes in population density and population age structure (*the demographic change*)?

3. To what extent are firm-level fixed and marginal costs affected by those demographic changes?

³ Aksoy et al. (2019) investigate the effect of changes in demographic structure on longer term macroeconomic trends. Liao (2011) study the link between demographic transition and economic growth, while Bielecki et al. (2020) investigate the impact of demographics on the natural interest rate in the Euro area. Feyrer (2007) analyze the relationship between workforce age composition and productivity growth, whereas Jaimovich and Siu (2009) and Mennuni (2019) explore the consequences of demographic change for business cycle analysis. Chadwick et al. (2015) and Ge et al. (2018) study how demographic variation affects savings in China.

We quantify the impact of the demographic status quo and demographic changes on production, productivity growth, and costs by means of a structural production function framework following Olley and Pakes (1996) and Ackerberg et al. (2015). This model allows us, first, to model demand structure changes as a consequence of demographic changes and second, to determine firm-level productivity growth and marginal costs of production. This framework has been applied to different empirical problems.⁴ Our production model includes four inputs (labour, capital, external services and intermediate goods) to produce water as output. Drinking water service heavily depends on local environmental factors (such as geology, topography, water sources, and climate) that affect each firm's input. Our unique data set allows us to control for the production environment heterogeneity to disentangle the impact of demographics from other environmental factors that influence production.

The empirical analysis is based on a unique and extensive panel data set for Germany, including 751 municipally owned water utilities observed between 2003 and 2014. In Germany, water utilities are locally organised and usually operate in the area of the owning municipality. Thus, demand is given by the demand of the local population living within the municipality and utilities are affected by the respective demographic situation of the municipalities. Germany is particularly well suited for the analysis as it has faced fundamental changes in demographics and demographic trends differ remarkably between regions.⁵ We exploit this cross-sectional heterogeneity and the variation over time to identify the impact of demographics and demographic changes on water utilities.

There are four main results from the empirical analysis. First, the current demographic structure with regard to population density and population age affects the supply of drinking water. The more densely settled an area is and the higher the share of children under 18 in the local population, the higher is the demand for water. Second, demographic changes affect the water utilities' productivity, but the effect differs between growing and shrinking regions, highlighting the regional differences. We note a positive productivity effect from an increase in population density in growing regions, whereas there is a negative productivity effect in shrinking regions. Third, regions that are affected by demographic changes are faced with substantial short-term cost increases, especially since the rise in marginal costs is accompanied by a rise in unit fixed costs as fixed costs must be borne by fewer customers. Fourth, our results suggest that changes in the household composition play an important role in explaining increases in the cost of drinking water service triggered by demographic changes. It is not just the number of persons living in the service area that matters to the water utility but who lives there in terms of age as an (imperfect) proxy of consumption patterns.

The results have important policy implications. The productivity decreases and cost increases in shrinking and aging regions could result in higher prices for the provision of water as a public service and, therefore, would lead to increasing regional disparities in water tariffs (Hellwig and Polk, 2021; Destatis, 2014). In 2013, German water tariffs differed by up to 79 per cent between municipalities, with several depopulated East German regions being among the most expensive ones. The growing disparities in the prices and quality of local public services fuel a political debate about the decoupling

⁴ De Loecker et al. (2016), De Loecker (2011a), Pavcnik (2002) study the effects of trade liberalization, Doraszelski and Jaumandreu (2013), Aw et al. (2011) the returns to R&D investments, Richter and Schiersch (2017) analyse the CO2 emission intensity of exporting firms, and Stiel (2022), Stiel et al. (2018) examine the ownership composition in (public) utilities. Syverson (2011) gives a broader overview.

⁵ The number of inhabitants living in large cities throughout Germany increased by 1.4 million between 2005 and 2015 (BBR, 2017). In the same time period, half of the peripherally located municipalities in the former German Democratic Republic (GDR) lost more than 10 percent of their population compared to 8.1 percent of the municipalities in western Germany. We also note fundamental changes in the population age structure. The median age increased from 37 in 1990 to 45 in 2013; by 2060, 33 percent of the population is expected to be 65 or older (Destatis, 2015a)

of living standards in peripheral regions from those in urban agglomerations. Thus, quantifying the influence of the demographic situation and its changes on public services is useful for governments' strategic decision-making, i.e., for choosing between tariff subsidies, tariff restructuring and financial subsidies for infrastructure adjustment in declining regions (Barraqué, 2020; Crase et al., 2020).⁶

The organisation of this article is as follows: The next section discusses the theoretical background and derives hypotheses. Section 3 presents the population demographics data as well as the firm-level data on water utilities and summarises first descriptive statistics. Section 4, describing the econometric model, explains our strategy to estimate firm level productivity growth and marginal costs of production. Section 5 discusses our results whereas Section 6 concludes.

2. Literature and hypotheses

The productivity and cost efficiency of local utilities is of long-standing interest to scholars because of the natural monopolies in the technical infrastructure and the public interest in service provision (Baumol, 1977; Panzar and Willig, 1977; Sappington and Stiglitz, 1987). In these markets, relative firm productivity cannot easily be determined through comparisons with competitors, while public interests sometimes collide with the goal of profit maximization, all resulting in implications for firm productivity and cost efficiency. Consequently, an abundant literature has emerged with theoretical considerations on the optimal structure and regulation of these firms (Vickers and Yarrow, 1988; Estrin and Pérotin, 1991; Pint, 1991; Laffont and Tirole, 1991; Vining and Boardman,1992; Shleifer and Vishny, 1994; Hood, 1995; Schmidt, 1996; Shleifer, 1998); these are accompanied by empirical investigations into firm productivity and cost efficiency (Byrnes et al., 1986; Atkinson and Halvorsen, 1986; Sing, 1987; Hjalmarsson and Veiderpass, 1992; Kwoka, 2006; Farsi et al., 2008; Farsi and Filippini, 2009; Florio, 2013; Stiel et al., 2018; Stiel, 2022). A key issue in this context is which factors influence productivity and, in particular, which factors are endogenous to the firm (e.g., managerial slack) and which factors are rooted in the production environment, potentially justifying higher output prices.

The literature identifies population demographics as exogenous determinants of firm productivity and costs since universal service obligations require utilities to connect and serve all consumers in the respective service area, regardless of profitability. Since the supply of utilities is heavily dependent on technical infrastructure, which is not proportional to the number of customers, utilities in urban regions benefit from economies of density. Consequently, studies find that utilities in densely populated areas are more productive and have lower costs (Guerrini et al., 2018; Filippini et al., 2008; Antonioli and Filippini, 2001). Therefore, our first hypothesis is

Hypothesis 1. *Firm-level productivity is higher in densely populated regions than in sparsely populated regions.*

Existing empirical literature considers population density from a static perspective, analysing productivity and costs under the current demographic situation and ignoring any dynamic implications from changes in the demographic structure. However, changes in the population structure can pose considerable problems for water utilities. The main challenge for the water utilities is the long service

⁶ The costs of adjusting technical infrastructure to changing demographics are high. For Germany, for instance, the adjustment costs of municipal infrastructure to changing demographics are estimated to equal 25 billion EUR within 5 years, amounting to 20 percent of total investment plans (Köller, 2013).

life of the infrastructure and the universal service obligation, which results in an extreme inflexibility to adapt the infrastructure to changing demand. The fixed costs deriving from the pipe networks and pumping stations, as well as from the maintenance work must be borne by fewer customers and total factor productivity as a measure of output (water) delivered in relation to input usage might decrease. Therefore, we formulate the following hypothesis.

Hypothesis 2a. *Firm-level productivity decreases and fixed unit costs increase if population density decreases.*

In addition, another problem occurs that is very specific to water service. Not only do water utilities in a shrinking region have inefficient infrastructure, but the under-utilisation of this infrastructure also leads to additional input requirements to prevent sedimentation and nucleation. As a result, water utilities must also increase their variable input use (e.g., additional flushing), which further reduces their productivity. Total fixed costs remain unchanged, but marginal costs of production increase.

Hypothesis 2b. *Firm-level marginal costs increase if population density decreases.*

Another stream in the literature, focusing on individual water demand over the lifecycle, studies the link between population age and water demand. These studies hypothesize that families with children have a higher per-capita demand as they consume more water for washing, cleaning, and laundering, while elderly persons consume less water than average. However, empirical evidence is ambiguous. Nauges and Thomas (2000), Martinez-Espiñeira (2002), and Arbués et al. (2010) find that water demand decreases with age; Lyman (1992) suggests a U-shaped demand curve over a person's life, with children's per capita consumption being the highest; and Mazzanti and Montini (2006) and Koegst et al. (2008) find no difference in water demand by age group. We retain the original hypothesis.

