Untapped potential: leak reduction is the most cost-effective urban water management tool

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Abstract

Providing sufficient, safe, and reliable drinking water is a growing challenge as water supplies become more scarce and uncertain. Meanwhile, water utilities in the United States lose approximately 17% of their delivered water to leaks each year. Using data from over 800 utilities across four U.S. states, California, Georgia, Tennessee, and Texas, we characterize the heterogeneity in water losses across the U.S., develop a model to assess the economically efficient level of losses, and use this model to compare the net benefits of several proposed water loss regulations and modeling approaches. Combining economic and engineering principles, our model shows that for the median utility, it is economically efficient to reduce water losses by 34.7%, or 100 acre-feet (AF) per year. The median cost of water savings from leak management is $277/AF, which falls well below the cost of traditional water management tools. However, the optimal level of water losses strongly depends on utility-specific characteristics, leading to large differences in the potential for cost-effective leak reduction across utilities. We show that water loss management can lead to water savings that generate net economic benefits, but only if management approaches incorporate economic and engineering principles.

1. Introduction

Climate change, aquifer depletion, and population growth are increasing water scarcity worldwide. In the United States, almost half of the watersheds may soon lack sufficient water supplies to meet monthly demand [1]. Urban water suppliers are tasked with satisfying water demand under growing uncertainty [2]. Historically, water utilities have met projected deficits in water supplies with new water sources, such as drawing from previously unused surface water or aquifers. In the past few decades, utilities have also implemented conservation tools to achieve end-user water savings through information campaigns, mandates, and rebate programs. Missing from this water management portfolio are water savings that could occur through improved management of the water distribution system.

At least 100 million acre-feet (AF) of water are lost or unaccounted for each year by water utilities globally, based on assumed rates of water loss [3]. While large pipe failures are the most visible examples, water lost in the distribution system is usually imperceptible from the surface, occurring as background or unreported leakage. Although leak repair and pressure management are two well-known ways to reduce distributional losses, their potential as part of a water-saving strategy has been largely underutilized. This may be because water losses in distribution systems in the U.S. are not systematically tracked or regulated. Only seven states require standardized water loss audits, and no state regulates the level of water losses. However, the regulatory environment governing water losses is rapidly evolving, and is currently under debate and design in several states [4, 5].
In this paper, we use the most comprehensive collection of water audit data from over 800 water utilities spanning four states with available data, California (CA), Georgia (GA), Tennessee (TN), and Texas (TX), to provide the first large-scale assessment of utility-level urban water losses in the U.S. We find that reducing distributional losses is often more cost-effective than usual supply augmentation and household water conservation strategies, but the potential water savings and cost-effectiveness of this management strategy varies substantially across utilities. For the median utility, the optimal level of water loss reductions amounts to 34.7%, and the average cost to reduce these water losses is $277/AF. This is well below the average per-unit cost for alternative water management strategies, such as recycled water and desalination.

To arrive at these results, we build a utility-specific economic model to estimate economically efficient levels of water leak reduction for each utility and then compare this strategy to traditional water management methods. Typical engineering approaches simply calculate a break-even point, i.e., the point where total benefits equal total costs [6, 7]. Our model improves upon previous methods by calculating the economically efficient solution, i.e., by quantifying all the costs and benefits accrued by a utility when undertaking a water loss reduction activity and solving for the quantity of water losses that maximizes the difference between total benefits and total costs. A second departure from engineering models is that we explicitly calculate the optimal frequency with which a utility should survey for leaks, a decision characterized by fixed search costs and benefits and repair costs that accrue over time as leaks grow.

We compare these optimal utility-specific leak reductions to alternative performance standards that are currently under consideration or have already been deployed in other countries. We show that a uniform standard, similar to that used in Denmark, which applies the same loss reductions to each utility, results in water loss reductions that are too stringent for some utilities, and too relaxed for others. This is because the costs and benefits of water loss reductions vary across utilities. We then consider recent water loss performance standards proposed in California. These standards incorporate utility-specific information on costs and benefits, but adhere to the engineering conventions of a break-even point and a fixed survey frequency. Relative to optimality, the proposed water loss reductions are on average too onerous and too costly, where this wedge is primarily driven by the assumption of a fixed survey frequency. Under this currently proposed regulation, the median utility would be required to reduce water losses by 51.3% at a cost of $374/AF, well above the economically efficient cost of $277/AF. California’s policy is the first attempt at regulating water losses in the United States and is being closely monitored by utility managers and decision makers alike. Our paper provides a policy-relevant and timely analysis of water loss control to inform urban water management at both the state and local level in the face of increased water scarcity.

