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Assessment of smart-meter-enabled dynamic pricing at utility and river basin scale

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ABSTRACT

The advent of smart metering is set to revolutionize many aspects of the relationship between water utilities and their customers, and this includes the possibility of using time-varying water prices as a demand management strategy. These dynamic tariffs could promote water use efficiency by reflecting the variations of water demand, availability and delivery costs over time. This paper relates the potential benefits of dynamic water tariffs at the utility and basin scale, to their design across a range of timescales. On one end of the spectrum, sub-daily peak pricing shifts use away from peak hours in order to lower a utility's operational and capital expenses. On the other end, scarcity pricing factors in the variations of the marginal opportunity cost of water at weekly or longer timescales in the river basin where water is withdrawn. Dynamic pricing schemes that act across timescales can be devised to yield both types of benefits. The analysis estimates these benefits separately for Greater London (United Kingdom) and its 15 million inhabitants. Scarcity pricing implemented on a weekly timescale equates the marginal cost of residential water with estimates of the marginal economic values of environmental-recreational flows derived from tourism, property values, etc. Scarcity pricing during droughts could result in a 22 to 63% average reduction in environmental flow shortage whilst residential price increases would be capped at 150% of base levels. Yet, its ability to protect environmental flows could decrease in extreme shortage situations. The net present value of savings from peak pricing is conservatively evaluated approximately at £10 million for each initial percentage point in daily peak hour price increase.

INTRODUCTION

Smart metering is garnering increasing attention for its potential to bring about new ways of managing water demand (Boyle et al. 2013; Cominola et al. 2015a). Although volumetric water pricing is effective in controlling residential water demand (Olmstead and Stavins 2009; Grafton et al. 2011) when consumers have regular information on pricing (Gaudin 2006) and on their own consumption (Strong and Goemans 2015), residential water pricing policies are still generally based on fixed pricing schedules designed to cover average costs.

The advent of high-resolution smart water metering makes the design of daily and even hourly variable fares feasible (e.g., Vašak et al. 2014), contrary to ordinary metering that provides a measurement only when read manually. The information this generates can help users to understand how to modulate their daily water consumption for different end-uses such as showering, laundry, garden watering, etc., in order to manage their water bills. Indeed, high temporal resolution water consumption data retrieved from smart meters enables the extraction of end-use consumption data (e.g., Piga et al. 2016; Creaco et al. 2017) and to profile water customers' behaviors in response to external stimuli, including pricing schemes and awareness campaigns (e.g., Nguyen et al. 2013; Cominola et al. 2015b). This information could be conveyed either through regular water bills or real-time feedback provided by phone applications and/or in-home displays, prototypes of which are being conceived (e.g., Rizzoli et al. 2014).

The idea of time-differentiation of residential prices per unit consumed dates back to the 1970s in the electricity sector (e.g., Atkinson 1979). It soon led to the concept of "dynamic pricing", based on the idea that efficient pricing should, with a time resolution of an hour or less, equate power prices with the marginal (incremental) cost of producing electricity and conveying it through the grid (Rosenfeld et al. 1986). Since then, ever more sophisticated schemes have been proposed to manage demand during periods of peak loading in the power network (Herter 2007; Faruqui and Sergici 2010; Joskow and Wolfram 2012; Siano 2014).

Similar to power networks, water distribution infrastructure experiences stress at peak hour. Daily demand varies year-round, and within-day demand is generally characterized by morning and evening peaks (Lucas et al. 2010; Cole and Stewart 2013; Beal and Stewart 2014). Peak-hour demand during the days of highest consumption impacts the way the network design and the needs for capacity expansion. Different parameters exist in the literature to describe an annual maximum in daily demand, including peak day (Lucas et al. 2010; Beal and Stewart 2014; Gurung et al. 2015), peak week (Padula et al. 2013), or mean day maximum month (Gurung et al. 2014). Regardless of which is used, reducing peak demand leads to substantial financial savings at the utility scale (Cole et al. 2012; Gurung et al. 2014).

At the river basin scale, the marginal economic value of water evolves on weekly or longer timescales, which is much slower than for electricity due to the significant natural and artificial storage capacity that typically exists in water systems. Marginal water values increase when water becomes scarce, and therefore using rising water prices as a signal of this scarcity is an appealing way of promoting a more efficient allocation of a limited supply of water over time and across uses (Young 1996; Griffin 2006; Pulido-Velazquez et al. 2008; Ward and Pulido-Velazquez 2012; Pulido-Velazquez et al. 2013; Macian-Sorribes et al. 2015). One example where this approach has been backed by regulation is in Europe with the Water Framework Directive (European Union Commission 2000) and subsequent efforts (e.g., European Union Commission 2012), which promote the inclusion of environmental and resource costs in the calculation of recovery costs for water services. Such regulation also regards water pricing as an instrument to create incentives for efficient water use (Riegels et al. 2013). The concept of resource cost has been linked to the opportunity cost of water use under scarcity (Pulido-Velazquez et al. 2006; Heinz et al. 2007; Tilmant et al. 2008). In these circumstances, unadjusted water use would impose an opportunity cost on other users. Scarcity-induced pricing would signal this to residential users.

In order to help bridge the gap between the practice of residential water tariffs and the possibilities offered by smart metering, this paper links tariff design across a range of timescales to potential benefits at the utility and river basin scale. In particular, tariffs that use sub-daily price variations can be designed to yield benefits by reducing the cost of supply in distribution networks, whereas weekly or monthly variations are appropriate for scarcity pricing. This exploratory paper focuses on these two timescales separately, but readers should keep in mind that tariffs that mix these timescales might be able to yield benefits at both the utility and river basin scale. Tariff changes at annual or longer timescales to reflect investments that affect the supply-demand balance also have impacts at both organizational scales (Sahin et al. 2016), but they do not require the use of smart meters, and are therefore not the focus of this work.

The remaining sections are as follows. First, dynamic tariffs are presented through economic concepts. Following that, potential benefits at the scale of the utility and river basin are presented. They are then evaluated separately for London's water resource system. Finally, result implications and limitations are discussed, and concluding remarks are presented.

ECONOMICS OF TARIFF DESIGN

Managing demand through dynamic tariffs

Price changes from the baseline price p_0 to a new price p_1 can be used to manage demand over any arbitrary period of time – hour, day, week, etc. They aim to achieve a relative change X in demand D, with $X < 0$ in the case of a demand reduction:

$$\frac{D(p_1)}{D(p_0)} = 1 + X \tag{1}$$

This work uses the concept of price elasticity of demand to compare the relative proportions by which demand varies when price varies at the utility scale:

$$E(p) = \frac{dD/D}{dp/p} \tag{2}$$

This elasticity is generally negative, since demand typically decreases when prices increase. Besides, residential water demand is price inelastic, i.e., the relative change in water consumption is smaller than the relative change in price (Espey et al. 1997; Dalhuisen et al. 2003; Sebri 2014). Using equations (1) and (2), elasticity $E(p)$ determines the relationship between price change from p_0 to p_1 and the target demand change X:

$$\exp\left(\int_{p_0}^{p_1} E(p)\frac{dp}{p}\right) = 1 + X \tag{3}$$

This relationship is described by the demand curve (Figure 1).

Because residential water demand is price inelastic, immediate effects of a higher (lower) price are a revenue gain (loss) for utilities and a financial loss (gain) to customers as a whole, and diverse outcomes for the individual customers. Tariff design should therefore comprise a revenue target while ensuring the sustainable provision of water services. To ensure a revenue target while managing demand, it is sufficient for the marginal value of residential water to be at p_1 (Figure

1). For instance with a price increase, there is an excess revenue (black rectangle) which can be forsaken through tariff design not to increase overall payments by customers.

More generally, dynamic tariffs designed with efficiency objectives have regulatory, financial and social implications that should not be overlooked. For instance, tariffs should sustain utilities' financial flexibility in planning for an uncertain future (Hill and Symmonds 2011; Sahin et al. 2016), yet that should be balanced with the imperative of serving and protecting customers (Ofwat 2009).

Sub-daily demand shifting

Over smaller time frames such as a day – or a week if weekdays demand is shifted to weekends – some end-uses can be shifted from times where prices are higher towards times where they are lower. In theory, there can be an arbitrary number of different prices, but experience from the electricity sector indicates that the many users may be unwilling or unable to implement sophisticated scheduling strategies (Hubert and Grijalva 2012), which would thwart the objective of shifting demand. The simplest demand shifting tariffs, and the easiest to understand for customers, considers only two periods, with the objective of shifting demand from period 1 to period 2 (Figure 2).

Sub-daily demand shifting tariffs are expected to provoke a more elastic demand response than tariffs that apply over longer timescales (Cole et al. 2012), because over sub-daily timescales users can shift portions of their uses towards off-peak hours. Assuming elasticities E_1 and E_2 for both time periods, equation (3) also applies to demand shifting, and can be used to design a two-period tariff with a revenue target.

POTENTIAL BENEFITS OF DYNAMIC WATER PRICING

In principle, benefits are expected to come from efficient pricing, i.e., by defining residential prices according to the marginal cost of supply. Hydro-economic modeling (Harou et al. 2009) enables the computation of the opportunity cost of water in a river basin at weekly or longer timescales (Pulido-Velazquez et al. 2008; Pulido-Velazquez et al. 2013), but to the best of our knowledge, network engineers and water economists have yet to team up to produce methodologies that would evaluate the marginal cost function of peak demands in a pipe network. Therefore, utility-scale benefits focus instead on the direct financial and engineering impacts of reducing peak demand.

