RESEARCH ARTICLE

A review of frontier approaches to efficiency and productivity measurement in urban water utilities

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Despite the rapid global revitalisation of urban water policy, and the universal need to measure and improve organizational efficiency and productivity in all suppliers as a means of ensuring the sustainability of this key resource, only recently have the most advanced econometric and mathematical programming frontier techniques been applied to urban water utilities. This paper provides a synoptic survey of the comparatively few empirical analyses of frontier efficiency and productivity measurement in urban water utilities in Australia, the UK, Spain, the US, Mexico, Brazil, Canada, Germany, Italy, Malaysia, and Slovenia, among others. The survey examines both estimation and measurement techniques and the non-discretionary structural and regulatory determinants of efficiency and productivity. There is particular focus on how the results of past studies inform regulatory policy and managerial behaviour and key directions for future research.

Keywords: Stochastic frontier analysis; data envelopment analysis (DEA); urban water utilities; technical efficiency; cost efficiency; scale efficiency

1. Introduction

A number of factors have combined to reignite global interest in water policy as it relates to urban water utilities in the 21st century. Starting from their essential nature as natural monopolies operating within network industries, countries around the world with initially similar settings in delivery networks and treatment systems have progressively evolved very different approaches to urban water utilities, especially in the chosen mix of privately and publicly owned entities and the extent of regulatory intervention governing pricing and standards (Bakker 2010). However, recent circumstances have added impetus to these longstanding developments. These include declining rainfall associated with climate change, pressing needs for maintaining and expanding expensive water supply infrastructure, jurisdictional, sectoral, and environmental conflicts over existing surface and groundwater supplies, and rapid population growth and urbanisation (Uitto and Biswass 2000, Productivity Commission 2011, CSIRO 2012, UN 2012, NWC 2012, OfWat 2012). In response, governments and international agencies worldwide have refocused on improving the management and delivery of urban water services.

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There is now substantial ongoing concern about the ability of the urban water sector as it stands to achieve productive and efficient outcomes and thereby reassure key stakeholders, especially users, of the sustainability of the sector and this key resource. Part of this draws on the conventional view that the inherent conditions of urban water utilities (supply variability, high transport costs, scale economies, and public health) place significant limits on the scope for effective competition and efficient markets in urban water (Frontier Economics 2008). Part is also from the observation that the inefficiencies associated with current pricing arrangements, water restriction regimes, and deficiencies in supply and demand planning and investment processes, have caused additional and ongoing problems for the sector in terms of deteriorating infrastructure, threats to water quality, rising supply costs and reductions in consumer welfare (Productivity Commission 2011, NWC 2012). A final part reflects the apparent inability of the urban water sector to maintain the needed pace of policy reform (Frontier Economics 2008). In fact, on World Water Day 2011 United Nations Secretary-General Ban Ki-moon urged the world's governments "…to recognize the urban water crisis for what it is—a crisis of governance, weak policies and poor management, rather than one of scarcity" (UN 2012).

In response to these pressing policy demands, an increasing number of studies worldwide have sought to estimate and measure efficiency and productivity in urban water utilities. By assessing the efficiency and productivity of the sector, these studies endeavour to highlight current deficiencies in the management of urban water utilities, recognise and quantify the impacts of the regulatory and structural factors surrounding them, provide recognition of the barriers to productive and efficient outcomes in the sector, and yield quantitative inputs into the future reform process. Three main measures of efficiency meet the needs of researchers, managers, and policymakers in this regard (Coelli 2005). First, *technical efficiency* refers to the use of productive resources in the most technologically efficient manner. Put differently, technical efficiency implies the maximum (minimum) possible output (input) from (for) a given set of inputs (outputs). Within the context of water utilities, technical efficiency may then refer to the physical relationship between the resources used (say, piping infrastructure, labour and equipment) and some service outcome, including the number of households served and the amount of potable water supplied.

Second, *allocative efficiency* reflects the ability of a utility to use these inputs in optimal proportions, given their respective prices and the available production technology. In other words, allocative efficiency is concerned with choosing between the different technically efficient combinations of inputs used to produce the maximum possible outputs. Consider, for example, a policy of changing to electronic household meters with a fully automatic meter reading system. Electronic meters may need fewer labour inputs (for reading the meter) but do require the use of another resource in the form of electronic technology. As different combinations of inputs are being used, and notwithstanding differences in the quality of the outputs (such as the easier detection of meter tampering and improved accuracy), the choice of metering is then based on the relative costs of these different inputs. Finally, when taken together allocative efficiency and technical efficiency determine the degree of *productive efficiency* (also known as total economic efficiency). Thus, if an urban water utility uses its resources completely allocatively and technically efficiently, then it has achieved total economic efficiency. Alternatively, to the extent that either allocative or technical inefficiency is present, then the utility will be operating at less than total economic efficiency.

The empirical measurement of economic efficiency centres on determining the extent of technical and possibly allocative efficiency in a given utility or utility industry. Most recently, economists have employed frontier measurement techniques to measure the productive performance of water utilities. These techniques use a production possibility frontier to map a locus of potentially technically efficient output combinations a utility is capable of producing at a point in time. To the extent a utility fails to achieve an output combination on its production possibility frontier, and falls beneath this frontier, it is technically inefficient. Similarly, to the extent to which it uses some combination of inputs to place it on its production frontier, but which do not coincide with the relative prices of these inputs, it is allocatively inefficient. Finally, recognising expansion of the production frontier over time through technological improvements, regulatory reform, and improved workplace practices, we can recognise that total factor productivity (TFP) improvements include technical efficiency improvements for those utilities catching up to the existing frontier and the technological gains possible for all (including efficient) utilities. Coelli *et al.* (2005) provide a useful technical introduction to efficiency measurement techniques.

Accordingly, if we can determine production frontiers that represent total economic efficiency using the best current production techniques, then we can use this idealized yardstick to evaluate the economic performance of actual organisations and industries, here individual urban water utilities and the urban water utility industry, typically in a chosen jurisdiction (national, regional, state or provincial). By comparing the actual behaviour of organisations against the idealized benchmark of economic efficiency, we can determine the degree of efficiency exhibited. This survey concentrates on selected efficiency and productivity studies of urban water utilities using frontier efficiency measurement techniques published since 1990. We searched *EconLit*, the Journal of Economic Literature electronic database, to identify journal articles representative of the contexts and techniques associated with frontier efficiency measurement in urban utilities. References from these studies helped identify other relevant articles. We also used *Google Scholar* to locate books and book chapters and yet unpublished conference and working papers.

<INSERT TABLE 1 HERE>

Of the selected studies in Table 1, 30 per cent are based on urban water utilities in the UK, 11 per cent each in the US and Australia, 7 per cent in Spain, and the remainder in other contexts (including Mexico, Brazil, Italy, Slovenia, Malaysia and Canada). About 41 per cent employ cross-sectional observations with the balance relying on panel (pooled time-series, cross-sectional) data. However, despite their dissimilar contexts and techniques, these studies share a common step-by-step empirical procedure that determines first the choice of frontier efficiency measurement approach, second the specification of inputs and outputs to be used in the selected approach, and finally, the method used to explain efficiency differences and the factors thought to be associated with these differences.