2. Background

Historically, water quality and supply reliability have been the two primary objectives of water utilities. This may explain why distributional water losses have traditionally been unregulated and unmonitored in the United States. When supply augmentation is not feasible, utilities have typically met demand by deploying strategies to encourage household conservation such as information campaigns, mandates, and rebate programs. Several barriers prevent utilities from imposing economic instruments, such as pricing, as a water conservation tool. For example, California’s Proposition 218 prevents utilities from charging rates that are greater than the cost of service. In recent years, as droughts and population growth have placed additional pressure on utilities to manage supply and demand, the concept of leak management has entered into the water management discussion.

Discussions on water loss control and measurement are global in reach, with active debates about monitoring occurring in Australia, Israel, Canada, and the United States [8–11]. The United Kingdom, for example, requires water companies to submit water resource management plans every five years and set their own annual leakage targets [12]. In the few examples where water losses in the distribution system are regulated, a single standard is often applied uniformly to all systems. The City of Oslo, Norway, for example, has a goal of bringing leakage levels down to 20% from 32% in all water systems by 2030 [13]. The rationale for a uniform approach may stem from a lack of utility-specific data required to design individualized standards. California is leading efforts in the U.S. to regulate water loss reductions, with its recent approval of Senate Bill 555 [14]. This regulation mandates that utilities monitor and report water losses and that the State Water Resources Control Board (SWRCB) develop and implement utility-specific performance standards. Regulating water loss can have economic and engineering benefits to an individual water system, but can also be undertaken to satisfy political will, or achieve larger societal or environmental benefits such as, increased water security or delayed development of new water sources.

Various practices exist for reducing water losses in a water distribution network: leak detection and leak repair, asset management (pipe replacement), and pressure management are the three options that are associated with the largest reductions [7]. These methods affect different types of leakage within a distribution system. Leak detection and repair can reduce unreported leaks, and pressure management
is the primary method for reducing background leaks [15]. Asset management is rarely economically viable from a water loss perspective, and pipes tend to be replaced only when repairs are not feasible. Properly accounting for other leak reduction activities would require highly granular utility-specific data, but might be appropriate for some utilities. For these reasons, our analysis restricts its attention to two loss management options—pressure reduction, and leak detection and repair. A detailed discussion of the leak reduction methods, including those excluded from the model, appear in the supplemental information (SI) section (available online at stacks.iop.org/ERL/17/034021/mmedia).

Leak detection surveys help utilities locate small leaks that have yet to come to the surface [16]. Small undetected leaks in the water distribution system may occur from corrosion, poor installation practices, soil movement, and high pressure [17]. While each leak can be small, they often go unnoticed for long periods of time, leaving total water losses to accumulate. As more leaks form and existing leaks endure, water losses grow and these small leaks collectively account for the majority of a utility’s water losses. Once a leak is detected and located, a utility can develop a repair or replacement strategy to eliminate the leak and reduce water losses.

Pressure reduction in a distribution system can lower leak flow rates and reduce the frequency of pipe failures [7]. However, pressure in water systems must be maintained to deliver water to customers at varying elevations and distances, to limit contaminant intrusion, and to provide adequate flow for firefighting [18]. The pressure a pipe segment experiences influences flow rates within the pipes as well as the leak flow rates from holes and cracks along the length of the pipe [19].

Given that utilities vary in a number of features that influence distributional losses, leak management strategies are not a one-size-fits-all tool. Distribution systems differ in the pipe age, pipe materials, system size, and elevation, all of which influence the costs of leak management. The benefits from saving water are also location specific. As an example, drought-prone regions place a higher value on the next unit of water compared to relatively water-rich areas. This heterogeneity has implications for the optimal frequency with which utilities should survey for leaks, and in turn influences the design of water loss regulation. Utility-specific mandates that do not reflect underlying differences across utilities are likely to be too costly.