Utility-scale benefits

Reducing peak demand, e.g. through peak pricing, lowers the cost of a water distribution network operation, maintenance and expansion. It has the potential to reduce the size of new mains when a city expands and new areas have to be served (Carragher et al. 2012; Lucas et al. 2010), or during the replacement of leaky mains in network maintenance operations; both translate into financial savings. Alternatively, peak pricing can help delay investment in new mains, by postponing the date at which existing mains will no longer be able to handle a rising demand, and by lowering the risk of pipe bursts caused by high pressure. Pressure management is a recent subfield of water distribution network design and management (see e.g., Gomes et al. 2011; Vicente et al. 2016). Yet, available literature does not seem to address the potential impacts of reducing peak use on pressure management.

Besides, reducing peak demand is expected to reduce operational costs. It could lower peak-hour energy consumption because the daily morning and evenings water use peaks often correspond to times of peak-hour electricity tariffs. Therefore, if a utility does not have enough in-network water storage, it must incur higher energy costs to deliver water during peak time. Optimal pumping scheduling then becomes a significant source of savings (McCormick and Powell 2003; Martínez et al. 2007), and reducing peak use can add substantially to these operational savings. Alternatively, if a utility has enough in-network storage, but expects peak demand to grow, reducing peak use delays the investment in new in-network storage.

Basin-scale benefits

The opportunity cost of scarce water allocation over time and across uses can be determined from the marginal value of water (e.g., Pulido-Velazquez et al. 2008), which will depend on the cross-sectoral value of water, from all other uses – agricultural, industrial, environmental, etc. Net benefits from water allocation in a river basin are maximal when the net marginal benefits per additional unit of water are equal in all use sectors. For the case of two sectors, or when an efficient cross-sectoral price of water already exists for all non-residential uses, this equimarginality principle can be illustrated graphically (Figure 3; Young 1996) by representing the demand curves for residential (from upper left to lower bottom) and for other uses (from the right-hand axis).

In a non-scarcity situation (left panel on Figure 3), there is enough water for all competing uses, so water itself has no value. Then, residential water is delivered at its base volumetric rate p_0, which is typically a reflection of the utility's average costs in the common case where prices equal average cost. On the contrary, when there is water scarcity (right panel on Figure 3), the two curves are crossing, and the optimal allocation corresponds to the price given by their intersection – if prices reflect marginal opportunity costs. This price π represents the marginal economic value of water as a resource, also referred to by economists as its shadow value. Scarcity price p_s at the tap is then given by:

$$p_s = \pi + p_0 \tag{4}$$

Figure 3 along with equation (4) serve as a basis for determining cross-sectoral and residential water prices and associated consumptions.

GREATER LONDON APPLICATION: DATA AND METHODOLOGY

Context

London (UK) is an administrative entity comprising over 8.5 million (M) inhabitants, at the core of a metropolitan area topping 13M inhabitants. Population in that area is growing, fueling concerns about future water supplies in the Thames River basin, that is already classified as water stressed (Environment Agency 2007). These concerns have motivated Thames Water, the utility that serves most of Greater London, to launch a 15-year smart metering roll-out set to equip a sizable proportion of the 3.3M households they serve (Rasekh et al. 2016).

The purpose of this case-study is to give order-of-magnitude estimates of the possible concrete benefits of dynamic pricing, not to provide precise figures. This proof of concept is meant to help motivate water utilities and other stakeholders to consider these potential at utility- and basin-scale benefits. Another aim is to pinpoint what the data limitations are, so as to motivate the development of more accurate estimates. Data and code used in this section can be found on `https://github.com/charlesrouge/Dynamic_Pricing`.

Dynamic pricing and demand response

This application proposes an economic-engineering (Lund et al. 2006) approach for evaluating the benefits of smart-metered enabled dynamic pricing mechanisms. It considers two tariffs, a sub-daily peak pricing scheme aimed at reducing peak-hour residential demand for financial utility-scale benefits, and a scarcity pricing scheme with prices changing every week, and leading to a more efficient use of available water in the Thames River basin, especially when it comes to the environmental benefits of Thames waters.

Peak demand is generally peak-hour demand at the most use-intensive time of year, so that peak pricing can be achieved by shifting demand from a peak period 1 to an off-peak period 2 (similar to Figure 2), possibly combined with demand management during a well-identified period of exceptional peak demand. Scarcity pricing implements variable prices on a regular basis – e.g., weekly – to track the variations in water availability, and in water value.

The demand curve for residential water is derived using the point expansion method (Jenkins et al. 2003; Griffin 2006), assuming a constant price elasticity E in both assessments of peak and scarcity pricing. Equation (3) becomes:

$$p_1 = p_0 \cdot (1 + X)^{1/E} \tag{5}$$

where $p_0 = £2.05$ per m^3 is the total 2016 uniform volumetric water price by Thames Water (Thames Water 2015). In the absence of real-world trials for dynamic water tariffs such as those investigated in this London case-study, or of any indication of how smart metering and dynamic pricing may impact the price response, three time-invariant estimates of the price elasticity of water demand are used, $E - 0.3$, -0.4 and -0.5. They come from a recent study that introduced a new approach to extrapolate results from a meta-analysis of the price elasticity of residential demand (Marzano et al. 2017).

Partial estimation of utility-scale financial savings

There are gaps in the literature pertaining to impacts of lowered peak-hour demand, and the impacts of daily water demand variations on a water distribution network is still a topic of active research (Liu et al. 2016). Due to data availability, this London case study focuses exclusively on savings due to reduced expansion and replacement costs associated with reducing peak use. These savings have been estimated using the following steps.

First, lowered peak-hour demand has been analytically linked with reduced costs in mains expansions. Lucas et al. (2010) is one of few studies that explore this relationship. For a newly-built suburb of Melbourne, Australia, these authors design the water network according to different estimates of peak consumption. Using data from that work, we fitted a quadratic relationship between relative peak usage reduction and the relative cost of new mains (Figure 4). This quadratic fit is the simplest way to capture both the decreasing cost and the decreasing returns of peak demand reduction in the 0-50% range without overfitting the data. In a similar way, if mains have to be replaced, e.g. because they are leaky, lowering peak use might prompt water managers to replace such leaky existing pipes with smaller ones, in areas where consumption is not expected to grow in the future. London's Victorian mains were first installed in the late nineteenth and early twentieth century. Due to their age, they are leaky and need to be replaced in the decades to come.

Second, this evaluation extrapolates the quadratic relationship between peak use and investments in Figure 4 to both network expansion and replacement in London. This relationship is applied to the average per-property cost of mains installation or replacement, evaluated at £2,000 by two different ways, and confirmed by the figures from Lucas et al. (2010). One evaluation relies on an average cost per meter of mains, while the other comes from a per-property cost evaluation from different property types, then averaged thanks to a classification of property by type (Thames Water 2014). The data at the origin of these evaluations is confidential.

Third, this per-property evaluation of savings associated to peak pricing and resulting decrease in peak use is then multiplied by the number of properties for which mains expansion or replacement are needed each year to yield annual utility-wide benefits over a 45-year period (2016-2060). These numbers are derived from 1) population growth projections (Thames Water 2014) that are assumed to reflect the rate of construction of new properties for which new mains will be required, and 2) an estimate of the average rate of replacement of Victorian mains. These two latter numbers are expressed as a number of properties for which mains expansion or replacement are needed each year. Thus, a 200-year turnover is interpreted to be equivalent to installing new mains for 1/200 of properties on any given year. This very conservative estimate reflects the actual age of some of those mains – over 100 years old – while leading to conservative estimates on the savings potential of reducing peak use, which is appropriate for a proof-of-concept study. Computed estimates assume that all 3.3M properties existing in 2016 are equipped with smart meters and have a peak pricing tariff.

Finally, annual savings are computed over a 45-year period (2016-2060) to find the utility scale net present value (NPV) of savings, using the UK government's reference interest rate (3.5%; HM Treasury 2003). Parameter values are summarized in the second column of Table 1.

Basin model and scarcity pricing

The evaluation of the potential basin-scale benefits of scarcity pricing post-processes results from an adapted version of the IRAS-2010 rule-based simulation model by Matrosov et al. (2011) for the Thames Valley and Greater London (panel (a) of Figure 5). This model uses historical flows from 1920-2004 with a weekly time step, and combines them with projected demands for 2050. This scenario is supported by the fact that demand increase is expected to play a greater role than changes in supply by mid-century (Thames Water 2014).

In the IRAS-2010 model, water use restrictions are enforced there when LAS drops below certain levels which vary seasonally according to the Lower Thames Control Diagramme (Matrosov et al. 2011). These restrictions lower both London's water consumption, and the minimum Thames river flow requirement at Teddington weir upstream of London (panel (b) of Figure 5). This requirement reflects benefits such as navigation, recreational and environmental values, and reducing it implies losses to these sectors.

This analysis post-processes simulation results from the IRAS-2010 model. Scarcity pricing impacts are evaluated for the wide range of supply-demand conditions that arise over the course of the 85-year simulation. Scarcity pricing is used to efficiently reallocate water during each weekly timestep downstream of London's Aggregated Storage (LAS). For each time step, post-processing finds the unique efficient price π that equates the marginal environmental benefits of Thames flow below Teddington weir to the marginal value of "raw" water for residential use, similar to Figure 3 and equation (4). Yet, for many simulated weeks, results suggest different urban and environmental marginal prices (p_u and p_e), deduced by reporting the simulated allocation on the demand curves. These prices are made to converge towards the unique efficient price π through a simple dichotomic search that reduces the difference between p_u and p_e by a factor of at least two at each iteration (see Appendix I for details). In this way, water is allocated in an efficient way (the equimarginal principle holds) and the water allocated to both the river and the residential users by the IRAS-2010 simulation model is rebalanced on a week-by-week basis by post-processing.