2. New contribution and limitations

At least two studies, Walter *et al*. (2009) and Abbott and Cohen (2009), have partially surveyed efficiency measurement as it applies to urban water utilities. However, these include a more general range of methods and applications (including data envelopment analysis, stochastic frontiers, average cost and production functions, and partial and total factor productivity indices). They also tend to focus on the implications of the results for economies of scale and scope in the latter and the role of regulation and ownership in the former, not the methodology used to obtain these measures.

The current paper is the first attempt to examine each of the main frontier efficiency measurement approaches as they apply to urban water utilities. Moreover, apart from discussing the strengths and weaknesses of the different approaches, this paper also examines the steps faced by researchers as they move from a selected approach, to the specification of inputs and outputs, to the means of explaining efficiency differences and their policy implications. This highlights the empirical problems that have received attention in the literature, and the efforts by researchers to overcome these problems. It therefore provides guidance to those conducting empirical research in efficiency and productivity and serves as an aid for policymakers, managers, and practitioners interpreting the outcomes of frontier efficiency studies.

However, the survey does suffer from two major limitations. First, we do not attempt to compare frontier efficiency techniques with non-frontier approaches, principally the estimation of production and cost functions using least squares regression. These approaches place emphasis on comparisons with average not frontier or best-practice performance [see, most recently, Fabbri and Fraquelli (2000), Antonioli and Filippini (2001), Torres and Morrison (2006), Mosheim (2006), Garcia *et al*. (2007), Nauges and van den Berg (2008) and Bottaso and Conti (2009)]. However, with few exceptions, these techniques were prior to 1990 and now superseded by the more recent frontier approaches considering evidence that DEA is now generally superior (Cubbin and Tzanidakis 1998). Nevertheless, many of the issues involving the specification of the inputs and outputs in frontier efficiency analysis of urban water utilities are included in these studies, so we sometimes make selected reference to these works.

Second, this survey is necessarily general in that there are many and substantial differences in the objectives and behaviour of urban water utilities across countries. In varying degrees, this relates to differences in regulation and competition in their respective markets. Consider just urban water utilities in Australia, the US, and the UK. In Australia, large, publicly owned, corporatized water utilities operate under regulated prices in each state [such as the Independent Pricing and Regulatory Tribunal in NSW]. In contrast, small water and sewerage utilities owned by local councils (municipalities) (in NSW) usually operate without formal independent price regulation under the *Water Act 1912*, the *Water Supplies Authorities Act 1987*, *Local Government (Water Services) Regulation 1999* and the *Local Government Act 1993*, with the latter stipulating that water services are provided independently of other council functions. This, of course, lies under the overarching goals of the Australia-wide National Water Initiative in providing safe, reliable, and efficient water services to urban areas in a sustainable manner.

In contrast, in the US, community water systems encompass a mix of private and public ownership with state public utility commissions regulating rates of return with federal regulations by the Environmental Protection Agency and others stipulating standards for water quality and environmental protection. Finally, in the UK, large privatised regional water authorities holding responsibility for water and sewerage service and small public limited liability water-only companies operate under a price cap administered by the Office of Water Services (Ofwat) with environmental and drinking water regulation respectively administered by the Environmental Agency and the Drinking Water Inspectorate. Unfortunately, it is not possible to deal at any length with the exceedingly complex regulation and regulatory reform found in the many countries in this survey.

3. Choice of approach

All efficiency measures assume we know the production frontier of the fully efficient organisation. As this is usually not the case, the production frontier must be estimated using sample data. Two approaches are possible. These are: (i) a non-parametric piecewise-linear convex frontier constructed such that no observed point should lie outside it (known as the *mathematical programming* approach), or (ii) a parametric function fitted to the data, again such that no observed point should lie outside it (known as the *econometric* approach). These approaches use different techniques to envelop the observed data, and therefore make different accommodations for random noise and for flexibility in the structure of the production technology.

First, the econometric approach specifies a production or other function and normally recognizes that deviation away from this given technology (as measured by the error term) is composed of two parts, one representing randomness (or statistical noise) and the other inefficiency. The usual assumption with the two-component error structure is that the inefficiencies follow an asymmetric half-normal distribution and the random errors are normally distributed. The random error term is generally thought to encompass all events outside the control of the utility, including both uncontrollable factors directly concerned with the ‘actual’ production function (such as differences in operating environments) and econometric errors (such as misspecification of the production function and data measurement errors). This type of reasoning has primarily led to the development of the ‘stochastic frontier approach’ (SFA) which seeks to consider these external factors when estimating the efficiency of some real-world utility. Examples include Bhattacharyya *et al*. (1995), Estache and Rossi (2002), Aubert and Reynaud (2005), da Silva e Souza *et al*. (2007), and Fillippini *et al*. (2008).

In the primal (production) form of the SFA, we specify an output as a function of inputs. Unfortunately, it is difficult to incorporate multiple outputs in this form, though not with the dual-cost frontier. Accordingly, the stochastic frontiers we typically see in water utility efficiency analysis are cost frontiers where the dependent variable (some measure of costs) is regressed against a set of independent variables comprising outputs and input prices and input quantities. A simpler earlier version of the econometric approach, known as the ‘deterministic frontier approach' (DFA) assumes that all deviations from the estimated frontier comprise inefficiency, but is presently unapplied to urban water utilities. We can estimate stochastic frontiers using a range of general statistical software, which through user programming and maximum likelihood methods can be adapted for the desired estimation (including Shazam, GAUSS, SAS, EViews, etc.). However, specialised software is now also available for estimating stochastic frontiers, including LIMDEP 9.0 <www.limdep.com/> and Frontier 4.1 <www.uq.edu.au/economics/cepa/>.

Second, and in contrast to the econometric approach that attempts to determine the *absolute* economic efficiency of utilities against some imposed benchmark, the mathematical programming approach seeks to evaluate the efficiency of a utility *relative* to other organisations in the same industry. The most commonly employed version of this approach is a linear programming tool referred to as 'data envelopment analysis' (DEA). DEA essentially calculates the economic efficiency of a given utility relative to the performance of other utilities producing the same sorts of services, rather than against an idealised standard of performance. DEA is also a non-stochastic method in that it assumes all deviations from the frontier are the result of inefficiency. Norman and Stoker (1991), Thanassoulis (2000), Tupper and Resend (2004), García-Sánchez (2006), Reznetti and Dupon (2009) and Munisamy (2010) have applied this approach to urban water utilities. Once again, most general purpose mathematical optimisation software (GAMS, SAS, Solver in Microsoft Excel) can be adapted to solve DEA problems, though specialised applications are increasingly common, including LIMDEP 9.0 <www.limdep.com/>, DEAP 2.1 <www.uq.edu.au/economics/cepa/>, Frontier Analyst <www.banxia.com>, DEASoft 2.0 <www.deasoftware.co.uk/>, and OnFront 2.0 <www.emq.com>. Thanassoulis (2001), Ramanathan (2003), Ray (2004) and Cooper *et al*. (2006) provide useful technical introductions to DEA.

