Measuring Energy Efficiency of Water Utilities

by

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ABSTRACT

Water infrastructure systems worldwide use large amounts of energy to operate. Energy efficiency efforts are relevant because even relatively small gains in efficiency have the potential to bring significant benefits to these utilities in terms of financial savings and enhanced sustainability and resiliency. In order to achieve higher efficiency levels, energy usage must be measured and controlled.

A common tool used to measure energy efficiency in water utilities and perform comparisons between utilities is metric benchmarking. Energy benchmarking scores are intended to measure how efficient water systems are among their peers, in a simple and accurate fashion. Although many different benchmarking methods are currently used, we chose to use the segregated benchmarking scores proposed by Carlson on his research report from 2007 (Carlson, 2007).

The research objective is to improve these production energy use and treatment energy use benchmarking scores by analyzing the system's particular characteristics that might skew the results, such as topology, water loss and raw water quality. We propose that benchmarking metrics should be always used within a particular context for each specific utility being analyzed. A complementary score (Thermodynamic Score) was developed to provide context on how energy efficient is the utility not only compared with other utilities, but also compared with the potential maximum efficiency the utility can reach itself.

We analyzed eight utilities from Virginia to obtain production and treatment energy use benchmarking scores and also thermodynamic scores using the minimum required energy approach. Benchmarking scores were skewed in 50% of the studied utilities. This means that benchmarking scores should never be used as a black box. The thermodynamic score proved to be useful for measurement of energy efficiency of a water utility on its production phase. In addition, some utilities can detect significant financial saving opportunities using the minimum required energy analysis for production operations.

DEDICATION

To my wife **Beatriz** for supporting me always, even through the most daring and unlikely enterprises with quiet patience and loving, forgiving, steady support. This project would not be possible without you.

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CHAPTER 1. INTRODUCTION

BACKGROUND

Water-Energy nexus

Water and wastewater infrastructure systems are essential to contemporaneous society. Their adequate performance, usually unnoticed, allow us to have healthy and well organized urban population centers. Water is a basic need for life but beyond that basic fact, water for human consumption must meet minimum quality standards to guarantee it does not imply a health hazard for users. A sustained water quality is achieved not just through delivery of safe drinking water, which is a first step, but also considering the whole urban water cycle as a single system. The urban water cycle is a closed loop, where drinking water delivery and wastewater treatment are not different fields but only different stages of the same process (fig.1.)

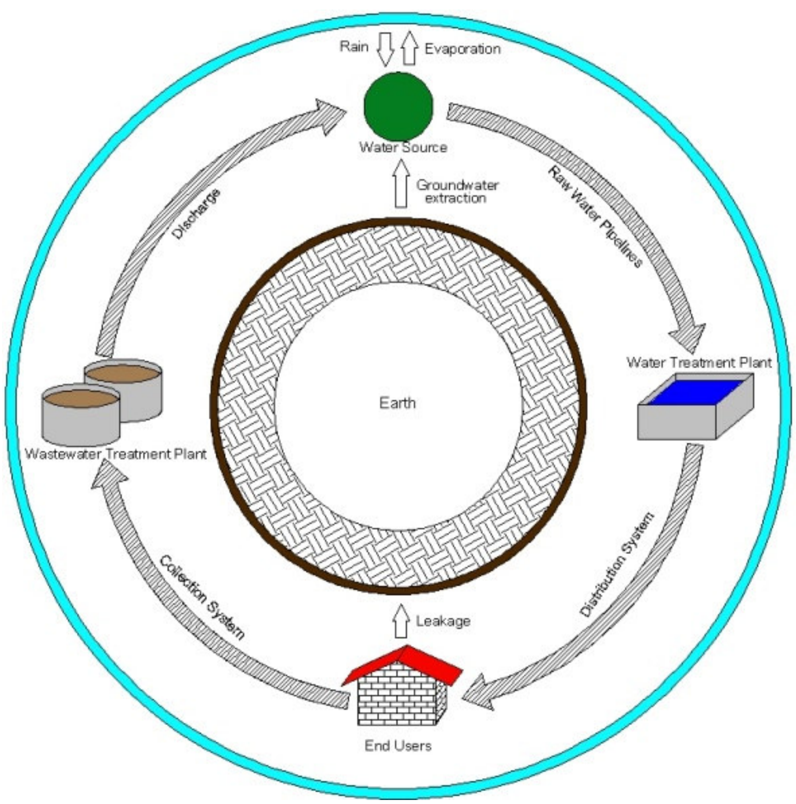


Fig.1.Urban water cycle

Given its importance, the water infrastructure is subject to significant research efforts ranging from optimizing plant design, enhanced operation and maintenance, to further understanding of sustainability and resiliency issues associated with these systems.

When conducting research regarding any infrastructure system, it is necessary to address the fact that such system is not isolated from other infrastructure, since all of them are interconnected and thus interdependent at various degrees. All infrastructure systems are elements of a vast network supporting modern society. A particularly strong interdependency in civil infrastructure systems is found between the one required to support the urban water cycle (including extraction, treatment and distribution of drinking water to a proper disposal of wastewater) and the one to provide energy. The Water-Energy nexus within civil infrastructure systems is emerging as a strategic research field for the future.

Water and energy infrastructure systems are thus highly interrelated. Water systems require huge amounts of energy to operate, wastewater systems that collect and treat used water also require large energy inputs to keep functioning, and energy generation requires important water withdrawals.

The diagram in fig.2 Shows different aspects of the water-energy interdependency and its relationship with natural systems. First, the water-energy interdependency is represented by the small top loop. These two infrastructures belong to the category of engineered systems. The other small loop in the bottom of diagram represents the natural system constituted by environment and climate.

Environment and climate also affect each other: for instance, deforestation affects climate in a region and the changed climate comes back to impact the environment. The top and bottom loops of engineered and natural systems are also interrelated between them. Energy generation activities have an impact on the climate through release of emissions into the atmosphere; water infrastructure impacts the environment through water withdrawals and leakage, and conversely those impacts in environment and climate affects infrastructure back: Climate change is a good example of this cycle.

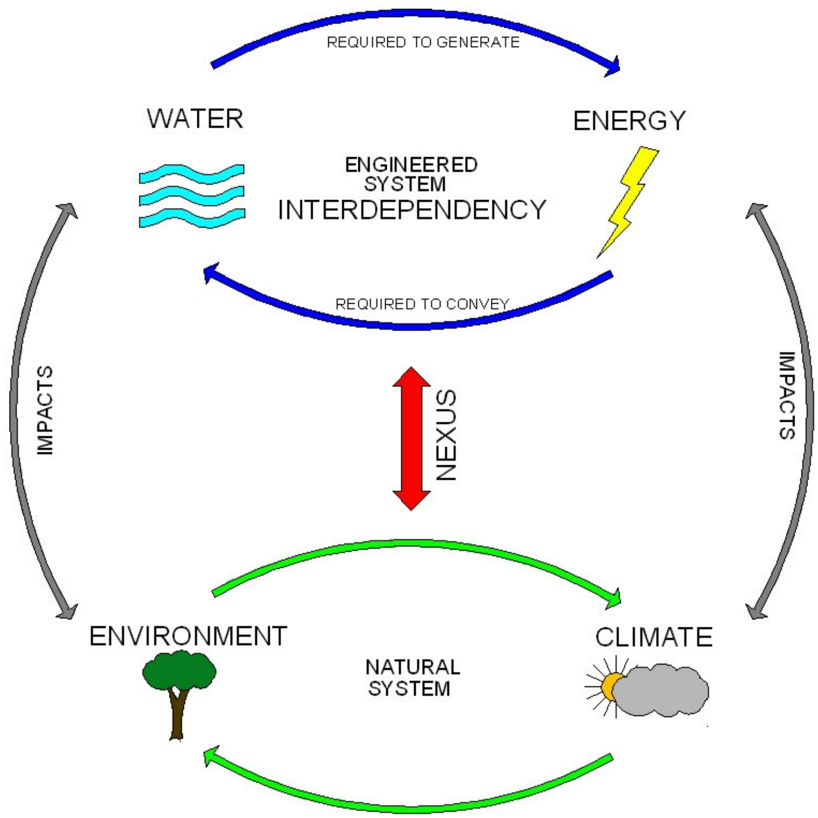


Fig.2 Water-Energy interdependency and Climate-Environment nexus

Water systems require large energy inputs. Estimates point out that around 4% of the U.S. National electricity generation is used solely to power water and wastewater infrastructure, from water extraction to the discharge of treated wastewater. According to the same authors, in average 80% of the costs in municipal water systems is for electricity (Ghimire, 2007).

Furthermore, more stringent standards for drinking water quality and new treatment processes that they will require, such as Ozonation or UV disinfection are increasing the energy demand in the sector.

In the other hand, water withdrawals required by energy generation plants are very important as well. Power generating plants use significant amounts of water for generation and cooling. Energy operations typically use water in two ways: Water withdrawals that account for the water that is taken, used and then returned to source; and water consumption, that is taken, used, and then released usually in the form of steam. Even water withdrawals for energy generation have negative impacts on the environment: Although this water is not consumed but released back in its original form, it is usually released at higher temperature than the surrounding water at the discharge point, thus implying pollution and stress over the environment.

Efficiency measures aimed to reduce the water and energy consumption should target both sectors simultaneously. Every time energy is being used, water is used to provide that energy; and conversely, water demand each time implies an important energy demand.

Due to the tight interdependence of water and energy, the required approach to enhance the performance, sustainability and resiliency of these infrastructure systems should be integrated under one holistic strategy. In this way we are able to avoid negative feedback loops and undesired effects from short sighted policies and actions.

The study and comprehension of the water – energy nexus field currently present important and exciting opportunities to increase the efficiency, performance and sustainability of these infrastructure systems. New approaches to achieve deeper understanding and integrated management strategies for both resources and their interdependencies are being explored (Wilkinson, 2007; Global Green, 2002; de Monsabert, 1998).

Importance of Energy Efficiency for Water Infrastructure

The energy efficiency of water utilities is important because it represents a necessary step towards higher objectives, like increasing the sustainability of those infrastructure systems and enhancing their resiliency by reducing their dependence on traditional energy reserves.
Since interdependency between water and energy is a technological issue and it will continue to be important, efficiency efforts represent an area with huge potential benefits. Energy efficiency practices in the water sector are diverse. For example, actions aimed to reduce water consumption and waste have a positive impact on the energy sector in virtue of the reduced demand for energy that would be otherwise required to provide more water. In addition, enhanced energy efficiency can be achieved through deliberate design of the new required water infrastructure. For already existing infrastructure, energy efficiency can be increased by a variety of methods, from pump operation scheduling, demand forecasting, retrofitting of facilities, and energy recovery practices.
Another benefit of energy efficiency in water systems comes from the fact that one of the main barriers for utilizing renewable and clean power sources in water works is the large amount of

energy required. By having a more efficient energy use, the utilities can get closer to more sustainable and resilient alternative energy sources that currently reach limited power generation capacity.

Financial Implications of Energy Efficiency

Energy efficiency practices have important financial implications for water utilities. As mentioned earlier, water utilities use significant amounts of energy to extract, treat, convey and deliver safe drinking water. As a result, even relatively small increases in energy efficiency could bring important financial benefits to these utilities. For example, since electricity costs represent near 80% of operating costs for municipal water systems, and through energy efficiency measures this consumption can be reduced by just 10%, that will mean financial savings of 8% in public funds.

Implementation order of energy efficiency practices in water utilities usually follow the path of financial savings from biggest to smallest, as any economic rationale would suggest. One clear example of this logic is the repair of pipeline breaks and leakage: Bigger breaks will be repaired immediately, since they imply an important revenue loss, a public risk, and damage to the utility's image. In the other hand, leakage is usually repaired just if the size of the losses they cause is bigger than the price of repair. Under that benefit threshold, repair of individual leaks is more expensive than the financial loss they cause, and then are usually tolerated.

Of course, the financial logic behind energy efficiency practices and programs is of the same kind: Energy efficiency measures are taken in those cases where the benefit exceeds cost, starting from the areas with maximum benefit/cost ratio. Some of the energy efficiency practices that are commonly found are:

a) Pumping Operations. Pumping is responsible for most of the energy consumption in any water utility. Pumping efficiency can be improved from a financial standpoint by:
    a. Replacing old pumps that have become inefficient or obsolete,
    b. Installing variable speed controls, and
    c. Scheduling pumps for off-peak electricity hour operation
b) Water Demand. Educating the public about a more efficient water use reduces demand, then the need for energy. It is very important at all times to have in mind that through the

pipe network does not flows just water, but also energy. When somebody opens a tap, water and energy come out together.

c) Protecting water quality. Water extracted from a watershed that is cleaner will require also less treatment process to meet drinking water standards. Less treatment means less energy requirements.

Resiliency Implications of Energy Efficiency

By applying energy efficiency practices, the water utilities increase their resiliency to disruptions. Resiliency is defined as the ability of a system to recover from disruption. Resiliency is commonly measured by four parameters: Robustness, Redundancy, Rapidity and Resourcefulness. Robustness refers to the capacity of the system to withstand attacks, intentional or not. Redundancy means the ability to redistribute loads in case some parts in the system stop working, and thus keep function of the system as a whole. Rapidity is a measure of how fast the system can start working again after a disruption, and resourcefulness refers to the availability of different resources to face an emergency.

The effective implementation of energy efficiency measures can enhance the resiliency of the system. First, a water utility that requires less energy will recover from disruptions faster than that which requires larger energy inputs. Second, somewhat reduced energy consumption allows the utility to explore alternative energy sources other than fossil fuels, for example. Third, energy efficiency measures will result in financial savings that may be used to construct an emergency resource fund and preparedness plan.

Sustainability Implications of Energy Efficiency

Energy efficiency programs also have a positive impact on the water infrastructure system sustainability. Probably one of the most obvious effects is the reduced energy demand, which allows the generation of less energy then reducing the impact of generation activities over the environment, like gas emissions.

There are other sustainability benefits of energy efficiency. Sustainability requires the most efficient possible use of limited resources: An economic development model based upon unrestricted use of finite resources is inherently unsustainable and will collapse sooner or later.

Sustainability starts with efficiency. While it is usually hard to change existing technologies and mindsets towards more sustainable options in one step, gradual changes in the right direction are not only possible but desirable. Efficiency measures are the first logical step in transforming our current technology into more sustainable processes and methods.

Importance of Measuring Energy Efficiency

It is well known that a process that is not measured cannot be improved. In order to achieve better efficiency stages in development of water and energy infrastructure, we must have a series of metrics that allow us to keep track of whether we are making progress. This research is intended to strengthen the metrics currently used to measure energy efficiency in water utilities, specifically benchmarking models.

The use of diverse indices to support the decision making process within complex issues is not new. Indices are meant to represent current status of a complex system in such way to achieve an optimal balance between simplicity and accuracy. Since every index is a simplification of the real system, the underlying challenge is how to represent in a simple fashion any real, complex, multi-dimensional situation in an index that captures the essential information sufficiently well to be accurate and reliable, and simple enough to be useful for practical purposes.

Benchmark metrics are commonly used in the water sector. In order to achieve better energy efficiency, development of adequate metrics is a must. A very intuitive measure of energy efficiency of water infrastructure is to calculate directly the energy intensity of the water we use. Energy Intensity of the water is defined as “the total amount of energy, calculated on a whole-system basis, required for the use of a given amount of water in a specific location. All steps in the process, starting with initial extraction from a natural source through conveyance, treatment, distribution, end-uses, waste collection, treatment, and discharge are included” (Wilkinson, 2000).

By using an energy intensity approach, we can know how much energy we are putting into the water we use. The meaning of energy intensity of water is very straightforward and easy to understand.

A serious disadvantage of the energy intensity of water is that does not works to perform comparisons between water utilities. If we want to know how energy efficient is any given utility with respect to another, we cannot use this metric alone since energy intensity of water varies accordingly to specific characteristics of the place where the utility operates. This metric is seriously affected by parameters out of the utility's control, such as topography, water source quality, treatment requirements, and so on and so forth. For this reason, we can have equally efficient water systems, and yet each one with very different energy intensities of its water. Energy intensity of water will be used in this study as a complementary information source to assess the performance of benchmarking metrics. This indicator will be used segregated into production energy intensity and treatment energy intensity, meaning the amount of energy per water unit that is put on each stage of the process.

A second approach specifically designed to perform comparisons among peers is benchmarking. Benchmarking is defined by the Water Research Foundation (formerly AwwaRF) as "the process of identifying, sharing and using knowledge and best practices. It focuses on how to improve any given business process by exploiting topnotch approaches rather than merely measuring the best performance. Finding, studying and implementing best practices provides the greatest opportunity for gaining a strategic, operational and financial advantage" (WERF, 2006). This kind of benchmarking is known as "process benchmarking". Benchmarking processes involve learning from peers: "Benchmarking is the continuous search for and adaptation of significantly better practices that leads to superior performance by investigating the performance and practices of other partners" (Kulshrestha et al, 2004).

There is also metric benchmarking, which refers to the benchmarking indicators themselves. Since benchmarking is specifically designed to work for comparisons among peers, it is widely used as a measure of energy efficiency of water utilities. Benchmarking can be done in many different ways. One approach is to select key indicators and assign them weights, then assembling a single score over certain scale (Kulshrestha et al, 2004). Another approach is to use a benchmark case study to compare different methods for achieving energy efficiency for the same process (Wu, 2007).

Energy use in Water Utilities

In order to understand the energy use by water utilities, it is convenient to start by looking at the big picture. Process begins by extracting raw water from a source (see fig.3) that can be groundwater or surface water (lake, river). Some utilities use purchased water that has been extracted by somebody else and put into the distribution system. Purchased water as well as reused water don't come from a natural raw water source directly, but certainly was extracted from such source at some point in the past. The process from raw water extraction, treatment and distribution is represented in fig.3 in the central diagram.

Energy inputs in this process are indicated by the small squares representing pumps. First one is raw water pumping, which extracts water from the source and conveys it to the treatment facility. The amount of energy required in production (E_1) is comprised by the energy required to overcome the static head (ΔZ) and the friction head loss to convey water to treatment facility.

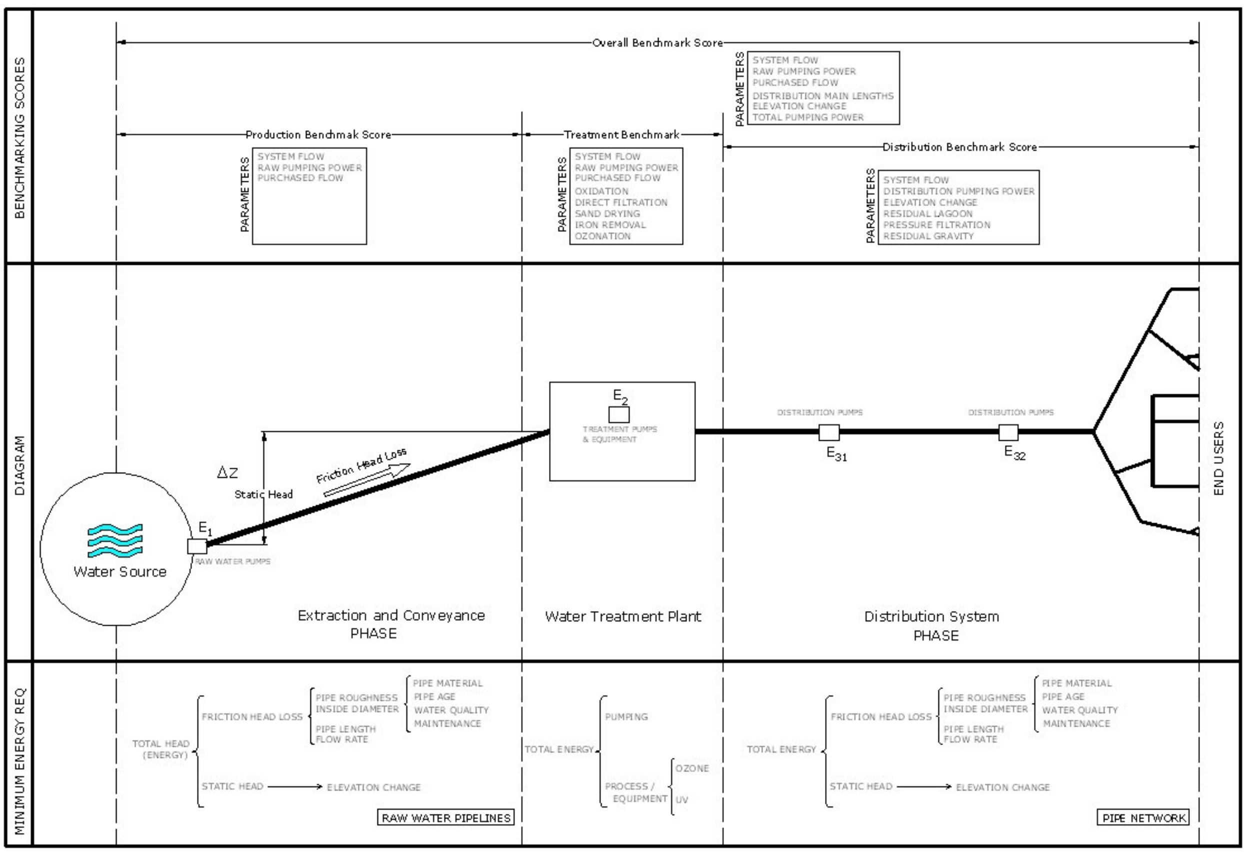


Fig.3 Diagram for the process of drinking water production, treatment and distribution

Once we have raw water in the treatment plant, additional energy inputs are required to treat the water (E_2). The amount of energy depends on the amount of water and on treatment process utilized, which in turn depends on raw water quality and drinking water standards to meet.