Demand curves for both urban and environmental water uses are needed to post-process IRAS-2010 results and assess the possible impacts of scarcity pricing in London. The residential demand curve is derived from equation (5). The environmental demand curve represents the population's willingness to pay for different levels of environmental flows, and it has not been estimated for London yet. In this data-scarce context, a simple linear environmental demand curve approximation is used, which is consistent with previous theoretical studies (Yang et al. 2009; Giuliani et al. 2014). In this case it is sufficient to know the aggregate environmental benefits of river flow in the Thames in order to derive the whole demand curve. Environmental benefits are the area underneath the linear demand curve.

Parameterizing the demand curve is challenging because there are many ways in which river flows are valuable (Kulshreshtha and Gillies 1993). Two willingness-to-pay studies provide a similar evaluation of the environmental value of Thames River flows (Thames Water 2005; Eftec 2015). Both are based on stated-preference studies from respondents in the Thames Water region in the context of the construction of the Thames tideway tunnel, a large new infrastructure aimed at eliminating combined sewers overflow. They report an aggregate annual value of around £250M that encompasses a series of ecosystem services brought by the river thanks to this infrastructure. This annual aggregate value of £250M is interpreted as a lower bound for the ecosystem value of the Thames' water, and can therefore be used as a baseline value of environmental flows, and then disaggregated at the weekly time step. Specific ecosystem services used by a fraction of the population add to this total, but willingness to pay studies report comparatively much smaller value for these (e.g., £12M for angling, Peirson et al. 2001).

The value for flows in London's Thames River goes beyond ecosystem services and associated recreational benefits. For instance, riverfront location bolsters the value of both new and existing real-estate developments (Cassidy 2013). The river contributes both directly – cruises, touristic attractions, riverfront venues – and indirectly – through its place in popular culture – to tourism revenues, estimated at £15 billion a year from overnight visitors and up to £26 billion a year when accounting for day trips to London (Visit England 2016). Given the amounts at stake, even a minor contribution of a few percentage points to the value of riverfront development and to the revenues of tourism might represent several hundred £M. To investigate the possible implications for scarcity pricing, total values of instream flows worth £500M per year and £750M per year are compared to the base estimate of £250M per year.

GREATER LONDON APPLICATION: RESULTS

Financial savings from reducing peak use

The potential utility-scale financial impact on London of peak hour pricing is computed using the parameter values from the second column of Table 1. Results from Figure 6 suggest that price increases see diminishing returns, but that doubling or tripling peak prices could have an important impact both on peak consumption and on associated benefits. This ability to design and install less costly mains is estimated at around £100 to £200 per property NPV of savings – recall that there are 3.3 million properties. This figure is reasonable given NPV saving estimations of AUS \$20M for 30,000 properties in Mackay, Australia for a 10% reduction in monthly peak demand (Beal and Flynn 2014). These savings come from delayed network investment. Extrapolated over London and its 3.3M properties, this would correspond to £1 billion NPV, well over the £240M found by the calculation presented in this section.

A sensitivity analysis has been performed on the various parameters used for the calculations (Table 1). Results do not contradict the idea that the potential benefits of peak pricing might be worth evaluating further. Uncertainty about future population growth is particularly large (Thames Water 2014), and that translates into a large uncertainty affecting the benefits from less costly mains expansions, which could be almost negated if population growth is only 0.2%, or almost doubled if it reaches 1%; in both cases this has a major impact on the total potential benefits from peak pricing.

Environmental benefits of scarcity pricing in the Lower Thames basin

Scarcity pricing is post-processed from IRAS-2010 results for three annual values of environmental flows (£250M, £500M and £750M) and three values of the price elasticity of demand (E=-0.3, -0.4, -0.5). Recall that each elasticity value represents a possible price response; a combination of values of environmental flows and price elasticity defines a scenario. These nine distinct scarcity pricing scenarios are compared with the current rule-based management simulated with the IRAS-2010 simulation model, where environmental flows are reduced as levels drop in London's storage reservoirs. Results are summarized in Tables 2 and 3, and the modeled consequences of scarcity pricing on the 1943-1944 drought are presented in Figure 7.

Results illustrate that scarcity pricing would reduce environmental flow shortage overall. Shortage events happen almost 25% of the time during rule-based allocation simulations. In those weeks, scarcity pricing leads to 22% average decrease in shortage in the most unfavorable scenario (less elastic demand, lower value of environmental flows), a figure that raises up to 63% in the most favorable scenario. Environmental valuation scenarios have more impact on the results more than price elasticity scenarios, stressing the importance of properly valuing environmental flows. Scarcity pricing is more effective for events of mild severity than for situations of severe shortage (e.g, August to October 1944 on Figure 7). Then, residential consumers are willing to pay for water even at prices that deplete available water for the environment. This happens regardless of the parameter values chosen, which suggests that during severe drought events, scarcity pricing should sometimes be used alongside other regulatory instruments such as water usage restrictions, lest environmental flows become depleted.

When it comes to price increases, mild increases are very common but price increases over 50% happen infrequently, and occur more often when environmental flows are valued more. In fact, the sharpest price increases – around 150% for E=-0.3 – correspond to no-flow events in these simulations (see Figure 7). This implies that scarcity-induced price increases are limited in magnitude, since they become unnecessary once environmental flows have been depleted. In those situations, pricing would be complemented or even replaced by other regulatory tools.

DISCUSSION

This paper outlines the potential benefits at the utility and river basin scale of dynamic pricing, which can be implemented through price variations at a range of timescales. In particular, the case study application to London provides a proof of concept of the potential of those pricing mechanisms for reaching their objectives. Yet, the water sector is still in the early phases of smart metering diffusion and dynamic pricing implementation. Further assessment of the technological and institutional challenges raised by dynamic pricing will be necessary.

The development of smart metering takes place at a time when new avenues for engaging the public, and modeling their behaviors, are being explored (Fraternali et al. 2012). In particular, user modeling is seen as a promising tool to help designing personalized water demand management strategies with highly customized feedbacks (Cominola et al. 2015a; Cardell-Oliver et al. 2016). This can lead to reduced water consumption on its own (Sonderlund et al. 2016). For instance, individually targeted behavioral messages indicate an interesting potential for reducing or shifting residential peak diurnal daily water end-use demand 8-15% during the morning hours and 12-23% at night (Beal et al. 2016).

Dynamic pricing could therefore support comprehensive strategies that manage demand through a combination of customer engagement, awareness campaigns, detailed personalized feedback on consumptive behavior, gamification, etc (Harou et al. 2014). Beyond, the complementarity and respective roles of price and non-price instruments are topics of active research and debate (Michelsen et al. 1999; Inman and Jeffrey 2006; Olmstead and Stavins 2009; Garcia-Valiñas et al. 2015). However, while research on urban water pricing has made significant advances in recent years, greater efforts to collect data and to evaluate alternative regulatory approaches such as use regulations and other non-price instruments remain necessary (Worthington and Hoffman 2008; Katz et al. 2016).

The possible combinations of dynamic pricing with use regulation, awareness campaigns, and all the new ways to engage with residential users that are being made available, may have an effect on the price response. Likewise, the price elasticity of demand, which describes this response, is known to evolve over time after a price change (Dalhuisen et al. 2003). Until a dynamic water tariff is trialled in a real-world situation, it may seem bold to make assumptions about how the price response may be impacted by such factors as the time resolution of the tariff, the rhythm and magnitude of the price changes, or the interaction with other smart-metered-enabled technologies and policy tools. In addition, in sectors where dynamic pricing has been implemented, surveys of multiple trials (e.g. Faruqui and Sergici 2010, for the power sector) reveal that price response may depend on a number of sector- and location-specific factors. This stresses that one should be cautious with assumptions on the price response to dynamic water tariffs in a given context and location. At the same time, evaluating – and demonstrating – the potential benefits of dynamic pricing is a necessary step towards real-world implementation. Therefore, the approach taken in this paper is to evaluate dynamic pricing with simple, neutral assumptions on price response, e.g., by using several constant values for the price elasticity of demand (see e.g., Renzetti et al. 2015).

The case study application also shows the interest of extending environmental flow valuation to all instream usages (e.g. recreation, riverfront property valuation) in order to represent the interests of all stakeholders. Attempts by ecological and environmental economists to assess the value of protecting instream flow services are increasing and can provide valuable guidance in proposing reasonable scarcity charges. Overall these attempts focus on specific services, such as recreation (Duffield et al. 1992; Weber and Berrens 2006) and protection of aquatic fauna

(Berrens et al. 1996) or a wider combination of them (Loomis et al. 2000; Holmes et al. 2004). Possible improvements of instream flow services are highly location-specific, and wide in scope. Accordingly, the economic evaluation of direct and indirect resource uses should make use of qualitative, quantitative and monetary assessments (Eftec 2010), including spatial analysis tools and hydro-economic modeling.

In this work, scarcity pricing only looks at marginal water values given a total water allocation determined by system rules in a system with limited storage capacity. Yet, the value of water also depends on its future availability. Therefore, scarcity pricing could also be used to balance present and future allocation; this is already the case in some water-scarce river basins with substantial use of inter-temporal storage (Pulido-Velazquez et al. 2008; Pulido-Velazquez et al. 2013). In such cases, one must also account for the uncertain nature of future water availability (Tilmant et al. 2008; Macian-Sorribes et al. 2015).

CONCLUSIONS

This paper provided an economic engineering conceptual framework for smart meter-enabled dynamic pricing, a proof of concept application to London's water supply system and a discussion of some salient issues. It starts from the observation that dynamic tariffs can be implemented at a broad range of temporal scales, and that they may be beneficial at the utility and river basin scales.