We also find applications that use Malmquist productivity indexes (MI) (as derived from DEA-like linear programs) to measure changes in efficiency over time in the urban water utility literature. In this approach, a production frontier representing the efficient level of output produced from a given level of input is constructed, and the assumption made that this frontier can shift over time. We thus obtain different frontiers for different periods and these correspond to differences in the available 'technology'. Note that 'technology' in an economic sense refers to both physical plant and equipment and work practices and regulation. When inefficiency exists, the relative movement of any given utility over time will therefore depend on both its position relative to the current frontier (technical efficiency) and the position of the frontier (technical change). If we were to ignore inefficiency, then productivity growth (the increase in outputs relative to inputs) over time would be unable to distinguish between improvements that derive from a utility ‘catching up’ to its own frontier (eliminating efficiency), or those that result from the frontier itself shifting up over time for all utilities included (or the industry). Studies of urban water utilities using this technique include Woodbury and Dollery (2004), Coelli and Walding (2006), Saal and Parker (2006), and Byrnes *et al*. (2010).

The discussion thus far addresses two separate, though conceptually similar, theoretical approaches to the assessment of efficiency. These are the econometric frontier approach (principally DFA and SFA), and the mathematical programming approach (including DEA and MI). Table 1 details the approach taken by selected studies. While the selection of any particular approach is likely to be subject to both theoretical and empirical considerations, it may be useful to summarize the strengths and weaknesses of each. The emphasis here is not on selecting a superior theoretical approach, as the mathematical programming and econometric approaches address different questions, serve different purposes, and have different informational requirements. An important subtle terminological distinction at this point is that the mathematical programming approach strictly involves ‘measurement’ or ‘calculation’, while the econometric approach comprises ‘estimation’.

The first approach is the construct of the DFA. While no study employs this method the survey period, it is evident in the broader efficiency literature, and serves as a useful benchmark for the more complex techniques. Using statistical techniques, we derive a deterministic frontier, such that all deviations from this frontier are the result of inefficiency. That is, we make no allowance for noise or measurement error in the data. Once again, in the primal (production) form the ability to incorporate multiple outputs is difficult, whilst using the dual cost frontier such extensions are possible. However, if we use the cost frontier approach, it is not possible to decompose inefficiency into allocative or technical components, and therefore we necessarily attribute all deviations to overall cost inefficiency.

In terms of computational procedure, the DFA necessitates a large sample size for statistical reasons. In addition, it is generally regarded as a disadvantage that the distribution of the technical inefficiency has to be specified, i.e. half-normal, normal, exponential, lognormal, etc. Ideally, we would base this on knowledge of the economic forces that generate such inefficiency, though in practice this may not be feasible. If there are no strong a priori arguments for a particular distribution, analytical tractability determines the choice. Similarly, we also impose a particular production technology in the form of the functional form on the sample, and once again, this may be a matter of empirical convenience (i.e.

Cobb–Douglas, translog, etc). Moreover, the choice of a particular production function may place severe restrictions on the types of analysis possible, and therefore the content of managerial and policy prescriptions, using this particular approach.

The second approach discussed, namely the SFA, removes some of the limitations of the deterministic frontier. Its chief advantage lies in that it introduces a disturbance term representing noise, measurement error, and exogenous shocks beyond the control of the water utility. This permits the decomposition of deviations from the efficient frontier into two components, the first reflecting inefficiency, and the second noise. However, in common with the deterministic approach, we must make an assumption regarding the distribution (usually normal) of this noise along with those required for the inefficiency term and the production technology. The main effect here is that under both approaches, especially the SFA, we impose considerable structure upon the data from stringent parametric form and distributional assumptions. In addition, SFA estimation usually uses information on prices and costs in addition to quantities, and these may introduce additional measurement errors alongside the more demanding requirements for data.

The programming approach (DEA and MI) differs from both statistical frontier approaches (DFA and SFA) in that it is non-parametric, and from the SFA in that it is non-stochastic. Thus, we make no (direct) accommodation for the types of bias resulting from environmental heterogeneity, external shocks, measurement error, and omitted variables. Consequently, the entire deviation from the frontier is the result of inefficiency. This may lead to either an under or over-statement of the level of inefficiency, and as a non-stochastic technique there is no possible way in which probability statements of the shape and placement of this frontier can be made. These problems are especially likely when the number of individual utilities included is small (implying the possible influence of outliers), when the number of inputs and/or outputs is relatively large (thereby providing poor discrimination in indentifying the benchmark utilities), or when non-discretionary ‘environmental’ factors (factors outside management control) influence efficiency. In view of erroneous or misleading data, some critics of DEA have questioned the validity and stability of these measures of efficiency.

However, there a number of benefits implicit in the mathematical programming approach that makes it attractive on a theoretical level. To start with, given its non-parametric basis, we have substantial freedom in the specification of inputs and outputs, the formulation of the production correspondence relating inputs to outputs, and so on. Thus, in cases where the usual axioms of production activity breakdown (i.e. profit maximization) then the programming approach may regardless offer useful insights into efficiency (though there are still some assumptions regarding the production technology, such as those relating to convexity). Similarly, it is entirely possible that the types of data necessary for the statistical approaches are neither available nor desirable, and therefore the imposition of as few as possible restrictions on the data is likely to be most attractive. Simulation studies have also indicated that the piecewise linear production frontier formulated by DEA is generally more flexible in approximating the true production frontier than even the most flexible parametric functional form. Nonetheless, very recent theoretical efforts attempt to synthesize the best features of SFA and DEA in the estimation of production efficiency: namely, allowance for statistical noise and outliers (as in SFA) and the modelling of multiple inputs, multiple output technologies without the imposition of parametric assumptions on the production relationship (as in DEA). Unfortunately, as these are presently unapplied to urban water utilities, they are beyond the scope of this survey. The interested reader is directed to Cooper *et al.* (1998), Li (1998) and Huang and Li (2001) for theoretical guidance.

These theoretical and empirical considerations explain part of the dominance of DEA in water utility efficiency measurement studies, comprising some 59 per cent of the studies included in this survey. The obvious desirability of quantifying multiple inputs and outputs in different units of measurement is one consideration. For example, many water utility studies define inputs as the amount of or expenditures on labour, energy, or materials. In turn, outputs are the number of households connected, the amount of potable water produced, and the length of the mains. Finally, and once again in a context where the usual axioms of production activity breakdown [i.e. the replacement of strict profit maximisation with bounded cost minimisation], there is the ability to define inputs and outputs depending on the conceptualization of water utility performance thought most appropriate.

Problematically, the inability of conventional DEA modelling to take account of statistical error is also likely to cause complications in very many urban water contexts. For example, most urban water sectors comprise both large (regional) and small (local) utilities, with a least some likely to be candidates for outliers (especially given the small number of individual entities in any particular milieu) and hence a source of bias in the results. Further, many sectors include a mix of both public and private entities, such that competing behavioural assumptions governing the determination of inputs and outputs for superficially similar entities, may not reflect the actual or intended behaviour of the utilities included.