Treated water is sent through the distribution system to end users. Depending on service area conditions and size, one or more pumping stations might be required (E_{31}, E_{32},…). Usually the distribution system required energy for pumping is the sum of these inputs: $\Sigma E_{3i.}$

Although this diagram depicts in a simple way any water system, in practice few systems have as clearly established boundaries among the three phases: production, treatment and distribution. In most systems, energy inputs in one phase also provide some energy for the next one. For example, some of the energy inputs in the production phase may be needed to power some treatment processes, like filtration. Additionally, pumps located inside treatment plant push the water through a fair section of distribution system. Fuzziness of these boundaries is one of the main challenges in characterizing energy use in water systems, when it comes to classifying energy inputs among phases.

In top of fig.3 we have the benchmarking models that will be used throughout this project. First we have an overall benchmarking score that is intended to measure energy efficiency throughout the utility, from raw water extraction to the end user. This overall benchmarking score is also segregated in three scores for production, treatment and the distribution parts of the system.

The segregated scores are very useful since many utilities do not own the whole process. Some of them just produce and treat water; others extract raw water and distribute it but treatment is done by somebody else. In our case, we used for this research just production and treatment segregated benchmarking scores because among surveyed utilities, just one owned the whole system. All surveyed utilities owned the production phase, however.

The parameters required to calculate each one of the benchmarking scores are shown in the boxes. Fuzziness of boundaries among process phases is clear in those parameters. For example, calculation of treatment benchmarking score requires the installed raw water pumping power, which clearly belongs in production phase. This makes sense within some contexts where raw pumping power is also used as part of the treatment energy inputs. In some other contexts, like gravity-fed systems, this feature distorts the resulting score for treatment.

These benchmarking scores work by comparing a predicted energy use (obtained from a statistical normalized model) with actual energy use. If the actual energy use is higher than the predicted amount, the utility obtains a low benchmarking score. Conversely, if the predicted energy use is lower than actual energy usage, the resulting score will be high, thus indicating higher energy efficiency. In the case of Gravity-fed treatment plants, they have little or no raw pumping power installed at all, making the predicted energy use artificially low. When actual energy use is compared, it looks very high and then benchmarking score turns out very low. Gravity-fed systems will then obtain very high production benchmarking scores (realistic) and very low treatment scores (unrealistic).

Finally, in the bottom third of fig.3 we have some notes on the minimum required energy approach that we used to provide context to the benchmarking scores. The approach was used just for the production phase, to keep the project as simple as possible. The objective of this method is to have an estimate of how much energy is thermodynamically required by the utility in the production phase, and then compare that figure with the predicted energy use from the benchmarking scores.

Parameters considered for minimum required energy are shown also. Maintenance practices impact the energy required by the system, but this was not considered because it was out of the scope of research.

The minimum required energy approach is useful for constructing a simple but meaningful ratio that we called the thermodynamic score. This score is simply the minimum energy required by the utility to extract and convey raw water to treatment, divided by the actual energy consumption, expressed as a percentage. In this way, if the actual energy used equals the minimum required, the score is 100, and if the actual energy consumption is bigger than the minimum, as expected, the score tends to 0.

The method for metric benchmarking proposed in the report “Energy Index Development for Benchmarking Water and Wastewater Utilities” (Carlson, 2007) is very sound. Nevertheless, we feel that it still can be improved in a significant way by addressing the thermodynamic context in which the raw water extraction and conveyance process takes place.

Metric Benchmarking for Energy Efficiency in Water Utilities by AWWARF

Among existing benchmarking metrics, those proposed in the study “Energy Index Development for Benchmarking Water and Wastewater Utilities” (Carlson, 2007) are very sound technically. The present research intends to build on those metrics by pointing out some weaknesses we found and proposing a few improvements.

The benchmarking method proposed in the Carlson study is based upon the ENERGY STAR rating system used by USEPA for buildings.

These benchmarking scores are percentiles. The score obtained by any given utility represents the percentage of utilities that are less energy efficient. For example, if a utility achieves production energy use score of 75 that means 75% of the utilities are less energy efficient in raw water extraction and conveyance to treatment facility operations (production phase).

Benchmarking scores are calculated by comparing the utility’s actual energy use with a predicted energy use. If the actual energy use is less than the predicted level, utility obtains a score above 50. The major the distance between actual and predicted energy amounts, the closer the resulting score to 0 or 100, depending on the case.

Predicted energy use was obtained in the AWWARF study by constructing a statistical model, and it represents the average energy consumption of a utility with the same characteristics. The predicted energy use comprises a normalized distribution based on a sample of 125 utilities from throughout the U.S.

There is a benchmarking model for overall energy use, and three segregated scores for the different parts of the system such as production, treatment and distribution. This is very convenient since the utilities not always own the whole system: Sometimes they extract raw water, treat it and deliver the water and are not responsible for distribution. In other cases, the utility provides raw water and receives the treated water, not having ownership over the treatment part of the system. This study analyzes the production and treatment benchmarking scores only due to information and time constraints.

Minimum Required Energy Analysis

The contribution of this research is the thermodynamic score, obtained from the minimum required energy analysis. The thermodynamic score is applied only to the production phase of the system, where the energy required for the process to take place can be easily calculated as friction head loss and static head to overcome.

The idea is not only use a benchmarking score from a black box, but measure how efficient is the utility compared with its own potential. For example, we can have a utility that is more energy efficient than the average system in the U.S., thus obtaining high benchmarking score. Nevertheless, this utility may be able to reach even higher energy efficiency standards if it has favorable imposed conditions.

The minimum required analysis objective is to evaluate what is the amount of energy the utility requires to extract raw water and convey it to the treatment facility, considering basic physical factors such as friction and static head. The name of thermodynamic score comes from this fact.

Obviously, such a score cannot be calculated for treatment operations. These operations are based mostly in chemical reactions, filtering, and other unquantifiable processes from a mechanical stand point.

The thermodynamic score measure how close is the energy efficiency of the utility compared with the best efficiency it can reach based upon its particular characteristics. If a utility has very favorable conditions and hence requires very little energy, may achieve undeserved high benchmarking scores. Conversely, if the imposed conditions of the utility demand high energy consumption, it will have undeserved low benchmarking scores when compared with the national average.

CHAPTER 2. LITERATURE REVIEW

Energy Efficiency of Water Utilities

Literature regarding the energy efficiency of water utilities is primarily focused on the optimization and scheduling of pumping operations (Wu, 2007). This is understandable since pumping is responsible for nearly all of the energy consumption in those utilities. It is also common to find references to efficiency in those documents interested in sustainability of the built environment. Also, with the raise of environment preservation and sustainability concerns, the energy infrastructure systems are under increased pressure to deliver cleaner, safer, reliable power (Jefferson, 2006). For this reason, better energy management is a critical issue towards sustainability and security goals worldwide (Vera, 2007; Unander, 2005). Regarding benchmarking and other efficiency measures, the use of indices as a decision making tool to address energy-related issues has received increased attention lately (Patterson, 1996; Bor, 2007). Other infrastructure systems such as water and wastewater utilities are looking to energy management strategies as means to strengthen their financial position.

Water and Energy infrastructure systems are highly interdependent. Large amounts of energy are required to deliver water, while large amounts of water are required to produce energy. Given the tight interdependence between both of them, many authors rather propose an integrated approach to the asset management of these two strategic resources, water and energy (U.S.DOE, 2006; Wilkinson, 2000; Wilkinson, 2007). By using an integrated approach, the understanding and improvement of energy efficiency in water systems and their impact on the water-energy interdependence will be greatly enhanced.

Sustainable development is a huge challenge. The use of indices to measure it is a natural and appealing idea, given the complexity of the issue. Nevertheless, the assembly of adequate and useful measures has proven to be a very challenging task itself (Abdalla, 2005; Spangenberg, 2002). Development of such indices is required to support the achievement of environmental and economic development goals, given that a process which cannot be measured cannot be improved.

In the water and wastewater infrastructure systems, many approaches have been used to measure the sustainability of the assets (Ashley, 2004; Garcilaso, 2006). To achieve higher sustainability levels, currently the most important single factor is to use both resources (water and energy) as efficiently as possible. Some research projects focus on efficient life cycle resource use (Racoviceanu, 2007; Filion, 2004), or studying ways to increase the efficiency for the particular case of specific utilities (Elliot, 2003; Chang, 2007).

The use of indices to address the energy efficiency in the urban hydraulic infrastructure (water and wastewater) is rather scarce. Existing research in this field is directed towards energy intensity of water, mainly for financial purposes (reducing operating costs) or benchmarking of the utilities among peers (Colombo, 2002; Ghimire, 2007; Carlson, 2007). We feel there is a real need for an energy index for hydraulic infrastructure that could go well beyond immediate benefits like short and medium term financial viability. Although financial benefits are very important as strong drivers to achieve better efficiency levels, the measures developed should also have the potential for further applications and advances beyond finance.

Infrastructure systems have an essential role to play in the successful implementation of sustainable development models at present. Furthermore, we believe that indices such as described above for water and wastewater infrastructure are a solid foundation to advance a series of indicators capable of addressing sustainability in such systems, while promoting research in the area of water-energy nexus on infrastructure. That is an important reason behind this work.

Benchmarking and Water Utilities

There is an important amount of literature regarding benchmarking. The term was introduced in 1981 by Xerox as a business strategy. Benchmarking was not early applied to the water industry, because as noted by the International Water Association (IWA): “water services are monopolistic by nature (on a local level) and are not naturally driven to increase efficiency and achieve best practices” (Cabrera, 2008).

Two terms exist when referring to benchmarking, as proposed by WRF and WEF:

a) Metric benchmarking, a comparison tool for potentially many numeric performance indicators among utilities, and
b) Process benchmarking, an improvement tool which comprises the identification and adaptation of best practices in the industry to achieve higher performance levels.

This research is mainly concerned with metric benchmarking. One of the main promoters of metric benchmarking is the World Bank through the International Benchmarking Network for the Water and Wastewater Utilities (IBNET). Some authors say that metric benchmarking is nothing but a collection of performance statistics about utilities (IWA), and for a benchmarking study to be complete is required to include a detailed performance analysis, in addition to the metrics themselves.

Critics to metric benchmarking have a point. Benchmarking has become a fuzzy term that often describes metric benchmarking or/and best practices mixed. Also, metric benchmarking faces a huge challenge, since comparisons among very different systems is, at least, challenging if not impossible. Benchmarking indicators can provide useful information, but certainly they should not be the only source upon which to take decisions and establish a definitive ranking among utilities. That is one of the reasons why the present study is relevant: The scope of the project is to provide not only some benchmarking scores, but also define and analyze a context within which those scores can be better understood, questioned, utilized and improved. Contextualized scores are more useful and less skewed than only benchmarking scores isolated from all context.

Another fundamental question that needs to be addressed before attempting a benchmarking effort is the quality of data being used. Since benchmarking is widely used to perform comparisons among peers, fairness would require that all of them have reliable and high-quality data. Ideally all data should have same format and collection standards. In real world this is not the case, and thus the meaning and validity of the comparison itself might be questioned. Many utilities starting a benchmarking effort find out that their data quality is not as good or as readily available they might have thought at the beginning.

World Bank efforts to advance benchmarking in the water sector through IBNET deserve some special comments. IBNET has some special features that allow the system to be unique and powerful. One is that provides public information on performance of water and wastewater utilities around the world, over a basis of voluntary participation of utilities, associations, and other entities. This achievement required important milestones, like standardization of information, non-disclosure of sensitive information agreements with participants, and others.

Other special feature of the IBNET system is that is intended to construct time-series data about participants. This is very important since without time-series, impacts due to policy and regulation changes are hard to detect. Most information currently available from other benchmarking efforts is on a snapshot format. Time-series construction information requires overcoming considerable challenges such as the mentioned standardization of data, agree on the frequency of data updating, and others (Van Den Berg and Danilenko, 2008).

Although the effort in benchmarking form the World Bank has result in some interesting achievements, it has been criticized for being self-nominated, which raises questions about its validity (Olstein, 2004). This same author defines efficiency measures as those that involve dollar amounts, and effectiveness measures all others. We don't fully agree with these definitions, since each measure could be defined as efficiency or an effectiveness measure, depending on what is being measured and with what purpose.

Despite criticism, benchmarking is a powerful tool for successfully managing water and wastewater systems. In other studies, the experience (including benchmarking) acquired by the water sector on industrialized countries is being applied to developing countries, through international agencies like The World Bank. Rationale is that it is not enough to build brand new water and wastewater infrastructure in developing countries: For the long term success of these projects is necessary to ensure that the country has the knowledge and skills to manage the new built infrastructure. As a key component of the tool set to successfully manage the recently constructed facilities, benchmarking metrics and processes are used (Liner et al, 2004).
The same authors (Liner et al, 2004) point out that an excessive use of metric benchmarking could generate a heavy "information" load that should be overcome by taking the next step from metric benchmarking into process benchmarking. They argue that metric benchmarking is just a first step in the improvement process of any firm and water industry has been rather slow to adopt benchmarking practices, paying more attention to metric benchmarking than process overall improvement. We could not agree more.

It is important to remember that the water industry has a big issue with its information. Unlike other infrastructure systems, such as highways, the water industry is comprised by thousands of small and medium utilities with no centralized agencies. This fragmentation makes information standardization and other required steps harder to achieve, even with the effort put by federal agencies like EPA or international organizations such as The World Bank.

Formal benchmarking efforts in the U.S. water industry began in 1994 with the elaboration of a guidance study to perform benchmarking in water utilities, project funded by the American Water Works Association Research Foundation, now known simply as Water Research Foundation. At the beginning benchmarking was aimed to the development and use of adequate metrics. After the first research project in this topic was released, others studies followed, like those by WERF (Water Environment Research Foundation), NAWC (National Association of Water Companies) and AMSA (Association of Metropolitan Sewerage Agencies).

Olstein proposed some conclusions in his paper (Olstein, 2004) that are still current and continue to have great importance:

- "Benchmarking requires an understanding of the system and operations being studied. This is not a numbers exercise.
- It is important to understand why the benchmarking is being done and adjust the approach accordingly.
- No two utilities are exactly the same, but that doesn't mean that you can't learn anything from well crafted performance measure comparisons…
- In benchmarking, the movement of key performance measures over time can be more valuable than looking only at one point in time."

Finally, it is important to remember that as it was pointed out at the beginning of this chapter, most literature that has to do with energy efficiency of water and wastewater systems is related to pumping operations. We are realizing that there are other areas where higher energy efficiency could be pursued, like analyzing the system design and the effect of water quality and climate change over the built environment.

Climate change deserves a special mention. A changing climate will affect the water industry. It will mean unprecedented challenges and opportunities. Amid this changing scenario, efficient operation of the infrastructure is a must. Disrupted precipitation patterns, flash floods, droughts, and stronger climatic events such as hurricanes will add pressure to water and wastewater systems for enhanced resiliency.

Benchmarking Scores for the Utilities by AWWARF

Benchmarking scores for Energy Efficiency were calculated for eight utilities, using the benchmarking model proposed in the AwwaRF report (Carlson, 2007). The following benchmarking scores could be calculated for each one of the utilities:

1. Production Energy Use Benchmarking Score
2. Treatment Energy Use Benchmarking Score
3. Distribution Energy Use Benchmarking Score
4. Overall Energy Use Benchmarking Score

It is important to notice that not all four scores can usually be calculated for each utility, since the organization scheme in the utilities varies widely. Some utilities do not have control over the distribution system, for example, and then neither this score nor the overall can be calculated for that specific case. In other cases, they might not have authority over treatment, so that cannot be calculated either. The idea, of course, is that makes sense to calculate only those benchmarking scores upon which the utility has power to modify. For this research, we will calculate only the production energy use score and treatment energy use.

For this project we utilized the benchmarking method detailed in the report "Energy Index Development for Benchmarking Water and Wastewater Utilities" published by AwwaRF in 2007 (Carlson, 2007). This benchmarking is based upon the benchmarking method utilized under the EPA's ENERGY STAR rating system for buildings. It utilizes the same philosophy and approach.

A statistical sample of water utilities is gathered and analyzed. A regression method is used to correlate energy usage to parameters that might be relevant to energy consumption. Those parameters that best correlate with energy consumption and are not under utilities' control are normalized into the model. The parameters are included into the model one by one, starting from the one with most significance accordingly to a t-test.

Once a model has been obtained that has a coefficient of determination high enough, this normalized statistical model is used to predict the energy usage of any given utility. By comparing this predicted energy usage with the actual energy use, the utility obtains a score. The benchmarking score represents a percentile, so if the score is say 55, that means the utility is more efficient that 55% of the utilities with similar characteristics.

This benchmarking study provided statistical models to predict overall energy usage in the utility, as well as disaggregated models for production, treatment and distribution energy use. This is very convenient, since many utilities do not own the whole system. They may own production, but not distribution; or production and distribution, but not treatment.

It is important to notice that the statistical prediction model described is not intended to be an accurate energy usage predictor, instead is a benchmark against which the utility will be scored. It means that in average, the utilities have the predicted energy usage.

All the used models have the following form:

$$E_P = a_0 + \sum a_i x_i$$

Where:

E_P	Predicted source energy use, kBTU/yr
a_0	Constant (independent term)
a_i	Coefficients
x_i	Parameters

The constant and coefficients are calculated statistically. The parameters usually are natural logarithms of the considered factors, or just a 1/0 input indicating that a treatment process is or is not present in the utility.

The process of calculating the benchmarking scores is as follows: First, we calculate the predicted energy use by using the parameters in the statistical model. We obtain the natural logarithm of the predicted energy use, in terms of kBTU/yr. Second, we calculate the actual utility's energy usage in a year, by adding up all the energy consumption from all kinds of energy (electricity, natural gas, diesel…) and converting them to source energy using the appropriate conversion factors to BTU per unit of given kind of energy.

The actual energy usage is adjusted to enter the normalized model. Adjustment factor is calculated by dividing the predicted energy use by the model's mean. The score is obtained by entering the adjusted energy use in the normalized curve, which is also tabulated for each case.

The benchmarking models utilized for this research are just the following:

a) Production Energy Use

Table 1. Production Benchmarking Model

Coefficient (a_i)	Parameter (x_i)	Units
8.0924		
0.6904	ln(Total Inflow)	kGD
0.4423	ln(Total Raw Hp)	HP
-0.0748	ln(Purchased inflow)	kGD

Model Mean: 17.340

For the predicted production energy use, this model includes the constant (a_0) and three parameters: Natural logarithm of the total inflow entering the water system, adding all of the sources; natural logarithm of the used raw water pumping power, excluding backup; and the natural logarithm of the purchased water inflow. Notice that the coefficient of the purchased water inflow is negative, since that water does not pass through the raw water extraction system in the studied utility, thus apparently decreasing the total amount of energy used for the given system flow. Purchased water enters the system without going through the raw water extraction phase. When calculating this predicted energy use, a 1 must be added to the purchased water inflow to avoid a zero value input to the logarithm.

The reason to use just these two production energy use and treatment energy use benchmarking models is that in case study we found that most utilities do not own the whole system: Production, Treatment, and Distribution. These two benchmarking scores could be applied to almost every utility.

b) Treatment Energy Use

Table 2. Treatment Benchmarking Model

Coefficient (a_i)	Parameter (x_i)	Units
10.8346		
0.61	ln(Total Inflow)	kGD
0.1221	ln(Total Raw Hp)	HP
-0.0861	ln(Purchased inflow)	kGD
0.7279	Oxidation	-
-0.7214	Direct Filtration	-
-0.8312	Sand Drying Bed	-
-0.9315	Iron Removal	-
0.7946	Ozonation	-

Model Mean: 16.380

Following the same general structure, the model for treatment energy use has the following eight parameters: The three first parameters after independent term are the same of the previous production energy use model, with different coefficients. After those, we have whether the system has oxidation process or not, expressed by a 1 in case there is or a 0 if there is not; whether the system has sand drying bed, also represented by a binary (1/0) entry; whether or not the system has iron removal process; and whether the system uses ozonation. One more time, is interesting to notice that some of the parameters have a reducing effect on predicted energy consumption, while others usually increase that consumption.

There are some interesting facts of these statistical models. First, that all of them use as the first parameter the total system inflow. The benchmarking study from which the models were constructed, found that the single main factor determining how much energy a water system consumes is precisely how much water is entering the system. This single parameter explains around 70% of the energy use. Also notice that some parameters that are relevant to explain energy consumption of a utility were not included, like water loss. The reason is that since the model works as a benchmark, it should not normalize factors that are arguably under utility control. If water loss is normalized into the model, even utilities experiencing important amounts of water loss would obtain good scores.

We have the normalized distribution curves for the production and treatment models in the following figures.

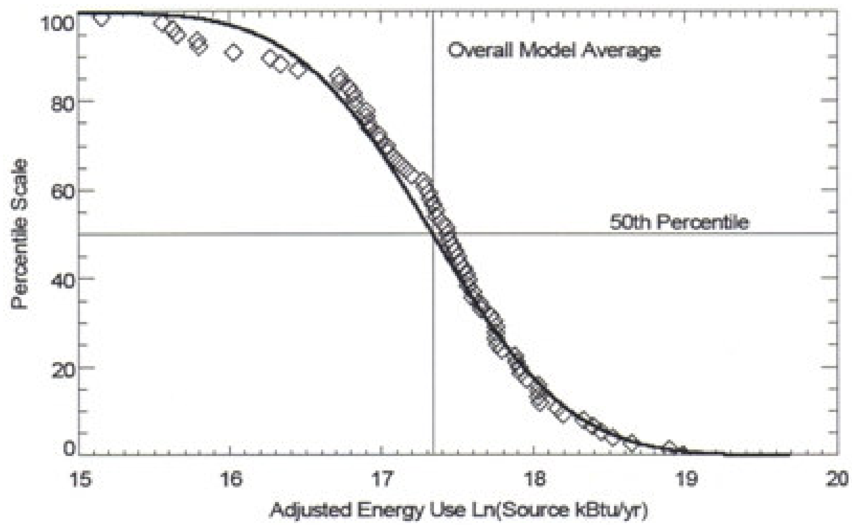


Fig. 4 Normalized distribution curve for production energy use. Source: Carlson and Walburger 2007 © 2007 AWWA Research Foundation. Reproduced with permission.