Hypothesis 3a. *Firm-level productivity is higher in regions with a younger population than in regions with an older population.*

To our knowledge, no existing study combines both strands of the literature – the firm-level perspective and individual consumer behaviour – to study the influence of population age on water utilities' productivity and costs. We investigate to what extent changes in the population age structure affect the utilities' productivity and costs. If water demand declines with age, population ageing will have similar effects to that of depopulation on productivity and marginal costs, while unit fixed costs should remain the same since the total number of customers does not change.

Hypothesis 3b. Firm-level productivity decreases and marginal costs of production increase with population ageing, whereas unit fixed costs remain unaffected.

The effects in growing regions are less clear. *A priori*, we expect increasing population density to positively affect productivity and to reduce the level of unit fixed costs. However, population growth might also create needs for additional investments into infrastructure (e.g., more mains and connection points), therefore, preventing fixed unit costs from decreasing in the short term.

Hypothesis 4. Firm-level productivity increases and fixed unit costs weakly decrease if population density increases.

Population ageing will have the same detrimental effect in growing regions as in shrinking regions. However, the reduced demand by population ageing could be offset by increasing demand through population growth. Hence, it is very likely that we observe no effect or weak effects in growing regions as these two effects – from population growth and population ageing – intertwine.

3. Data

3.1. Demographics

German water utilities usually operate in the area of the owning municipality and therefore are affected by demographics within the municipality. We analyse two different facets of demographics in the service areas, the population density and age structure and use official regional data at the municipal level from the databases *Regionaldatenbank Deutschland* and *Statistik Lokal*. Further information on the different datasets is given in Appendix A.3.

3.1.1. Population density

We approximate the population density D_{it}^p in the water service area by the population density of the municipality where the water utility is located. The water service areas in our sample have an average population density of 393 inhabitants per km2, which corresponds to *suburban regions* in the classification of the Federal Institute for Research on Building, Urban Affairs, and Spatial Development (Milbert and Krischausky, 2012). The sample includes sparsely populated rural areas with less than 43 inhabitants/km2 and cities with more than 2,032 inhabitants/km2. Table 1 lists the summary statistics.

	q1	q25	med	mean	q75	q99	sd	N[≠0]	Ν
population density									
levels [inhabitants/km²]	43	153	283	393	494	2,032	388	5,770	5,770
growth [%]	-2.87	58	06	29	.46	2.43	4.58	5,733	5,770
share under 18 years									
levels [%]	12	17	18	18	20	24	2	5,770	5,770
growth [%]	-1.12	46	29	28	11	.70	.37	5,770	5,770
share above 60 years									
levels [%]	18	23	25	26	28	36	4	5,770	5,770
growth [%]	70	.11	.32	.32	.53	1.35	.49	5,769	5,770
share household supply	.20	.77	.86	.83	.92	1.00	.14	5 <i>,</i> 099	5,770
Pearson's r between levels and growth		са	$or(D_{it}^p, \Delta D_{it}^p)$)	сот	$C(D_{it}^{18},\Delta D_{i}^{18})$	$\binom{18}{t}$	$cor(D_{it}^{60})$	$^{0},\Delta \mathrm{D}_{it}^{60})$
		.06				13		.1	.4

Table 1: Summary statistics demographics

Notes: Summary statistics for "share household supply" show the proportion of household supply $[m^3]$ in total endconsumer supply $[m^3]$ for the subset of utilities that supply households. 671 utilities do not supply households. The rows "share under 18 years/above 60 years" show summary statistics on the proportion of the respective age group in the local population. The column N[\neq 0] lists the number of utilities with positive shares and non-zero growth rates.

To analyse the population density changes we calculate the annual growth rate of population density ΔD_{ir}^p from

$$\Delta D_{it}^{p} = \frac{D_{it}^{p} - D_{it-1}^{p}}{D_{it-1}^{p}} \quad . \quad (1)$$

It is negative with a median of -0.06 per cent. In other words, most water service areas face declining population rates, with their water mains potentially being affected by under-utilisation. The distribution's tails include fast-growing and fast-shrinking municipalities, with an annual rate of +/- 2.5 per cent (Table 1, second row). While 2.5 per cent appears to be small for a single year, these amounts lead to cumulative rates of +28/-22 per cent within ten years. These effects on the settlement structure can be significant, especially for shrinking regions. However, high growth rates can also create substantial challenges for the respective regions.⁷

Furthermore, Table 1 shows that, for half of the utilities, households account for more than 86 per cent of the supply to end-consumers, thus highlighting the importance of household deliveries in end-consumer supply and the vulnerability of local water utilities to demographic changes. Households constitute the largest customer group for 95 per cent of the utilities; three out of four utilities sell more than 77 per cent of their end-consumer supply to households.⁸ Their other end-consumers are businesses and industry (manufacturing, energy supply). However, industry customers play a minor role since they meet 92 per cent of their water demand through own production (Destatis, 2016).

Figure 1 maps the population density growth in all German municipalities between 2003 and 2014. Two aspects are particularly clear: first, regions in the former GDR in the east of Germany are particularly affected by depopulation and, second, it is common to find growing regions coexisting next to shrinking regions, especially in the western parts of Germany. There are several explanations for the latter. During the suburbanisation trend in the second half of the 20th century, sparsely populated areas surrounding larger cities began to grow, while densely populated cities lost inhabitants (Wiechmann and Pallagst, 2012; Adam, 2002). Likewise, two equally populated districts close to each other can start to diverge following changes in local employment opportunities. Local disparities are one of the key characteristics of German intra-country migration movements and we exploit this heterogeneity between municipalities in the empirical analysis to identify the impact of demographic changes on locally operating water utilities.

⁷ For instance, the city of Berlin, which has been growing at an annual rate of 1.3 percent between 2010 and 2017, is struggling to accommodate a yearly surplus of 40,000 inhabitants.

⁸ Table 1 does not show the results for the q5 and q25-quantile.

Figure 1: Population density growth in German municipalities between 2003 and 2014



Population data: Destatis 2003-2014 (own calculations) Geographical data: © GeoBasis-DE / BKG 2018

Notes:

Population growth data for the municipalities in the state Saxony (2008-2014), Saxony-Anhalt (2007-2014), and Mecklenburg-Western Pommerania (2011-2014) are only available for shorter time periods.

The last row in Table 1 lists the correlation rates between levels D_{it} and growth rates ΔD_{it} , showing that demographic changes are unrelated to the initial situation, e.g., towns can shrink and rural municipalities can grow, or *vice versa*, confirming the pattern of local disparities revealed in Figure 1. Thus, to examine more systematically heterogeneous trends between regions, we define two region types: growing regions and shrinking regions. Growing regions are water service areas where the overall change in population density between 2003 and 2014 was positive, whereas shrinking regions saw an overall reduction in population density over this period. Table 2 compares their demographic situation. In line with the overall figures for Germany, there are slightly more shrinking regions in our sample than growing regions, and the population density in shrinking regions on average fell faster (-0.8 per cent per year) than it increased in growing regions (0.3 per cent). The population decline in shrinking regions is reinforced by its population ageing faster than that in growing regions. Growing regions are primarily found in suburban or urban agglomerations (78 per cent), whereas 42 per cent of the shrinking regions are located in rural parts of the country. Further, shrinking regions are more often found in the east of Germany than in western Germany.

	growing regions	shrinking regions
	(mean)	(mean)
annual population density growth [%]	3	8
annual growth share young [%]	2	3
annual growth share old [%]	.3	.4
share urban	.03	.01
share suburban	.75	.58
share rural dense	.18	.23
share rural sparse	.05	.19
share Eastern Germany	.03	.12
% of all regions	.47	.53

Table 2: Characteristics of growing and shrinking regions

3.1.2. Age composition

We analyse the changes in the population age structure for all German municipalities between 2003 and 2014. We distinguish three age groups in the underlying dataset: children under 18, adults between 18 and 60 years, and elderly people 61 and older. Figures 2 and 3 illustrate the changes in the population age structure for all German municipalities between 2008 and 2014.⁹

The share of elderly persons in the total population has increased across Germany, with dynamics being particularly pronounced in the Eastern *Bundesländer* of Germany, i.e., in the former GDR (see Figure 2). We observe a diverging trend for the share of children, with an increase in the Eastern *Bundesländer* since 2008 against a negative trend in the Western *Bundesländer* (see Figure 3). However, we note a recent turnaround in the population trend: since 2013, the number of children under 18 is increasing again in the west. The early positive trend in the east is actually a catch-up process after the reunification shock, when birth rates dropped dramatically, leading to a share of children in the total population around 13 per cent in 2008 against the German average of 16 per cent. Note that the catch-up process in the east takes place despite an overall negative trend in population growth, whereas the aggregate population growth for the western *Bundesländer* is positive. However, the overall process of population ageing is not reversed: the growth of the elderly population outweighs the growth of the young population (compare Figures 2 and 3).