4. Scope and outcomes of past studies

Within the broad scope of urban water, frontier measurement techniques apply to a number of different types of utilities. As shown in Table 1, these include both water or sewerage (wastewater) only companies (Norman and Stoker 1991, Thanassoulis 2000, Woodbury and Dollery 2004 Byrnes *et al*. 2009) and water and sewerage companies (Thanassoulis 2002, Tupper and Resende 2004, Erbetta and Cave 2006) and both public and private utilities (Lambert *et al*. 1993, Kirkpatrick *et al*. 2006, da Silva e Souza *et al*. 2007, Munisamy 2010). As discussed, past studies principally concern urban water utilities in the UK, but also in the US, Australia, Italy, Mexico, Germany, Brazil, Malaysia, Canada, Spain, Slovenia, and Mexico. The only known international studies are Estache and Rossi's (2002) analysis of water companies in 29 Asia-Pacific countries and Kirkpatrick's *et al*. (2006) study of 110 water utilities across 13 countries in Africa.

Interestingly, unlike the general frontier efficiency literature (principally applications in financial services, education, and health) with its overwhelming US focus, the extant urban water utility efficiency studies largely comprise work outside the US. These especially include the UK (Cubbin and Tzanidakis 1998, Erbetta and Cave 2006, Saal *et al*., 2007) and, to a much lesser extent, Spain (Garcia-Sánchez 2006, Picazo-Tadeo *et al*. 2008) and Australia (Woodbury and Dollery 2004, Coelli and Walding 2006). The reason the UK is a common setting is not hard to find, with OfWat (the regulator of water services in the UK) being an early provider (since 1994) of comparative information on urban water utilities. The UK regulator has also been an enthusiastic user [see Cubbin (2004) for a critique] of both SFA and DEA in disentangling cost variations arising from differences in operating environment from genuine efficiency differences in RPI-X price capping (OfWat 2010a, 2010b, 2010c). However, several other countries have subsequently employed efficiency analysis, especially DEA, for the regulation of urban water utilities, including Italy, Columbia, and the Netherlands (Walter *et al*., 2009). Elsewhere, reasons for policy interest are also not hard, with Spain being the driest country in the European Union and Australia recently suffering its longest drought on record, both encompassing concerns with the sustainability of urban water supplies.

The measures of efficiency obtained by these studies have varied widely. In Australia, Woodbury and Dollery's (2004) analysis of 73 water supply authorities in NSW found mean technical efficiencies between 73.7% (constant returns-to-scale) and 79.8% (variable returns-to-scale) using data from the Australian Water Association and the NSW Departments of

Local Government and Land and Water Conservation. Conversely, Byrnes *et al.* (2010) calculated technical efficiencies of 45.6–48.2% in urban water utilities in regional NSW and Victoria using data from the Department of Energy, Utilities and Sustainability and VicWater. In the US, Aubert and Reynaud (2005) estimated cost inefficiencies of up to 12.5% in Wisconsin water utilities, while Bhattacharyya *et al*. (1995) used a similar approach to obtain cost inefficiencies of close to zero (0.32%) in private utilities and 5.09% in publicly-owned firms.

More interestingly, in the UK, Erbetta and Cave (2007) and Saal *et al*. (2007) used almost identical data from OfWat to calculate respective mean technical efficiencies of 90.9 per cent over the period 1993–2005 in the first instance and 92.7–96.4% over the period 1985–2000 in the second. There is also wide and somewhat startling variability elsewhere. For example, respective analyses of Australian water utilities by Woodbury and Dollery (2004) and Coelli and Walding (2006) both employed the MI approach to efficiency and productivity measurement. Over the period 1997–2000, Woodbury and Dollery (2004) concluded that TFP increased only slightly (0.20%), primarily because of technological gains (2.2%) combined with a decrease in technical efficiency (2.1%), while Coelli and Walding (2006) observed that over the period 1995–2003, TFP fell by 1.2%, comprising an efficiency improvement of 1.1% and a technological loss of 2.2%. Unfortunately, there is currently only limited comparison between the alternative efficiency measurement techniques and their impact on efficiency measurement and estimation. For the exceptions, see Kirkpatrick *et al*. (2006) and Saal and Parker (2006)

5. Specification of inputs and outputs

The only conceptualisation used in defining the input–output relationship in urban water utility behaviour follows a production approach. This principally views water utilities as producers of physical water outputs, typically the volume of potable water (Norman and Stoker 1991, Thannassoulis 2000, Andwandter and Ozuna 2002, Tupper and Resende 2004, Coelli and Walding 2006, Byrnes *et al*., 2010) and the number of proprieties supplied with water (Coelli and Walding 2006, Saal and Parker 2006, García-Valiñas and Muñiz 2007). However, they may also include the length of mains supplied or the service area (Thanassoulis 2002, Munisamy 2010), the proportion of non-households supplied with water and/or the average pumping head (Guder *et al*. 2009), and indexes of water quality assessments, service outages, and customer complaints (Woodbury and Dollery 2004, Byrnes *et al*. 2010).

Of course, the arguments supporting the use of the alternative outputs vary markedly (somewhat cynically, they may also chiefly depend on the nature of the data readily available). For example, Byrnes *et al.* (2010) argue that non-residential (industrial and commercial) customers place fewer input demands on utilities because of their smaller number, are usually not subject to water restrictions, and have more predictable patterns of demand. However, these users may also require water of a higher quality (typically pressure) and this imposes additional costs/input requirements on water utilities. Similarly, yet other studies have specified the proportion of water supply from surface or groundwater supplies to proxy for the variation in capital costs associated with different sources of water (Bhatttacharyya *et al.* 1995, Aubert and Reynaud 2005, Filippini *et al.* 2008). They may also include water losses as a proxy for the age of the capital stock (Thanassoulis 2000, Andwandter and Ozuna 2002, Estache and Rossi 2002).

While there is obviously substantial variation in the specification of outputs across studies, the use of the number of properties connected and/or the volume of water supplied is common in many network industries (including water, electricity, and gas), and is largely an attempt to take account of the scale of operations. Further, most dedicated studies of economies of scale in water utilities have not employed frontier measurement techniques. For instance, Garcia *et al.* (2007) in the US and Filippini *et al.* (2008) in Slovenia found economies of scale prevailed up to 2.30 million m^3 using translog functions, while Fabbri and Fraquelli (2000) concluded they held up to 18.86 million m^3 when using ordinary least squares. Nevertheless, most frontier studies employ at least some output measures, principally as a means of allowing for scale economies, even if this is not their declared focus.

There is also often an attempt to reflect that the inputs required (and costs) of providing services to geographically dispersed customers are relatively larger, so many studies include a measure of ‘network density’ by dividing the number of properties served or the population by the network length (Bottasso and Conti 2003, Fraquelli and Moiso 2005, Byrnes *et al.* 2010). In effect, these measure the input savings available from increasing the number of customers and total output, holding all other variables constant (whereas economies of scale/increasing returns to scale prevail when costs/inputs increase less than proportionally than the increase in output). In general, the empirical evidence is that urban water utilities are heavily characterised by economies of density. One basic argument is that water collection and connections require fewer inputs than capital-intensive pipe laying and dam building (Walter *et al.* 2009). Of course, as in all network industries, there is also the suggestion of diseconomies of density (congestion) as the number of customers increases further relative to the length of mains, causing falls in pumping pressure, higher frequencies of bursts and greater infrastructure investment.