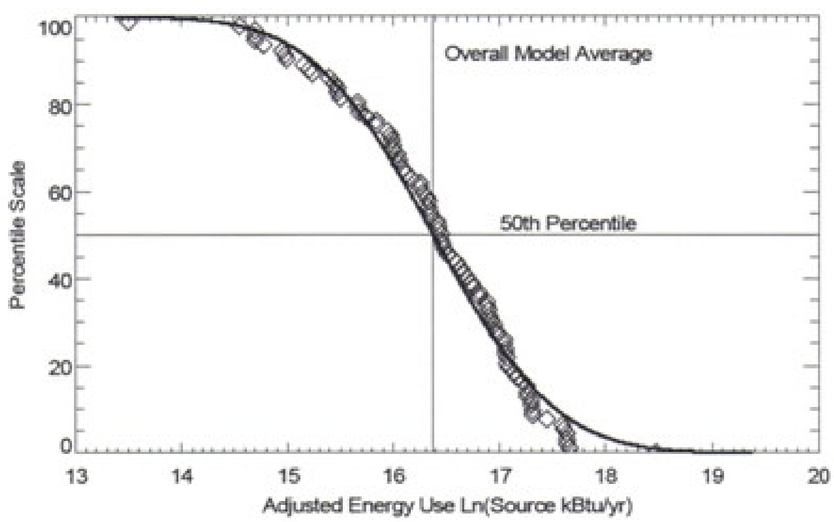


Fig. 5 Normalized distribution curve for production energy use. Source: Carlson and Walburger 2007 © 2007 AWWA Research Foundation. Reproduced with permission.

These curves are not convenient for use when calculating benchmarking scores, so a better way to do that is to tabulate the curves. The tables are shown in figs 6 and 7.

Water Utility Production Energy Performance Rating Score Based on Adjusted Source Energy Use

Score	Adjusted Energy Use ln(kBtu/yr)	Score	Adjusted Energy Use ln(kBtu/yr)	Score	Adjusted Energy Use ln(kBtu/yr)
100	14.990	66	17.049	33	17.650
99	15.699	65	17.068	32	17.670
98	15.892	64	17.087	31	17.689
97	16.014	63	17.106	30	17.709
96	16.105	62	17.124	29	17.730
95	16.180	61	17.143	28	17.750
94	16.244	60	17.161	27	17.772
93	16.299	59	17.179	26	17.793
92	16.349	58	17.197	25	17.815
91	16.394	57	17.215	24	17.837
90	16.436	56	17.233	23	17.860
89	16.475	55	17.251	22	17.884
88	16.511	54	17.269	21	17.908
87	16.545	53	17.286	20	17.933
86	16.578	52	17.304	19	17.959
85	16.609	51	17.322	18	17.985
84	16.638	50	17.340	17	18.012
83	16.667	49	17.357	16	18.041
82	16.694	48	17.375	15	18.070
81	16.721	47	17.393	14	18.101
80	16.746	46	17.411	13	18.134
79	16.771	45	17.428	12	18.168
78	16.795	44	17.446	11	18.204
77	16.819	43	17.464	10	18.243
76	16.842	42	17.482	9	18.285
75	16.864	41	17.500	8	18.330
74	16.886	40	17.518	7	18.380
73	16.908	39	17.537	6	18.436
72	16.929	38	17.555	5	18.499
71	16.950	37	17.574	4	18.574
70	16.970	36	17.592	3	18.665
69	16.990	35	17.611	2	18.788
68	17.010	34	17.631	1	18.980
67	17.029				

Fig. 6 Table for production energy use benchmarking score calculation. Source: Carlson and Walburger 2007 © 2007 AWWA Research Foundation. Reproduced with permission.

Water Utility Treatment Energy Performance Rating Score Based on Adjusted Source Energy Use

Score	Adjusted Energy Use ln(kBtu/yr)		Score	Adjusted Energy Use ln(kBtu/yr)		Score	Adjusted Energy Use ln(kBtu/yr)
100	13.378		66	16.007		33	16.774
99	14.284		65	16.031		32	16.799
98	14.530		64	16.055		31	16.825
97	14.686		63	16.079		30	16.850
96	14.803		62	16.103		29	16.876
95	14.898		61	16.127		28	16.903
94	14.979		60	16.150		27	16.930
93	15.050		59	16.174		26	16.957
92	15.113		58	16.196		25	16.985
91	15.172		57	16.219		24	17.014
90	15.225		56	16.243		23	17.043
89	15.274		55	16.265		22	17.073
88	15.321		54	16.288		21	17.104
87	15.364		53	16.310		20	17.135
86	15.406		52	16.333		19	17.168
85	15.445		51	16.355		18	17.202
84	15.483		50	16.378		17	17.237
83	15.520		49	16.401		16	17.273
82	15.554		48	16.423		15	17.311
81	15.588		47	16.446		14	17.350
80	15.621		46	16.469		13	17.392
79	15.652		45	16.491		12	17.435
78	15.683		44	16.514		11	17.482
77	15.713		43	16.537		10	17.531
76	15.743		42	16.560		9	17.585
75	15.771		41	16.583		8	17.643
74	15.799		40	16.606		7	17.707
73	15.827		39	16.630		6	17.777
72	15.854		38	16.653		5	17.858
71	15.880		37	16.677		4	17.954
70	15.906		36	16.701		3	18.071
69	15.932		35	16.725		2	18.227
68	15.957		34	16.750		1	18.472
67	15.982						

Fig. 7 Table for treatment energy use benchmarking score calculation. Source: Carlson and Walburger 2007 © 2007 AWWA Research Foundation. Reproduced with permission.

We chose to work with these benchmarking scores because they are technically sound. Among the many different benchmarking metrics that are currently used, these are really good.

CHAPTER 3. METHODOLOGY FOR ANALYSIS

Minimum Required Energy Approach

Energy efficiency means to use the less possible energy to adequately perform the intended system function. The resulting performance must comply with the regulation standards and expected levels of service. For instance if there is a utility that uses very little energy but delivers water below established performance level is not being energy efficient, nor a water utility that delivers high quality water at an adequate pressure and flow rate with disregard of the energy used.

From this basic concept of energy efficiency, we intend to measure how energy efficient is a water utility on its production and treatment phases calculating the minimum required energy to perform the task while meeting standards.

The first step is to draw a simple diagram of the system, from raw water extraction to the treatment facility. By using this network diagram, we can track energy inputs that are required on each step of the process. It is important that we have three dimensional locations of the nodes, since the system is not all contained in the same plane. Most terrains have different elevations. A sample network is shown in perspective on fig 4.

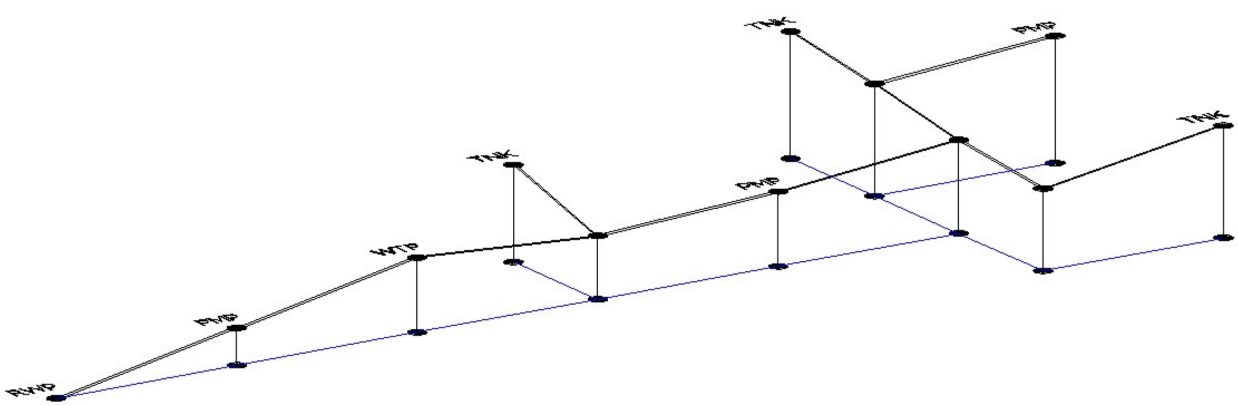


Fig 8 Network Diagram with elevations

The network diagram shall include all features in the system that impact energy usage and are under the utility's authority. For example, many utilities deliver the water up to a certain point but do not have ownership over the distribution system. The aim is to assess the energy usage within any given water utility.

When we have our network diagram of the system, we analyze how much energy is required to deliver water through the system assuming ideal conditions. The ideal conditions refer to the following:

1. Water is delivered at almost zero pressure at delivery point.
2. There is no water loss in the system
3. Wire- to-Water pumping efficiency is 100%
4. There is no minor head loss due to fittings

Requirements that are not being considered at this point are those that imply an energy input above the strict minimum of making the raw water reach delivery node in the network.

Depending of the complexity of the network, this analysis might be feasible in a very simple manual way, or might require the use of software to determine the flows and head loss on each edge. In this research, however, we are limiting our study to the first phase of the system, from raw water extraction to treatment.

In our case, we proceed in order edge by edge, following the same path of the water in the pipes. Starting from the water source node, we calculate the pumping head required to deliver the water to the next node. Let's consider the edge from node i to node j as follows:

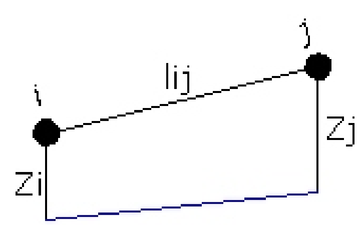


fig.9 Typical edge between nodes i and j

The total head required to overcome for this edge is calculated as

$$Th_{ij} = (Z_j - Z_i) + Hl_{ij}$$

Where

Th_{ij}	Total water head required to get the water from node i to node j
Z_j	Elevation of starting node i
Z_i	Elevation of ending node j
Hl_{ij}	Head loss from i to j

This expression is based upon Bernoulli's Theorem. The elevation difference $(Z_j - Z_i)$ is the elevation head, and Hl_{ij} is the friction head loss. This equation represents the total head we must provide to the water to make it advance from point i to point j under ideal conditions.

The friction head loss on any given edge can be calculated using the Darcy-Weisbach equation as:

$$Hl_{ij} = \frac{f L_{ij} Q_{ij}^2}{2g D_{ij} A^2}$$

Where

Hl_{ij}	Head loss from node i to node j
f	Coefficient of Friction
L_{ij}	Length of pipe from node i to node j
Q_{ij}	Flow rate from node i to node j
g	Acceleration of gravity, 32.174 ft/sec^2
D_{ij}	Inner diameter of the pipe between i and j
A	Cross-sectional area of the inner diameter of pipe, D_{ij}

Usually the problem with the Darcy-Weisbach equation for head loss is the estimation of the friction factor f. Since the water flow in pipes is usually turbulent, is common practice in the industry to use the Moody's diagram to estimate an approximate value for this factor.

Moody's diagram comes from the Colebrook-White equation to estimate the coefficient of friction:

$$\frac{1}{f^{0.5}} = -2log_{10}\left(\left(\frac{\epsilon}{3.7D}\right) + \frac{2.51}{R_E\, f^{0.5}}\right)$$

Where

f	Coefficient of Friction
ϵ	Absolute roughness parameter
R_E	Reynolds Number
D	Pipe diameter

The Colebrook-White equation inconvenience is that it is an implicit function of the friction factor, f. This equation is usually solved by successive iterations until both sides are equal. Instead of doing that, we will apply a direct formula for the friction factor that is approximated within 1% of the Colebrook-White result. This formula was developed in 1976 by Swamee-Jain:

$$f = \frac{1.325}{\left(\ln\left(\frac{\epsilon}{3.7D} + \frac{5.74}{R_E^{0.9}}\right)\right)^2}$$

In order to be able to use this expression, we need to calculate the Reynolds number

$$R_E = \frac{v\, D}{\vartheta}$$

v	Velocity of water
ϑ	Kinematic viscosity of water

The velocity of water in the pipe can be estimated by using:

$$v = \frac{Q}{A}$$

In this equation, Q is the flow rate and A is the internal cross-sectional area of the pipe.
At this point we need to be even more careful. The estimation of an adequate roughness parameter is not easy, resembling more an art than an exact science. We would need to know what the actual condition of the pipe is and perform some measurements to have an exact value. Since we usually do not have that information, we must make a reasonable estimate based mainly upon pipe material, age, and water quality. Even with estimates carefully calculated the interior roughness of pipe remains with huge uncertainty.
In addition to the uncertainty in estimating a roughness value, the Reynolds number varies according to the kinematic viscosity of water, which in turn varies depending upon water composition and temperature.
Although due to these factors the estimation of an adequate friction factor for the Darcy-Weisbach equation is not an exact science and is full of uncertainty, a reasonable value for practical purposes can be reached in our case.

Effect of aging on pipe wall roughness

In order to estimate as accurately as possible the interior roughness of pipes, we will follow the next process:

1. Estimate the absolute roughness of pipe, given the material as if it were new. This absolute roughness ϵ is expressed in feet.
2. Apply Mostkov method to estimate the absolute roughness growth based on pipe age and water quality.

Mostkov method represents a systematic way to reasonably estimate the deposit forming tendencies of pipe walls conducting water, resulting on increased roughness. The proposed equation is

$$\Delta_t = \Delta + \alpha_t t$$

Where

Δ_t Absolute roughness of pipe after t years

Δ Absolute roughness of new pipe, mm

α_t Rate of increase in asperity, mm/yr

t Age of the pipe, years

We need to work this expression in millimeters because the table for the α_t values is expressed in mm/yr. After the operation we make the conversion to feet. Since the roughness growth is a complex phenomenon that depends on pipe material, age, water quality and hydraulic characteristics, the values for alpha were derived from experimental tests and they represent averages.

The suggested values of α_t are shown in the following table:

Table 3. Suggested values for roughness growth rates

Water Quality Group	α_t mm/year	
	Limits	Most Probable
I	0.005 - 0.055	0.025
II	0.055 - 0.180	0.070
III	0.180 - 0.400	0.200
IV	0.400 - 0.600	0.510
V	0.600 - 3.000	

The water quality group refers to a classification made by Kamershtein for water supplying pipelines:

Group I. Weakly saline, noncorrosive water with a moderate content of organic substances and free iron. No carbonates.

Group II. Weakly saline, corrosive water containing organic substances and free iron in quantities below 3 g/m^3

Group III. Very corrosive water with a small content of chlorides and sulfates (less than 100-150 g/ m^3); water with an iron content above 3 g/ m^3

Group IV. Corrosive water with high content of sulfates and chlorides (above 500-700 g/ m^3); nontreated water with high content of organic substances.

Group V. Water distinguished by appreciable carbonate and low constant density; heavily saline and corrosive water.

Once we know the total head we need to provide to the water in order to convey it from the source to the treatment facility, we need to convert this head in energy requirements. This can be done through the power equation

$$P_w = Q_{ij}\gamma Th_{ij}$$

In this expression,

P_w	Power of water, lb-ft/sec
Q_{ij}	Flow rate on edge from i to j,
γ	Density of water, 62.4 lb/ft^3 on average
Th_{ij}	Total head of water required in section from i to j

Any pump would require providing water that total head, at a flow rate Q, to overcome the system conditions (friction and topology). This power can be easily converted to BTU. This Minimum Required Energy can then be compared with the actual energy consumption.

It is very important to remember that this energy has being calculated for a system under ideal conditions. The energy so calculated represents the energy that water should have (Power of the water). In order to achieve that energy level in the water, we need to provide more energy to account for real world conditions, such as pumping efficiency, water loss, minimum pressure, etc.

Converting ideal conditions to Minimum Achievable Energy Consumption

We cannot use the ideal minimum energy required by the system to perform comparisons directly. By doing so, we would be comparing the actual energy consumption of the utility with an energy level that is not reachable under any real conditions. To overcome the ideal condition status, application of the corresponding factors described below is required.

Pumping efficiency effect

No machine is 100% efficient converting energy into work. There are always losses, so the method must account for them. In order to achieve certain level of power of water, P_w, there are two prior stages where inefficiencies must be overcome: First, the energy required to operate the pump in brake horsepower. The expression for this is:

$$P_p = \frac{P_w}{\eta_P}$$

Where

P_p Pump power, brake horsepower

η_P Pump Efficiency, decimal

The pump efficiency factor is to account for energy losses in the pump caused by various phenomena such as internal friction, leakage, recirculation and others.

After accounting for pumping losses, we must take into consideration the efficiency of the motor of the pump itself. So we have:

$$P_m = \frac{P_p}{\eta_E}$$

Where

P_m Pump power

η_E Motor Efficiency, decimal

Both efficiency factors η_P and η_E are frequently combined in one factor by multiplying them, called wire-to-water efficiency in the case of electric pumps, or fuel-to-water efficiency for engine driven pumps.

$$\eta_{ww} = \eta_P \eta_E$$

Wire-to-water efficiency factor takes into consideration what fraction of the electricity (in this case) is lost in the motor, and from the remaining energy, how much is lost in the pump itself. The resulting reduced energy is then transmitted to the water. The wire-to-water efficiency varies with the size of the pump and the flow rate. Some examples of wire-to-water efficiencies are included in the following table.

Table 4. Sample wire-to-water efficiencies

Flow Rate	Flow Rate	Head	Motor	Pump Efficiency	Motor Efficiency	Wire-to-Water Efficiency
gpm	ft^3/sec	ft	HP	%	%	%
20	0.045	10	0.25	38	50	19
60	0.134	15	0.5	53	60	32
80	0.178	25	1	57	82.5	47
120	0.267	50	3	60	86.5	52
300	0.668	70	7.5	80	88.5	71
500	1.114	80	15	84	91	76
1000	2.228	90	30	84	92.4	78
1000	2.228	110	40	84	93	78
1600	3.565	100	50	86	93	80
2000	4.456	120	75	89	94.1	84
2900	6.461	120	100	90	94.1	85

Delivery pressure effect

We are assuming under our ideal conditions that water will be delivered at zero pressure in the delivery point. This is clearly not realistic. To account for this, we must add certain pressure to the system. How much pressure do we need to add depends on the particular characteristics and processes of each system, but we can propose a minimum pressure that most of all would have. In a real distribution system pressures are not equal at every point. There is usually a range of acceptable pressures that runs from 30 psi to over 100 psi. In our case, we suggest using a much lesser value of 15 psi. The reason for this is that this value does not imply a high pressure that would increase the required energy, and is not zero pressure either.

The equivalent water head for pound of pressure for any liquid depends on its specific weight, which varies according to the liquid's temperature:

$$h = \frac{144}{\gamma}$$

h Equivalent head, feet

γ Specific weight, lb/ft^3

Variations of water specific weight and kinematic viscosity with temperature are shown in the next table.

Table 5. Properties of water at different temperatures

Temperature	Specific Weight γ	kinematic viscosity ν
°F	lb/ft^3	$x10^{-5}\ ft^2/sec$
32	62.42	1.93
40	62.42	1.67
45	62.42	1.54
50	62.38	1.41
55	62.38	1.31
60	62.34	1.21
65	62.34	1.14
70	62.31	1.06
75	62.27	1.00
80	62.19	0.93
85	62.15	0.88
90	62.11	0.83

Using a standard value for water specific weight of 62.4 lb/ft^3 we obtain 2.31 ft of head for each pound of pressure. For 15 psi (gauge) that means 34.65 ft of extra head required. This extra head can be added to the total head before calculating the required water power, or adding the resulting power from this head to the ideal required power.

Minor Head Loss effect

When conducting water through a pipeline, there are head losses due to fittings such as elbows, tees, and so on. This head loss is present in addition to the friction head loss. Although named minor head loss, these losses might be really important in some cases. Some standard values for head loss factors k for almost each fitting have been estimated through laboratory testing.

The minor head loss calculation is not recommended to be performed as a percentage of the total losses, as sometimes suggested, since its value actually varies widely. The best way to estimate minor losses is to use a case-by-case approach, taking into account every fitting characteristic. Estimating minor head losses for the studied systems is out of scope of this research. In the present study minor head losses will not be taken into account. It is necessary, however, to be aware of their existence and potential importance on specific systems.

Water loss effect

Another factor that will increase the energy consumption in the system is water loss. In addition of the obvious water and energy losses through breaks, leakage also implies losses. In the case of energy, these losses are mainly of two kinds:

a) Energy wasted in water that is lost. This is the energy that was put into the water by extracting it from the source and pumping it through the pipe. This loss represent the energy intensity of the water that is leaking out, expressed in units such as kWh/MG for example.
b) Energy loss through pressure drop. Usually the water pressure at delivery point must be maintained within a value range; leakages cause the pressure to drop, so extra pressure must be provided to the system to account for this.

The effect on extra energy consumption derived from leaks is known to be rather important (Colombo, 2002). However, it appears like a simple "rule of thumb" for estimating such an impact does not exist. For our research project, we will suppose that the pressure drop by leakage is negligible, thus focusing on the energy intensity of the water lost. Even when this assumption is not accurate or complete, it will provide a certain amount of the effect of water loss on our energy considerations. The difficult in calculating the energy lost due to pressure drop in the pipe comes from the facts that this loss magnitude depends on the characteristics of leak.

The effect we will consider is just a percentage of the real impact, since we are considering one out of two implications of water loss in overall energy consumption.