⁹ Due to territorial reforms in the Eastern *Bundesländer* of Germany in 2007, 2008, and 2011, a comparison with the years before 2008 is difficult to represent geographically.

Figure 2: Changes in the share of the population older than 60 years in German municipalities between 2008 and 2014



Population data: Destatis 2008-2014 (own calculations) Geographical data: © GeoBasis-DE / BKG 2018

Notes:

In the empirical analysis, we consider the share of children and elderly persons in the municipality's total population against adults of 18 to 60 years as a reference group. This approach allows us to model changes in the age composition in greater detail (instead of relying, for instance, on the median age) and to model heterogeneous water consumption patterns over a person's life cycle. Looking at our sample of water service areas, Table 1, rows 3 and 5 show that, on average, 26 per cent of the inhabitants in the water service areas are older than 60 and 18 per cent are younger than 18. We compute yearly growth rates by subtracting the past year's share D_{it-1}^{18} from the current share D_{it}^{18} to obtain

Due to a territorial reform in 2011, data on changes in the population age structure for the municipalities in the state Mecklenburg-Western Pommerania are only available for 2011 to 2014.

$$\Delta D_{it}^{18} = D_{it}^{18} - D_{it-1}^{18} \quad (2)$$

$$\Delta D_{it}^{60} = D_{it}^{60} - D_{it-1}^{60} \quad . \quad (3)$$

In line with the general trend of population ageing in Germany, the share of younger inhabitants is decreasing in the majority of the water service areas in our sample between 2003 and 2014, whereas the share of older inhabitants is increasing (Table 1, rows 4 and 6).

Figure 3: Changes in the share of the population younger than 18 years in German municipalities between 2008 and 2014



Population data: Destatis 2008-2014 (own calculations) Geographical data: © GeoBasis-DE / BKG 2018

Notes:

Due to a territorial reform in 2011, data on changes in the population age structure for the municipalities in the state Mecklenburg-Western Pommerania are only available for 2011 to 2014.

3.2. Data on water utilities

In Germany, water service is provided by a public or privately managed water utility with monopoly rights (Cullmann et al., 2019). The production process includes raw water abstraction and treatment, the transmission of treated water, and the final distribution of drinking water to end consumers. German water utilities usually own some raw water abstraction facilities but also purchase treated water from pure bulk water supply firms and other water utilities. Some are horizontally integrated into larger public utilities that supply natural gas, electricity, or heat. Most of the water utilities are publicly owned: in 2019, 91 per cent of potable water in Germany was supplied by municipally owned utilities (VKU, 2021). As in other countries, Germany's water service is capital-intensive with large-scale infrastructures. Most of this infrastructure has a service life of up to 80 years, with capital costs associated with depreciation and replacement investment. Other costs include labour for operations and maintenance as well as materials and supplies (e.g., energy, bulk water, and chemicals for water purification). Both capital and personnel costs are considered fixed costs in the short term, i.e., costs unrelated to the amount of water sold, resulting in a fixed cost share of 70 per cent of total costs on average (Destatis, 2017). Local taxation policies may incur different water extraction and concession fees.

We consider a sample of 751 German municipally owned water utilities, observed between 2003 and 2014 (N=5,770).¹⁰ Ensuring the comparability of the water utilities in the sample, we restrict our sample to single product utilities that deliver water and have no other activities such as energy provision or sewerage. We neglect bulk water supply firms without deliveries to end-consumers.

We obtain firm-level data on input usage, output supplied, and costs from two official datasets collected by the German Federal Statistical Office: the newly available dataset *Energiestatistiken* on energy and water utilities, and the financial statements of public firms *Jahresabschlüsse öffentlicher Fonds, Einrichtungen, und Unternehmen.* We merge them with physical data on raw water usage, river basin location, and customer structure obtained from the *Statistik über die öffentliche Wasserversorgung.* Since the latter survey is only conducted on a three-year-interval (2004, 2007, 2010, 2013), we compute the mean values for water sources, river basin location, and customer structure over the whole observation period 2003 to 2014. We obtain data on the service areas, including land use and demographics, for each year from official regional data at the municipal level in the databases *Regionaldatenbank Deutschland* and *Statistik Lokal.* Further information on the different datasets is given in Appendix A.3.

3.2.1. Utilities' inputs and output

The utilities use four inputs to produce water Q_{it} , measured in cubic meters: labour L_{it} , measured by the wage bill, which is deflated by the German index of labour costs in the water and sewerage industry (NACE category E); external services S_{it} , measured by expenditure and deflated by the German PPI for technical services (NACE category M); intermediate goods M_{it} , composed of material expenditure and bulk water purchases and deflated by the German PPI of intermediate goods; and capital K_{it} . We construct a measure for capital from information on investments and the capital stock using the perpetual inventory method with $K_{it} = (1 - \delta_i)K_{it-1} + I_{it}$. We compute the depreciation rate δ_i as the consumption of fixed capital over fixed gross capital and averaged across all years for each firm i.

¹⁰ The lack of adequate data source precludes us from considering water utilities that are majority-owned by the private sector. However, we do include utilities in mixed ownership with private minority shares, which comprise about 5 percent of the utilities in the German water sector (Stiel, 2022). Since more than 90 percent of the water delivered in Germany is supplied by municipally owned utilities, it should not constitute a major restriction.

Yearly investments and the capital stock are deflated with the German PPI for investment goods. Table 3 lists the summary statistics for the whole sample.

	q1	q25	med	mean	q75	q99	sd
labour, L [mio €]	.00	.09	.21	.63	.49	6.74	1.43
external services, S [mio €]	.00	.08	.16	.43	.34	5.82	1.12
intermediate goods, M [mio €]	.02	.11	.24	.55	.50	6.50	1.22
capital, K [mio €]	.98	3.66	6.66	14.16	13.59	148.84	27.02
water, Q [mio m³]	.21	.42	.66	1.61	1.31	16.00	4.28
N				5,770			

Table 3: Summary statistics: inputs and output

3.2.2. Utilities' structure and production environment

Drinking water service depends heavily on environmental factors such as geology, topography, the local availability of water sources, raw water composition, and climate (Crase et al., 2020; Abbott and Cohen, 2009). While the general process technology, i.e., raw water abstraction, treatment, storage, distribution through pipelines, is identical, local environmental conditions affect each firm's input usage. For example, the operation of water networks in mountainous regions requires more pumping facilities and energy input to confront shifts in altitude, while regions with intensive farming or mining require specialised water treatment to eliminate residues such as sulphate and nitrate. Under the assumption of no self-selection into locations,¹¹ production conditions are exogenous to the utilities. They are usually unknown to the researcher, but ignoring them leads to biased productivity scores, where managerial productivity is confused with differences in exogenous production characteristics. Therefore, it is necessary to control for the production environment as accurately as possible to disentangle the impact of demographics from other environmental factors that influence production. We use a set of observable characteristics to proxy for the production environment, controlling for raw water composition, river basin location, topography, and altitude.

Table 4 lists the topographic characteristics in the municipalities where the utilities are located. On average, 41 per cent of the areas are farmland, potentially influencing the quality of groundwater sources, and about 2 per cent are covered with surface water. The mean altitude is 284 m above sea level, ranging from below 7m to above 809m (not listed).

	med	mean	sd
share residential and infrastructure area	.17	.19	.10
share forest	.29	.31	.18
share water	.01	.02	.03
share agriculture	.41	.41	.20
altitude [m]	249	284	181
N	5,770		

Table 4: Summary statistics topography in supply areas

Most water utilities are vertically integrated and serve all steps of the supply chain from water extraction to distribution to end-consumers. However, some utilities purchase water from third parties

¹¹ We focus on municipally owned utilities, which usually operate in the area of the owning municipality.

and sell bulk water to neighbouring utilities.¹² The degree of vertical integration and own bulk water supply activities affect the choice of inputs, particularly capital. External procurement requires less extraction and treatment facilities, whereas bulk water supply is more capital-intensive. To account for the importance of water extraction in the firm's production portfolio, we consider the share of external procurement and the production of bulk water in total supply. Tables 5 and 6 summarise the utilities' vertical structure and the firm's water supply sources. About 73 per cent of the utilities source water externally, of which 30 per cent rely entirely on external sources and 43 per cent complement internal water abstraction with external sources. Considering utilities with own water abstraction facilities, Table 5 shows that 41 per cent produce more water than they need and sell the excess to other utilities. Among them, the share of wholesale supply in total supply accounts for 24 per cent on average, but the median value is only 9 per cent, i.e., wholesale activities are negligible for the majority of these utilities.

	med	mean	sd	N[>0]	Ν
utilities using external sources				4,217	5,770
share water from external sources	.53	.52	.40		
utilities active in wholesale				1,915	5,770
share wholesale in total output	.09	.24	.32		

Table 5: Summary statistics: utilities' vertical structure

Notes: Summary statistics for the subset of utilities with positive shares, N[>0] is the number of utilities with positive shares. A total of 1,553 utilities do not source water externally, and 3,855 utilities do not pursue wholesale activities. The share of water from external sources is defined as water from external sources $[m^3]$ over total water input $[m^3]$. The share of wholesale in total output is computed from water supplied to other water utilities $[m^3]$ over total water supplied $[m^3]$.