Closely related to the concepts of economies of scale and density in urban water utilities studies is that of economies of scope—where a single utility can produce different products at lower cost than several specialised utilities—of which there are three main potential sources, all of which impact upon the specification of outputs. The first potential source of economies of scope concerns those that may exist with the provision of water outputs of varying characteristics to different customers, say, households and non-households (industrial and commercial users). For example, while industrial and commercial consumers may have different demands for water quality and/or pressures than households, a single utility is generally able to service both types of user more cheaply than would a specialised provider for each, thereby lowering input requirements and improving efficiency.

The second potential source of economies of scope is where some water providers are also providers of sewerage services. This is especially common in the UK where larger regional water-only companies and smaller local water and sewerage companies are often included in a single analysis [see, for example, Thanassoulis (2000), Bottaso and Conti (2003) and Saal and Parker (2006)]. While the jointness argument for water and sewerage services is certainly compelling—environmental improvements, water quality and the avoidance of some treatment costs, the indirect or indirect reuse of recycled water, the attainment of a larger organisational scale for administrative and other fixed costs, and the sharing of pipe laying and pumping technology, access and infrastructure—the fundamental problem is that specifying water-only and water and sewerage utilities in a single analysis is likely to result in misspecification. This is because they do not share a common production frontier and at least some of the utilities included will have zero sewerage outputs (Saal and Parker 2006).

In the UK, Ofwat (2010c) partly addresses this by separately assessing different aspects of water and sewerage services using only partial performance measures given the inability of separating water and sewerage operations in the one firm. Nonetheless, it would generally be better to include only those utilities in a single analysis where some degree of certainty exists that they share a common conceptualisation of performance (and therefore a common frontier). A final source of economies of scope concerns cost economies from conventionally unrelated network utility services provided to households and other users. In terms of the economies of scope existing alongside water utilities, this is known only by a single (albeit non-frontier) analysis by Fraquelli *et al.* (2004) of the joint provision of water, gas and electricity.

As discussed, the specification of outputs in urban water utilities is primarily to control for the largely exogenously determined factors that impact upon the use and costs of inputs. That is, there is often no suggestion that utilities would intentionally seek to increase the volume of water supplied or the number of properties serviced. In some cases, this would not be possible as the existing network limits utilities (and any feasible competition) to a specific geographic area. In other cases, such as increasing the volume of water provided, this may lie counter to efforts aimed at demand management and the avoidance of future investment in supply infrastructure. This lies well with the underlying assumption that the principal role of these utilities is the production of quality water services for their existing customers and given the usual input-orientation in DEA, focus is on the reduction of inputs relative to some level of outputs. Nevertheless, the utility may seek to maximize some outputs, such as service quality, and as this likely reflects discretionary actions taken by management: that is, if suitable data were available, it should be included in the efficiency measurement process. Byrnes *et al*. (2010) is one of the few existing DEA studies that have explicitly attempted to include service standards as an urban water utility output.

Turning now to inputs, we specify these in both the dependent variable as average variable or total costs and in the independent variables as the price and quantities of the separate inputs with SFA cost frontiers. In terms of the left-hand side of the cost function, it is conventionally desirable to include as many of the costs of provision we can gather, including management, maintenance, and operation expenses, energy and chemical expenditures, and capital replacement costs. In practice, capital replacement costs especially are sometimes difficult to obtain, so many studies use the length of mains (or equivalent) to proxy the utility’s commitments to dams, treatment works, pump stations, and reservoirs along with the costs associated with the reticulation system included in maintenance and operation costs.

Other studies, such as Byrnes *et al*. (2010), instead argue that only operating expenses (including network maintenance, treatment, wages and salaries, and administration and energy consumption) are relevant given the sunk cost nature of water infrastructure and the fact that while additions to capital over time are likely through renewal, the opposite (implying the decommissioning of infrastructure) is not. Coelli and Walding (2005) and Bhatttacharyya *et al*. (1994) also exclude the costs of fixed capital. As for the input prices and quantities on the right-hand side of the cost function, these also vary by study. For example, Aubert and Reynaud (2005) and da Silva e Souza *et al*. (2007) specify the input prices and quantities of labour and electricity; Filippini *et al*. (2008) adds materials; and Fraquelli and Moiso (2005) further include the price and quantities of services and capital. The obvious advantage of a fuller specification is that the estimated results can elaborate most fully on allocative efficiency and its source(s).

By its nature, DEA is unconstrained by the actual specification of inputs. This means that researchers can specify inputs in, say, money and/or quantity and/or percentage or ratio terms in a single analysis. For example, Lambert *et al*. (1993) specify inputs as the amounts of labour, energy, and materials used, while Garcia-Sanchez (2006) includes the number of staff and the number of treatment works. For the most part, however, many DEA studies restrict themselves to a single input (likely because of data availability) in the form of operating expenditure (Cubbin and Tzanidikas 1998, Thanassoulis 2000, Kirkpatrick *et al*. 2006, Garcia-Valinas and Muniz 2007, Byrnes *et al*. 2010). Nevertheless, there are also some attempts to divide expenditures more finely into operating and capital costs (Saal and Parker 2006), labour and non-labour operating and capital costs (Tupper and Resende 2004), operating and maintenance costs (Kirkpatrick *et al*. 2006), or even personnel, electricity, materials, chemicals, outside services and wastewater treatment costs (Andwandter and Ozuna 2002). In an unusual alternative, Guder *et al*. (2009) specify revenue as the single input in their study of German water utilities. Typically, revenue efficiency focuses on errors in the choice of output mix, such as too little output. By specifying revenue as an input, Guder *et al*. (2009) may instead be attempting to proxy for costs by assuming zero profits.

Somewhat confusingly, a number of DEA studies also specify variables as inputs that elsewhere serve as outputs. For example, in their analysis of water and sewerage companies in England and Wales, Erbetta and Cave (2006) specify the number of household and non-household connections as inputs, while Munisamy (2010) includes network length and the volume of non-revenue water in a study of Malaysian water supply authorities. This is primarily a reflection of alternative means for controlling for non-discretionary inputs and outputs, that is, inputs and outputs beyond the direct control of management, either at all (e.g. water quality standards and environmental and structural factors) or during the sample period (i.e. an input that cannot be changed in the short run but can in the long run). There are two main approaches available for dealing with non-discretionary inputs and outputs.

The first approach, now common in many DEA software programs, is where we modify the input (or output) orientated envelope program so that we only include non-discretionary inputs (outputs) in deciding the efficiency improvements possible relative to benchmark. The second approach combines DEA and regression in two stages. In the first stage, we use DEA to obtain efficiencies without including non-discretionary inputs (or outputs). The resulting efficiencies are then regressed on the non-discretionary factors to filter their effects on the efficiency scores and the regression residuals provide the final regression score (Ramanathan 2004). As shown in Table 1, this approach is substantially more common in the urban water utility literature, including applications by Tupper and Resende (2004), Woodbury and Dollery (2004), Erbetta and Cave (2006), Garcia-Sanchez (2006), Guder *et al*. (2009), Reznetti and Dupont (2009) and Byrnes *et al*. (2010).