Dynamic pricing can be used to pursue the objectives of scarcity pricing and peak pricing policies. Scarcity pricing uses tariffs that reflect the marginal opportunity cost given by the value of leaving water in the river for other uses, human or ecological. This pricing is efficient and leads to greater basin-wide benefits from water allocation. Contrary to enforcing demand reductions while charging water at the same fixed rate, it can also lead to water savings without hurting a utility's finances. Peak pricing uses demand shifting, and sometimes demand reduction, to reduce peak-hour demand. Since water distribution network are designed to handle demand peaks, these reductions lead to substantial savings in network design, maintenance and deferred expansion.

Application to London outlines the potential of both pricing schemes. Evaluated using historical flow data, scarcity pricing helped reduce environmental flow shortages in London by about half (22 to 63%) depending on the valuation of these flows and on the demand response. Corresponding residential price increases are relatively limited (prices at least doubled less than 2% of the time). Yet, economic instruments alone may not be able to protect environmental flows in situations of extreme scarcity. The benefits of peak pricing are in terms of network investment; doubling peak-hour prices could result in conservative estimate of savings of about £200 per property in NPV. These results underscore the potential of smart metering to enable demand management of large metropolitan areas which depend on nearby high value environments as their source of water. They also highlight the importance of bridging gaps in research and practice that hinder accurate evaluations of the benefits of dynamic pricing. Last but not least, dynamic pricing impacts utilities' costs and benefits in the long run, as peak pricing decreases costs and scarcity pricing might raise extra revenues. Dynamic tariffs could therefore be considered as long-term planning instruments by utilities.

ACKNOWLEDGMENTS

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APPENDIX I. FINDING EFFICIENT PRICE π

Let us assume that there is limited water availability between two sectors like on Figure 8, but the allocation is not efficient and favors a sector α above a sector β. Then, scarcity is more felt by the latter than by the former, and $p_\alpha < \pi < p_\beta$. To find π, the dichotomic search uses initial values $p_\alpha^0 = p_\alpha$ and $p_\beta^0 = p_\beta$, and then define $[p_\alpha^{k+1}, p_\beta^{k+1}]$ from $[p_\alpha^k, p_\beta^k]$ using $p^{k+1} = (p_\alpha^k + p_\beta^k)/2$ and the iterative formula:

$$p^{k+1} = \begin{cases} p_\alpha^{k+1} & \text{if} \quad p^{k+1} < \pi \\ p_\beta^{k+1} & \text{if} \quad p^{k+1} \geq \pi \end{cases} \tag{6}$$

Since the demand curves are monotonous, to a price p_α^{k+1} (or p_β^{k+1}) corresponds a unique way to allocate water. Equation (6) means to keep $p_\alpha^k < \pi < p_\beta^k$ for all iterations k of the search. Graphically (see Figure 8) this ensures that the points defined on the demand curves at iteration $k+1$ are within the "triangle" defined by A, B and C at iteration k. It is a smaller triangle, so we have $p_\alpha^k \leq p_\alpha^{k+1} < \pi < p_\beta^{k+1} \leq p_\beta^k$. Finally, equation guarantees that $p_\beta^{k+1} - p_\alpha^{k+1} \leq (p_\beta^k - p_\alpha^k)/2$, which guarantees the convergence of the search.

REFERENCES

Atkinson, S. E. (1979). "Responsiveness to time-of-day electricity pricing: First empirical results." *Journal of Econometrics*, 9, 79 – 95.

Beal, C. D. and Flynn, J. (2014). "The 2014 review of smart metering and intelligent water networks in australia and new zealand." *Report no.*, Report prepared for WSAA by the Smart Water Research Centre, Griffith University.

Beal, C. D., Gurung, T. R., and Stewart, R. A. (2016). "Demand-side management for supply-side efficiency: Modeling tailored strategies for reducing peak residential water demand." *Sustainable Production and Consumption*, 6, 1 – 11.

Beal, C. D. and Stewart, R. A. (2014). "Identifying residential water end uses underpinning peak day and peak hour demand." *Journal of Water Resources Planning and Management*, 140(7), 04014008.

Berrens, R. P., Ganderton, P., and Silva, C. L. (1996). "Valuing the protection of minimum instream flows in new mexico." *Journal of Agricultural and Resources Economics*.

Boyle, T., Giurco, D., Mukheibir, P., Liu, A., Moy, C., White, S., and Stewart, R. (2013). "Intelligent metering for urban water: A review." *Water*, 5(3), 1052.

Cardell-Oliver, R., Wang, J., and Gigney, H. (2016). "Smart meter analytics to pinpoint opportunities for reducing household water use." *J. Water Resour. Plann. Manage.*

Carragher, B. J., Stewart, R. A., and Beal, C. D. (2012). "Quantifying the influence of residential water appliance efficiency on average day diurnal demand patterns at an end use level: A precursor to optimised water service infrastructure planning." *Resources, Conservation and Recycling*, 62, 81 – 90.

Cassidy, R. (2013). "River, front and center." *Planning*, 79(1), 24–31.

Cole, G., O'Halloran, K., and Stewart, R. A. (2012). "Time of use tariffs: implications for water efficiency." *Water Science and Technology: Water Supply*, 12(1), 90–100.

Cole, G. and Stewart, R. A. (2013). "Smart meter enabled disaggregation of urban peak water demand: precursor to effective urban water planning." *Urban Water Journal*, 10(3), 174–194.

Cominola, A., Giuliani, M., Piga, D., Castelletti, A., and Rizzoli, A. (2015a). “Benefits and challenges of using smart meters for advancing residential water demand modeling and management: A review.” *Environmental Modelling & Software*, 72, 198 – 214.

Cominola, A., Giuliani, M., Piga, D., Castelletti, A., Rizzoli, A., and Anda, M. (2015b). “Modelling residential water consumers’ behaviors by feature selection and feature weighting.” *Proceedings of the 36th IAHR World Congress*, The Hague (the Netherlands) (28 June – 3 July).

Creaco, E., Blokker, M., and Buchberger, S. (2017). “Models for generating household water demand pulses: Literature review and comparison.” *Journal of Water Resources Planning and Management*, Just released.

Dalhuisen, J. M., Florax, R. J. G. M., de Groot, H. L. F., and PeterNijkamp (2003). “Price and income elasticities of residential water demand: A meta-analysis.” *Land Economics*, 79(2), 292–308.

Duffield, J. W., Neher, C. J., and Brown, T. C. (1992). “Recreation benefits of instream flow: Application to montana’s big hole and bitterroot rivers.” *Water Resources Research*, 28(9), 2169–2181.

Eftec (2010). “Scoping study on the economic (or non-market) valuation issues and the implementation of the wfd – final report.” *Report no.*, Defra.

Eftec (2015). “Update of the economic valuation of thames tideway tunnel environmental benefits. final report..” *Report no.*, Defra.

Environment Agency (2007). “Areas of water stress: final classification.” *Report no.*, GEHO1207BNOC-E-E. Bristol.

Espey, M., Espey, J., and Shaw, W. D. (1997). “Price elasticity of residential demand for water: A meta-analysis.” *Water Resources Research*, 33(6), 1369–1374.

European Union Commission (2000). “Directive 2000/60/ec of the european parliament and of the council of 23 october 2000 establishing a framework for community action in the field of water policy.” *Official J. L*, 327(1), 1–73.

European Union Commission (2012). “A blueprint to safeguard europe’s water resources, european commission, brussels, 14.11.2012." *COM*.

Faruqui, A. and Sergici, S. (2010). "Household response to dynamic pricing of electricity: a survey of 15 experiments." *Journal of Regulatory Economics*, 38(2), 193–225.

Fraternali, P., Castelletti, A., Soncini-Sessa, R., Ruiz, C. V., and Rizzoli, A. (2012). "Putting humans in the loop: Social computing for water resources management." *Environmental Modelling & Software*, 37, 68 – 77.

Garcia-Valiñas, M. A., Martínez-Espiñeira, R., and To, H. (2015). "The use of non-pricing instruments to manage residential water demand: What have we learned?." *Understanding and Managing Urban Water in Transition*, Springer Netherlands, 269–281.

Gaudin, S. (2006). "Effect of price information on residential water demand." *Applied Economics*, 38(4), 383–393.

Giuliani, M., Castelletti, A., Amigoni, F., and Cai, X. (2014). "Multiagent systems and distributed constraint reasoning for regulatory mechanism design in water management." *Journal of Water Resources Planning and Management*.

Gomes, R., Marques, A. S., and Sousa, J. (2011). "Estimation of the benefits yielded by pressure management in water distribution systems." *Urban Water Journal*, 8(2), 65–77.

Grafton, R. Q., Ward, M. B., To, H., and Kompas, T. (2011). "Determinants of residential water consumption: Evidence and analysis from a 10-country household survey." *Water Resources Research*, 47(8), n/a–n/a W08537.

Griffin, R. C. (2006). *Water Resource Economics. The Analysis of Scarcity, Policies, and Projects.* London, MIT press.

Gurung, T. R., Stewart, R. A., Beal, C. D., and Sharma, A. K. (2015). "Smart meter enabled water end-use demand data: platform for the enhanced infrastructure planning of contemporary urban water supply networks." *Journal of Cleaner Production*, 87, 642 – 654.

Gurung, T. R., Stewart, R. A., Sharma, A. K., and Beal, C. D. (2014). "Smart meters for enhanced water supply network modelling and infrastructure planning." *Resources, Conservation and Recycling*, 90, 34 – 50.