To estimate energy loss embedded in water loss, suppose we have the following pipe section, where we are losing a certain amount w of water:

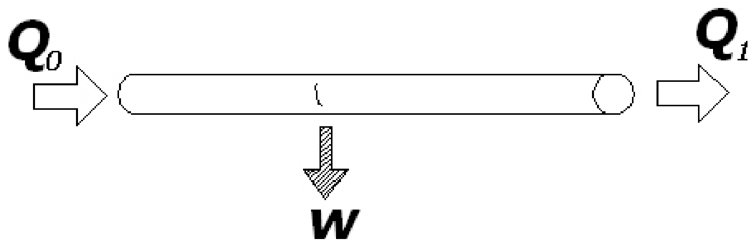


Fig.10 Section of Pipe with a leak

Then:

$$Q_1 + w = Q_0$$

Usually we know the value of the unaccounted for water U_w as decimal:

$$U_w = \frac{w}{Q_0}$$

Thus:

$$Q_0(1 - U_w) = Q_1$$

Finally we obtain a factor by which energy intensity of water increases after the leak, hence increasing the required energy consumption:

$$\frac{Q_0}{Q_1} = \left(\frac{1}{1 - U_w}\right)$$

This factor will be applied after we have the value of required water power.

When we apply more realistic conditions to the system, the total required energy amount will increase accordingly to a theoretically achievable E_{min}. A very intuitive energy efficiency measure is obtained dividing the Minimum energy required to run the system, by the actual source energy consumption, as

$$TS = \left(\frac{E_{min}}{E_{actual}}\right)$$

We called this ratio the thermodynamic score and expressed it in percentage form. Although it is very useful, it has also some drawbacks as we will see later in the case study.

Sensitivity Analysis

Due to uncertainties associated with many of the parameters estimated for the minimum required energy analysis, a sensitivity analysis is a natural step. The analysis objective is to answer the question of how much do the variations on these uncertain variables impact the final result obtained on each analysis.

The following parameters will be varied over a range of values to estimate the impact upon final results of energy consumption and benchmarking scores:

a) Absolute roughness of pipe wall

The roughness of the pipe wall affects the friction factor for the Darcy-Weisbach equation. We calculated a likely roughness measure based on pipe material, age and water quality. However, this estimation is not accurate at all. We will vary pipe roughness from half to twice of estimated value.

b) Water temperature

Water temperature plays a role through changes in kinematic viscosity of water and specific weight. In Virginia, temperatures vary from winter to summer. We are using in the analysis an average, but in real life the energy required during the cold months and the warm ones will vary. We will suppose the temperature of water varies between 40 and 70 degrees Fahrenheit.

c) Water Loss

Although the utilities reported very low unaccounted for water from the water source to the treatment plant, is interesting to analyze the effect of water loss over energy consumption. Water Loss will be varied between 0 and 20%.

d) Wire-to-Water efficiency

We know that the wire-to-water efficiency of the pumps vary with the flow rate, output head and pumping power. Unfortunately we have no reasonable way to estimate that efficiency without more information like the manufacturer's head-capacity curves that are specific for each pump. We will vary this efficiency from 40% to 90%

The following curves were obtained varying the absolute roughness of the pipe from half to twice of the estimated value on each case. In some cases, the vertical axis represents the natural logarithm of energy required to extract and convey the raw water. This natural logarithm is used to calculate the desired benchmarking scores through tables included in appendix C.

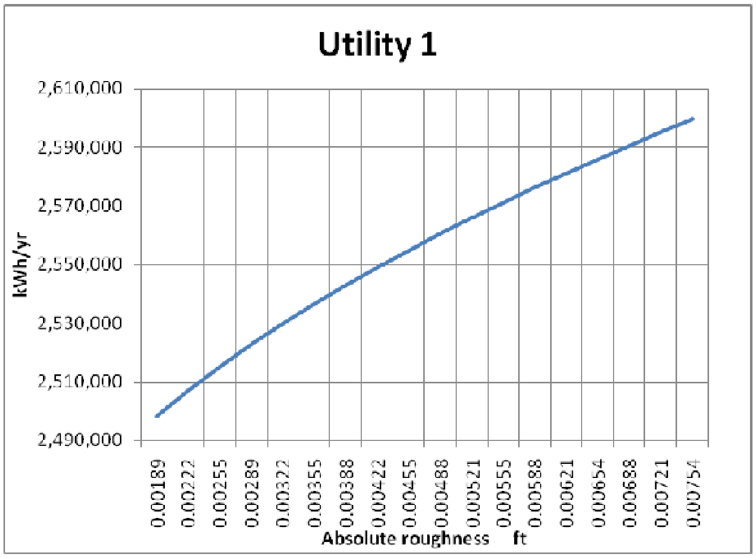


Fig 11 Utility 1 Roughness effect over electricity consumption chart

As we can see in fig.6, the pipe wall roughness variation between the proposed limits has an effect on the total amount of electricity. In this case, double roughness value causes around a 3% increase in electricity consumption. Next figure shows roughness variation impact on the natural logarithm of source energy.

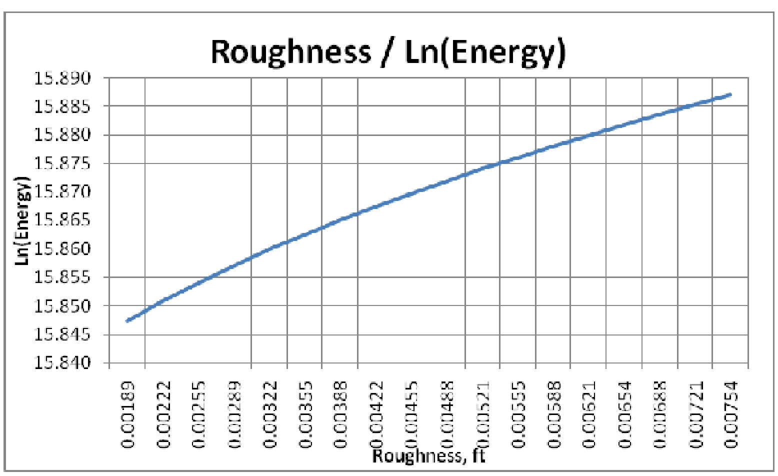


Fig.12 Utility 1 Roughness effect over adjusted source energy use

In this case, even with roughness variation from half of estimated value up to double that number, the change in the adjusted energy natural logarithm (which we use as entry to calculate benchmarking score) varies around 4 hundredths. That causes a benchmarking score change smaller than 1 point. Utility 1 sensitivity to pipe roughness change is very small because two main factors: First, a distance between raw water source and treatment facility of 1.50 miles is not very large; second, it has to overcome a static head close to 300 ft. which requires most of the energy utilized.

To analyze a very different case, we will use Utility 7. This utility has a relatively long distance between raw water and treatment facilities (35 miles) and a small static head to overcome of just 22 ft. Given these conditions, the effect of pipe roughness over energy consumption and benchmarking scores is more dramatic.

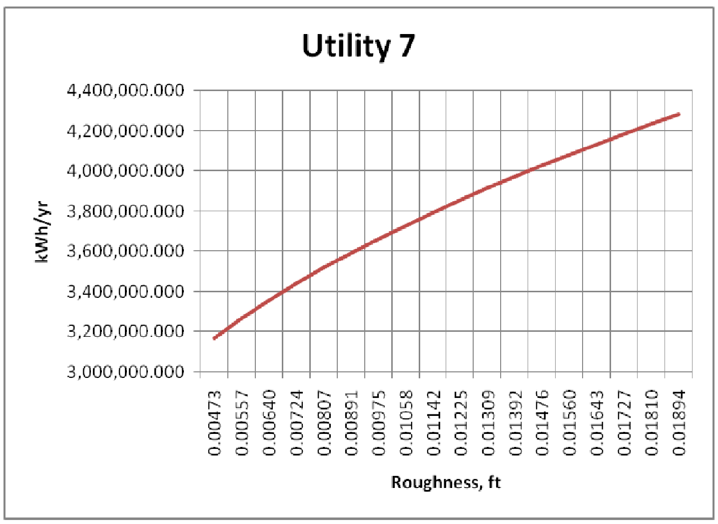


Fig. 13 Utility 7 Roughness effect over electricity consumption chart

For Utility 7, if the pipe roughness is double of the estimated, electricity requirement increases around 19%. If the roughness is instead half of estimation, electricity consumption would be 12% less.

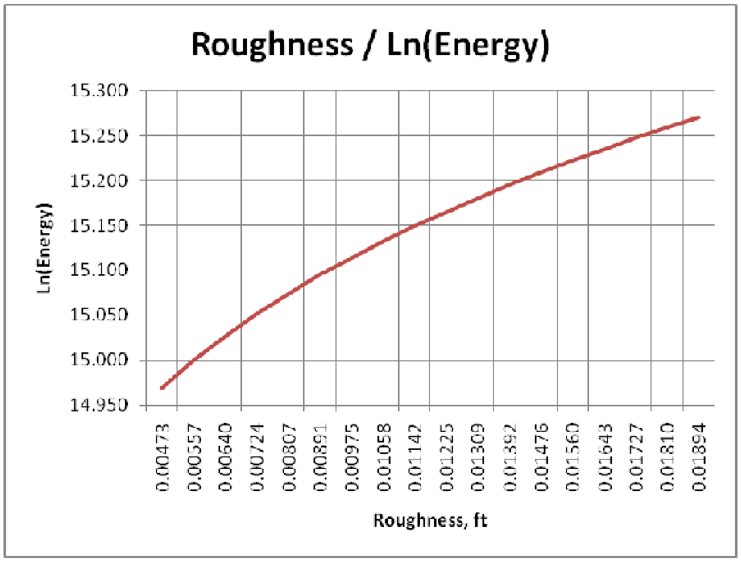


Fig.14 Utility 7 Roughness effect over adjusted source energy use

In terms of benchmarking scores, we can see that even when the effect is more pronounced than in the case of utility 1, is not enough yet to change the maximum benchmarking score the utility can reach. Nevertheless, since we are dealing with a curve, effects vary accordingly to the curve slope on each point. For that reason, if the benchmarking score is around 79, a roughness variation like this could cause that benchmarking score to move 1 or 2 points.

Pipe roughness certainly has an impact over the total amount of energy a utility consumes: For the roughness variation range in utility 7, there is a total variation in consumed energy equivalent to more than 1,000,000 kWh/yr. However, in terms of maximum benchmarking score it does not have an important impact on the utility. For all practical purposes, calculated maximum reachable benchmarking scores will remain the same for roughness values half of the estimated value to twice that value. The benchmarking score corresponding to the minimum required energy is thus not very sensitive to pipe wall roughness variations.

The pipe wall roughness effect over the energy consumption depends mainly of two factors: Pipe length and elevation change. At more length and less elevation change, more impact from roughness variations. Conversely, at more elevation change and less pipe length the roughness impact will be smaller.

Water Temperature

Variations of water temperature will have even a smaller effect on the energy consumed by the utility and the resulting benchmarking scores.

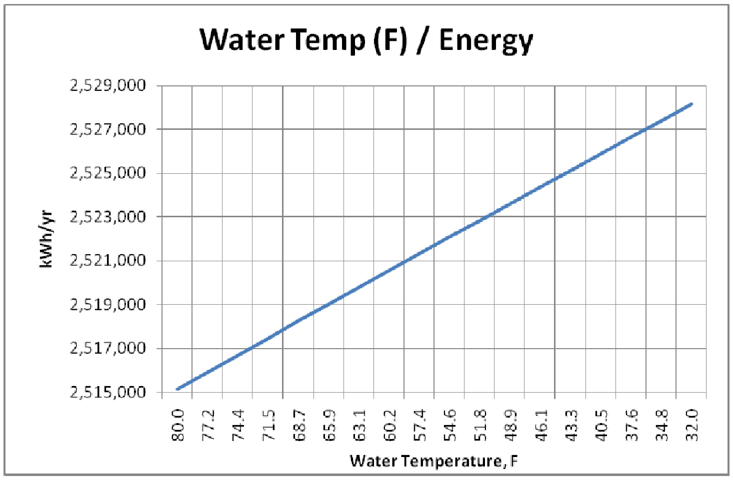


Fig.15 Utility 1 Water temperature effect over electricity consumption

For utility 1, the effect of water temperature variation is maximum 13,000 kWh/yr. For all other utilities the temperature variation of raw water does not imply significant energy consumption changes.

Water Loss

Water loss has a more important effect over the energy consumption of the utility than pipe roughness and water temperature. We have the curves for some utilities summarized in the following chart (fig.12): It is interesting to notice that variations of water loss over the magnitude of the energy used to calculate benchmarking scores appears linear, even when it is not.

The area comprised between the marks 15 and 19 in the vertical axis are related to benchmarking scores. Under 15, scores are 100; above 19 scores are 0. These are the maximum calculated scores any utility can reach depending on how much water loss it has.

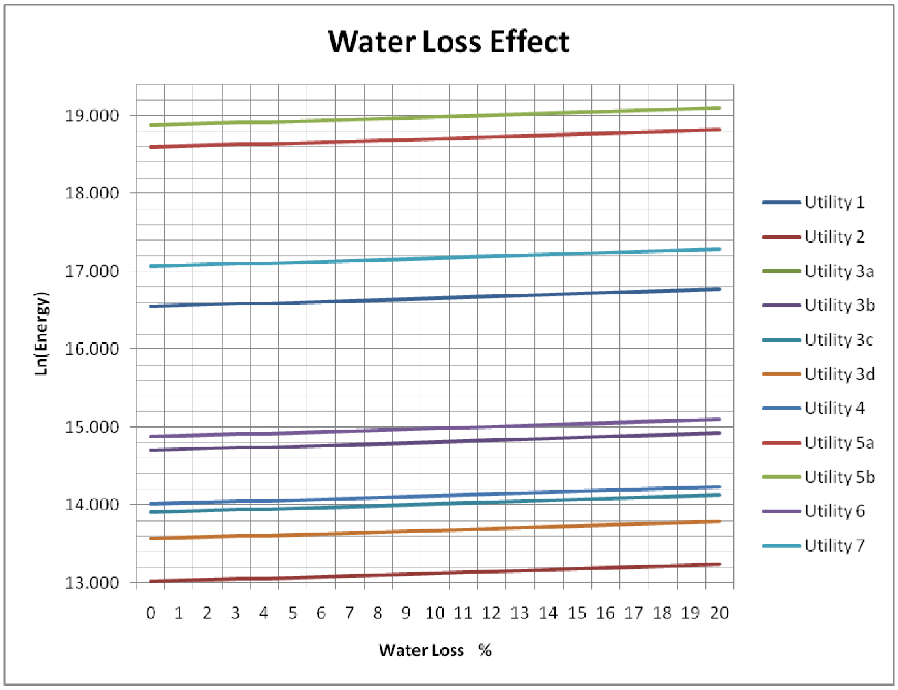


Fig.16 Water loss effect over energy levels for maximum scores

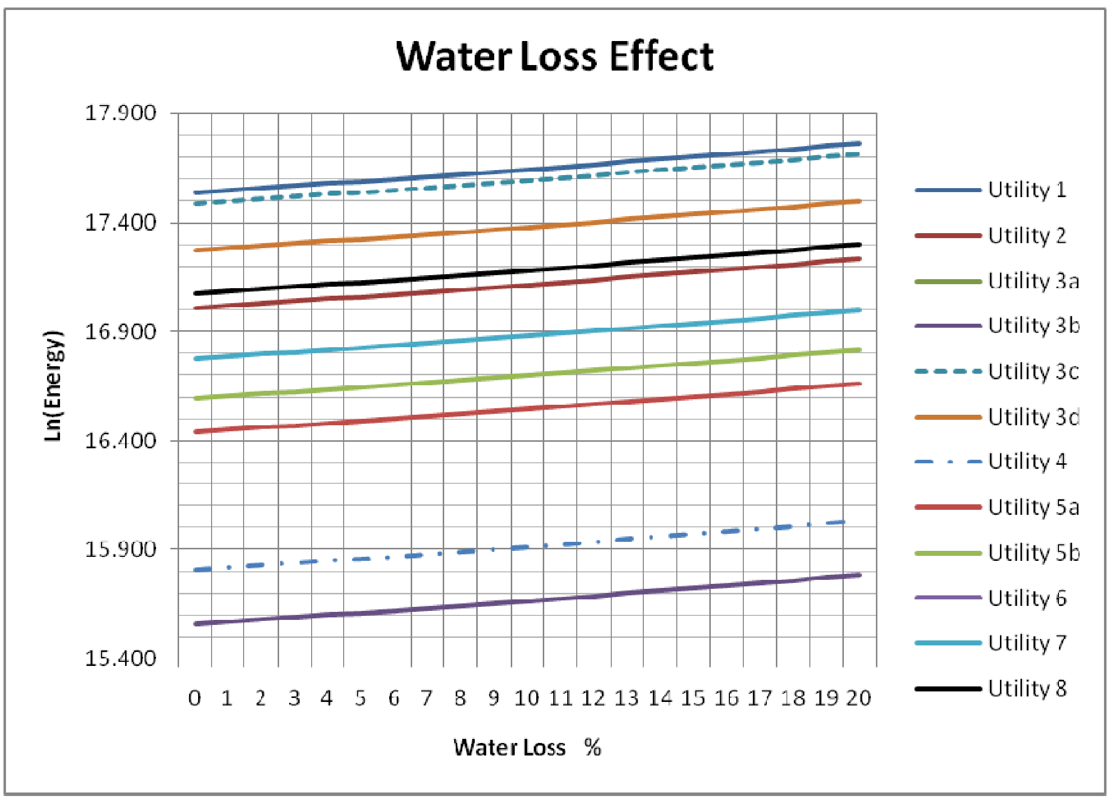


Fig.17 Water Loss effect over current energy levels used to estimate actual scores

Chart in fig.13 is still more interesting. It represents the change in the natural logarithms of the actual energy consumption levels for each utility due to water loss. This chart can be used to assess change in production energy use benchmarking scores resulting from change in water loss levels. For example, if utility 4 had a water loss of 20%, the benchmarking score would go from 98 to 95.

Wire-to-Water Efficiency

The combined efficiency of the pump design and the pump motor (wire-to-water efficiency) will have an important effect over the energy consumption and the benchmarking score for the utility. This efficiency needs to be measured for each pump to estimate accurate values on each case. For utility 1 this factor alone might cause the maximum calculated benchmarking score to vary between 95 and 68, while in other cases like utilities 3a and 5a this factor will have little effect. In general, due to the logarithmic nature of these curves, utilities with curves in the center of the chart will see greater impacts than those utilities with curves on the extremes.

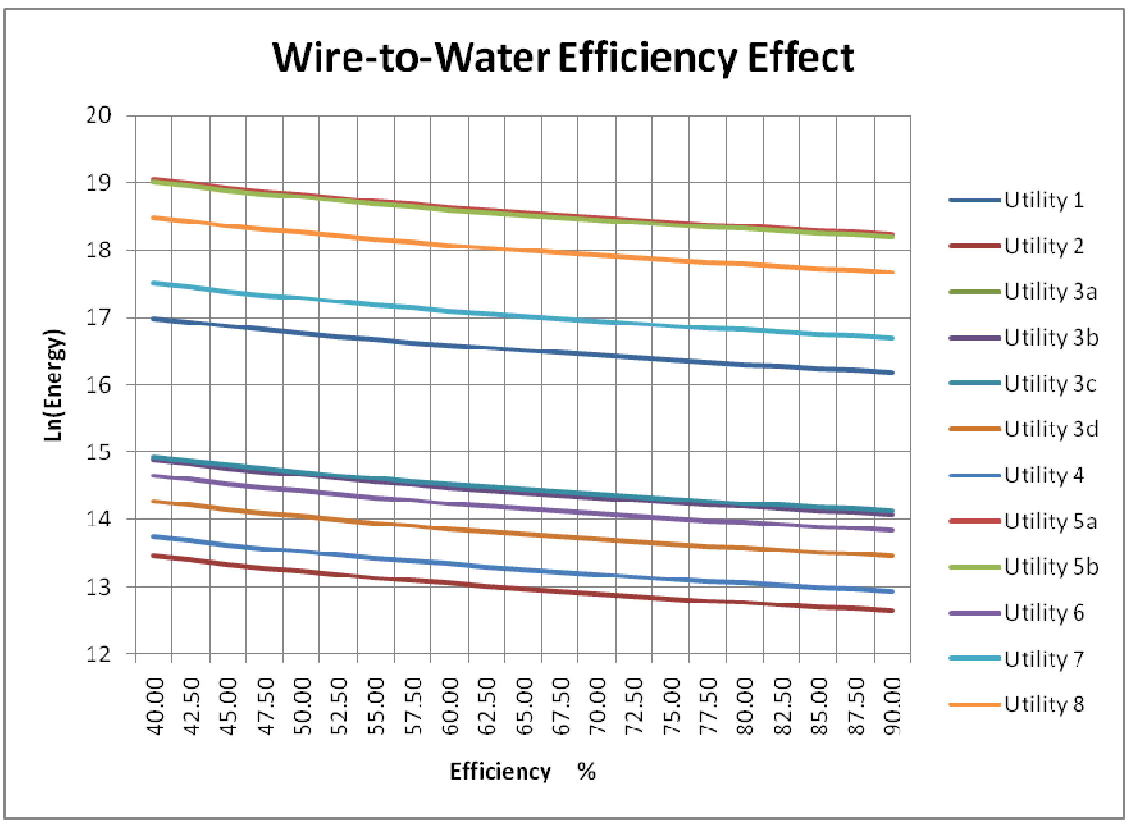


Fig.18. Wire-to-Water efficiency effect over maximum reachable score

As with water loss, is interesting to observe the effect over current benchmarking scores from changes in wire-to-water efficiency. Some of the utilities have water flow rates high enough to reasonably assume they also have wire-to-water efficiencies higher than that considered of 62.47%. The estimation of all maximum reachable benchmarking scores is based upon this last value. The rationale is that although in those cases we know efficiency almost for sure is higher than the one considered, we have no systematic way of proposing a well founded value.