6. Ownership and regulation

Alongside the empirical research into the measurement of efficiency in urban water utilities, there has been an at least equal amount of attention directed to the factors influencing efficiency. Very often, these involve the use of descriptive statistics and parametric and non-parametric tests of efficiency differences between different types or attributes of water utilities. The other equally common approach is the specification of the estimated or calculated efficiencies as dependent variables in ordinary least squares, logistic, Tobit, probit and seemingly unrelated regression models. We have already partly discussed this in relation to the attempts to purge efficiency scores of confounding factors or at least better appreciate the possible efficiency effects of non-discretionary inputs/outputs, especially those concerning the structure of the sector and the role of environmental factors.

Overwhelmingly, the main objective of many urban water utility studies of efficiency has been to examine the role of ownership and regulation. Obviously, this well serves the policy purposes of water utility regulators in deciding among other things the preferred mix of private and public ownership and the impact of regulation, including standards and pricing. In terms of the first area, much of the literature has examined the argument that privately owned water utilities are relatively more efficient than publicly-owned water utilities [see, for example, Lynk (1993), Lambert et al. (1993), Bhattacharyya et al. (1995), Estache and Ross (2002), Kirkpatrick *et al*. (2006), da Silva e Souza *et al*. (2007), and Munisamy (2010)]. This fittingly parallels an equally sizeable literature examining efficiency differences using non-frontier techniques [see, for instance, da Silva e Souza *et al*. (2008) and Faria *et al*. (2005)].

Unfortunately, the results arising from both the frontier and non-frontier approaches are somewhat mixed, with no clear consensus emerging on the relative efficiency of private over public water utilities. For example, in the US Bhattacharyya *et al*. (1995) counter intuitively finds that publicly-owned water utilities are more efficient, while Garcia-Sanchez (2006) concludes there is no significant difference between publicly and privately-owned utilities in Spain. A similar pattern appears to hold in the developing world. For instance, in a wide-ranging cost frontier analysis of 50 water utilities across 19 Asia-Pacific countries, Estache and Rossi (2001) found no strong evidence that private providers were more efficient than public operators (in fact, county-level corruption and governance were found to be more important in explaining the efficiency of individual utilities).

Likewise, Kirkpatrick *et al*. (2006) considered 110 water utilities across 13 African countries and employed both DEA and SFA to study whether state-owned utilities in Africa outperformed those involving at least some private capital. The results were very weak: while DEA pointed tentatively to the superiority of the private sector and the SFA provided some evidence that state-owned utilities were cost efficient, none of the efficiency differences was statistically significant. Lastly, in Malaysia, Munisamy (2010) concluded that while privately owned utilities were slightly less efficient in terms of overall technical efficiency, after excluding scale effects, there was no difference in the level of pure technical efficiency.

Instead of comparing public and private water utilities operating at the same point of time, a second but rather narrowly focused body of work considers the impact of privatisation on the efficiency and productivity of the sector, mostly in the UK. Following the privatisation of water utilities in England and Wales in 1989, Saal and Parker (2000, 2001) cite arguments in early (non-frontier) studies that privatisation should improve efficiency based on a number of arguments. These include the premise that privatisation removes soft-budget constraints and any political or special interest group interference associated with public ownership, exposes utilities to the market for corporate control, and incentivises management and employees with performance pay structures and the market for managerial talent.

Using cost function and TFP measures, Saal and Parker (2000, 2001) concluded that there was no statistically significant reduction in the trend growth rate of total costs following privatisation using the former and that privatisation had any impact on TFP in the latter. Estache and Trujillo (2003) employed a similar approach to examine Argentinean water and sewerage utilities and concluded TFP improvements, albeit with rather poor quality data, following privatisation. Later, Saal *et al*. (2007) used a cost frontier to re-examine English and Welsh water and sewerage utilities, arguing that this technique allowed more careful consideration of the productivity gains associated with privatisation. Importantly, while Saal *et al*. (2007) found that technological change improved after privatisation, productivity growth did not, and they attributed this to efficiency losses as firms struggled to come to terms with the new regulatory regime.

One challenge with these studies is the appropriate recognition of the differences in the underlying production technology. Consider a comparison of the efficiency of privately and publicly owned urban water utilities. While there are clear similarities in the specification of inputs and outputs for a water utility regardless of ownership, we can reasonably expect (and trust) that profit maximisation especially will play at least some role (even in a stakeholder model) in privately owned utilities. As a result, at the least the weights (or emphasis) these utilities place on particular inputs and outputs, and possibly the inclusion or exclusion of certain inputs and outputs, will differ from publicly owned firms and vice versa. This is not a trivial exercise and may mean that the production correspondence relating inputs and outputs in some firms will be misspecified, thereby rendering the measures of efficiency obtained invalid. This is especially likely in non-stochastic approaches, including DEA.

Now consider changes in efficiency or productivity arising from the full or partial privatisation of the entire sector, as in the UK. Here there may not only be problems in comparing the productive behaviour of utilities before and after privatisation but also the data gathered in the previous regime for public providers (even where commercialised) may be inconsistent with the data gathering process in even a heavily regulated sector. In fact, the quality and quantity of data gathered on urban water utilities has generally improved in all institutional milieus over time, and the policy desirability of comparing utility efficiency and productivity over time may lead researchers to re-engineer mistakenly past data drawn in different contexts and for different purposes to meet current data requirements. Some studies are more careful. For example, Saal *et al.* (2007) go to some effort when comparing the productivity of UK water and sewerage companies that the outputs of water, river and bathing quality are consistent in both the transitional/pre-privatisation (1985–90) and post-privatisation (1991–99) periods by using the quality-adjusted output measures in Saal and Parker (2000, 2001).

A final area applying frontier efficiency techniques focuses on the impact of regulation, primarily in public, though often commercialised, water utilities. For example, Andwandter and Ozuna (2002) measure the impact of public sector reforms as an alternative to privatisation in Mexico. Using DEA, they find that neither decentralisation to the municipal level nor the establishment of an autonomous regulator had a positive impact on the efficiency. Lastly, again in their 2001 non-frontier analysis, Saal and Parker (2001) hypothesise that a regulatory change of the price cap in 1995 led to a statistically significant change in performance at the industry and individual level for UK water and sewerage companies. Upon finding that the price cap review was not effective in generating efficiency gains, Saal and Parker (2001) conjectured this may have been because of diminishing returns to legally mandated environmental investment taking place at the same time, rather than regulatory failure per se.

7. Concluding remarks and directions for future research

As discussed, a small but steadily increasing amount of work using frontier efficiency techniques has been directed towards urban water utilities, primarily in the UK, but also in Australia, the US, Spain and elsewhere. The body of work surveyed in this article has provided useful insights into efficiency in this economically and developmentally important sector. We have also indicated how utilities operate in increasingly deregulated and demanding environments. However, there are at least several ways in which we could extend this research. First, there are few studies including urban water utilities from different countries. One difficulty with such an exercise is that the mixing of utilities from different contexts may potentially entail some problems in specifying a set of common behavioural objectives, even though the central purposes of water utilities are ubiquitous. However, once addressed, the results may offer useful insights into the varying impact of regulation, particularly quality standards and price capping. A related extension would be take advantage of the increasing availability of panel data to assess efficiency both within and across time, especially as so many existing studies rely on a single cross section.