3. Materials and methods

This study applies the economic model developed in the SI section to 882 urban water retailers across four states. This model builds a framework that first uses utility-specific data to calculate the costs and benefits from leak detection and repair and pressure management, and then determines the optimal water loss reductions that maximize the difference between benefits and costs for each utility. The resulting optimal leakage level can then be calculated as shown in equation (1) (SI equation (15)) where the first term represents what a utility is currently leaking, the second term represents the optimal leak reduction due to pressure management, the third term represents the optimal leak reduction due to regular leak detection and repair, and the final term represents the backlog of leakage in the utility that would be removed by repairing leaks found during the first leak detection survey. Assuming no explicit benefits, only costs, the optimal survey frequency, which denotes how often a utility should search for and repair leaks in their distribution system, was calculated as in equation (2) (SI equation (3)) such that total costs were minimized. Equation (2) considers the cost of water lost in between leak detection surveys as well as the cost to repair found leaks all discounted to the present. Figure 1 provides a schematic of the model, where inputs are shown in gray at the top and outputs at the bottom in blue. More detailed discussion of the variables, inputs, and equation development can be found in the SI section.
Figure 1. Model Diagram. Diagram of the economic efficiency model for water loss considering pressure management and leak detection and repair activities. The model inputs include utility-specific data and output an optimal leak reduction standard that maximizes the difference in the benefits and costs to an individual utility.

\[ D = \text{leak detection full survey cost (defined in SI equation (9))} \]

To measure benefits, costs, and baseline water losses, we obtained the universe of water audit data from four states between 2016 and 2018, and combined these data with additional cost information available in the literature [20]. Water audit data, collected according to the American Water Works Association water audit methodology using a water balance to estimate leakage levels, provide standardized, utility-specific information on water losses, distributed volumes, utility size, pressure, and variable production costs. However, questions arise about their data quality and reliability [21]. Water audit data were only included if they were labeled accurate, as determined by thresholds utilized in previous studies [22]. In our study, water losses are defined as real water losses: these encompass the physical water losses from the pressurized system (water mains and customer service connections) and the utility's storage tanks, up to the point of delivery to water customers. Real water losses may occur due to pipe failures or background leakage.

Utility-specific data also allow for an examination of how efficient reduction levels vary based on location, leakage levels, and system size. The economic benefits of leak reduction derive primarily from the value of water saved. We proxy for the value of water saved using variable production costs, shown in panel B of figure 2. Variable production costs tend to be higher in California and Texas, with median costs at $341/AF and $427/AF respectively, reflecting the higher opportunity cost of water use in these states. The costs of leak reduction also vary by utility depending on the size and type of distribution system. Supplemental Information provides a detailed discussion of the utility-specific costs. It is worth noting that this analysis is based off variable data as well as assumptions with regards to costs and operations, the numbers we report should be taken to include a degree of uncertainty not estimated here.

4. Results

Our analysis reveals that water losses are sizable and vary widely across and within states, accounting for 4%–25% of each state's distributed water volume. Panel A of figure 2 presents a histogram of real losses in gallons per connection per day (GPCD), and illustrates that losses vary from 10 to greater than 250 GPCD, and are lowest on average in California. This amounts to between $26.6 and $215.9 million in water production costs each year, and excludes additional social costs such as avoided carbon emissions. At the utility level, losses comprise between 1% and 55% of distributed water volumes, with the average utility losing 17% of its delivered water due to leaks. Some fraction of estimated water losses is difficult to avoid due to aging pressurized infrastructure, but some portion is recoverable through common water loss control techniques such as leak detection and repair and pressure reduction [7]. Summary tables
Applying our economic model to utility-specific data, we find that it is almost always economically efficient to reduce water losses in distribution systems, but that there is large between-utility variation in the efficient levels of distributional losses. When maximizing the difference between the monetized savings from avoided water losses and the costs of implementing water loss control technologies, we find that the average optimal level of loss reduction by state ranges between 30.1 and 39.6% of current water losses. For the median utility, this amounts to a reduction in real losses of 34.7% and an increase in the available water supply of 105.3 acre-feet annually. Aggregate water savings from the introduction of efficient water loss standards are limited in terms of water supply recovered, averaging 6.5% of total annual deliveries across all utilities in our sample. However, as shown in figure 3(A), there is substantial heterogeneity in relative water savings from leak reductions across states. We estimate that imposing efficient water loss standards would only yield aggregate water savings of 1.8% in California, but would generate savings of 10.1% in Tennessee.