The European Union's water framework directive 2000/60/EC defines the river basin districts corresponding to the drainage basins of the main European rivers and coastal areas. The river basin districts differ in their hydrological conditions, which determine the availability of raw water sources for water utilities. Table 6 reports that 67 per cent of the water utilities in our sample are in the Rhine river basin, and 16 per cent are in the Danube river basin. We group the smaller number of utilities in the Oder basin and at the coast with those in the adjacent Elbe basin.

The source of raw water determines the technology required for abstraction, transportation, and treatment. Data on the composition of raw water sources for own water abstraction are available but not for external sourcing. Groundwater is the most important raw water source for own abstraction, with an average share of 81 per cent in total abstraction (Table 6). More than 50 per cent of the utilities rely entirely on groundwater sources. Although spring water collection accounts for 9 per cent of raw water abstraction in Germany (Destatis, 2015b), 36 per cent of the utilities collect it.

¹² There are also bulk-water-only supply firms, which usually operate at the regional level and provide treated water to several utilities. Due to different scale and focus, pure bulk-water supply firms, which do not distribute water to end-consumers, are not considered in this study.

	med	mean	sd	N[>0]	Ν
raw water consumption					
share groundwater	1.00	.81	.28	3,548	5,770
share spring water	.51	.53	.36	2,054	5,770
no internal sources					1,661
river basin location				_	share
Danube				_	.16
Rhine					.67
Ems					.02
Weser					.06
Elbe, Oder, coast					.09

Table 6: Summary statistics: utilities' water supply sources

Notes: Notes: Summary statistics for the subset of utilities with positive shares, N[>0] is the number of utilities with positive shares. Raw water composition is only available for utilities with own pumping activities (internal sources).

4. Econometric model and estimation strategy

In this section, we set up a structural production model for the water service sector. This model allows us to determine the total factor productivity and the marginal costs of production. We follow the control function approach of Olley and Pakes (1996) and Ackerberg et al. (2015), assuming that productivity, as a residual to the production function, can be expressed by a set of observables through a control function. Furthermore, the control function approach allows for measuring the impact of endogenous and exogenous factors on productivity growth, which we exploit to analyse the productivity effect of demographic changes.

4.1. Production

Assume that water utility *i* at time *t* uses four inputs – capital K_{it} , labour L_{it} , intermediate goods (including bulk water) M_{it} , and external services S_{it} – to produce output \tilde{Q}_{it} . Furthermore, the firm's production depends on (unobserved)¹³ total factor productivity ω_{it} . We then obtain the production function

$$\tilde{Q}_{it} = F(K_{it}, L_{it}, M_{it}, S_{it}) \exp(\omega_{it} + \epsilon_{it})$$
(4)

where ϵ_{it} is a measurement error assumed to be *iid*. Assume that the intermediate goods, M_{it} , are a flexible, static input whose level can be adjusted in each period without adjustment costs.¹⁴ On the

¹³ Hereby we mean unobserved to the econometrician.

¹⁴ *Static* relates to timing, whereas *flexible* characterises the production technology. The distinction between static and dynamic describes the costs and, thus, the frequency at which the input can be adjusted. *Flexibility*, on the other hand, is the concept of divisibility, denoting the technical possibility of adjusting the input in proportion to changes in output. The distinction between static and dynamic inputs is important for the correct identification of parameters during the estimation process (Flynn, 2020). See Section A.1 in the Appendix for details.

other hand, capital, K_{it} , and labour, L_{it} , have dynamic implications such that current input levels are partially pre-determined through past input decisions. Investments into water facilities are long-term oriented, and Germany's strict union contracts in the public sector prevent immediate labour force adjustment. While contracts on external services, S_{it} , a priori can be renegotiated in each period, they are less flexible than intermediate goods: it is not possible to adjust the demand for external services in proportion to actual water output since some of the services are unrelated to water volumes, e.g., maintenance work of water pipelines.

Drinking water production depends heavily on environmental factors (see Section 3.2.2). We use four observable characteristics to proxy for the individual production environment: raw water composition, river basin location, topography and altitude, summarised in the vector X_{it} . As outlined in Section 3.2.2, the extent of vertical integration and own bulk water supply activities affect the choice of inputs, particularly capital. Therefore, we add two measures for the importance of water extraction in the firm's production process, controlling for the share of external procurement and the production of bulk water in total supply. For notational simplicity, we also include them in the vector X_{it} as follows:

$$\tilde{Q}_{it} = F(K_{it}, L_{it}, M_{it}, S_{it}) \exp(\omega_{it} + \gamma X_{it} + \epsilon_{it}).$$
(5)

We estimate the production function following the control function approach of Ackerberg et al. (2015), which was initially proposed by Olley and Pakes (1996). The advantage of this approach over other techniques is that it explicitly considers the possibility that firms observe their productivity level and choose inputs accordingly. We argue that one of the channels where demographic changes could affect firm-level productivity is through higher input requirements, e.g., additional flushings and chemicals to avoid nucleation of the oversized networks. Furthermore, there is good reason to believe that other components of total factor productivity (such as managerial ability and labour force skills) are known to the firm and taken into account when making input choices. The identification strategy exploits the fact that current shocks to productivity (e.g., demand shocks, weather conditions) immediately affect utilities' demand for a fully flexible, static input but not those of dynamic inputs, which react more slowly to productivity shocks, given the adjustment costs. The inverted input demand function of a flexible, static input can then be used to express productivity in terms of observables. Thus, we take into account that firm-level productivity may correlate with input choice, a well-known simultaneity problem that otherwise leads to biased estimates of the output elasticities (Mundlak and Hoch, 1965; Olley and Pakes, 1996; Levinsohn and Petrin, 2003; Wooldridge, 2009). Further details on the estimation procedure are given in Appendix A.1.

4.2. Costs structure

To assess the impact of demographic changes on the utilities' cost structure, we analyse changes in the fixed costs of production and the marginal costs of production. We define fixed costs as costs that arise regardless of the amount of water supplied, including capital costs (depreciation, interests), labour costs, expenditures for external services, and rents. Utilities' fixed costs are observed in the data. On the other hand, the marginal costs of production must be estimated. We model the marginal costs of production following De Loecker (2011b) and De Loecker and Warzynski (2012). The approach does not impose any assumptions on the specific demand system or long-term production technology.

Let all utilities determine their levels of intermediate inputs in a short-run cost minimisation problem, taking input prices and output at time t as given, and consider the Lagrangian function

$$\mathcal{L}(K_{it}, L_{it}, M_{it}, S_{it}, \lambda_{it}) = \varpi_{it}^k K_{it} + \varpi_{it}^l L_{it} + \varpi_{it}^m M_{it} + \varpi_{it}^s S_{it}, +\lambda_{it} (Q_{it} - Q_{it}(\cdot)), \quad (6)$$

where ϖ_{it}^X are the input prices. Note that the assumption of cost minimisation only concerns the choice of static, flexible inputs: dynamic decisions related to the production technology (capital) or staff composition and wages (labour) can deviate from cost minimisation, as public utilities may want to implement a specific public agenda. If $Q_{it}(\cdot)$ is continuous and twice differentiable, then the first order condition with respect to the intermediate goods M_{it} is given by

$$\frac{\delta \mathcal{L}_{it}}{\delta M_{it}} = \varpi_{it}^m - \lambda_{it} \frac{\delta Q_{it}(\cdot)}{\delta M_{it}} = 0 , \quad (7)$$

where $MC_{it} \equiv \lambda_{it}$ is the marginal cost of production at a given level of output. Define the output elasticity for the intermediate goods as

$$\theta_{it}^{m} \equiv \frac{\delta Q_{it}(\cdot) M_{it}}{\delta M_{it} Q_{it}} , \qquad (8)$$

Multiplying equation (7) by (M_{it}/Q_{it}) , we use the definition in (8) to obtain the following expression for marginal costs

$$MC_{it} = \frac{1}{\theta_{it}^m} \frac{\varpi_{it}^m M_{it}}{Q_{it}} .$$
 (9)

Since observed output in the data differs from the actual output by the measurement error ϵ_{it} , we adjust equation (9) with the estimate for the measurement error from the production function to obtain an estimate for firm-level marginal costs as

$$\widehat{MC}_{it} = \frac{1}{\widehat{\theta}_{it}^m} \frac{\varpi_{it}^m M_{it}}{Q_{it}/e^{\widehat{\epsilon}_{it}}} \quad . \quad (10)$$

The output elasticity of the intermediate goods can be calculated from

$$\hat{\theta}_{it}^m = \hat{\beta}_m + \hat{\beta}_{mm} m_{it} + \hat{\beta}_{km} k_{it} + \hat{\beta}_{lm} l_{it} + \hat{\beta}_{sm} s_{it} \qquad (11)$$

with the estimated coefficients of the production function. In summary, marginal costs depend on the expenditure for intermediate goods divided by firm output and the corresponding output elasticity.