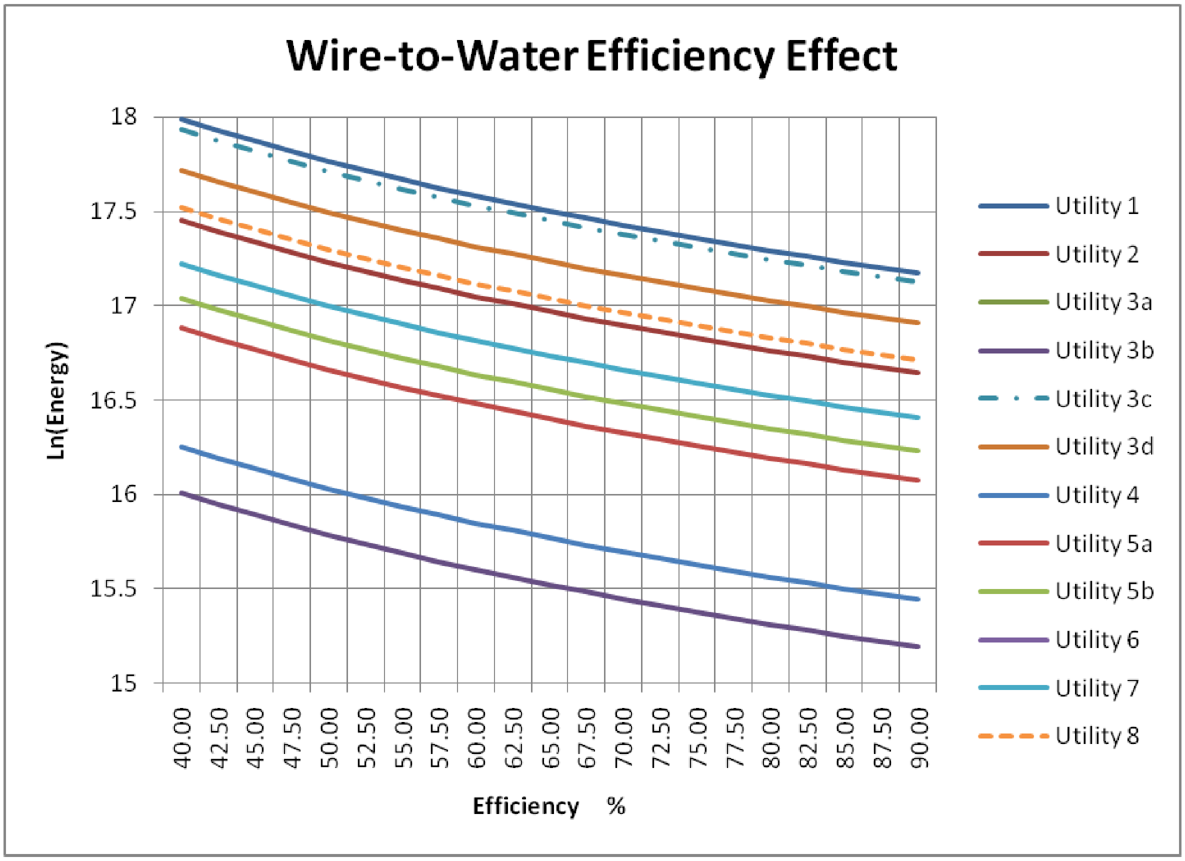


Fig.19. Wire-to-Water efficiency effect over natural logarithm of source energy, utilized to estimate benchmarking scores.

Sample Calculations

In this section we will perform step-by-step the numerical analysis that was later performed on each utility as supporting information for the obtained benchmarking scores analysis.

Suppose we have the information for utility number 1 in the survey. We start our analysis by calculating the benchmarking scores (Carlson, 2007):

a) Production Energy Use Benchmarking Score

To use the benchmarking model previously described, we have the following parameters for utility number 1:

Total Water Inflow: 6.860 MGD = 6,860 kGD

Raw Water Pumping Power: 1,625 HP

Purchased Inflow: 0

According to the statistical model, predicted production Energy Use is:

$$E_P = \ln\left(\frac{kBTU}{yr}\right) = 17.461$$

Now, dividing this predicted energy use by the model mean, we obtain an adjustment factor as

$$F_a = \frac{17.461}{17.340} = 1.007$$

Now we need to know what the actual energy consumption is in the raw water system. From the survey we know that:

Electricity use: 352,000 kWh/mo. Average for raw water pumping, what means 4,224,000 kWh/yr. converting this value to source energy:

$$E_a = 46{,}886{,}400\ kBTU/yr$$

$$lnE_a = 17.663$$

Dividing this actual energy consumption value over the adjustment factor, we obtain the adjusted energy use for the utility. This adjusted energy use will enter directly into the normalized model to get the corresponding score:

$$E_a = \frac{17.663}{1.007} = 17.540$$

From the production energy score table, we have that

Production Benchmarking Score: **39**

b) Treatment Energy Use Benchmarking Score

For this same utility, we have the following additional parameters to calculate the Treatment Energy Use Benchmarking score:

Oxidation:	yes	1
Direct Filtration:	no	0
Sand Drying Bed:	no	0
Iron Removal:	yes	1
Ozonation:	no	0

Applying the same process described for the production energy use benchmarking score, we have:

$$E_P = 16.922$$

And

$$F_a = 1.0331$$

The natural logarithm of actual source energy use is

$$E_a = \frac{17.555}{1.033} = 16.992$$

By entering this value in the corresponding normalized model we obtain the Treatment Energy Use Benchmarking Score as **26**.

Remember that those scores are percentiles, so they represent the percentage of utilities that perform below our utility number 1 in the list. The numbers for the utilities in our list are assigned randomly, so utility number 1 does not mean the better or the worse in any sense.

Utility number 1 does not own the distribution system, so we cannot calculate neither score for distribution nor for the overall energy use.

Now we know where the utility is ranked against its national peers. Nevertheless, something we don't know is in fact how energy efficient the utility is. The underlying question is: How energy efficient the utility is, given its own characteristics? How do we know whether the utility is performing great or poorly given its own characteristics? One thing is to do well against peers, and other different issue is to perform well or not in absolute terms.

To answer that question is that we require calculating the minimum required energy for that utility. If we can have a reasonable estimate of what is the energetic demand to operate the utility under ideal conditions, and then compare it to the actual energy usage, we may know how energy efficient really is this utility in physical terms.

We start by estimating a reasonable value of the friction factor in the pipelines between the raw water extraction point and the water treatment plant. Average yearly temperature in location of utility 1 is 52^{o}F . Then, the average kinematic viscosity of water should be close to $1.41\text{x}10^{-5}$ ft^2/sec. Since the system has two pipelines of diameter 16", the velocity of water in each one is:

$$v = \frac{Q}{A}$$

In this equation Q is the flow rate and A is the cross-sectional area of the pipe. In our case we have Q=3.43 MGD and A=1.3963 ft^2 thus obtaining a velocity of 3.801 ft/sec.

In order to convert the flow rate to ft^3/sec, we need to agree on the meaning of "day". Many utilities work around 20-22 hrs/day, since during early morning there is usually almost zero water demand. However, in order to establish a standard, usually day means whole 24 hrs for flow rate calculations. Considering 24 hrs/day, the flow rate is Q=5.307 ft^3/sec.

So, the Reynolds number is around:

$$R_E = 359{,}432 \approx 3.59 \text{ x } 10^5$$

Well into turbulent regime. This is normal for water pumped into pipes, where turbulent regimes are the rule. Now, the two pipelines have very different ages. First one is 52 yrs old, and the other one 33 yrs old. Both are made out of Ductile Iron. Here is where we have the biggest uncertainty: What is a reasonable value for the roughness of the pipes? We know that depends mainly on pipe material, age, and local water chemistry. From the Ductile Iron Pipe Research Association, we know that roughness varies from 0.0002 ft for a 4" pipe, to 0.0006 ft for a 64" pipe at a constant velocity of 2.50 ft/sec. Although this relationship is not linear, reasonable values for absolute roughness in our case are around 0.00028 ft. It is important to remember that even new pipes of the same material may have different roughness values resulting from different fabrication processes.

Applying the Mostkov-Kamershtein method to estimate the effect of aging on roughness, using Group I (very good) water we obtain:

$$\epsilon_{33} = 0.00299$$

$$\epsilon_{52} = 0.00455$$

Through the Swamee-Jain expression,

$$f = \frac{1.325}{\left(\ln\left(\frac{\epsilon}{3.7D} + \frac{5.74}{R_E^{0.9}}\right)\right)^2}$$

We obtain the Darcy Friction factors:

$f = 0.0247$ 33 yrs old pipe

$f = 0.0276$ 52 yrs old pipe

In addition to the friction factors, we have the following parameters to apply the Darcy-Weisbach equation:

Length of pipelines: 7920 ft

Flow Rate: 5.307 ft^3/sec

Diameter: 1.333 ft

We obtain for the head losses of the pipes new and old 32.995 ft and 36.811 ft, respectively. The elevation difference between raw water level and treatment facility level in our utility is 288 ft. Then total heads we need to provide to raw water to convey it to the treatment facility is on each pipeline

$$Th_{ij} = 320.955\ ft$$

$$Th_{ij} = 324.811\ ft$$

Now we calculate how much energy this total water heads represent. Using the water power equation

$$P_w = Q_{ij}\gamma Th_{ij}$$

We have that water specific weight is γ = 62.38 lb/ft^3 at location's average temperature of 52°F

Thus:

$$P_{w(33)} = 106{,}265.36\ \frac{lb-ft}{sec}$$

$$P_{w(52)} = 107{,}528.85\ \frac{lb-ft}{sec}$$

We know that 1BTU = 778.26 lb-ft (Rishel, 2002). Then, adding up both pipelines and converting the result to yearly total consumption, we obtain:

$$E_{ideal} = 8{,}663{,}190.30\ kBTU/yr$$

This energy consumption level is not reachable by the utility, since it was calculated using ideal conditions, and hence should be too low. If we apply the corresponding factors to bring that number from ideal to real world, we have:

Wire to water efficiency:	62.47%
Delivery Pressure:	15 psig or 34.65 ft for each pipeline
Water loss:	0 %

The minimum required energy theoretically attainable for this system should be around:

$$E_{min} = 15{,}353{,}093.39\ kBTU/yr$$

The last step is to convert the two obtained energy values in a form that we can compare to our benchmarks. Using natural logarithms:

$$Ln(E_{ideal}) = 15.974$$

$$Ln(E_{min}) = 16.547$$

If we assume the utility has these energy consumption levels, it would obtain benchmarking scores of 98 and 90, respectively. If we agree that E_{min} represents a minimum energy use level attainable by the utility, the conclusion would be that this utility cannot get a better score above 90.

We propose an index named thermodynamic score expressed as percentage as follows:

$$\text{Thermodynamic score} = \left({E_{min}}/{E_{actual}} \right) 100$$

For utility 1, we obtain TS = 32.75%.

We analyzed each one of the surveyed utilities utilizing the process shown with utility number 1. Those analyses are included for each utility or facility. Further discussion of each case will take place in next chapter.

The following table shows the benchmarking scores obtained by the utilities, along with the calculated maximum reachable scores based upon the minimum required energy approach. The numbers shown here are obtained without correcting the analyses for the utilities with high flow rates towards better wire-to-water pumping efficiencies. It is also necessary to remember that the maximum achievable scores for the utilities are based upon a series of uncertain variables. For that reason, those scores should not be taken as fixed or well determined. They are subject to a probabilistic distribution that is out of the scope of this research.

Table 6. Overview of production scores, case study

Utility	Production Bench. Score	Treatment Bench. Score	Average Bench. Score	Thermodynamic Score	Prod Max Score
1	**39**	**26**	**32.5**	32.75	90
2	**68**	**0**	**34.0**	13.57	100
3a	**100**	**14**	**57.0**	100	94
3b	**99**	**74**	**86.5**	42.89	100
3c	**41**	**56**	**48.5**	3.66	100
3d	**54**	**35**	**44.5**	9.99	100
4	**98**	**60**	**79.0**	17.45	100
5a	**90**	**49**	**69.5**	37.14	93
5b	**86**	**55**	**70.5**	85.58	90
6	**100**	**2**	**51.0**	100	97
7	**79**	**66**	**72.5**	14.30	99
8	**64**	**n/a**	**64.0**	29.74	94

CHAPTER 4. CASE STUDY

Water Utilities Sample: Commonwealth of Virginia

In order to apply the benchmarking metrics and compare them to thermodynamic scores obtained through the minimum required energy approach, we surveyed eight water utilities from throughout Virginia. The state of Virginia was divided in five regions according to a system proposed by the State Government on its website. These five regions are Mountains, Valley, Northern, Central and Coastal.

For each one of these five regions we chose two utilities at random. The idea is that participant utilities will have very different characteristics from one another, such as size, water source, topography, technology and organizational structure. Surveys where sent to each utility and a personal visit and interview was scheduled on each one. We received eight responses.

It is interesting to notice that actually each one of the utilities have unique characteristics. In most cases the differences are important enough to make any comparisons challenging. In the beginning of this research, more uniformity among water utilities was expected, since they essentially perform the same operation: Provide drinking water according to same general standards, within the same geographical area. The fact that each one has different characteristics and face unique challenges to perform its operations according to standards, certainly added interest to the research project.

The survey instrument applied to utilities is included in appendix A. This survey is divided into five main areas, in the following order:

a) General and follow-up Information
b) Parameters to calculate Production Energy Use Benchmarking score
c) Parameters to calculate Treatment Energy Use Benchmarking score
d) Parameters to calculate Distribution Energy Use Benchmarking score
e) Network characteristics from production to treatment (To calculate minimum required energy).

Before entering the survey, there is an executive summary explaining the scope of research and the objective of the survey. The last question in the survey refers to whether the utility can provide a drawing of the system from raw water production to treatment.

As it was already explained, water utilities face very different scenarios each one. Some of them are from the beginning in a better shape to achieve less energy consumption than others, due to site conditions such as topography. Despite this, definitely each one should be able to reach high energy efficiency scores, once its unique imposed characteristics are normalized out.

It is important to notice that we have some utilities divided into sections using letters (a, b, c,…). The reason to do this is that some utilities have more than one raw water treatment plant. In that case, each treatment facility was analyzed by separate and identified using letters. Since in the present study production energy use plays such an important role, this separation makes sense instead of having just one number depicting a variety of different sources and conditions all mixed together. However, they are still recognized as the same utility, thus having the same utility number.

In the following table we have some general information about the surveyed utilities. As it was previously mentioned, we have many different sizes: some utilities provide less than 1 MGD, while other produces 87 MGD. If we take into consideration how many people each utility serves, we will notice that all utilities provide approximately the same average amount of water per person each day. Utility 8 is a special case since it appears to have the lowest water availability per capita. However, this is not necessarily the case. The water flow specified for that utility is added to purchase water from other source. Even when the purchase water enters the system of utility 8, it comes from another utility and thus is not counted here for production energy use.

Table 7. Water produced per person/day

Utility	Region	Population Served	Production	Provided Water Average
			MGD	Gal/person/day
1	Mountain	65,000	6.86	105.54
2	Valley	10,000	1.40	140.00
3a	Valley	3,900	0.50	128.21
3b	Valley	85,000	11.00	129.41
3c	Valley	38,600	5.00	129.53
3d	Valley	27,500	3.60	130.91
4	Central	47,000	5.43	115.53
5a	Northern	900,000	87.00	96.67
5b	Northern	600,000	66.30	110.50
6	Northern	134,000	13.00	97.01
7	Coastal	406,000	40.00	98.52
8	Coastal	450,000	36.80	81.78

All these water utilities provide on average 113.63 gal of drinking water per person per day. Less water means more efficiency in water use only if all the people within service area have enough water to cover their needs.

Also, we have an overview of the utilities' raw water conveying system and the raw water quality in table 2. The raw water quality is a subjective assessment provided by the utility contact filling out the survey.

Table 8. Raw water systems overview

Utility	Region	Production	Number of Pipelines Raw-WTP	Material for Pipelines	Raw Water Quality
		MGD			
1	Mountain	6.86	2	Ductile Iron	Very Good
2	Valley	1.40	1	Ductile Iron	Fair
3a	Valley	0.50	2	Cast Iron	Good
3b	Valley	11.00	2	Cast Iron	Good
3c	Valley	5.00	1	Ductile Iron	Good
3d	Valley	3.60	1	Ductile Iron	Very Good
4	Central	5.43	2	Cast Iron	Fair
5a	Northern	87.00	2	PCCP Welded Steel	Good
5b	Northern	66.30	1	Welded Steel	Very Good
6	Northern	13.00	1	Ductile Iron	Good
7	Coastal	40.00	3	Ductile Iron	Good
8	Coastal	36.80	1	Ductile Iron PCCP	Good

The raw water quality refers to how easy is to clean up the raw water to meet drinking water standards. It was found that although most utilities consider their raw water good or very good, the main concern is turbidity and organic content.

For the analysis, we applied the Mostkov-Kamershtein method (Idelchik, 1994) to evaluate the impact of age over pipe wall roughness. The method is based upon a raw water classification as very good, good, fair, and so on. This method will be explained in the next section.

Although the method provides a reasonable approach to estimate the interior wall roughness of a water pipe, we acknowledge the fact that the obtained values for roughness will likely differ from the actual roughness, if observed.

When estimating friction head loss in water pipes, wall roughness is important. The roughness is known with more accuracy for new pipes, even when interior roughness of a new pipe depends not only on the material, but also on the fabrication method used. The uncertainty regarding roughness of the pipe grows each year the pipe is in service. For this reason, it is not expected that the roughness values here estimated correspond closely to the actual roughness of the pipes. It represents solely a likely value as “accurate” as possible. The only way to get a more accurate value for the pipe roughness is to measure it directly.

Another issue is the interior diameter of pipe. Sediment and incrusted build up reduce the inside pipe diameter at unknown rate. This depends on a combination of site conditions. Interior diameter reduction was not considered in this study due to the difficulty of estimating a value on each case.

Finally, it is also interesting to notice the elevation changes between raw water average level and treatment plant. Many utilities actually have the raw water average level above that of the plant. This represented an analytical problem for the minimum energy required approach, since in theory on those cases no energy input is required to convey the water except gravity. Some of the utilities are in fact only gravity-fed (like numbers 3a and 6), while in other cases some pumping is necessary to provide pressure to the system even when gravity takes the water from the source.

Table 9. Materials, water, age and roughness of pipes

Utility	Region	Number of Pipelines Raw-WTP	Material for Pipelines	Raw Water Quality	Elevation Change Raw-WTP	New Pipe Roughness	Age	Current Estimated Roughness
						ft	yrs	ft
1	Mountain	2	Ductile Iron	Very Good	288.00	0.00028	33	0.00299
						0.00028	52	0.00455
2	Valley	1	Ductile Iron	Fair	15.00	0.00028	8	0.00212
3a	Valley	2	Cast Iron	Good	-38.00	0.00205	80	0.01255
						0.00205	80	0.01255
3b	Valley	2	Cast Iron	Good	-8.00	0.00205	60	0.00992
						0.00205	60	0.00992
3c	Valley	1	Ductile Iron	Good	-62.10	0.00028	13	0.00199
3d	Valley	1	Ductile Iron	Very Good	10.00	0.00028	8	0.00094
4	Central	2	Cast Iron	Fair	-17.92	0.00205	109	0.02708
							69	0.01585
5a	Northern	2	PCCP	Good	178.50	0.00033	30	0.00427
			Welded Steel			0.00023	20	0.00285
5b	Northern	1	Welded Steel	Very Good	154.25	0.00023	50	0.00433
						0.00023	8	0.00089
6	Northern	1	Ductile Iron	Good	-17.50	0.00028	40	0.00553
7	Coastal	3	Ductile Iron	Good	22.00	0.00028	70	0.00947
8	Coastal	1	Ductile Iron	Good	121.00*	0.00028	14	0.00212
			PCCP			0.00033	14	0.00217

* This elevation change is between the raw water source and the highest point in the pipeline. After this point, raw water flows by gravity down to a lake. This lake itself is around 184 ft below raw water level.

Calculation of Benchmarking Scores

Metric benchmarking is an useful tool to evaluate the energy efficiency of water utilities among peers. It allows stakeholders to compare in a simple way utilities that otherwise are very difficult to compare. While keeping the benchmarking scores simple is a must, they can lose some accuracy due to lack of consideration of the conditions for each particular case. Of course, benchmarking scores are not intended as a perfect measure of energy efficiency. Nevertheless, in some cases the inaccuracy introduced by the benchmarking model might be important for decisions that are made upon these scores. Skewed benchmarking scores might suggest wrong decisions or disincentive the urgently required energy efficiency efforts in some utilities. Furthermore, some benchmarking metrics could be used to evaluate performance of personnel or equipment. These benchmarks should be as accurate as possible.

The benchmarking scores for energy use obtained by the utilities in the sample are shown in the next table. The calculated benchmarking scores are just for production and treatment, since some of the utilities don't have authority over all parts of the system. If a utility does not own the distribution system, their function is only to obtain the raw water, treat it to meet safe drinking water standards, and deliver the water. In some other cases, although the utility own the distribution system, the information required was not readily available.

Two of the utilities, where the raw water is fed by gravity to the treatment facility obtained a perfect score of 100. Although could seem otherwise, the negative elevation does not imply automatically a good energy efficiency score. Other utilities with raw water level above the treatment plant obtained much smaller scores. The reason is that benchmarking score is related not to the elevation change, but to the raw water pumping capacity. One of the utilities that achieved a 100 perfect score has some backup pumps in the water source, but they are never used, so their energy consumption is zero. These pumps are tested once a month, just to make sure they work properly in case they are needed. The pumps would be utilized only if the water in the source reaches a very low level, which had never happened so far. On these utilities, high production benchmarking scores are paired with very low treatment benchmarking scores due to some distortions of the benchmarking metrics as we shall see.