The baseline level of leakage is important in determining optimal levels of loss reduction as well as the fraction of total distributed water that can be efficiently recovered through water loss control. As shown in figure 3(B), high levels of initial water losses, measured in GPCD, are systematically associated with greater levels of efficient water loss reductions. Utilities with leak rates exceeding 60 GPCD have a median optimal target reduction of 4.8% from leak detection whereas those with leak rates of less than 20 GPCD have an optimal target of 0.3%. Individual median utility optimal reduction values by state and current level of leakage as shown in figure 3 are also included as a table in the SI section.

For the majority of utilities in our sample, leak reduction is the least-cost option to obtain additional water supplies. Figure 4 illustrates the normalized cost per recovered acre-foot of water for leak detection and pressure reduction compared to four commonly used water supply management tools. In figure 4 the range of recycling costs considers both onsite and at centralized facilities, traditional sources consider the costs of developing additional groundwater or surface water sources, and conservation includes a range of water activities that reduce consumption, such as the installation of water-efficient devices, water rates, and water reduction mandates. The costs for pressure reduction and leak detection are calculated using the quantity of water saved under the economically
efficient standard. The most expensive source is desalination followed by recycling, either at a centralized facility or at the user level [23–26]. The least-cost source is pressure reduction, followed by leak detection and repair or conservation, depending on current leakage levels. Where feasible, pressure reduction is the least-cost strategy irrespective of baseline leakage levels, utility size or location.

5. Comparing the performance of water loss regulations

Our findings suggest that regulating distributional leaks through the implementation of water loss standards could increase net benefits and generate water savings. However, setting the ‘correct’ water loss standard for each utility is crucial to achieving and maximizing net benefits. To our knowledge, no country or state has attempted to regulate water losses through a framework that combines economics and engineering principles. In this section, we review the main alternative regulatory approaches that have been proposed or implemented. We then estimate the hypothetical outcomes from these regulations when applied to the 882 utilities in our sample, and contrast these results with our economic model.

Countries that have set goals for water loss reductions, currently do so through a ‘uniform approach’: all utilities are required to bring their annual water losses below some percentage level of their total supply. Denmark, for example, which has some of the lowest water losses in the world, has achieved this by instituting a penalty on any water losses greater than a 10% leakage threshold [13]. The standard chosen is often influenced by political will, engineering constraints, and data availability. Uniform standards are unlikely to achieve the policy goal at the lowest possible cost. This is because utilities face different costs to achieve the same reductions in water losses.

Alternative regulatory proposals seek to set utility-specific standards that account for utility-level differences in benefits and costs, but adhere to the engineering standards of practice of a break-even point and a fixed survey frequency for leak detection. Under a break-even point, water losses standards will be set such that the economic benefits from the standard are equal to the costs of the standard; we refer to this as the ‘Benefit-to-Cost Ratio equal to 1’ regulation (BCR = 1). This approach has the desirable properties of accounting for heterogeneity in utilities characteristics, and also prevents utilities from losing money. However, this approach is not economically efficient, since the difference between benefits and costs is not maximized.

One last approach that has been put forward to regulate water losses is to impose prescriptive recommendations on the specific ways in which utilities reduce their leaks. In our setting, this engineering standard of practice or technology mandate is for water loss surveys and repairs. These must be conducted at a set frequency, and the leaks that are detected

Figure 3. Optimal Reductions. The capacity of the economically optimum application of each water management method to reduce leakage as a percentage of an individual utility’s total water distribution volume displayed by state (panel A) and gallon per connection day (GPCD) leakage levels (panel B)(the plotted boxes represent the 25–75 percentile interquartile ranges with the ‘whiskers’ extending to 1.5 ∗ interquartile ranges).
Figure 4. Comparison of Normalized Costs. Normalized cost per acre-foot (AF) of additional water supply via traditional (i.e. surface or groundwater) and alternative water supply management methods [8–11]. Leak detection and pressure reduction costs per acre-foot were calculated under the economic efficiency model for the 882 utility dataset. (The plotted boxes represent the 25–75 percentile interquartile ranges with the 'whiskers' extending to 1.5∗ interquartile ranges).  

must be fixed. This approach is fundamentally different from our model, in which utilities are assumed to choose the survey frequency so as to maximize their net profits. An engineering-based regulation or technology mandate will lead some utilities to lose money.  