4.3. Modelling the impact of demographics

We are interested in two aspects: the role that the demographic structure at a given point in time (the demographic status quo) plays in the provision of drinking water, as well as the effect of demographic *changes* on productivity growth and cost growth.

4.3.1. The demographic status quo

Water utilities usually operate in the area of the municipality that owns them with its water supplied depending on the local demographic structure. Given the local monopoly, the firm's customers correspond to the local population, with each member consuming an amount of water. For our purposes, water demand has two key components: (i) how much water is consumed and (ii) where it is consumed. Therefore, aggregate demand or the total amount of water supplied is determined by demographic factors such as the customer structure (e.g., the share of residential customers), the number of persons living in the municipality, and the population age structure. Secondly, the spatial distribution of demand matters, that is, how close connection points are to each other. Thus, the utility's production process is also influenced by the settlement structure and the geographical distribution of customers in the service area. Networks in urban areas tend to connect more people living closer together, providing economies of density to the urban utilities.

We call this static link between production and demographics the *status quo* and model heterogeneous demand patterns as an exogenous composite shock D_{it} to the current output level

$$Q_{it} = \tilde{Q}_{it} \exp(\boldsymbol{\eta} \boldsymbol{D}_{it}) \qquad (12)$$

where \tilde{Q}_{it} is the equilibrium output if all utilities operated under the same demand conditions and \tilde{Q}_{it} is the output realised under individual demand conditions. The term $\eta D_{it} = \eta_1 \log(D_{it}^p) + \eta_2 \log(D_{it}^{18}) + \eta_3 \log(D_{it}^{60}) + \eta_4 \log(D_i^h)$ controls for population density D_{it}^p , the share of inhabitants below age 18 D_{it}^{18} , the share of inhabitants above age 60 D_{it}^{60} , and the share of households in supply to end-consumers D_i^h as opposed to business and manufacturing consumers.

4.3.2. Demographic changes

Productivity growth The main interest of our article is to study what happens if the demographic situation *changes*. Demographic changes might affect firm-level productivity as utilities cannot immediately adapt dynamic input usage, i.e., capital or labour, to changes in demand. This challenge is particularly relevant in shrinking regions, where the long service life of the network infrastructure and treatment facilities, as well as the universal service obligations, prevent the utilities from dismantling pipelines and connection points even if the number of customers and, therefore, the amount of water consumption decreases. In the short term, firm-level productivity decreases as a measure of output (water) delivered relative to input usage. In addition, another problem, particular

to water service, arises. Not only does the water utility in a shrinking region dispose of inefficiently large infrastructure, but the under-utilisation of this infrastructure creates additional input requirements to prevent sedimentation and nucleation. Hence, the water utility must also increase its variable input use (e.g., additional flushings), further decreasing productivity while growing regions could benefit from increased capacity usage and higher productivity levels. More generally, when utilities are exposed to demographic changes, firm-level might increase or decrease. We consider recent changes in population density and changes in the age composition of the local population. To model this relationship, we assume deviations between the current level of firm-level productivity ω_{it} and its past year value ω_{it-1} can be potentially explained by changes in the population density ΔD_{it}^{18} , ΔD_{it}^{60} giving

$$\omega_{it} = g(\omega_{it-1}, \Delta D_{it}^{p}, \Delta D_{it}^{18}, \Delta D_{it}^{60}) + v_{it} \quad . \tag{13}$$

The productivity growth equation is estimated together with the production function (see Appendix A.1 for details).

Fixed costs Demographic changes directly affect unit fixed costs, i.e. fixed costs per capita or m^3 water sold, as the fixed costs of production will be distributed over more customers in growing regions and fewer customers in shrinking regions. Therefore, we will analyse the evolution of unit fixed costs in growing and shrinking regions in more detail using descriptive analysis.

Marginal costs Moreover, changes in demand due to demographic change may alter the input requirements of the intermediate goods – for instance, when additional flushings are needed to avoid sedimentation and nucleation in underused mains – which has direct implications for the marginal costs of production. To analyse the link between marginal costs and demographic changes, we regress marginal costs on changes in population density ΔD_{it}^p and in the population age structure ΔD_{it}^{18} , ΔD_{it}^{60} by

$$mc_{it} = \alpha_0 + \alpha_1 \,\Delta D_{it}^p + \,\alpha_2 \,\Delta D_{it}^{18} + \alpha_3 \,\Delta D_{it}^{60} + \mu_i + \,\mu_t + u_{it} \,, \qquad (14)$$

where mc_{it} are the log marginal costs and μ_i , μ_t denote firm and time fixed effects.¹⁵

5. Estimation results

5.1. Demographic status quo

We first consider the demographic status quo, i.e. the general link between water consumption and demographics. The results reported in Table 7 indicate that population density positively affects water service, although the coefficient for $log D_{it}^p$ is only weakly significant at the .07 p-level. It supports the general finding in the literature that population density matters, i.e., that water suppliers located in regions with higher population density sell more water than utilities located in sparsely populated

¹⁵ Note that the firm fixed effects include the demographic status quo, allowing us to disentangle the impact of demographic changes from static differences in demographic patterns, e.g., the water utility's location in a densely populated urban agglomeration.

regions, all other things being equal (hypothesis 1).¹⁶ Furthermore, we find that in regions with a one percentage point higher share of children under 18, water output is, *ceteris paribus*, three percentage points higher (hypothesis 3a). A possible reason could be that households with children use more water for washing machines and cleaning, which is in line with the findings in Arbués et al. (2010); Lyman (1992). We observe the negative relationship between elderly persons and water consumption suggested in Nauges and Thomas (2000); however, the coefficients are insignificant. The discussed parameters measure the effect of the status quo and explain differences in output levels according to the demographic characteristics in the water service areas. Provided the demographic conditions do not change, utilities can adapt to the demand structure in the long run and use their inputs as efficiently as possible *under the given demographic situation*.

Production		q_{it}	s.e.
log D ^p _{it}	population density	.054	(.029)
D_{it}^{18}	share young	2.939**	(.909)
D_{it}^{60}	share old	314	(.647)
	Ν	5,770	

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Notes: Notes: The coefficients for production are derived from estimating the specification given in equation (19), with blockbootstrapped standard errors in parentheses. P-values: 0 '***' 0.001 '**' 0.01 '*' 0.05.

5.2. Demographic changes

5.2.1. Productivity growth

Problems arise when the demand structure changes as a consequence of *demographic changes*. These changes can affect urban and rural regions and are, *a priori*, unrelated to the existing demographic pattern (see Section 3.1). Water utilities often have difficulties adapting to demographic changes over short time frames because of the long service life of their infrastructure equipment. As a result, two utilities operating under the same demographic conditions can have different productivity levels because one of the utilities experienced a recent demographic shock and struggles to adapt input usage to reduced output, whereas the other, which has been living with that same level of population density for a long time, has adjusted its water network accordingly.

Table 8 provides estimates for the impact of demographic changes on the water utilities' total factor productivity. A one percentage point increase in population density shifts productivity by .07 percent, confirming the positive correlation assumed in hypotheses 2a and 4. Given that the average growth rate in population density is -.3 percent (see Section 3.1), utilities experience an average annual decrease of .02 percent in total factor productivity resulting from changes in population density. The effect is pronounced for utilities in rapidly growing or shrinking regions at the tail of the distribution. With an absolute growth rate of 2.5 percent in population density, they experience hypothetical productivity shifts of around .2 percent within one year.

To explore whether the effect on productivity differs between growing and shrinking regions, we sort the utilities into two groups, based on the overall change in population density in their water service

¹⁶ A limitation of the ACF algorithm is the low efficiency of the block-bootstrapping of the standard errors. For comparison, the first column in Table 11 in the Appendix estimates equation (16) by OLS. The OLS point estimates of the coefficients are biased, but further support that population density matters.

area between 2003 and 2014, and estimate equation (13) again separately for each group (see columns (2) and (3) in Table 8). The results reveal asymmetry, as the positive productivity effect from an increase in population density in growing regions is 40 percent higher (coefficient of .089) than the negative productivity effect from declining population density in shrinking regions (coefficient of .063), suggesting that growing regions benefit relatively more from population growth than shrinking regions lose. It highlights the regional differences in productivity effects caused by demographic changes.