Harou, J., Garrone, P., Rizzoli, A., Maziotis, A., Castelletti, A., Fraternali, P., Novak, J., Wissmann-Alves, R., and Ceschi, P. (2014). “Smart metering, water pricing and social media to stimulate residential water efficiency: Opportunities for the smarth2o project.” *Procedia Engineering*, 89, 1037 – 1043 16th Water Distribution System Analysis Conference, {WDSA2014Urban} Water Hydroinformatics and Strategic Planning.

Harou, J. J., Pulido-Velazquez, M., Rosenberg, D. E., Medellín-Azuara, J., Lund, J. R., and Howitt, R. E. (2009). “Hydro-economic models: Concepts, design, applications, and future prospects.” *Journal of Hydrology*, 375, 627–643.

Heinz, I., Pulido-Velazquez, M., Lund, J. R., and Andreu, J. (2007). “Hydro-economic modeling in river basin management: Implications and applications for the european water framework directive.” *Water Resources Management*, 21(7), 1103–1125.

Herter, K. (2007). “Residential implementation of critical-peak pricing of electricity.” *Energy Policy*, 35(4), 2121 – 2130.

Hill, T. and Symmonds, G. (2011). “Sustained water conservation by combining incentives, data and rates to effect consumer behavioural change.” *WIT Transactions on Ecology and The Environment*.

HM Treasury (2003). “The green book on appraisal and evaluation in central government.” *Report no.*, UK Government.

Holmes, T. P., Bergstrom, J. C., Huszar, E., Kask, S. B., and III, F. O. (2004). “Contingent valuation, net marginal benefits, and the scale of riparian ecosystem restoration.” *Ecological Economics*, 49(1), 19 – 30.

Hubert, T. and Grijalva, S. (2012). “Modeling for residential electricity optimization in dynamic pricing environments.” *IEEE Transactions on Smart Grid*, 3(4), 224–231.

Inman, D. and Jeffrey, P. (2006). “A review of residential water conservation tool performance and influences on implementation effectiveness.” *Urban Water Journal*, 3(3), 127–143.

Jenkins, M. W., Lund, J. R., and Howitt, R. E. (2003). “Using economic loss functions to value urban water scarcity in california.” *J. Am. Water Works Assn.*, 95(2), 58–70.

Joskow, P. L. and Wolfram, C. D. (2012). “Dynamic pricing of electricity.” *American Economic Review*, 102(3), 381–85.

Katz, D., Grinstein, A., Kronrod, A., and Nisan, U. (2016). “Evaluating the effectiveness of a water conservation campaign: Combining experimental and field methods.” *Journal of Environmental Management*, 180, 335 – 343.

Kulshreshtha, S. and Gillies, J. (1993). “The economic value of the south saskatchewan river to the city of saskatoon: (i) valuation framework and value estimates for selected uses.” *Canadian Water Resources Journal / Revue canadienne des ressources hydriques*, 18(3), 199–215.

Liu, Y., Sun, F., Zeng, S., Lauzon, K., and Dong, X. (2016). “Integrated model driven by agent-based water end-use forecasting to evaluate the performance of water and wastewater pipeline systems.” *Journal of Water Resources Planning and Management*, 142(10).

Loomis, J., Kent, P., Strange, L., Fausch, K., and Covich, A. (2000). “Measuring the total economic value of restoring ecosystem services in an impaired river basin: results from a contingent valuation survey.” *Ecological Economics*, 33(1), 103 – 117.

Lucas, S. A., Coombes, P. J., and Sharma, A. K. (2010). “The impact of diurnal water use patterns, demand management and rainwater tanks on water supply network design.” *Water Science and Technology: Water Supply*, 10(1), 69–80.

Lund, J. R., Cai, X., and Characklis, G. W. (2006). “Economic engineering of environmental and water resource systems.” *Journal of Water Resources Planning and Management*, 132(6), 399–402.

Macian-Sorribes, H., Pulido-Velazquez, M., and Tilmant, A. (2015). “Definition of efficient scarcity-based water pricing policies through stochastic programming.” *Hydrology and Earth System Sciences*, 19(9), 3925–3935.

Martínez, F., Hernández, V., Alonso, J. M., Rao, Z., and Alvisi, S. (2007). “Optimizing the operation of the valencia water-distribution network.” *Journal of Hydroinformatics*, 9(1), 65–78.

Marzano, R., Rougé, C., Garrone, P., Grilli, L., Harou, J., and Pulido-Velazquez, M. (2017). “Data-driven explorations of the determinants of the price response to residential water tariffs:

meta-analysis and beyond." *Environmental Modelling & Software*, Submitted.

Matrosov, E. S., Harou, J. J., and Loucks, D. P. (2011). "A computationally efficient open-source water resource system simulator application to london and the thames basin." *Environmental Modelling & Software*, 26(12), 1599 – 1610.

McCormick, G. and Powell, R. S. (2003). "Optimal pump scheduling in water supply systems with maximum demand charges." *Journal of Water Resources Planning and Management*, 129(5), 372–379.

Michelsen, A. M., McGuckin, J. T., and Stumpf, D. (1999). "Nonprice water conservation programs as a demand management tool1." *JAWRA Journal of the American Water Resources Association*, 35(3), 593–602.

Nguyen, K. A., Zhang, H., and Stewart, R. A. (2013). "Development of an intelligent model to categorise residential water end use events." *Journal of Hydro-environment Research*, 7(3), 182 – 201.

Ofwat (2009). "Future water and sewerage charges 2010-15: Final determinations." *Report no.*, Ofwat, <http://www.ofwat.gov.uk/wp-content/uploads/2015/11/det_pr09_finalfull.pdf>.

Olmstead, S. M. and Stavins, R. N. (2009). "Comparing price and nonprice approaches to urban water conservation." *Water Resources Research*, 45(4), n/a–n/a W04301.

Padula, S., Harou, J., Papageorgiou, L., Ji, Y., Ahmad, M., and Hepworth, N. (2013). "Least economic cost regional water supply planning – optimising infrastructure investments and demand management for south east england's 17.6 million people." *Water Resources Management*, 27(15), 5017–5044.

Peirson, G., Tingley, D., Spurgeon, J., and Radford, A. (2001). "Economic evaluation of inland fisheries in england and wales." *Fisheries Management and Ecology*, 8(4-5), 415–424.

Piga, D., Cominola, A., Giuliani, M., Castelletti, A., and Rizzoli, A. E. (2016). "Sparse optimization for automated energy end use disaggregation." *IEEE Transactions on Control Systems Technology*, 24(3), 1044–1051.

Pulido-Velazquez, M., Alvarez-Mendiola, E., and Andreu, J. (2013). "Design of efficient water pricing policies integrating basinwide resource opportunity costs." *Journal of Water Resources Planning and Management*, 139(5), 583–592.

Pulido-Velazquez, M., Andreu, J., Sahuquillo, A., and Pulido-Velazquez, D. (2008). "Hydro-economic river basin modelling: The application of a holistic surface-groundwater model to assess opportunity costs of water use in spain." *Ecological Economics*, 66(1), 51 – 65 Special Section: Integrated Hydro-Economic Modelling for Effective and Sustainable Water Management.

Pulido-Velazquez, M., Joaquin, A., and Sahuquillo, A. (2006). "Economic optimization of conjunctive use of surface water and groundwater at the basin scale." *Journal of Water Resources Planning and Management*, 132(6).

Rasekh, A., Hassanzadeh, A., Mulchandani, S., Modi, S., and Banks, M. K. (2016). "Smart water networks and cyber security." *Journal of Water Resources Planning and Management*, 142(7), 01816004.

Renzetti, S., Brandes, O. M., Dupont, D. P., MacIntyre-Morris, T., and Stinchcombe, K. (2015). "Using demand elasticity as an alternative approach to modelling future community water demand under a conservation-oriented pricing system: An exploratory investigation." *Canadian Water Resources Journal / Revue canadienne des ressources hydriques*.

Riegels, N., Pulido-Velazquez, M., Doulgeris, C., Sturm, V., Jensen, R., Møller, F., and Bauer-Gottwein, P. (2013). "Systems analysis approach to the design of efficient water pricing policies under the eu water framework directive." *Journal of Water Resources Planning and Management*, 139(5), 574–582.

Rizzoli, A., Castelletti, A., Cominola, A., Fraternali, P., Diniz dos Santos, A., Storni, B., Wissmann-Alves, R., Bertocchi, M., Novak, J., and Micheel, I. (2014). "The SmartH2O project and the role of social computing in promoting efficient residential water use : a first analysis." *Proceedings of the 7th International Congress on Environmental Modelling and Software*, D. Ames, N. Quinn, and A. Rizzoli, eds., Manno, iEMSs, Manno, Switzerland.

Rosenfeld, A. H., Bulleit, D. A., and Peddie, R. A. (1986). "Smart meters and spot pricing:

Experiments and potential." *IEEE Technology and Society Magazine*, 5(1), 23–28.

Sahin, O., Siems, R., Stewart, R., and Porter, M. G. (2016). "Paradigm shift to enhanced water supply planning through augmented grids, scarcity pricing and adaptive factory water: A system dynamics approach." *Environmental Modelling & Software*, 75, 348 – 361.

Sebri, M. (2014). "A meta-analysis of residential water demand studies." *Environment, Development and Sustainability*, 16(3), 499–520.

Siano, P. (2014). "Demand response and smart grids – a survey." *Renewable and Sustainable Energy Reviews*, 30, 461 – 478.

Sonderlund, A. L., Smith, J. R., Hutton, C. J., Kapelan, Z., and Savic, D. (2016). "Effectiveness of smart meter-based consumption feedback in curbing household water use: Knowns and unknowns." *Journal of Water Resources Planning and Management*, 142(12).