In California, Senate Bill 555, aims to reduce water leaks through the imposition of utility-specific water standards. The proposed regulatory framework intends to set standards that are a function of data provided by water utilities. Importantly, the SWRCB framework combines two of the regulatory options listed previously: water loss surveys will be fixed and occur every two to three years, and the benefit to cost ratio must be greater than or equal to 1.  

To assess the impacts of these different regulatory approaches on water loss standards and net benefits, we compare the estimated regulation outcomes when applied to the utilities in our dataset. We consider five possible scenarios: (a) a uniform standard set at 8% losses, (b) a utility-specific standard set such as to yield cost-benefit ratios (BCR) equal to one, (c) a prescribed leak detection survey and repair frequency, (d) the California SWRCB standards which combine a minimum BCR equal to one with a fixed survey frequency across all utilities, and (e) the economic framework proposed in this paper in the SI section. These findings are presented in figure 5.  

We find that the standards set using our economic model are in general higher (less stringent) than the
standards set in any of the four alternative approaches as shown in figure 5(A). The median standard computed under BCR = 1 and under the SWRCB approach are 32.2 and 20.0 GPCD respectively, as compared to 24.3 in the economic model. This is largely driven by differences in the standards for utilities experiencing high baseline levels of water losses. By design, approaches (a)-(d) are not set to maximize net benefits, and as a result, underperform along this dimension relative to the standards generated by our model. In some cases, the standards set in these alternative frameworks would lead to net economic losses for water utilities whereas the standards derived from our economic model lead to non-negative profits, with a median net benefit of $186 990 yr$^{-1}$. The BCR = 1 criterion pushes the net economic profits from water savings down to zero, as plotted in figure 5(B), which mechanically implies higher average cost of avoided water losses.

Finally, we estimate that the proposed SWRCB regulation would lead to standards that are more stringent than those calculated by our model for 68% of utilities while also resulting in a smaller reduction in water losses by 1.2% at the state level. The reductions also would come at a higher cost: profits under the SWRCB regulation would be 77% lower than under our estimated economic standards. Because the proposed SWRCB standards are calculated under the double-constraint of a fixed survey-frequency as well as a BCR greater than 1179 utilities would not be required to reduce their water savings under the standard, whereas for 60 of them we estimate that doing so could lead to net positive profits. Additional comparison of the various modeling approaches can be found in the SI section.

6. Conclusion

Until very recently, managing distributional losses had been largely ignored as a potential urban water savings tool, in part because of the complexity involved with monitoring water losses and determining how to regulate them. At the time this paper was written, only four U.S. states had validated water loss datasets available, limiting our knowledge of water loss volumes and how best to manage them. As more entities begin collecting this data, we expect that knowledge of and interest in water loss management will increase. In this paper, we develop a model that is rooted in both economic and engineering principles, and show that managing distributional losses may be the cheapest way for urban water managers to augment water supplies. However, the extent to which water loss reductions prove to be a low-cost urban water management strategy depends on the level of water loss regulations set in each utility.

We use data from the universe of water utilities in four states to show the importance of utility specific characteristics. Regulations that impose a uniform standard across all utilities will result in water reductions that are too stringent in some cases, too relaxed in others, and too costly overall. Large differences in costs and benefits of water loss reductions across utilities imply that efficient water savings will likely require regulation that is either utility specific or that features a decentralized market-based instrument, such as a tax on water losses.

Water loss regulations that take a single disciplinary focus, either eschewing economic principles or engineering primitives, may lead to the mismanagement of urban water loss reductions. We
show that with an interdisciplinary approach and utility-specific data, water loss reductions may be the cheapest way for urban water utilities to manage supplies. This utility-centric approach does not account for many of the social benefits attributable to water loss reductions, such as water supply reliability, avoided carbon emissions, and alternative conservation values. Even with the exclusion of these benefits, our model shows that water loss regulations can deliver water savings at a profit. Their inclusion, something that our model is equipped to incorporate, would reflect the societal gains from reducing water losses. Clarifying what these benefits are, and accurately valuing their potential contributions to social welfare, is an important direction for future research.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Author contributions

Conceptualization, methodology, investigation, and writing (AR, JW, EB, KJ, FL); data curation, analysis, and visualization (AR); funding acquisition and project administration (AR, KJ, FL).

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