Regarding age composition, Table 8 shows that population ageing negatively impacts productivity, i.e., a one percentage point increase in the share of older adults reduces total factor productivity by .4 percent (hypothesis 3b). However, since the share of older adults grows at only .3 percentage points on average, the effect on total factor productivity is small. For utilities in rapidly ageing regions ($\Delta D_{it}^{60} = 1.35$), the annual productivity loss amounts to .5 percent.

Table 12 in the Appendix provides the results for estimating equation (13) as system GMM. The productivity effect from changes in population density is confirmed, but the share of older adults no longer significantly impacts productivity growth.

3)
1)
7)

Table 8: Productivity and demographic changes

Notes: The coefficients for production are derived from estimating the specification given in (19), with blockbootstrapped standard errors in parentheses. The coefficients for productivity are estimated according to equation (21), with WHITE standard errors given in parentheses. p-values: 0 '***' 0.001 '**' 0.01 '*' 0.05.

5.2.2. Evolution of fixed and marginal costs

We calculate the marginal costs of production for each water utility using equation (10). For the subsequent analysis, we discard negative marginal cost estimates and outliers beyond the .99-quantile.¹⁷ Furthermore, we report the evolution of average fixed costs per m³ sold.¹⁸ We compute average fixed costs per m³ and not per capita since we only observe the number of customers on a three-year interval.

Figure 4, showing the evolution of both cost types between 2004 and 2014¹⁹, provides evidence supporting hypotheses 2a and b. The deflated water service costs have increased over the years in all

 $^{^{17}}$ Negative marginal costs can arise mathematically for observations with a negative translog output elasticity of intermediate goods (see equation (10)). If another input (labour, capital, or external services) dominates the input bundle, the interaction terms in equation (11) can produce negative intermediate output elasticities given the negative estimates for β_{ls} , β_{ks} , and β_{ms} ; which are hard to interpret. This is the case for 6 percent of the observations.

¹⁸ Fixed costs are considered net of taxes and fees.

¹⁹ For comparison with the total factor productivity estimates, which are only available for 2004 to 2014, we let the marginal costs sample start in 2004.

regions. However, the marginal costs of production have increased much more in shrinking regions (11 per cent) than in growing regions (five per cent), while the unit fixed costs have increased in shrinking regions by 18 per cent but remained more or less stable in growing regions. The latter result might be surprising, as one would expect unit fixed costs to decrease with increasing consumption (see hypothesis 4). A possible explanation could be that adjustments to satisfy growing demand, e.g., additional mains and labour, raise fixed costs proportionally to population growth, at least in the short term.

Figure 5 zooms more closely into the two region types, comparing the cost levels of water suppliers in regions with different growth rates in population density. Plotting the median marginal cost level within eight quantiles of the total population growth distribution, Figure 5a shows that marginal costs are lower in growing regions and, more generally, seem to decrease along the population density growth distribution. A similar pattern holds for fixed costs per m³ sold (see Figure 5b). While the difference in marginal costs between fast shrinking and fast-growing regions lies around eight per cent, the unit fixed costs in fast-shrinking regions are almost twice as high (174 per cent) compared to fast-growing regions at the right tail of the distribution.



Figure 4: Evolution of costs between 2004 and 2014



Figure 5: Costs levels and total population density growth

Figures 4 and 5 do not control for differences in the production environment between service areas and do not provide information about how the different components of demographic changes (population density, population ageing) influence costs. To verify whether there is a statistically significant link between costs and population changes and to disentangle the strands of demographic changes, we regress marginal costs on changes in population density and the age structure according to equation (14). Table 9 lists the results. A one percentage point increase in population density decreases marginal costs on average by .2 per cent, confirming the negative correlation assumed in hypothesis 2b. The negative correlation is more pronounced in shrinking regions (.25 per cent) than in growing regions (.17 per cent), but only weakly significant (p=.07) in the case of shrinking regions and insignificant in the case of growing regions.

An increase in the share of children under 18 by one percentage point decreases marginal costs by four per cent. Note that the average annual growth rate of the young population is negative both in growing (-.2 per cent/a) and in shrinking regions (-.3 per cent/a, see Table 2). Therefore, the results suggest an opposite interpretation supporting hypothesis 3b. A decrease in the share of children causes marginal costs to rise because of underlying changes in the consumption patterns of households. Section 5.2.1 showed that water output positively correlates with the share of children under 18. Therefore, less water demand in oversized networks may effectively imply higher marginal costs resulting from the utilities' efforts to avoid nucleation. In rapidly ageing regions (ΔD_{it}^{18} = -1.12), the annual cost increase would amount to 4.5 per cent within one year.

		full sample		growing regions		shrinking regions	
		(1)		(2)		(3)	
margir	nal costs	mc _{it}		mc _{it}		mc _{it}	
ΔD_{it}^p	growth pop. dens.	225*	(.104)	177	(.143)	250	(.136)
ΔD_{it}^{18}	growth share young	-3.992***	(1.214)	-4.736*	(2.020)	-2.985*	(1.409)
ΔD_{it}^{60}	growth share old	2.325	(1.761)	-1.235	(1.524)	3.630	(2.357)
α_0	(Intercept)	4.855***	(.023)	4.858***	(.035)	4.856***	(.029)
μ_i	firm fixed effects	YES		YES		YES	
μ_t	time Fixed effects	YES		YES		YES	
	R^2	.01		.01		.01	
	Ν	4,350		2,053		2,297	

Table 9: Marginal costs and demographic changes

Notes: p-values: $0'^{***'} 0.001'^{**'} 0.01'^{*'} 0.05$. Bootstrapped standard errors clustered at the firm level with B = 2,000 replications.

The results in Table 9 suggest that demographic changes affect growing and shrinking regions heterogeneously, but the estimation is somewhat imprecise given the high standard errors. An alternative way to approach the issue is to analyse the magnitude of population effects for different levels of marginal costs, i.e., for different quantiles of the marginal-cost distribution. Applying the MM-QR estimator from Machado and Silva (2019), we compare the conditional effect of demographic changes on marginal costs for the .25 and .75 quantile of the marginal-cost distribution in Table 10. Table 13 in the Appendix provides more details for the .1, .3, .5, .7 and .9 quantiles. The impact of population density and the share of children on marginal costs increase along the marginal-cost distribution, even though the impact of population density is less precisely estimated at the right tail of the distribution (see Table 10, column (2)). This finding suggests two things: first, changes in the population age structure are an important criterion for assessing the vulnerability of regions to demographic changes and are more important than changes in the population number per se, especially in shrinking regions. Furthermore, cost increases from depopulation and population ageing are more relevant than cost savings from urbanisation and settling young families. The demographic changes considered tend to affect marginal costs negatively, confirming the asymmetry revealed in Figure 5 and the regression results for growing and shrinking regions.

			antile	.75-quantile				
		(1)	(2)				
margi	nal costs	mc _{it}		mc _{it}				
ΔD_{it}^p	growth pop. dens.	166**	(.066)	285	(.155)			
ΔD_{it}^{18}	growth share young	-3.159***	(.096)	-4.837**	(1.666)			
ΔD_{it}^{60}	growth share old	2.052	(1.507)	-2.604	(2.124)			
μ_i	firm fixed effects	YES		YES				
μ_t	time Fixed effects	YES		YES				
	Ν	4,350		4,350				
Notes	Notoc: p. valuec: 0 '***' 0 001 '**' 0 01 '*' 0 05							

Table 10: Regression for different quantiles of the marginal-cost distribution

Notes: p-values: 0 0.001 0.010.05.

5.3. Discussion and future research

When analysing the impact of demographics, a further interesting aspect is a decreasing household size trend observed across nearly all advanced economies (OECD, 2011). Arbués et al. (2004, 2010) and Domene and Saurí (2006) argue that each household has a minimum water demand (e.g., for domestic cleaning), such that the number of households influences water demand independently of the number of people living in them. Consequently, water demand might change following changes in the number of households, even if the population numbers stay constant. Engstler and Menning (2004) highlight that decreasing household size is not a phenomenon exclusive to the elderly but is also found in the younger generation. Unfortunately, the analysis of household size and composition is beyond our scope due to a lack of adequate data sources. We only observe total population numbers at the municipal level without their distribution to individual households. The impact of demographic changes on water demand caused by changes in household size and composition would be an interesting extension of our study that merits future research.

Furthermore, this article focuses on the supply side of water provision without empirically assessing consumer effects in terms of welfare economics. We argue that the interest in determining the productivity of water utilities stems from welfare considerations for natural monopolies and the importance of water service to local populations. At least in developed countries, where almost the entire population is supplied with water, firms' productivity has direct implications for consumer prices: A productive firm uses resources in a way that minimises the cost of supplying a given amount of water. Hence, more productive firms can set lower prices, which increases consumer surplus. Thus, high productivity is a precondition for charging low consumer prices without making losses. However, the actual gains in consumer surplus depend on the tariff structure and the pass-through of cost savings to consumers. The analysis of price-setting and pass-through is an analysis of its own, requiring price data and estimates of demand elasticities; we leave this empirical assessment of these welfare impacts for future research.