Table 10. Obtained Benchmarking scores

Utility	Region	Production Bench. Score	Treatment Bench. Score	Average Bench. Score
1	Mountain	**39**	**26**	**32.5**
2	Valley	**68**	**0**	**34.0**
3a	Valley	**100**	**14**	**57.0**
3b	Valley	**99**	**74**	**86.5**
3c	Valley	**41**	**56**	**48.5**
3d	Valley	**54**	**35**	**44.5**
4	Central	**98**	**60**	**79.0**
5a	Northern	**90**	**49**	**69.5**
5b	Northern	**86**	**55**	**70.5**
6	Northern	**100**	**2**	**51.0**
7	Coastal	**79**	**66**	**72.5**
8	Coastal	**64**	**n/a**	**64.0**

It is also noteworthy that the utility 3c obtained the second lowest benchmarking score, despite having the bigger gravity head to feed the water into the plant. This is due to the fact that raw water is taken from a pumped storage. Apparent energy savings are compensated with the pumping energy required to store the water in the reservoir.

Discussion

In this section we will discuss each one of the utilities of the sample. The objective of this discussion is to analyze closer the energy efficiency of these utilities for raw water extraction and conveyance, and on treatment process. Benchmarking scores and minimum required energy analysis in the form of thermodynamic score provide information to take a closer look. Those utilities that have more than one treatment plant are divided into facilities, keeping the utility number and a letter designating each facility.

Before entering each case discussion, is necessary to know which numerical limits we have for our calculations to remain reasonable. In the two following tables, we have those characteristics of the sample that was utilized by Carlson for its study (Carlson, 2007). The first table refers to the full sample of water utilities as included in the report (389 utilities), while the second refers to the filtered sample that was used to obtain the benchmarking models (125 Utilities).

Table 11. 389 Utilities' sample Energy Intensity

Energy Intensity of Water Production Phase	
	BTU/GAL
Average:	13.454
Standard Deviation:	14.560
Minimum Value:	0.005
Maximum Value:	121.206
Energy Intensity of Water Treatment Phase	
	BTU/GAL
Average:	9.565
Standard Deviation:	10.308
Minimum Value:	0.052
Maximum Value:	69.006

Table 12. 125 Utilities' sample Energy Intensity

Energy Intensity of Water Production Phase	
	BTU/GAL
Average:	12.774
Standard Deviation:	9.047
Minimum Value:	0.141
Maximum Value:	37.244
Energy Intensity of Water Treatment Phase	
	BTU/GAL
Average:	8.089
Standard Deviation:	7.435
Minimum Value:	0.138
Maximum Value:	33.212

Notice that in the sample of 125 water systems utilized to obtain the statistical models and distributions for the AwwaRF metric benchmarking, the energy intensities of water in production phase vary from 0.141 BTU/GAL to 37.244 BTU/GAL. The sample of 125 utilities was obtained from the one of 389, after applying some filters to the original data. The 389 utilities are the original data. For our research we consider possible values of energy intensity of the water, those that fall within limits shown in table 2.

Utility 1

Utility 1 in the survey is a rather small system. It produces around 6.86 MGD of drinking water. Raw water is taken from a nearby river, despite which the water quality is very good all the year round. The main issue they face sometimes regarding water quality is turbidity levels, but this only happens once in a while. Raw water is extracted from a river, and pumped through two 16-inch ductile iron pipelines. The parallel pipelines length is about 1.50 miles, and they elevate the raw water an average of 288 ft to the treatment plant. The ages of these pipes are 52 and 33 yrs old.

This utility does not own the water distribution system. Its role is to extract raw water from the river, treat it to meet drinking water standards, and deliver it to the service area through distribution mains. Operation of the treatment facility takes around 22 hrs each day. A series of storage tanks distributed over the service area are used to regulate the water supply. The water extraction and treatment operations stop daily for an approximate time of two hours in the early morning once the storage tanks are filled up and water demand is still low.

In the following chart we have the calculated benchmarking scores for production and treatment in this utility, as well as the production thermodynamic score (All thermodynamic scores in this research refer to production phase).

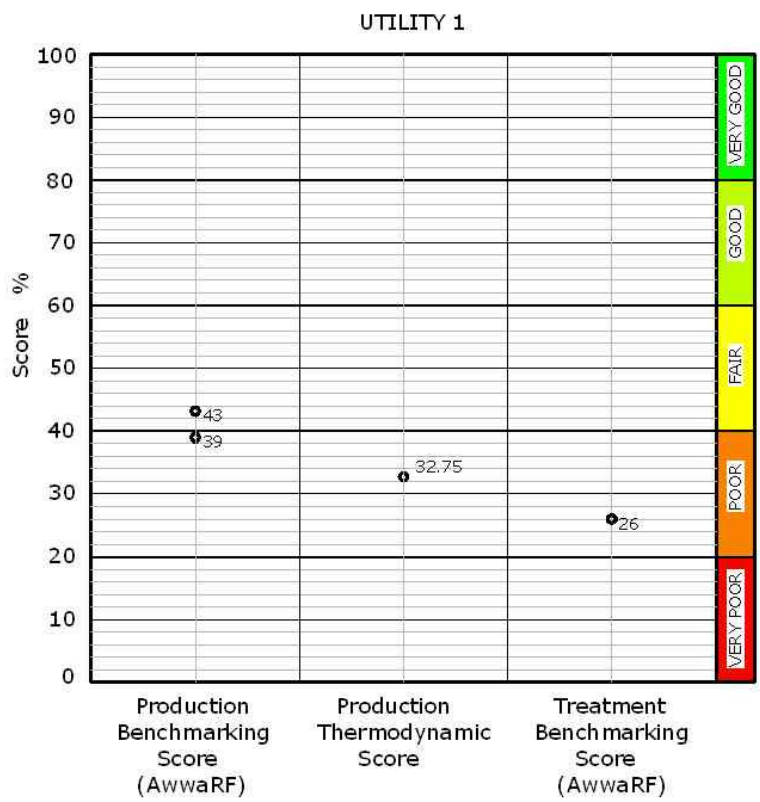


Fig. 20 Benchmarking and thermodynamic scores for utility 1

According to these benchmarking scores, since the benchmark metrics are percentiles the utility is more energy efficient than 39% of comparable utilities in the U.S. for raw water extraction and conveyance, and above the energy efficiency of 26% of those utilities regarding the water treatment process. Benchmarking scores have been grouped in five categories each one comprising 20 percent of score.

The Thermodynamic Score for the facility is 32.75%. It is important to remember that this score is the ratio of the minimum required energy divided by the actual energy consumed. This value indicates that the utility 1 uses around three times more energy than that estimated as minimum by simple physics.

From the Minimum Required Energy Analysis, we obtained also an estimated maximum benchmarking score for production for the utility, estimated as 90. This means that this utility can never achieve a production benchmarking score above 90 unless is able to use less energy than the minimum. Due to this maximum limit, we propose that the production benchmarking for the utility in fact is closer to 43 in a scale of 100.

It is also interesting to look at the energy intensities of the water in production phase:

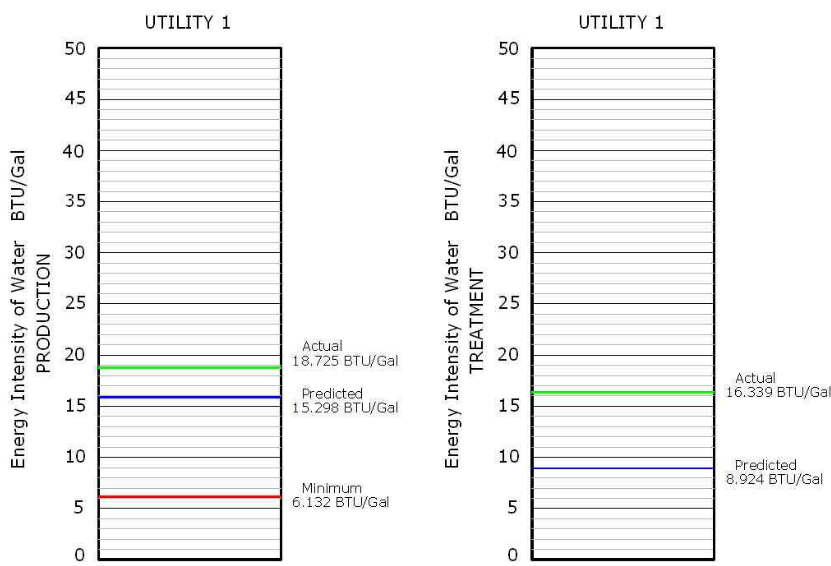


Fig. 21 Energy Intensity levels of water, utility 1

The predicted energy intensity of water refers to the energy intensity as predicted by the model used in the Carlson report (Carlson, 2007). If the actual energy intensity of water is above of the predicted level, the benchmarking score is under 50.

Minimum energy intensity of water is the value that comes from the minimum required energy analysis. According to our calculations, utility 1 cannot get energy intensities below 6.132 BTU/GAL due to its imposed characteristics.

The treatment process does not have a minimum required energy intensity level that can be calculated from simple physics as we did with the production phase. The difference is that while in production the amount of energy used depends on static head, friction head loss and other quantifiable measures, in treatment depends on water quality, technology available, standards, and other parameters hard to quantify in terms of energy requirements.

Utility 2

Utility 2 also takes the raw water from a river. In this case the river is smaller and much closer to the treatment plant, then reducing the need for energy inputs. Although the utility requires less energy, it also processes less water volume at 1.40 MGD. The elevation change between the water source and the treatment facility is just 15 ft. This utility uses one 16-inch diameter ductile iron pipe to convey raw water to the treatment facility, but given the low water volume it processes in relation to pipe diameter, head loss due to friction is not high.

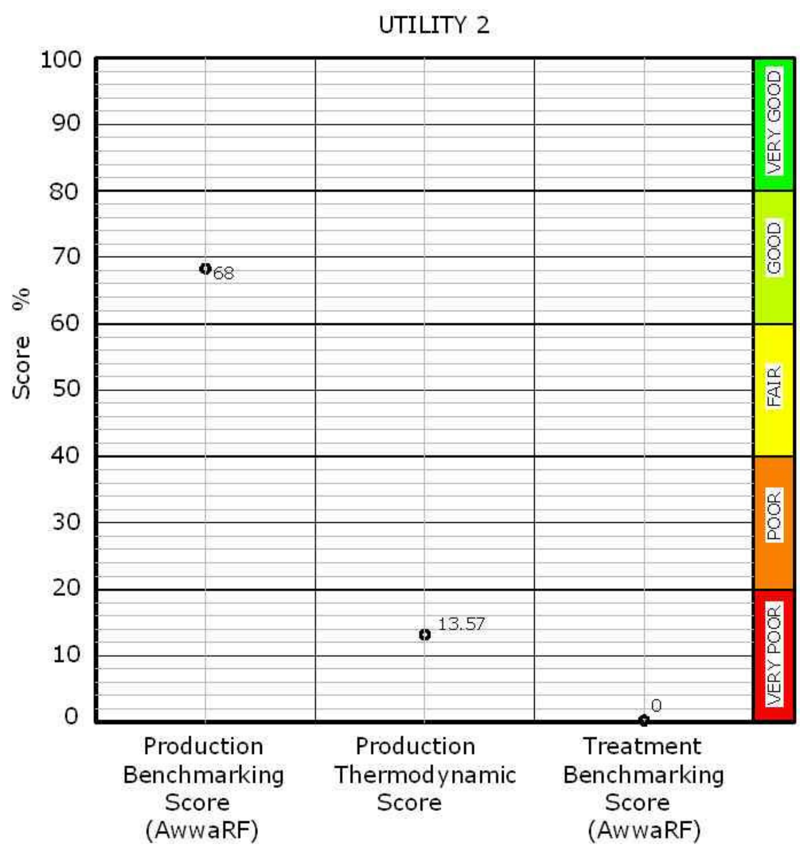


Fig.22 Benchmarking and thermodynamic scores for utility 2

Benchmarking scores are 68 for production (indicating of course that the actual energy intensity of water in this phase is less than the predicted level, as we shall see) and 0 for treatment. We found no obvious cause for this zero score. A revision of the energy consumption in the water treatment plant is suggested.

Actual Energy intensities of water for utility 2 are 6.513 BTU/Gal for production and 27.327 BTU/Gal for treatment. The low energy intensity of water for production stage comes from factors imposed on the utility: short raw water-treatment facility distance and small elevation to overcome. However, in treatment process the energy intensity of water is very high. The utility's personnel themselves said raw water quality is fair.

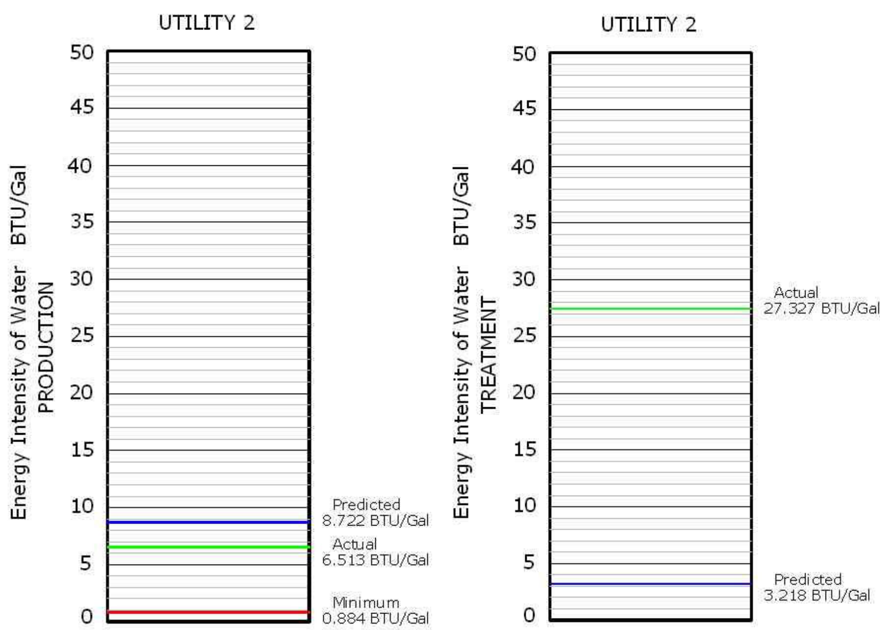


Fig. 23 Energy Intensity levels of water, utility 2

Thermodynamic score is 13.57%. Comparing this utility with utility 1, we notice that it produces 20% of the water, but use 31.86% of electricity and around 109% of the natural gas. The production phase has an installed raw water pumping power of 107.14 HP/MG.

The large gap between predicted and actual energy use for treatment relates to the zero benchmarking score for energy efficiency in treatment.

Utility 3

Utility 3 is comprised by four treatment plants, each one with its own water source. An analysis was performed for each one (Facilities 3a, 3b, 3c and 3d). This four water treatment plants serve one service area together.

Facility 3a

For the first of the four treatment facilities, named here 3a, we notice that it has a very small production of just 0.5 MGD. Although having a low production volume implies a low energy use level, it also could easily cause that equipment used in the raw water extraction and treatment be oversized, thus generating inefficient energy use.

Facility 3a has raw water level above the treatment facility level. This elevation change is on average 38 ft. The treatment facility is gravity-fed and it does not require pumping for extraction. In consequence, the obtained benchmarking scores for production and treatment energy use are 100 and 14, respectively. Thermodynamic score is estimated at 100.

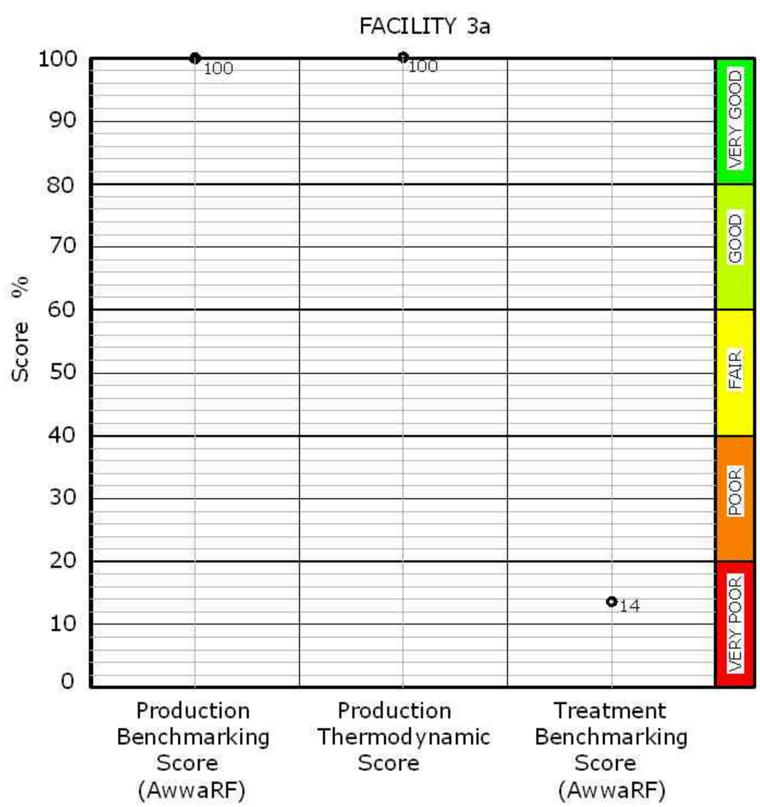


Fig. 24 Benchmarking and thermodynamic scores for facility 3a

In the case of a gravity-fed treatment plant like this, estimating the energy required for raw water extraction and conveyance to the facility seems to make no sense. Nevertheless, some interesting information can be derived from such analysis. First, we found that some pumping might still be required due to the need of increased flow rate or pressure in the system. If the elevation difference is small, the utility might need to provide some energy to increase production. Second, the system design features such as pipe diameter play a role in determining how efficiently raw water runs into the system using gravity. In the case of 3a, two 10-inch cast iron pipes conveying a very small flow of raw water cause very low water velocity and hence small friction head loss. Despite the low velocity, Reynolds number still indicates turbulent flow.

It is also important to point out that in this case the facility has a gravity fed system, so the static head estimated as 'required' to overcome was considered zero for required water power calculations. This unreal assumption was made to avoid negative numbers and is later corrected by acknowledgement of the pressure that favorable elevation change provides 'free' to the system.

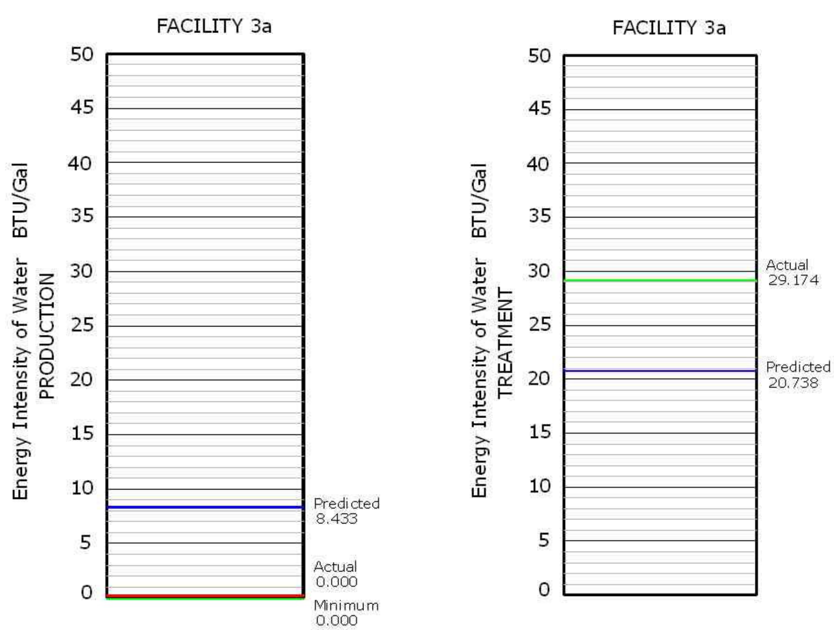


Fig. 25 Energy Intensity levels of water, facility 3a

As in the utility 2 case, very high energy efficiency of raw water production in 3a is paired with low efficiency on treatment operations. The low treatment score comes from the fact that not having raw water pumping power installed, the predicted energy usage is very low, making appear the actual energy use abnormally high. Using an average value for installed raw pumping power, the treatment score increases from 14 to 34. Although still low, we consider this score more accurate than the first one.

Facility 3b

This treatment plant is fed by two 36" cast iron pipelines, moving a production of 11 MGD. The pipes seem to be oversized for the water volume, thus resulting in low water velocities and a reduced head loss due to friction. Treatment facility in this case is also below raw water level, but it is not completely gravity-fed. Since it has a small elevation differential (8 ft) they use 4 small 75 HP pumps to convey the raw water to the plant, achieving a small pumping ratio of 27.27 HP/MG.