Strong, A. and Goemans, C. (2015). "The impact of real-time quantity information on residential water demand." *Water Resources and Economics*, 10, 1 – 13.

Thames Water (2005). "Thames tideway strategic study. cost benefit working group report.

Thames Water (2014). "Final water resources management plan 2015-2040.

Thames Water (2015). *Our Charges for household customers 2015/16*, <http://www.thameswater.co.uk/tw/common/downloads/literature-water-waste-water-charges/Our_Charges_2015-16_

Tilmant, A., Pinte, D., and Goor, Q. (2008). "Assessing marginal water values in multipurpose multireservoir systems via stochastic programming." *Water Resources Research*, 44, W12431, doi:10.1029/2008WR007024.

Vašak, M., Banjac, G., Baotić, M., and Matuško, J. (2014). "Dynamic day-ahead water pricing based on smart metering and demand prediction." *Procedia Engineering*, 89, 1031 – 1036.

Vicente, D. J., Garrote, L., Sánchez, R., and Santillán, D. (2016). "Pressure management in water distribution systems: Current status, proposals, and future trends." *Journal of Water Resources Planning and Management*, 142(2), 04015061.

Visit England (2016). "England tourism factsheet – april 2016.

Ward, F. A. and Pulido-Velazquez, M. (2012). "Economic costs of sustaining water supplies: Findings from the rio grande." *Water Resources Management*, 26(10), 2883–2909.

Weber, M. A. and Berrens, R. P. (2006). "Value of instream recreation in the sonoran desert." *Journal of Water Resources Planning and Management*, 132(1), 53–60.

Worthington, A. C. and Hoffman, M. (2008). "An empirical survey of residential water demand modelling." *Journal of Economic Surveys*, 22(5), 842–871.

Yang, Y.-C. E., Cai, X., and Stipanović, D. M. (2009). "A decentralized optimization algorithm for multiagent system-based watershed management." *Water Resources Research*, 45(8).

Young, R. A. (1996). "Water economics." *Water Resources Handbook*, L. W. Mays, ed., McGraw-Hill Education - Europe, Chapter 3.

List of Tables

Parameter	Value		Benefit sensitivity (20% price increase)	
	Average	Range ($\pm X$)	$+X$	$-X$
Price elasticity of demand	-0.4	±0.1%	-23%	+22%
Annual discount rate	3.5%	±1%	-15%	+19%
Per-property cost of mains	£2,000	± £500	+25%	25%
Annual population growth	0.6%	±0.4	+46%	-41%
Annual mains replacement rate	0.5%	±0.2	+18%	-18%

TABLE 1

Parameter values	Scarcity pricing									**Rule-based allocation**
Value of environmental flows	£250M/year			£500M/year			£750M/year			
Price elasticity of demand	-0.3	-0.4	-0.5	-0.3	-0.4	-0.5	-0.3	-0.4	-0.5	**(-)**
Average deficit (ML/day)	214	193	175	168	144	126	140	117	101	**275**
Events with flows under 400 ML/day										
Frequency of occurrence (weeks/year)	1.76	1.48	1.11	1.08	1.00	0.31	1.00	0.29	0.25	**5.29**
Number of events	10	10	9	9	7	6	7	5	5	**42**
Events with flows under 200 ML/day										
Frequency of occurrence (weeks/year)	0.69	0.29	0.26	0.26	0.22	0.20	0.22	0.20	0.19	**0.05**
Number of events	13	5	5	5	3	3	3	3	2	**3**
No-flow events										
Frequency of occurrence (weeks/year)	0.22	0.21	0.20	0.20	0.19	0.16	0.19	0.16	0.16	**0**
Number of events	3	3	3	3	2	4	2	4	4	**0**

TABLE 2

Parameter values	Scarcity pricing								
Value of environmental flows	£250M/year			£500M/year			£750M/year		
Price elasticity of demand	-0.3	-0.4	-0.5	-0.3	-0.4	-0.5	-0.3	-0.4	-0.5
10% residential price increase									
Frequency of occurrence (weeks/year)	10.7	10.6	10.6	10.8	10.7	10.7	10.8	10.7	10.7
Number of events	76	74	74	77	76	76	77	78	76
50% residential price increase									
Frequency of occurrence (weeks/year)	1.31	1.05	1.00	2.17	1.93	1.49	5.37	2.21	1.93
Number of events	8	7	7	15	11	10	41	17	11
100% residential price increase									
Frequency of occurrence (weeks/year)	0	0	0	1.00	0.29	0.25	1.28	1.00	0.31
Number of events	0	0	0	7	5	5	10	7	6
150% residential price increase									
Frequency of occurrence (weeks/year)	0	0	0	0.21	0.20	0.19	0.29	0.22	0.21
Number of events	0	0	0	3	3	2	5	3	3