Finally, other utilities providing local public services, such as electricity, gas, or sewerage, are also vulnerable to demographic changes since all these industries are characterized by a capital-intensive production process with large-scale infrastructure. We limit our empirical analysis to water utilities because the water sector is affected by demographic changes through different channels than other network industries. Thus, we have shown that a shrinking population does not just lead to higher fixed costs but simultaneously affects variable costs, as additional effort is required to prevent sedimentation and nucleation in oversized water networks. The impact of demographic changes on productivity in other sectors would likewise be worthy of further empirical investigation.

6. Conclusion

In this article, we analyse the provision of local public services during demographic changes taking the example of municipal drinking water service, where the lengthy lifecycle of technical infrastructure and universal service obligations preclude immediate adjustment to changing demand patterns. Analysing a panel of 751 German municipally owned water utilities between 2003 and 2014, we examine the production, productivity and cost implications of population demographics and their changes.

Our results highlight diverging productivity and cost trends between growing and shrinking regions, with significant cost increases in rapidly shrinking regions. Between 2004 and 2014, the marginal costs of production have increased twice as much in shrinking regions than in growing regions, and the fixed unit costs of production have increased by 18 per cent, whereas they remained roughly stable in growing regions. Furthermore, our results reveal that not just the number of persons living in the water service area matters to the utilities but also their age structure and consumption patterns.

These findings are relevant to economic policy. The rising water costs in depopulated regions increase the financial burden of local public services: the cost increases either have to be borne by the municipal budget through water tariff subsidies or passed on to consumers, which would further increase the differences in living standards between central and peripheral regions. Water tariffs in Germany vary substantially across regions, with several depopulated East German areas among the most expensive ones. The growing disparities in the prices and quality of public services fuel a political debate about decoupling living standards in peripheral regions from those in urban agglomerations. Eventually, municipalities must weigh expensive adjustments to the technical infrastructure against constant increases in operating costs from capacity under-utilisation. Thus, quantifying the impact of demographic change on the costs of public services is relevant for the strategic decision-making process by governments. In a broader sense, we show that appropriate strategies are needed to handle the significant regional disparities caused by demographic changes. Long-term strategies are required to compensate regions with a shrinking and aging population if the provision of basic public services is to be ensured despite massive cost increases.

Acknowledgements

The authors acknowledge financial support from the Leibniz Association for grant no. SAW-2013-DIW-5 and from the German Science Foundation for grant no. 411547861. The article uses restricted data that was analysed at the Research Data Centre of the German Federal Statistical Office and the Statistical Offices of the Federal States in Berlin. All results were reviewed to ensure that no confidential information is disclosed.

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A. Appendix

A.1. Production function estimation

We start by taking the logs of the production function given in equation (5). Combining it with equation (12) then obtains

$$q_{it} = f(k_{it}, l_{it}, m_{it}, s_{it}; \beta) + \omega_{it} + \gamma X_{it} + \eta D_{it} + \epsilon_{it}, \quad (15)$$

where the lower case letters denote logs. We assume a translog production function with median corrected inputs and output for $f(\cdot)$, which has the advantage of not imposing any restrictions on the elasticities of substitution between input factors and to allow output elasticities to vary between utilities.²⁰ As a result, q_{it} is given by

$$\begin{aligned} q_{it} &= c + \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} \\ &+ \beta_s s_{it} + 0.5 \ \beta_{kk} k_{it}^2 + 0.5 \ \beta_{ll} l_{it}^2 + 0.5 \ \beta_{mm} m_{it}^2 + 0.5 \ \beta_{ss} s_{it}^2 + \beta_{kl} k_{it} l_{it} + \beta_{km} k_{it} m_{it} \\ &+ \beta_{lm} l_{it} m_{it} + \beta_{ks} k_{it} s_{it} + \beta_{ls} l_{it} s_{it} + \beta_{ms} m_{it} s_{it} + \omega_{it} + \gamma X_{it} + \eta D_{it} + \epsilon_{it}. \end{aligned}$$
(16)

Assume that intermediate goods are a static, flexible input whose level can be adjusted at least once a year without adjustment costs in proportion to changes in output (see Section 4.1). The demand for intermediate goods $m_t(\cdot)$ then depends on the current level of the pre-determined and inflexible

²⁰ This corresponds to a second-order Taylor series approximation to the true production function with the median as the focal point.

inputs $\{k_{it}, l_{it}, s_{it}\}$, on unobserved productivity ω_{it} , individual input prices ϖ_{it}^X , demand patterns D_{it} , and further individual production conditions X_{it} . Subscript t implies that demand can depend on additional input costs, e.g., capital costs or costs for external services, which are assumed to be uniform across utilities. Productivity is assumed to be the only unobserved variable in the input demand function.

$$m_{it} = m_t \left(k_{it}, l_{it}, s_{it}, \omega_{it}, \overline{\omega}_{it}^X, X_{it}, D_{it} \right) \quad (17)$$

If m_t is strictly monotone in ω_{it} , the function can be inverted to obtain an expression for productivity

$$\omega_{it} = h_t \left(k_{it}, l_{it}, m_{it}, s_{it}, \overline{\omega}_{it}^X, \boldsymbol{X}_{it}, \boldsymbol{D}_{it} \right). \quad (18)$$

Inserting (18) into (16) yields an estimation equation for the production function that only depends on observables and the error term ϵ_{it} .

$$q_{it} = c + \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} + \beta_s s_{it} + 0.5 \beta_{kk} k_{it}^2 + 0.5 \beta_{ll} l_{it}^2 + 0.5 \beta_{mm} m_{it}^2 + 0.5 \beta_{ss} s_{it}^2 + \beta_{kl} k_{it} l_{it} + \beta_{km} k_{it} m_{it} + \beta_{lm} l_{it} m_{it} + \beta_{ks} k_{it} s_{it} + \beta_{ls} l_{it} s_{it} + \beta_{ms} m_{it} s_{it} + h_t (k_{it}, l_{it}, m_{it}, s_{it}, \varpi_{it}^X, X_{it}, D_{it}) + \gamma X_{it} + \eta D_{it} + \epsilon_{it}.$$
(19)

We approximate the nonparametric function h_t (·) through a second-order polynomial and estimate equation (19) by OLS. The (unbiased) prediction Φ_{it} can be used to express productivity in terms of observables

$$\omega_{it}(\beta) = \Phi_{it} - c - \beta_k k_{it} - \beta_l l_{it} - \beta_m m_{it} - \beta_s s_{it} - 0.5 \beta_{kk} k_{it}^2 - 0.5 \beta_{ll} l_{it}^2 - 0.5 \beta_{mm} m_{it}^2 - 0.5 \beta_{ss} s_{it}^2 - \beta_{kl} k_{it} l_{it} - \beta_{km} k_{it} m_{it} - \beta_{lm} l_{it} m_{it} - \beta_{ks} k_{it} s_{it} - \beta_{ls} l_{it} s_{it} - \beta_m m_{it} s_{it} - \gamma X_{it} - \eta D_{it} .$$
(20)

In a second step, we address the fact that the coefficients (β, γ, η) are biased because they cannot be uniquely identified from (19) in the first step of the estimation.²¹ Assume that productivity follows a first-order Markov process where current productivity depends on past year productivity, a random *iid* shock v_{it} , and is potentially affected by demographic changes ΔD_{it} . This gives

$$\omega_{it} = g\left(\omega_{it-1}, \Delta D_{it}^p, \Delta D_{it}^{18}, \Delta D_{it}^{60}\right) + v_{it} \qquad (21)$$

²¹ Note that the input vector $(k_{it}, l_{it}, m_{it}, s_{it})$ shows up both in the original translog production function and in the productivity control function $h_t(\cdot)$.

which we model as a quadratic function in ω_{it-1} . Exploiting the fact that any current *iid* shock v_{it} to productivity is uncorrelated with past and pre-determined input values as well as observable production conditions allows us to identify the vector $(\boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\eta})$ from the moment conditions $\omega_{it} = \mathbb{E}[v_{it}|I_{it-1}] = 0$ where $I_{it-1} = \{k_{it}, l_{it}, m_{it-1}, s_{it-1}, k_{it}^2, l_{it}^2, m_{it-1}^2, s_{it-1}^2, X_{it}, D_{it}\}$. The results are given in Table 11, column (2). Finally, the unbiased coefficients $(\boldsymbol{\beta}, \boldsymbol{\gamma}, \boldsymbol{\eta})$ allow us to calculate an estimate for firm-level productivity using equation (20).