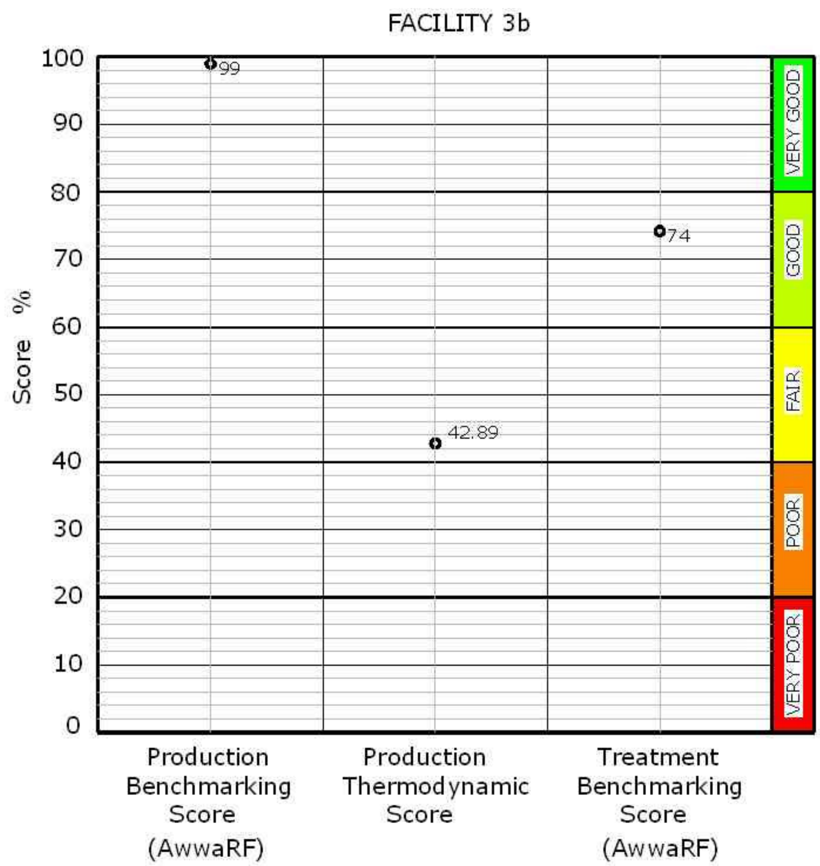


Fig. 26 Benchmarking and thermodynamic scores for facility 3b

Benchmarking scores for this utility are 99 and 74, which indicate good energy efficiency. The thermodynamic score is 42.89%. This efficiency is relatively high, since it uses around double of the energy amount that strictly requires. In this case system elevations play an important role in achieving high scores for production. Water energy intensity for production is 1.090 BTU/Gal.

As we can see, this treatment facility could theoretically reach perfect 100 score in production energy use score, as they almost do already.

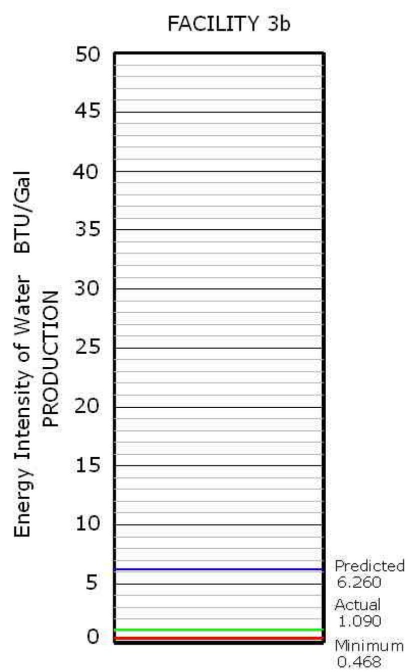


Fig.27Energy Intensity levels of water, facility 3b

Facility 3c

For facility 3c, we have a big ductile iron pipe of 36" diameter conducting 5 MGD of raw water at even lesser flow rate than 3b. This also results in low water velocities and reduced friction head loss. However, this utility is a special case: Despite having the biggest raw water and treatment facility elevation difference apparently working on its favor (62.10 ft), the benchmarking scores are 41 and 56 for production and treatment, respectively. Thermodynamic score is 3.66%.

The reason for those relatively low scores is that raw water is extracted from a pumped storage reservoir. The energy saved taking raw water from a higher elevation has been already used to elevate the water to the reservoir in first place. Although not very energy efficient, this scheme provides the facility other benefits like enhanced resiliency: By pumping water to a reservoir, the system has a water reserve that acts as a buffer against river water level variations.

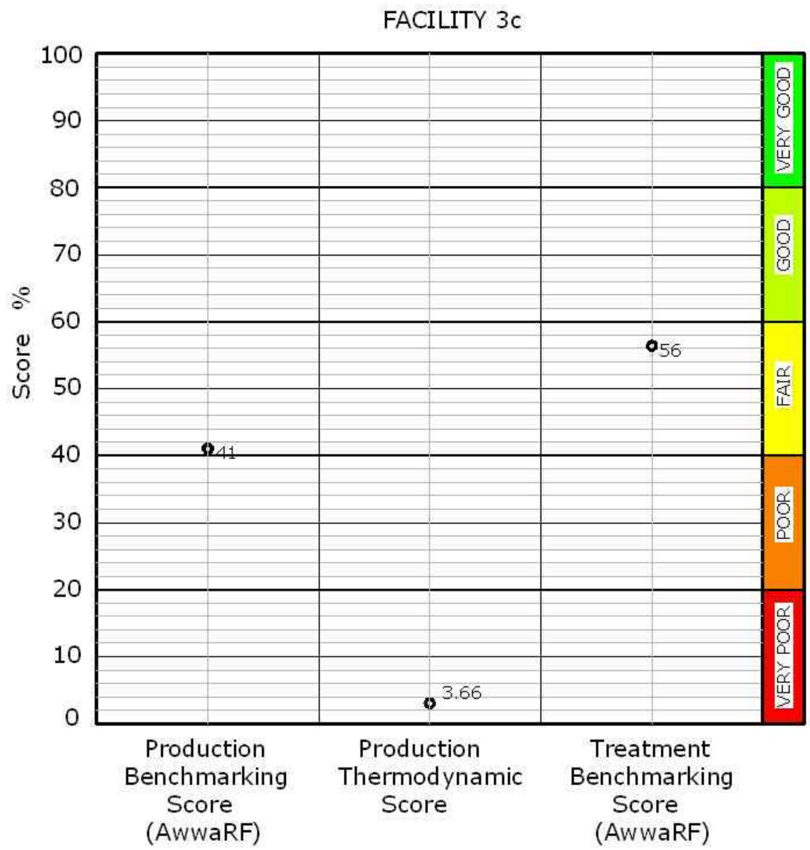
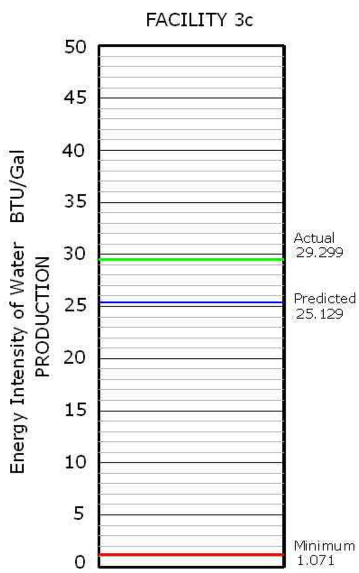


Fig. 28 Benchmarking and thermodynamic scores for facility 3c

From the minimum required energy analysis, we see that even considering the elevation change to overcome by pumping, the facility would be able to reach top benchmarking scores. The reason for the current 41 is most likely the huge installed pumping power ratio: 800 HP/MG.

The energy intensities for production and treatment are relatively high at 29.299 BTU/Gal and 24.742 BTU/Gal respectively, in line with that would be expected from not very high benchmarking scores.



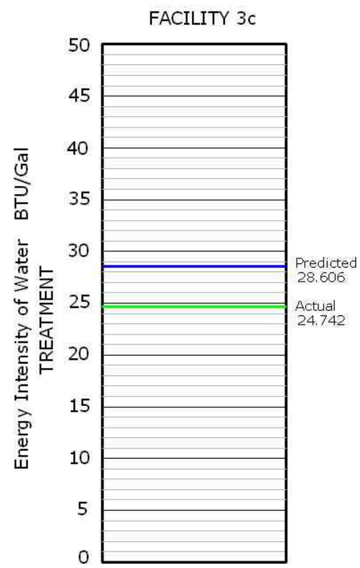


Fig 29 Energy Intensity levels of water, facility 3c

We can see that both predicted and actual energy use are far from the minimum required. However, in this case all these numbers might be distorted by the effect of the pumped storage with apparent favorable static head.

Facility 3d

Facility 3d has a 20-inch ductile iron pipeline to convey raw water. Raw water is obtained from spring water, at an average elevation of 10 ft below treatment facility level. The benchmarking scores for production and treatment in this case are 54 and 35. The production score is better than that of 3c, but the treatment score is lower. Thermodynamic score is 9.99%.

Installed pumping power ratio is 69.44 HP/MG. The system has virtually zero friction head loss and a small static head to overcome, so should be able to reach high benchmarking scores. Currently they use more electricity than expected, given that elevation change is not large or the distance between raw water pumps and treatment facility. A pump testing and review is also suggested.

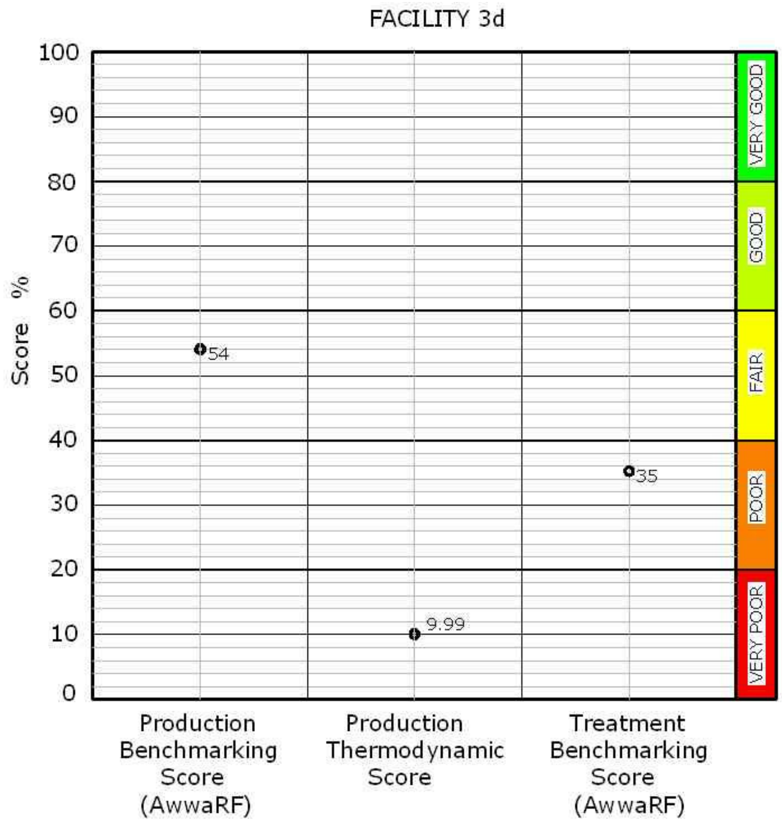


Fig.30 Benchmarking and thermodynamic scores, facility 3d

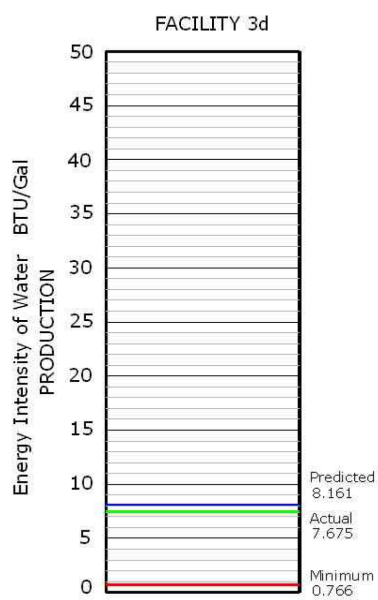


Fig. 31Energy Intensity levels of water, facility 3d

Utility 4

The fourth utility is a small system producing 5.43 MGD. As in many of other cases, they take water from a small reservoir in a river through two 24-inch diameter cast iron pipelines. Thermodynamic score for this utility is 17.45%.

Their treatment plant average level is below the average raw water level by 17.92 ft. However, they use a small pumping system to increase water flow rate. The installed pumping ratio is 49.72 HP/MG. The benchmarking scores obtained by this utility for production and treatment are 98 and 60 respectively. It is clear that the fact of having the water basically gravity-fed into the plant contributes to its high score.

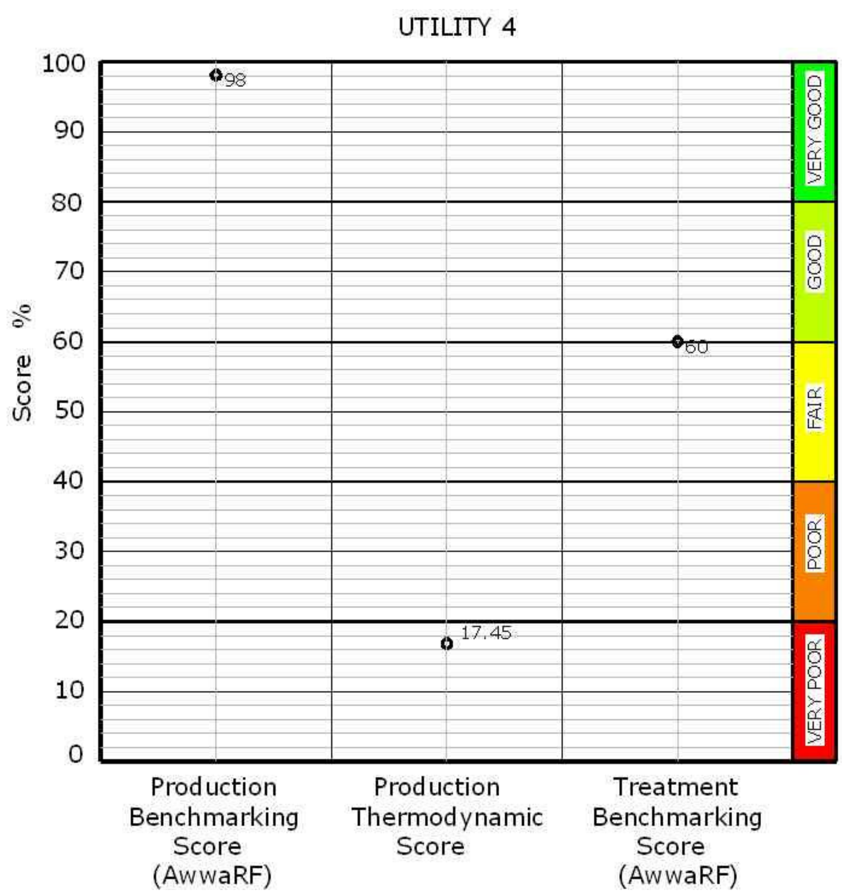


Fig. 32 Benchmarking and thermodynamic scores for utility 4

From the minimum energy analysis, we obtained that this utility could reach perfect 100 score in production given the imposed system characteristics, even with considerable pipe wall roughness. This high production benchmarking score is also paired with a fair treatment score. Water quality is fair, according to the survey. The main issue with raw water is that often has high turbidity levels. One reason for such high turbidity is that reservoir used to take raw water is really small, so it does not have enough size to let water coming from the river to settle before being taken to the plant. Water energy intensities are 1.730 BTU/Gal for production and 15.628 BTU/Gal for treatment.

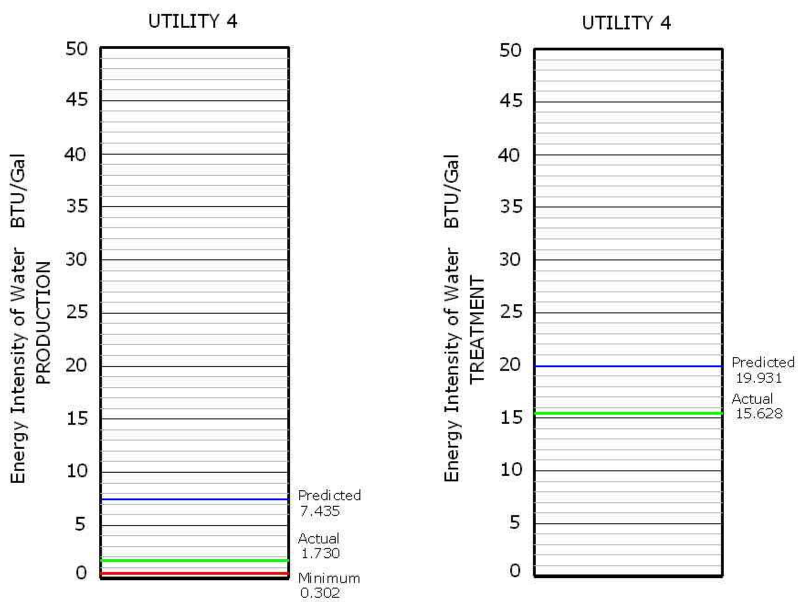


Fig. 33 Energy Intensity levels of water, utility 4

Utility 5

Utility 5 is a huge system near a metropolitan area. It has two treatment facilities named facilities 5a and 5b. In total it processes 153.3 MGD, providing water to around 1.5 million people.

Facility 5a

For the first plant, 5a, we have the following analysis. Two pipelines of diameters 60" and 84" provide 87 MGD of water. The first pipe is PCCP, and the other one welded steel. The water velocities are 2.316 ft/sec.

This plant has a production energy use benchmarking score of 90, and the analysis indicated that the maximum attainable score is around 93. Treatment benchmarking score is 49.The obtained Thermodynamic score for this facility is 37.14%.

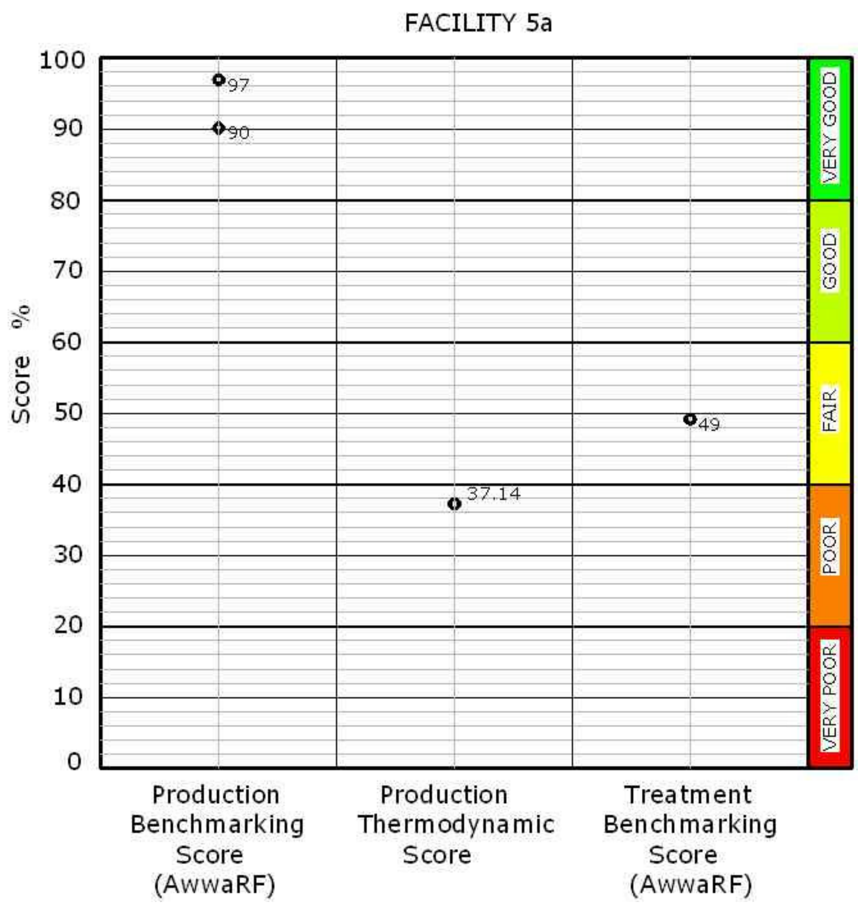


Fig.34 Benchmarking and thermodynamic scores for facility 5a

It is also interesting to notice that also in this case water energy intensities are in line with the benchmarking scores of 90 for production and 49 for treatment: 7.041 BTU/Gal and 25.439 BTU/Gal respectively. The installed pumping ratio is 206.90 HP/MG.

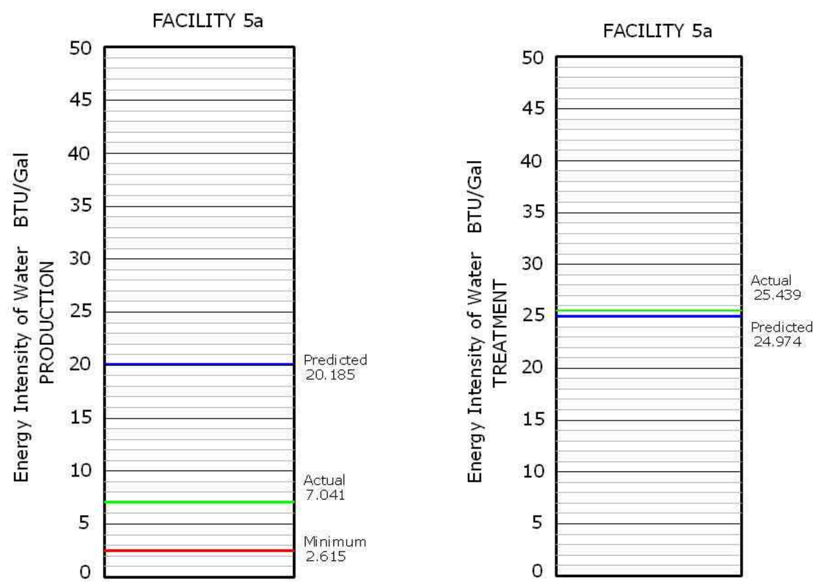


Fig.35 Energy Intensity levels of water, facility 5a

The treatment benchmarking score of 49 is due to the fact that the facility uses huge amounts of electricity to operate, and utility 5 is the only utility in the sample that uses ozonation.