Second, a more fundamental step would be to consult with industry and regulators on the precise nature of the behavioural objectives in urban water utilities. This would better inform all future studies of efficiency and productivity. Promising developments include the specification of customer satisfaction as an output by Byrnes et al. (2010). Nevertheless, researchers are commonly restricted in specifying inputs and outputs by the availability of comparative data often gathered by changing regulators and other bodies that may not be fully appropriate for efficiency and productivity measurement. A particular limitation in many contexts is that the input data especially are often poorly available and do not provide the fine detail required for useful analysis. That said, most outputs in past efficiency studies really serve only as (non-discretionary) controls, and future researchers need to address realistic and valuable qualitative outputs amenable to managerial control, including levels of customer satisfaction, water quality, the prevention of loss of supply, etc.

A final area of research would be to compare the efficiency measures obtained for the same set of urban water utilities from alternative approaches with different assumptions on the specification of inputs and outputs. As discussed, the underlying assumptions of the main efficiency techniques vary markedly, as potentially do the results obtained. Likewise, research elsewhere indicates some efficiency measurement techniques (especially DEA) are very sensitive to variable specification, further complicated by the naturally small number of water utilities in any one sector. Rigorous comparison of the techniques themselves and their outcomes may help facilitate their dissemination and acceptance by regulators, utilities, the public at large, and other stakeholders concerned with achieving efficient, reliable, and sustainable urban water supplies in the 21st century.

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Table 1. Selected empirical applications in urban water utilities.

Author(s)	Methodology[a]	Sample[b]	Specification[c]	Technique	Findings
Norman and Stoker (1991)	DEA	28 water-only companies, England and Wales, 1987/88.	Inputs: Manpower, power, chemical and others costs (including an allowance for capital renewal) Outputs: Potable water, properties supplied, average pumping head, length of mains, average peak. Input-orientated CRS.	Descriptive analysis.	Output quantities largely fixed, need to define measures of service quality.
Lambert, Dichev and Raffiee (1993)	DEA	238 public and 33 private utilities, US, 1989.	Inputs: Labour, energy used, materials used, Outputs: Capital value Wholesale and retail water delivered; Input-orientated VRS.	Descriptive analysis.	No significant differences in scale efficiencies between private and public utilities. Most inefficiency results from the overuse of capital.
Bhattacharyya, Harris, Narayanan and Raffiee (1995)	SFA	190 public and 31 private utilities, US, 1992.	Dependent: Variable costs. Independent: Volume of water; energy, labour, materials; water input produced or available for delivery, stock of capital; water input source (surface, ground, both), system loss, age of distribution pipelines, number of emergency breakdowns, length of distribution pipeline, customer type (residential or commercial).	Descriptive analysis.	Cost inefficiency higher in private utilities. Cost inefficiency also positively correlated with size and that major influence on cost inefficiency is breakdowns.
Cubbin and Tzanidakis (1998)	DEA	29 companies, England and Wales, 1992/93	Inputs: Operating expenditure. Outputs: Water delivered, length of mains, proportion of water delivered to non-households. Input-orientated CRS.	Descriptive analysis.	Regression analysis and DEA both suitable for measuring efficiency in water utilities.
Thanassoulis (2000)	DEA	21 water and sewerage companies, 10 water-only companies, England and Wales, 1992/93	Input: Operating expenditure. Outputs: Number of supply connections, length of main, amount of water delivered, measured water, unmeasured water, expenditure on volume. Input-orientated VRS.	Descriptive analysis	Comparison of DE measures of efficiency with efficiency estimates provided by industry regulator.
Anwandter and Ozuna (2002)	DEA	110 water utilities, Mexico, 1995.	Inputs: Personnel, electricity, materials, chemicals, outside services, other costs, specific wastewater treatment costs. Outputs: Water supply, primary treatment, secondary treatment. Non-discretionary inputs: Water losses (proxy for age of capital stock), population density, non-residential users. Input-orientated VRS.	Descriptive analysis, second-stage regression.	Decentralisation to the municipal level and appointment of autonomous regulator had no positive influence on efficiency in the absence of competition reform.

Author(s)	Methodology[a]	Sample[b]	Specification[c]	Technique	Findings
Estache and Rossi (2002)	SFA	50 water companies in 29 Asia-Pacific countries, 1995.	Dependent: Operational costs. Independent: Average salary, number of clients, daily production, number of connections, population density in area served, percentage of water from surface sources, number of hours of water availability per day, percentage of metered connections, qualitative treatment variables (chlorination, desalination)	Descriptive analysis.	Cost efficiency not significantly different in private and public sector utilities.
Thanassoulis (2002)	DEA	10 water and sewerage companies, England and Wales, 1994	Inputs: Operating expenditure. Outputs: resident population, length of sewer pipes, size of area served, capacity of pumping in sewerage network. Input-orientated CRS.	Descriptive analysis.	Highlighting of generic influences on efficiency measurement and use of comparative measures.
Bottasso and Conti (2003)	SFA	10 water and sewerage companies, 12 water-only companies, England and Wales, 1995–2001	Dependent: Operational expenditure. Independent: Water delivered, price of labour and capital. Explanatory: Sewerage dummy, length of mains, average pumping head, proportion of river sources on total water sources, population density, volume of water introduced into the distribution system.	Descriptive analysis.	Operating costs inefficiency has decreased over time with inefficiency differential between firms narrowing. Technical and structural requirements impact on cost efficiency.
Tupper and Resende (2004)	DEA	20 Brazilian water and sewerage utilities, 1996–2000	Inputs: Labour costs, operational costs, capital costs. Outputs: Water produced treated sewerage, population served-water, population served-treated sewage. Output-orientated VRS.	Descriptive analysis, second-stage regression.	Network densities and accounted-for water ratio influence efficiency.
Woodbury and Dollery (2004)	DEA and MI	73 water supply authorities, New South Wales, Australia, 1999–2000	Inputs: Management, maintenance and operation, energy and chemical, and capital replacement costs. Outputs: Number of assessments (services to properties), annual water consumption, water quality index (compliance with chemical and physical requirement and microbiological requirements, water service index (water quality complaints, service complaints and average customer outage). Non-discretionary inputs: Population, properties per kilometre of main, location, rainfall, percentage residential, unfiltered water, groundwater.	Descriptive analysis, second-stage regression.	Technical inefficiencies more substantial than scale inefficiencies. Need for inclusion of service quality outputs.
Aubert and Reynaud (2005)	SFA	211 water utilities, Wisconsin, 1998–2000.	Dependent: Variable costs. Independent: Volume of water sold, number of customers, price of labour and electricity, amount of capital, dummies for water purchased, surface water and average pumping depth.	Descriptive analysis.	Efficiency scores partly explainable by regulatory framework.