TABLE 3

List of Figures

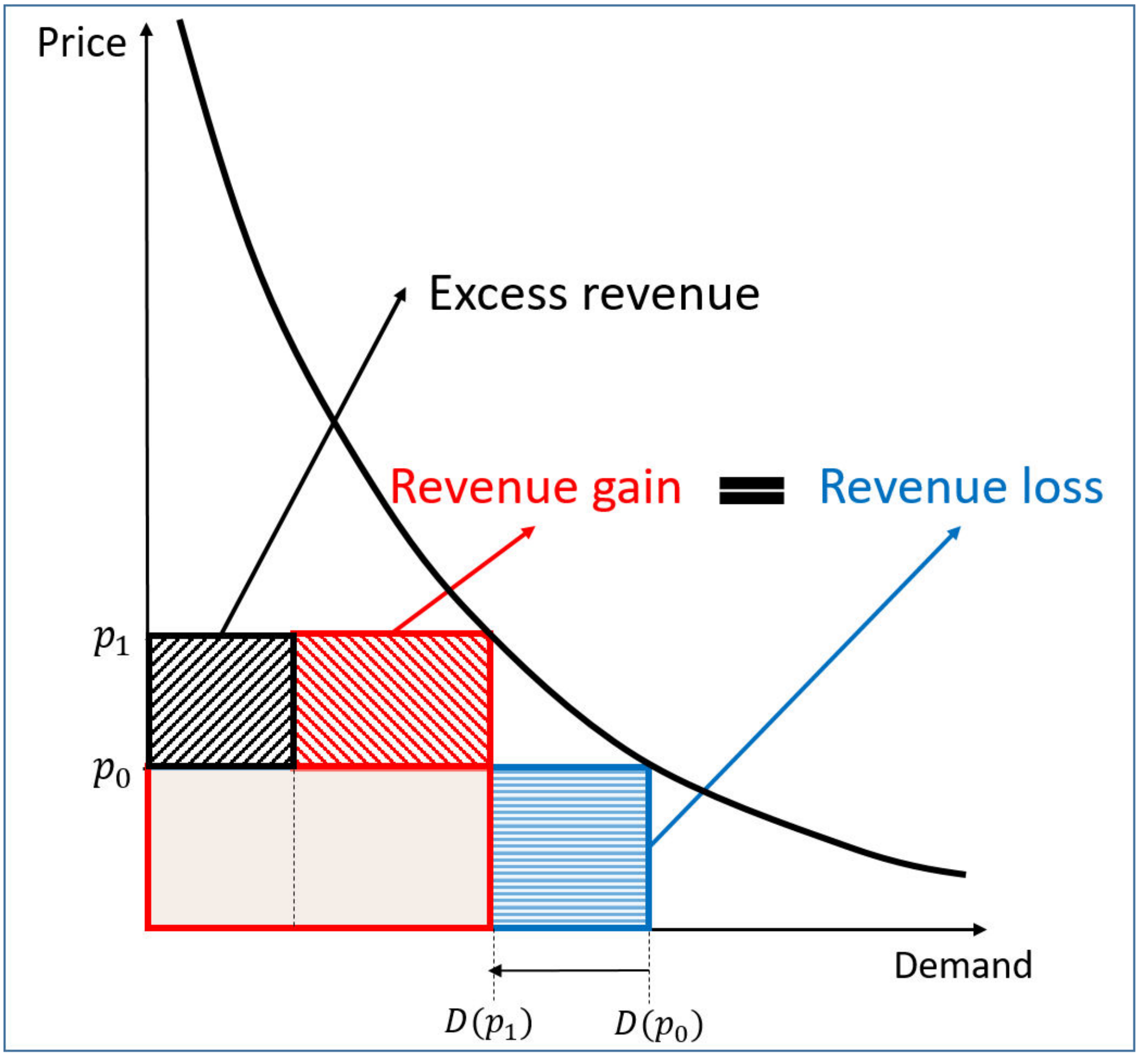

Price
Excess revenue
Revenue gain
Revenue loss
p_1
p_0
Demand
$D(p_1)$
$D(p_0)$

Fig. 1

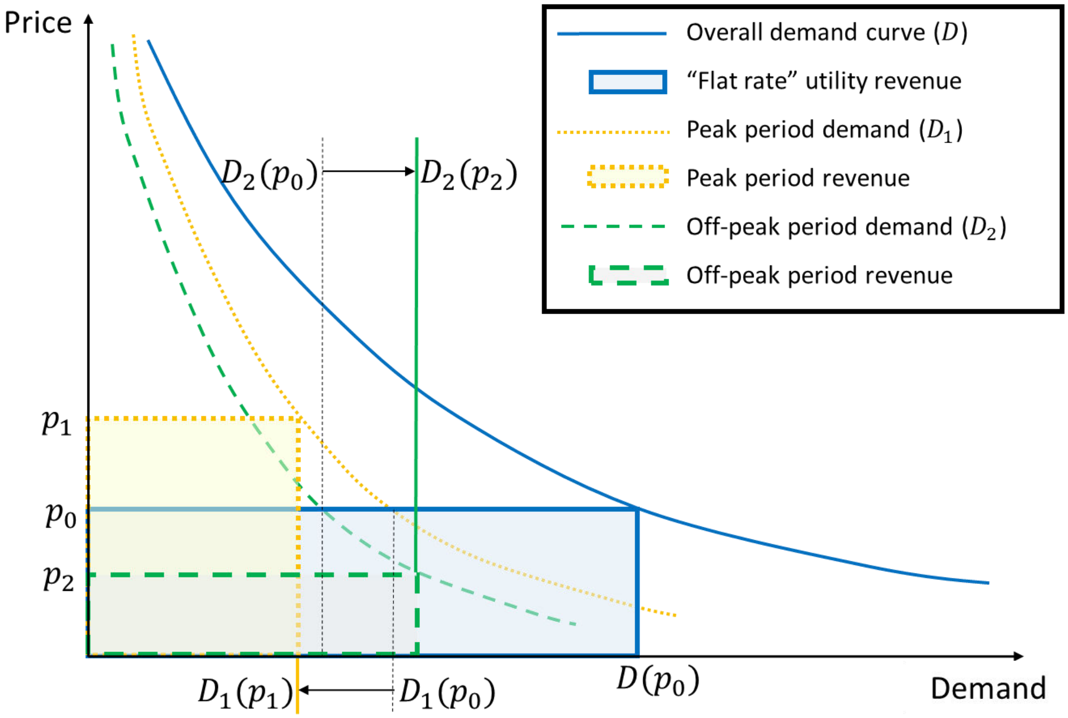

Price
Demand
p_1
p_0
p_2
$D_2(p_0)$
$D_2(p_2)$
$D_1(p_1)$
$D_1(p_0)$
$D(p_0)$
Overall demand curve (D)
"Flat rate" utility revenue
Peak period demand (D_1)
Peak period revenue
Off-peak period demand (D_2)
Off-peak period revenue

Fig. 2

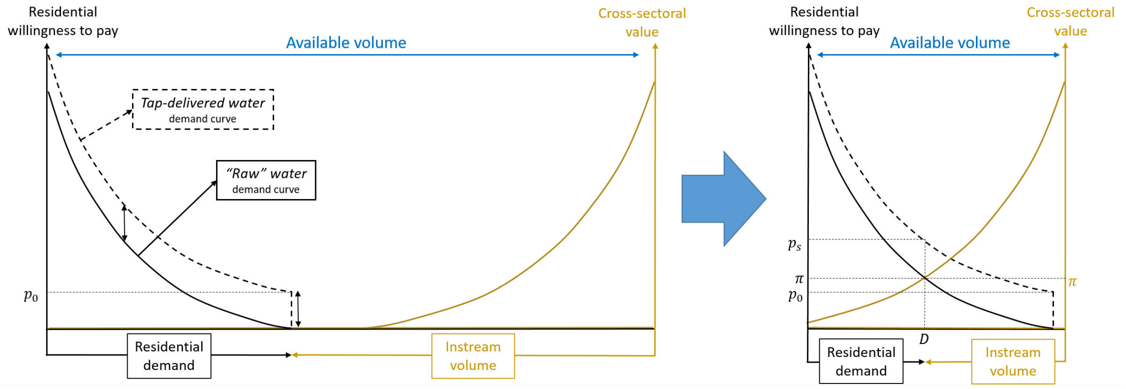
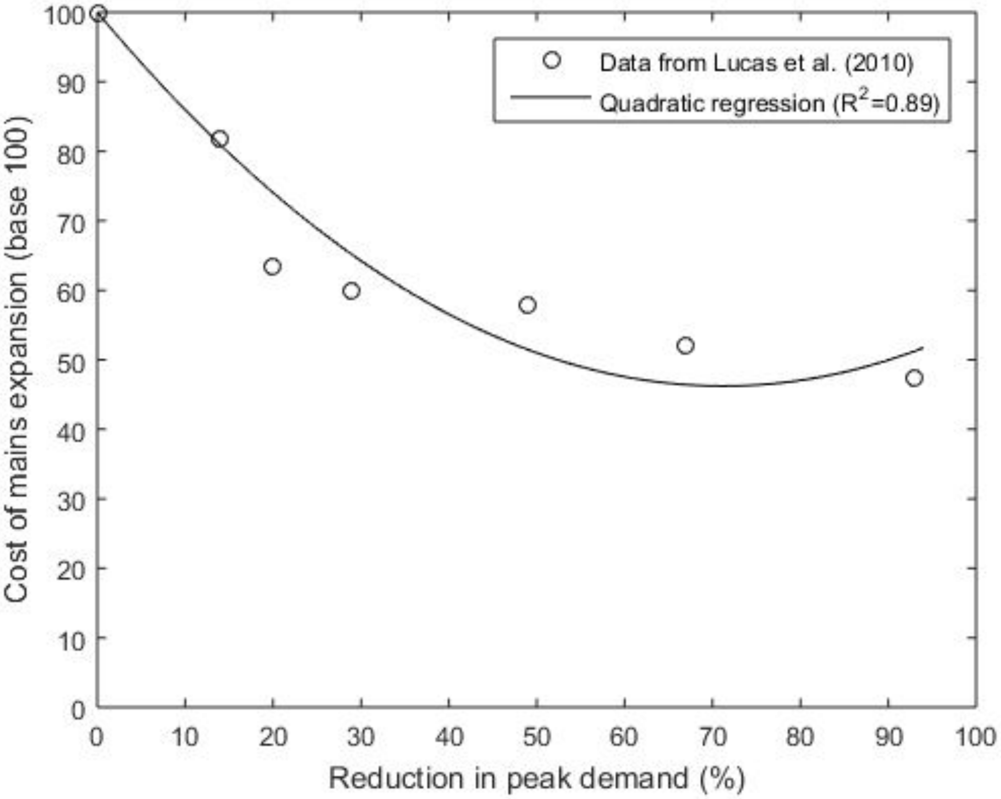

Residential willingness to pay
Available volume
Cross-sectoral value
Tap-delivered water demand curve
"Raw" water demand curve
p_0
Residential demand
Instream volume
Residential willingness to pay
Available volume
Cross-sectoral value
p_s
π
p_0
π
D
Residential demand
Instream volume

Fig. 3



100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Cost of mains expansion (base 100)
Reduction in peak demand (%)
Data from Lucas et al. (2010)
Quadratic regression (R2=0.89)