Finally, we would like to point out two things. Given the panel structure of the data, one might be concerned whether the presence of fixed effects biases the results of equation (21), which is estimated with OLS. First, note that any unobserved fixed effect in the production function (15) enters the residual and, therefore, the productivity term. Thus, firm fixed effects are subsumed with ω_{it} and are not part of the error term v_{it} . Furthermore, we try to purge the productivity term from firm fixed effects by controlling for a large set of observable characteristics. For completeness, we also estimate equation (21) as system GMM in the course of a robustness check.

Second, although the marginal costs are computed from estimates for θ_{it}^m and ϵ_{it} from the production model, the effect from demographic changes on marginal costs is not already accounted for in the law of motion for productivity (21). While the model set-up explicitly allows productivity to affect input usage, the control function approach of Olley and Pakes (1996) is designed to tackle this issue and provides unbiased estimates of the true underlying technology, i.e., the output elasticities, regardless of firm-level productivity. Furthermore, the measurement error ϵ_{it} is, by assumption, uncorrelated with productivity. The channel through which population decline (potentially) affects marginal costs is the higher input expenditure on intermediate goods $\varpi_{it}^m M_{it}$ – for instance, to avoid sedimentation.²²

²² See De Loecker et al. (2016) for a similar application to assess the influence of trade liberalisation on marginal costs of production in Indian manufacturing.

	OLS (1)		ACF (2)	
l	.244***	(.008)	.149***	(.040)
k	.194***	(.009)	.162***	(.048)
m	.203***	(.007)	.248***	(.053)
l^2	.082***	(.004)	.101***	(.018)
<i>s</i> ²	.062***	(.004)	.046*	(.020)
<i>k</i> ²	.053***	(.009)	.053	(.062)
m^2	.106***	(.006)	.164***	(.041)
kl	008	(.006)	053*	(.025)
km	031***	(.006)	054	(.041)
ks	.017**	(.006)	.058	(.039)
lm	036***	(.004)	028	(.030)
ls	034***	(.004)	044	(.026)
ms	020***	(.004)	002	(.031)
log(pop. dens.)	.089***	(.007)	.054	(.029)
share young	.029***	(.003)	.029**	(.009)
share old	003	(.002)	003	(.006)
share household	053**	(.018)	.006	(.105)
share spring water	020	(.015)	126	(.070)
share external sources	180***	(.016)	157	(.101)
share bulk water supply	.842***	(.023)	.774***	(.068)
share forest	357***	(.042)	343**	(.132)
share water surface	153	(.190)	155	(.425)
share farmland	095**	(.035)	139	(.117)
log(altitude)	105***	(.008)	083*	(.034)
River basin Elbe/Oder/coast	214***	(.023)	250*	(.107)
River basin Ems	.002	(.037)	003	(.155)
River basin Weser	049	(.026)	014	(.109)
River basin Rhine	203***	(.015)	170*	(.076)
log(wage)	.008	(.017)	021	(.036)
(Intercept)	018	(.132)	018	(.362)
R^2	.87			
Ν	5,770		5,770	

Table 11: Production function estimation
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Notes: The coefficients in column (1) are derived from estimating the specification given in (16) with OLS, subsuming ω_{it} with the error term ϵ_{it} . The coefficients in column (2) are derived from estimating the specification given in (19) within the ACF framework, with block-bootstrapped standard errors given in parentheses. p-values: 0 '***' 0.001 '**' 0.01 '*' 0.05.

A.2. Tables

	full sample (1)		growir	ng regions (2)	shrinking regions (3)		
	ω_{it}		ω_{it}		ω_{it}		
ω_{it-1}	.690***	(.076)	.745***	(.108)	.593***	(.099)	
ΔD_{it}^p growth pop. dens.	.072***	(.016)	.082***	(.019)	.068***	(.023)	
ΔD_{it}^{18} growth share young	.002	(.004)	003	(.005)	.007	(.005)	
ΔD_{it}^{60} growth share old	003	(.002)	004	(.004)	.004	(.003)	
Sargan test (p-value)	.23		.17		.14		
Walt test (p-value)	.00		.00		.00		
AR(1) test (p-value)	.00	.00			.00		
AR(2) test (p-value)	.02	.02			.03		
Ν	5,770		2,748		3,004		

Table 12: Demography and productivity (system GMM)

Notes: Results from estimating the specification given in (21) as system GMM following Blundell and Bond (1998), WHITE standard errors given in parentheses. p-values: 0 '***' 0.001 '**' 0.01 '*' 0.05.

Table 13: Detailed regression for different quantiles of marginal costs

	.1 quantile (1)		.3 quantile (2)		.5 quantile (3)		.7 quantile (4)		.9 quantile (5)		
Marginal costs		mc _{it}									
ΔD_{it}^p	growth pop. dens.	129*	(.058)	176*	(.071)	217*	(.097)	273	(.143)	337	(.204)
ΔD_{it}^{18}	growth share young	-2.640**	(1.000)	-3.297***	(.973)	-3.883***	1.118)	-4.668**	(1.590)	-5.555**	(2.188)
ΔD_{it}^{60}	growth share old	1.881	(1.483)	2.097	(1.559)	2.290	(1.791)	2.548	(2.060)	2.841	(2.396)
μ_i	Firm fixed effects	YES		YES		YES		YES			
μ_t	Time fixed effects	YES		YES		YES		YES			
	Ν	4,350		4,350		4,350		4,350			
Notes: . p-values: 0 '***' 0.001 '**' 0.01 '*' 0.05. Bootstrapped standard errors clustered at the firm level with B= 2,000 replications.											

A.3. Data sources

A.3.1. Data access

We use administrative firm-level data from the German federal and regional statistical offices. The data is subject to privacy conditions and can be accessed on-site at the statistical offices' Research Data Centres. Access is granted depending on the following conditions:

- Researchers must be associated with scientific facilities such as universities or research institutes and carry out independent scientific research. Commercial use of the data is prohibited.
- Researchers must commit themselves to statistical confidentiality in accordance with Section 16 of the Federal Statistics Act (BStatG). To ensure data confidentiality some descriptive analyses are prohibited.
- The data is granted project-specifically and can be accessed for three years (with possible extensions).

A full description of access conditions and the application procedure is given on the website of the Research Data Centres at <u>www.forschungsdatenzentrum.de/en</u>. We shortly describe the datasets used

in this article below, and provide more detailed information on the linkage strategy, including programming codes, at <u>https://modern-state-owned-firms.gitlab.io/landing-page</u>.

A.3.2. Energy statistics

Energiestatistiken is a bundle of 9 firm-level surveys conducted annually by the German federal and regional statistical offices among all firms in Germany with NACE ID 35 and 36 above a certain threshold (more than 10 employees/1MW installed capacity/200,000m³ water treatment). Firms are legally obligated to respond. The statistical offices use the data to publish aggregate data on German energy and water supply. As of 2022, anonymised microdata at firm-level are available for 2003 through 2017. We use the two main surveys, *Kostenstrukturerhebung* and *Investitionserhebung bei Unternehmen der Energieversorgung, Wasserversorgung, Abwasser- und Abfallentsorgung, Beseitigung von Umweltverschmutzungen* (doi:10.21242/43221.2014.00.01.1.1.0) to obtain information on the water utilities' input usage, cost structure, and output delivered. We use the participation in additional sector-specific surveys to separately identify pure water utilities from mixed utilities, which have also other activities such as electricity or gas supply. Stiel (2015) provides a full description of the dataset.

A.3.3. Statistics on public water supply

Statistik über die öffentliche Wasserversorgung (doi:10.21242/32211.2013.00.00.1.1.0) maintains physical information (raw water collection, output delivered, customer structure) on German drinking water supply at the firm-level, collected by the regional statistical offices every three years (see Zschille, 2016, for details). As of 2022, anonymised microdata is available for 2001 to 2016 with three-year intervals.

A.3.4. Statistics of annual accounts of public funds, institutions and enterprises

Jahresabschlüsse öffentlicher Fonds, Einrichtungen und Unternehmen (doi:10.21242/71811.2014.00.00.1.1.0) collects the financial statements of all German firms where public authorities hold more than 50 per cent of the shares and/or votes (see Wägner,2017, for details). It covers all sectors of the German economy. As of 2022, anonymised microdata is available for the years 1998 to 2019.

A.3.5. Firm register

The firm register *Unternehmensregister* (URS) (doi:10.21242/52121.2014.00.00.1.1.0) maintained by the statistical offices allows for deriving unique firm IDs to merge the above datasets.

A.3.6. Regional data

Regional data on German municipalities for the years 2008 to 2014 are taken from the official database, *Regionaldatenbank Deutschland*, maintained by the Federal and regional statistical offices. It is freely accessible at www.regionaldatenbank.de. Data for the years 2002 to 2007 are taken from Statistik Lokal, a DVD-based collection of regional official data published by the same authorities.