Author(s)	Methodology[a]	Sample[b]	Specification[c]	Technique	Findings
Fraquelli and Moiso (2005)	SFA	18 territorial regions, Italy, 1975–2005	Dependent: Total costs. Independent: Network length, number of employees, population served, ratio of population to network length, labour, electricity, materials, services and capital costs.	Descriptive analysis.	Inefficiency partly explained by network characteristics.
Coelli and Walding (2006)	DEA and MI	Australia, 18 water services businesses, 1995/96 to 2002/03	Inputs: Operating and capital expenditure. Outputs: Number of properties connected, volume of water delivered. Input-orientated CRS.	Descriptive analysis.	Need for improvement in specification of capital and provision of water industry price deflators.
Erbetta and Cave (2006)	DEA	10 water and sewerage companies, England and Wales, 1993–2005	Inputs: Number of household and non-household water connections, number of household and non-household sewerage connections, physical amount of wastewater, labour, other operating expenditure, capital expenditure. Outputs: Volume of delivered potable and non-potable water. Non-discretionary inputs: Water losses, water population density, sewerage population density, time trend, regulatory change dummies. Input-orientated VRS.	Descriptive analysis, second-stage regression.	Regulatory change promoted reduction in technical inefficiency. Price-cap regulation brings inputs closer to their cost-minimising level. Environmental factors influence observed efficiency.
García - Sánchez (2006)	DEA	24 Spanish water utilities, 1999.	Inputs: Staff, treatment plants, delivery network. Outputs: Water delivered, number of connections, chemical analyses performed. Non-discretionary inputs: Population, persons per household, municipal area, tourist index, average temperature, income, area of greenbelts, economic activity, number of houses, population density. Input-orientated VRS.	Second-stage regression.	Network and population density has a significant influence on efficiency.
Kirkpatrick, Parker and Zhang (2006)	SFA and DEA	110 public and private water utilities, Africa, 2000.	Dependent/Input: Operating and maintenance expenditure. Independent: Labour price, material price of water distributed, number of water treatment works. Output: Water delivered, hours of piped water per day. Input-orientated VRS.	Descriptive analysis.	No evidence of better performance of private utilities over state-owned utilities. Impact of water technology, transactions costs and regulation on efficiency scores.

Author(s)	Methodology[a]	Sample[b]	Specification[c]	Technique	Findings
Saal and Parker (2006)	MI and SFA	10 public regional water authorities and 29 private statutory water and sewerage companies, England and Wales, 1993-2003.	Inputs: Inputs: fixed physical capital, operating expenditure. Outputs: Water delivered and number of connected properties. Non-discretionary inputs: population served per kilometre length of mains (density), average pumping head and average quality compliance, dummy for water and sewerage company. Input-orientated CRS and VRS.	Descriptive analysis.	Scope for use of techniques in measuring operational efficiency. Inappropriate to assume water authorities and water and sewerage companies share a common frontier.
da Silva e Souza, Coelho de Faria and Moreira (2007)	SFA	149 public and 15 private companies, Brazil 2002	Dependent: Average costs. Independent: Volume of water produced, prices of capital and labour, average tariff. Explanatory: Private and public utilities, population density, percentage of above ground water sources, regional dummies.	Single-stage regression.	No evidence that private and public utilities differ in estimated efficiency. Significant impact of environmental factors.
García-Valiñas and Muñiz (2007)	DEA	3 water supplying municipalities, Spain, 1985–2000.	Input: Operational expenditures. Output: Volume of water delivered, length of mains, population supplied. Non-discretionary input: Rainfall. Input-orientated CRS.	Descriptive analysis.	Inclusion of non-discretionary factors increases observed level of efficiency.
Saal, Parker and Weyman-Jones (2007)	SFA	England and Wales, 10 water and sewerage companies, 1985–2000	Dependent: Water customers, connections with sewerage customers, physical water supply, physical sewerage load; quality adjustment indices (water and sewerage). Independent: Capital stock, current cost operating profits less current cost depreciation, infrastructure renewal expenditures, non-capitalised employment, labour.	Descriptive analysis.	Technical change improved after privatisation but not productivity growth. Excessive size of water supply companies contributed negatively to productivity growth.
Filippini, Hrovatin, and Zoric (2008)	SFA	52 water utilities, Slovenia, 1997–2003	Dependent: Total annual cost. Independent: Prices of labour, capital and materials, water supplied, number of customers, size of service area, treatment dummy, dummies for surface water, groundwater and low water losses.	Descriptive analysis.	Inefficiency estimates depend on econometric specification. Diseconomies of scale in larger utilities.
Picazo-Tadeo, Sáez-Fernández, and González-Gómez. (2008)	DEA	40 Spanish water utilities (with 20 providing sewerage services), 2001.	Inputs: Delivery network, sewer network, labour, operational costs. Outputs: Population served, water delivered, treated sewage. Output-orientated CRS.	Descriptive analysis.	Accounted-for water does not influence ranking of utilities. Quality matters in measuring technical efficiency.

Author(s)	Methodology[a]	Sample[b]	Specification[c]	Technique	Findings
Guder, Kittlaus, Moll, Walter and Zschille (2009)	DEA	373 water utilities, Germany, 2006.	Input: Total revenue. Outputs: Number of water meters, water delivered to households and non-households (industrial and other), network length, population. Non-discretionary inputs: Length of network, leak ratio, groundwater ratio, elevation differences, dummy for former East Germany. Input-orientated CRS and VRS.	Second stage regression.	Substantial differences in technical inefficiency after inclusion of structural factors. Network density and share of groundwater negatively influence efficiency.
Reznetti and Dupont (2009)	DEA	64 Canadian water utilities, 1996.	Inputs: Labour costs, materials costs, delivery network. Outputs: Water delivered. Non-discretionary inputs: Extreme temperatures, precipitation, dummy for surface water, population density, elevation, proportion of residential demand, number of dwellings. Input-orientated VRS.	Second-stage regression.	Differences in elevation, population density, and proportion of residential water use private dwelling have significant impact on efficiency.
Byrnes, Crase, Dollery and Villano (2010)	MI	14 Victorian water utilities and 38 NSW water utilities, 2000–04.	Input: Total operating costs. Outputs: Complaints index and total potable water delivered. Non-discretionary inputs: Proportion of residential consumption, water losses, production density, customer density, large and very large utilities, share of groundwater, filtration and reticulation dummies, dam maintenance, temperature, rain days, rainfall, rainfall intensity, state identifier, yearly dummies.	Second-stage regression.	Water restrictions reduce efficiency and larger utilities characterised by higher efficiency.
Munisamy (2010)	DEA	6 water supply authorities and 11 privatised water companies, Malaysia, 2005.	Inputs: Operating expenditure, network length, volume of non-revenue water. Outputs: Volume of water delivered, number of connections, size of service area. Input-orientated CRS and VRS.	Descriptive analysis.	Scale inefficiencies in (smaller) private sector utilities, technical inefficiencies in public providers.

Notes: (a) DEA – Data Envelopment Analysis, SFA – Stochastic Frontier Analysis, MI – Malmquist Indices, CRS – constant returns-to-scale, VRS – variable returns-to-scale; (b) Single dates are calendar or financial year cross-sections, intervals are time-series; (c) Specification SFA comprises dependent, independent and explanatory variables, DEA and MI is discretionary input(s), discretionary output(s) and non-discretionary input(s); (d) All SFA studies usually discuss the estimated coefficients, significance and elasticities for the production and cost parameters, as well as the measures of efficiency obtained. Descriptive analysis includes analysis of distributions (mean, standard deviations) and/or analysis of efficiency by groups within sample and correlation between efficiency scores obtained by different techniques. Second-stage regression involved regressing efficiency scores from DEA, MI, or SFA on additional explanatory variables in a separate regression (usually Tobit, probit or logit), single-stage regression refers to a stochastic frontier model where efficiency estimates are estimated simultaneously with the coefficients on the explanatory variables.