Fig. 4

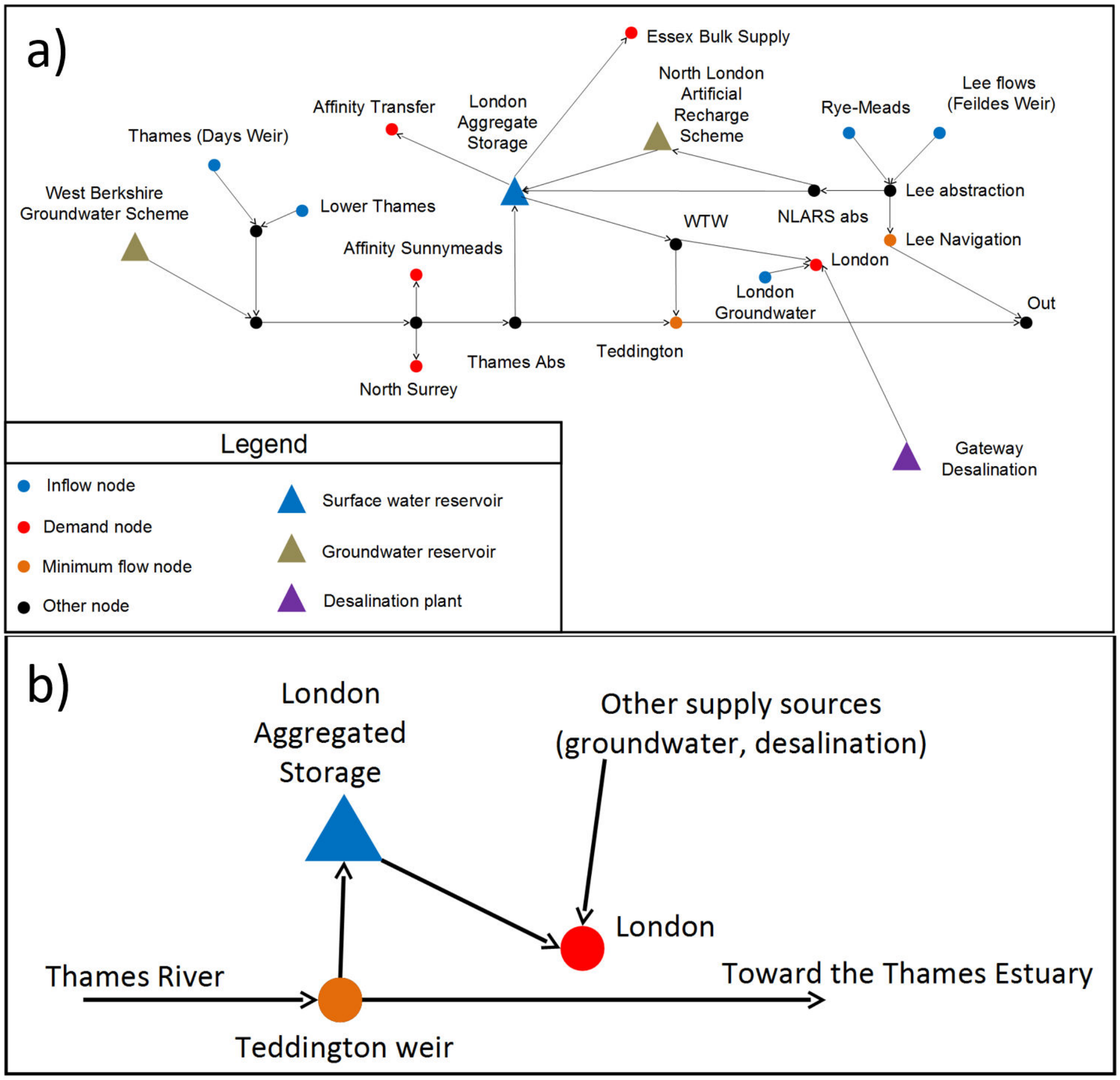

a)
Essex Bulk Supply
North London Artificial Recharge Scheme
Lee flows (Feildes Weir)
Rye-Meads
Affinity Transfer
London Aggregate Storage
Thames (Days Weir)
West Berkshire Groundwater Scheme
Lower Thames
Lee abstraction
NLARS abs
WTW
Lee Navigation
London
Affinity Sunnymeads
London Groundwater
Out
Thames Abs
Teddington
North Surrey
Gateway Desalination
Legend
Inflow node
Demand node
Minimum flow node
Other node
Surface water reservoir
Groundwater reservoir
Desalination plant
b)
London Aggregated Storage
Other supply sources (groundwater, desalination)
London
Thames River
Toward the Thames Estuary
Teddington weir

Fig. 5

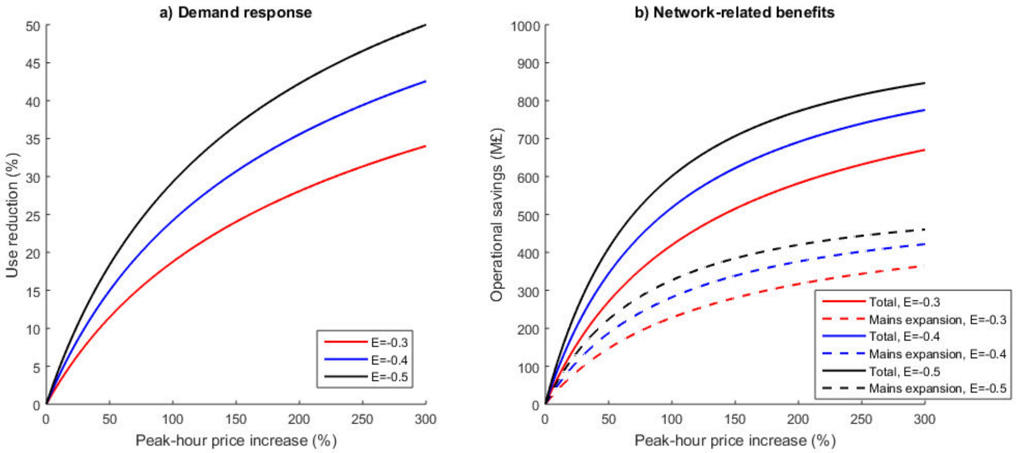

a) Demand response
Use reduction (%)
0
5
10
15
20
25
30
35
40
45
50
Peak-hour price increase (%)
0
50
100
150
200
250
300
E=-0.3
E=-0.4
E=-0.5
b) Network-related benefits
Operational savings (M£)
0
100
200
300
400
500
600
700
800
900
1000
Peak-hour price increase (%)
0
50
100
150
200
250
300
Total, E=-0.3
Mains expansion, E=-0.3
Total, E=-0.4
Mains expansion, E=-0.4
Total, E=-0.5
Mains expansion, E=-0.5

Fig. 6

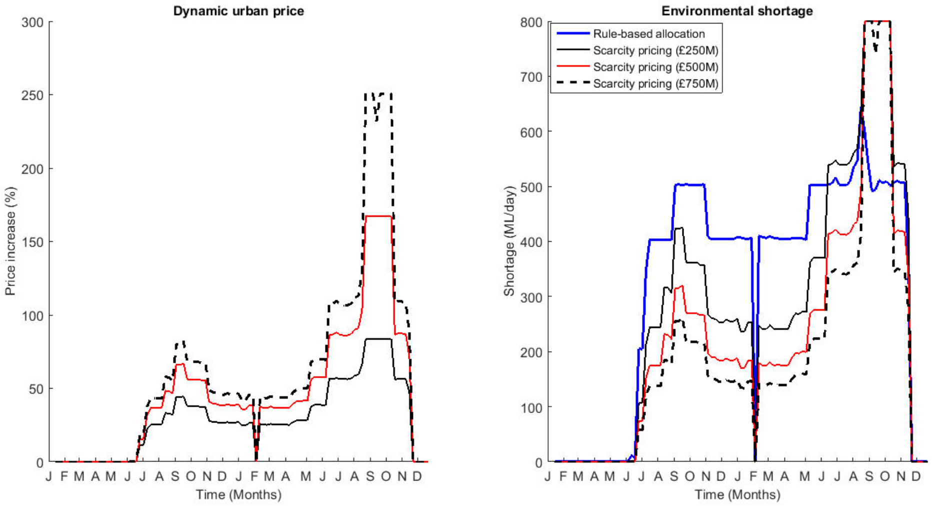

Dynamic urban price
300
250
200
150
100
50
0
Price increase (%)
J F M A M J J A S O N D J F M A M J J A S O N D
Time (Months)
Environmental shortage
Rule-based allocation
Scarcity pricing (£250M)
Scarcity pricing (£500M)
Scarcity pricing (£750M)
800
700
600
500
400
300
200
100
0
Shortage (ML/day)
J F M A M J J A S O N D J F M A M J J A S O N D
Time (Months)

Fig. 7

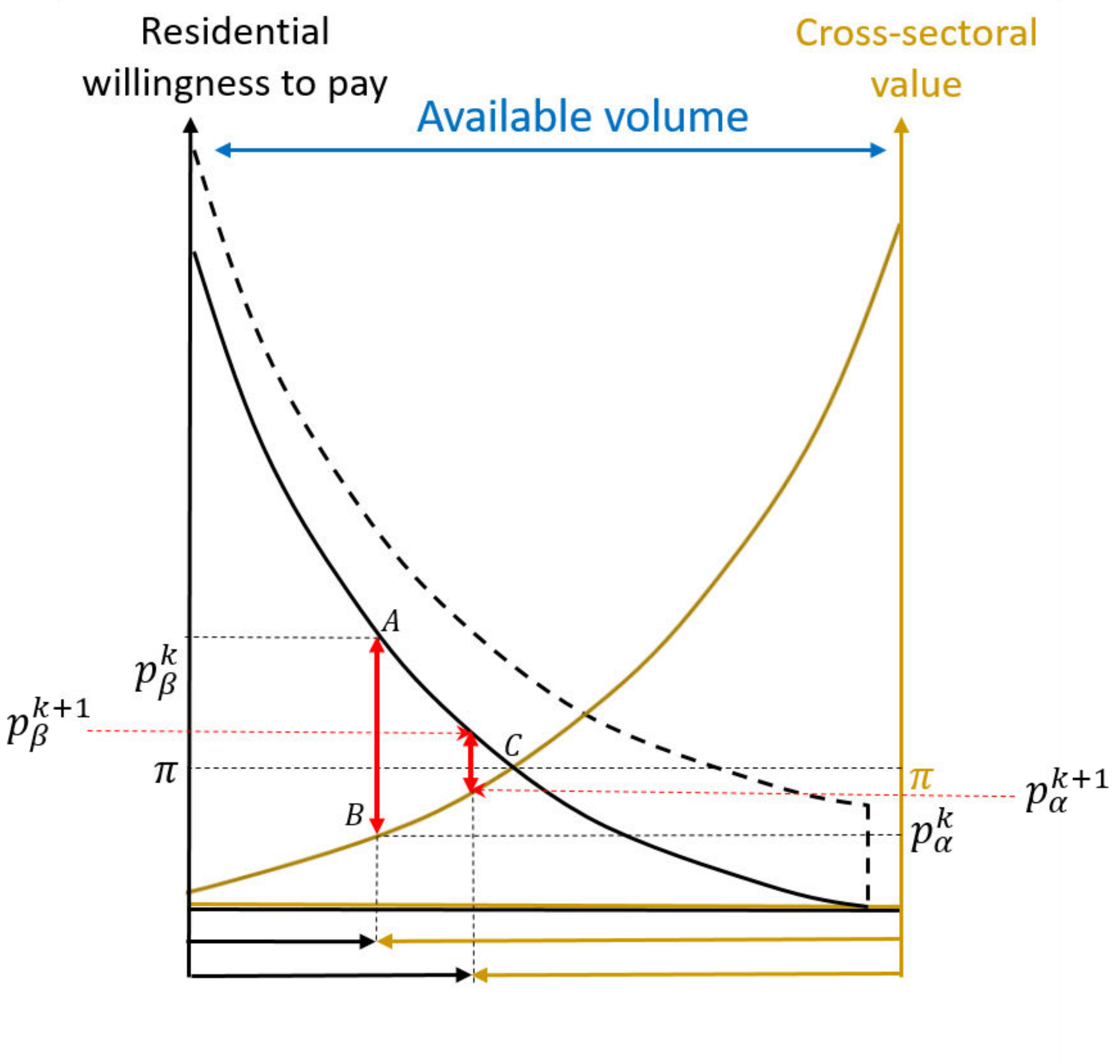

Residential willingness to pay
Cross-sectoral value
Available volume
A
p_β^k
p_β^{k+1}
C
π
π
p_α^{k+1}
B
p_α^k

Fig. 8