Facility 5b

In the case of facility 5b, it has less flow than 5a at 66.3 MGD but just one welded steel pipeline comprised of two different pipes in series: an 84-inch pipe for a mile, a pumping station, and then a 72-inch pipe for another 0.80 mile. The full flow of 66.3 MGD is conducted in each one. Of course the water velocity increases in the smaller pipe. The head loss induced by diameter reduction was not quantified, but may be important. Under the current assumptions, theoretically this plant's production energy use score could never go beyond 90. The actual score is 86, so adjusting this value that would mean a score of around 96 on a 100 scale. Thermodynamic score is 85.58%

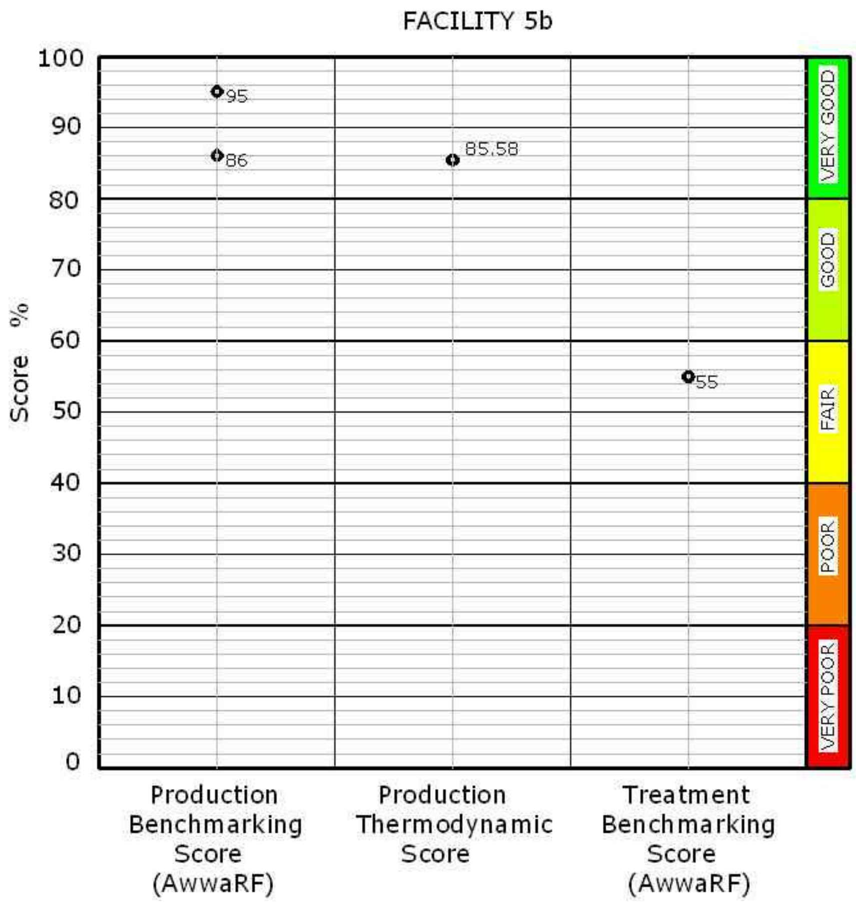


Fig. 36 Benchmarking and thermodynamic scores for facility 5b

Benchmarking scores are 86 and 55 for this facility for production and treatment. Water energy intensities are for production 4.337 BTU/Gal and for treatment 19.271 BTU/Gal. in line with previous shown score tendencies. This utility has also relatively small installed raw water pumping power ratio of 45.25 HP/MG.

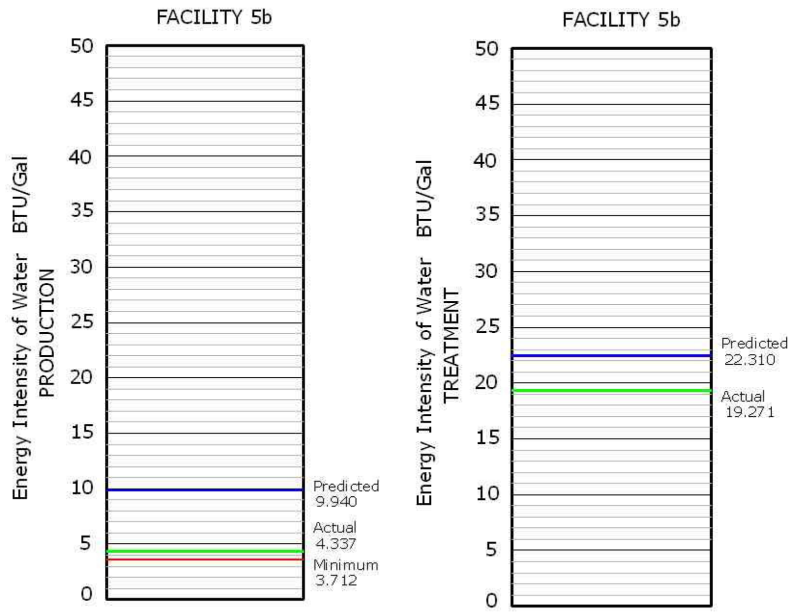


Fig. 37 Energy Intensity levels of water, facility 5b

Utility 6

This utility is another unique case. Raw water gets into the treatment plant completely by gravity through a 30-inch ductile iron pipe. They have some backup pumps that would extract the water in case the raw water level is too low in the lake to naturally flow into the plant. So far this has never happened. They got a benchmarking score for production of 100 (even the thermodynamic score is 100%). The treatment benchmarking score is 2. Water energy intensities are zero for production and 16.124 BTU/Gal for treatment.

The utility produces 13 MGD of water. They have an installed pumping power ratio of 6.92 HP/MG for backup purposes only. Even when they use a reasonable amount of energy for the produced water volume, don't have energy intensive processes such as UV or Ozonation, and receive a small quantity of purchased water, their treatment benchmarking score is low due to the influence of installed raw water pumping power. They have very small pumping power and then the predicted energy usage is low. When compared with actual energy consumption, the utility appears to be very inefficient in energy use. Actually, that score of 2 should not be that low. Introducing a virtual raw water pumping power based on the average of 135.197 HP/MG, the treatment score increases to 12.

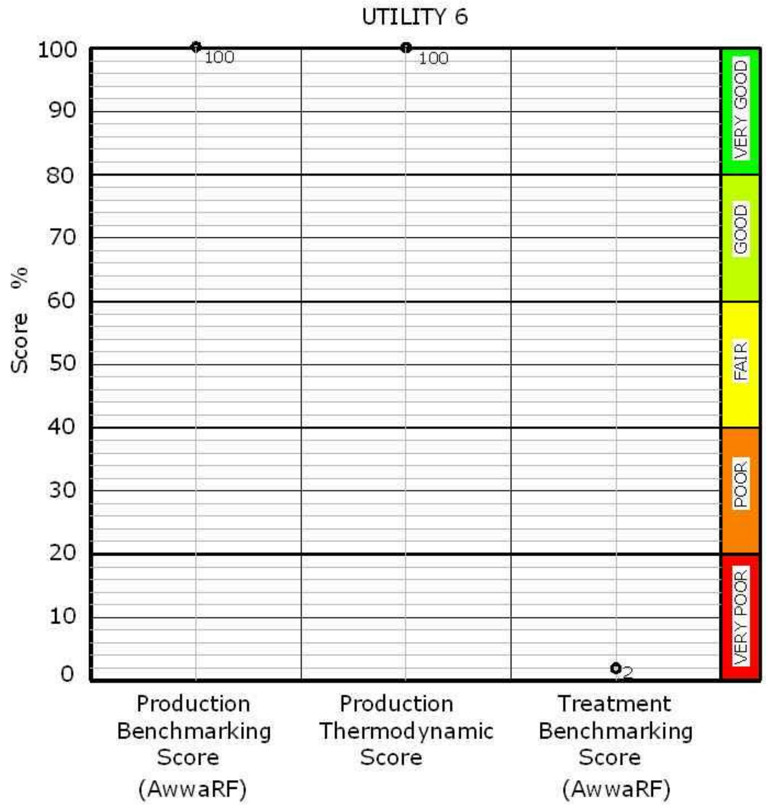


Fig.38 Benchmarking and thermodynamic scores for utility 6

From the minimum required energy analysis, we know that imposed conditions on the system allow the achievement of a maximum score of 100 in production. The two perfect 100 scores on production energy use benchmarking and thermodynamic score are due to the fcat that the utility is gravity fed. They require no energy input to extract raw water and convey it to the treatment facility. This explains also the zeros in energy intensity of water in the production phase.

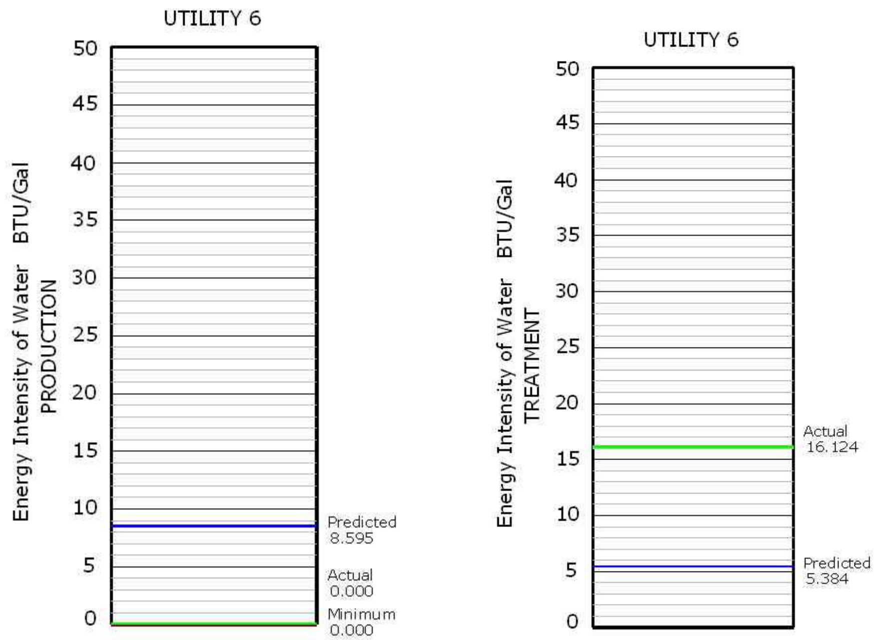


Fig. 39 Energy Intensity levels of water, utility 6

Utility 7

The raw water system for utility 7 is very unique. They have two water treatment plants but were not separated into 7a and 7b because they are both fed by the same three 42-inch ductile iron pipelines.

Raw water system takes raw water from a river 35 miles away. Raw water is extracted from the river, but is not conducted directly into the treatment facilities. Instead, it is stored in a system of five reservoirs. Three of these reservoirs receive rain water from their respective watersheds in addition to the pumped river water. Water from reservoirs is then pumped into the treatment plants as needed. The served area requires more water than that extracted from the river, so difference is provided from the water that naturally flows into the reservoirs from the watersheds.

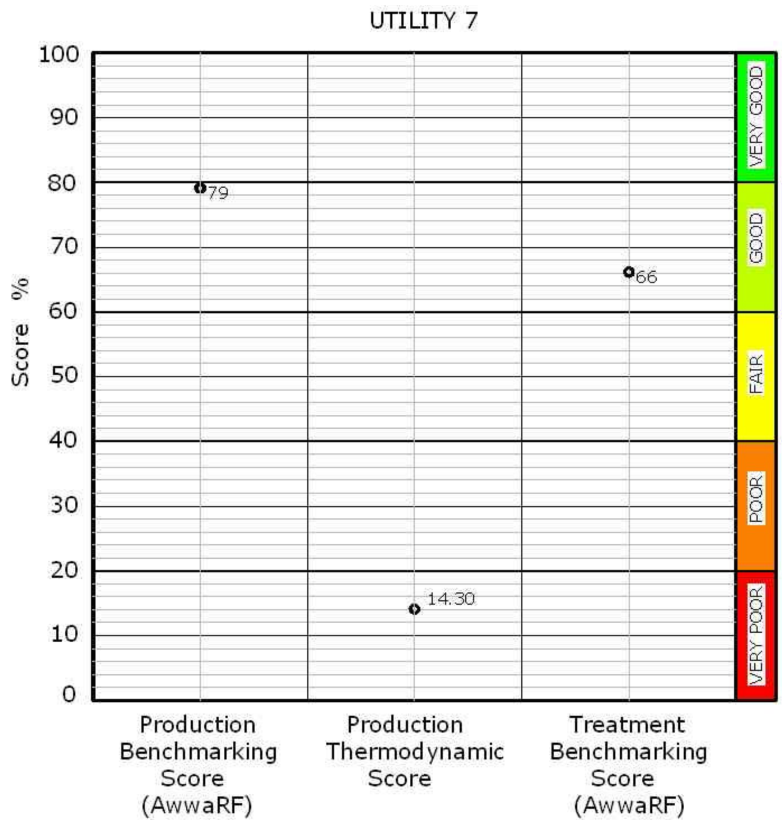


Fig.40 Benchmarking and thermodynamic scores for utility 7

The benchmarking scores for production and treatment for this utility are 79 and 66, respectively. The thermodynamic score is 14.30%. The elevation difference that has to be overcome by the system is on average 22 ft. This utility could reach higher benchmarking scores except for the long distance they pump water from. The reservoir system provides this utility enhanced resiliency against fluctuations in river level, but this resiliency is compromised by the fact that service area actually requires more water than that extracted, 40 MGD. The ratio of installed raw water pumping power is 180 HP/MG. The water energy intensities are 9.123 BTU/Gal and 19.449 BTU/Gal. The real energy intensity for water production is a little lower, since some of the water does not enter the system through pumping

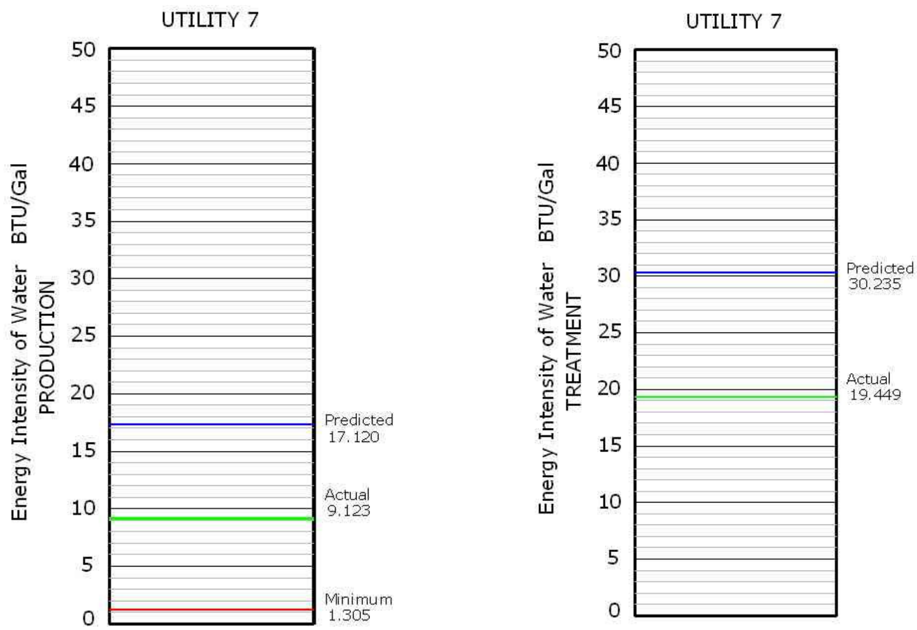


Fig.41 Energy Intensity levels of water, utility 7

Utility 8

This is also a very unique case. This utility is in the coastal region, but takes raw water from a lake located at 110 miles. Even with this system, desalination is still a very expensive and uncompetitive option for the utility.

Utility 8 historically purchased all of its water from a neighbor city. The pressure of population growth in both cities made necessary the identification of new drinking water sources. The problem was solved by constructing a pipeline that brings water from a lake at 110 miles. Around 45% of the 60-inch pipeline is made out of ductile iron, while the rest (55%) is PCCP pipe. The length of this pipeline is 76 miles. Another special feature about this system are the elevations. In the water source, average water elevation is 199 ft. Raw water is pumped up to a maximum elevation of 320 ft near the raw water, and then pipeline discharges in another lake at elevation 100 ft and 34 miles from the destination treatment plant. Before discharging the water into the second lake, the water is re-oxygenated.

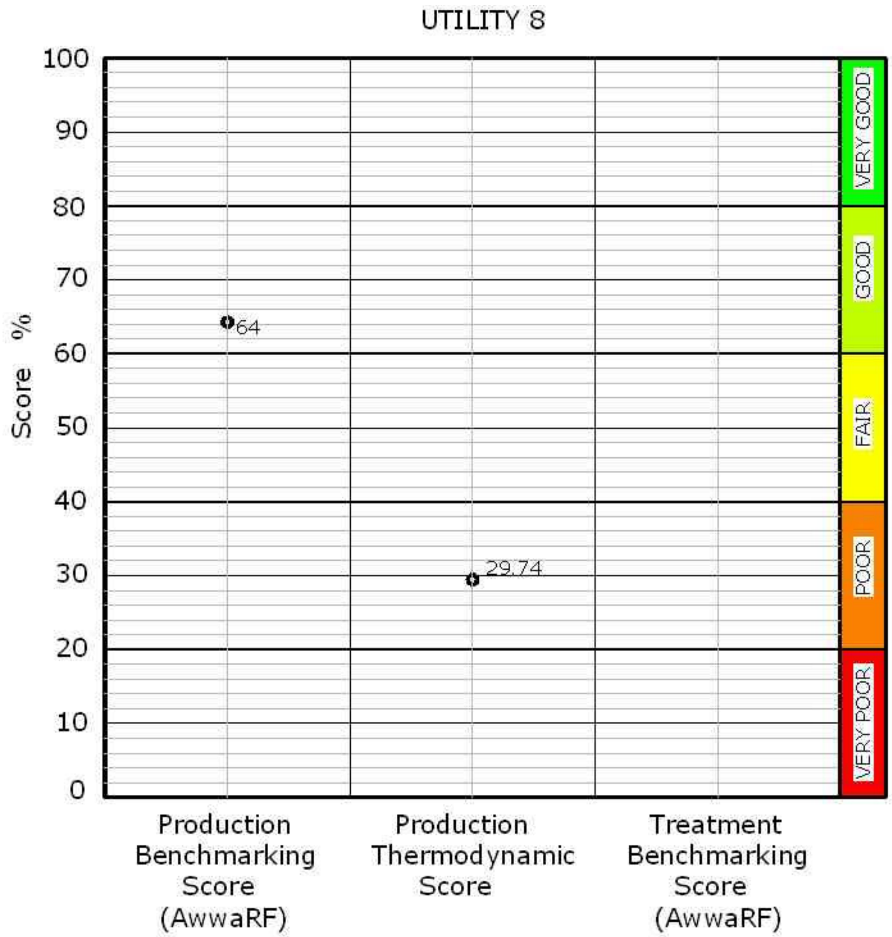


Fig 42 Benchmarking and thermodynamic scores for utility 8

Energy intensities of water in production phase are shown in the next chart. The treatment scores and energy intensities were not calculated because the utility does not own or operates the treatment plant, which is under authority of a neighboring city.

By using this system of elevating the raw water once and then using gravity, the utility is able to bring the water all that distance without need of any other pumping station but the one extracting raw water from the first lake. They have two pressure sustaining valve batteries in the 76 mile long pipeline.

As we said, another characteristic of this utility is that they not own the treatment process. For historical reasons, they only bring the water and receive it later already treated. We were not able to estimate a treatment benchmarking score. The utility has a production water energy intensity of 12.545 BTU/Gal which is at first glance, surprisingly low for the system layout. Installed pumping power ratio is 176.63 HP/MG.

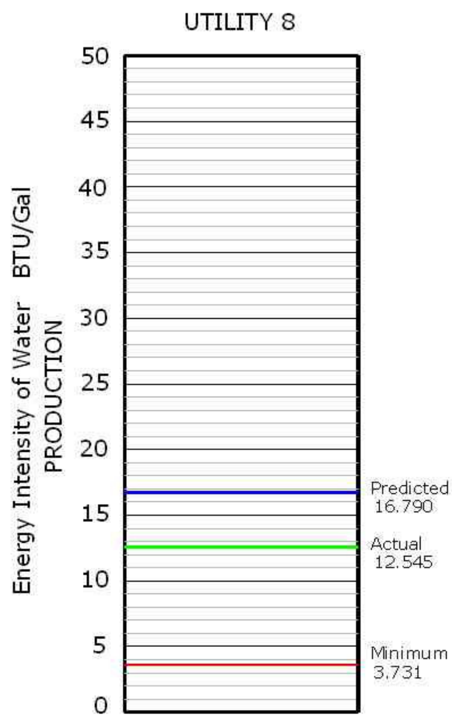


Fig. 43 Energy Intensity level of water, utility 8

Production benchmarking score is 64 for this system. This score is not bad considering that total friction head loss is estimated around 165 ft. Our analysis indicates this utility's maximum achievable benchmarking score for production is 94. An adjusted benchmarking score for production in consequence would be 68. The thermodynamic score is 29.74%.

Summary of Utility Cases

It is also interesting to see the cases together, so we can make comparisons and have a big picture of what is the current status of energy efficiency matters in the studied utilities' sample.

Benchmarking scores were calculated for eight utilities from the five regions of Virginia. The information provided by the benchmarking scores was complemented by the analysis of the minimum energy required by the utility to operate, and some other measures. We find that in many cases the benchmarking scores are accurate, but in some cases such as utility 6 the benchmarking scores can be skewed, in this case being much lower than it should.

The minimum required energy analysis was used to predict the maximum achievable benchmarking score for each utility, based on the minimum amount of energy required. It is also interesting to see next two figures. They represent the energy intensities of water and the benchmarking scores. Although water energy intensity is not a good indicator by itself, one would expect to find low energy intensities paired with high benchmarking scores, and conversely. If this happens, the resulting graph would show two curves one the opposite of the other, like seeing the same curve on a mirror. This happened in the production chart, and at less degree on the treatment chart.

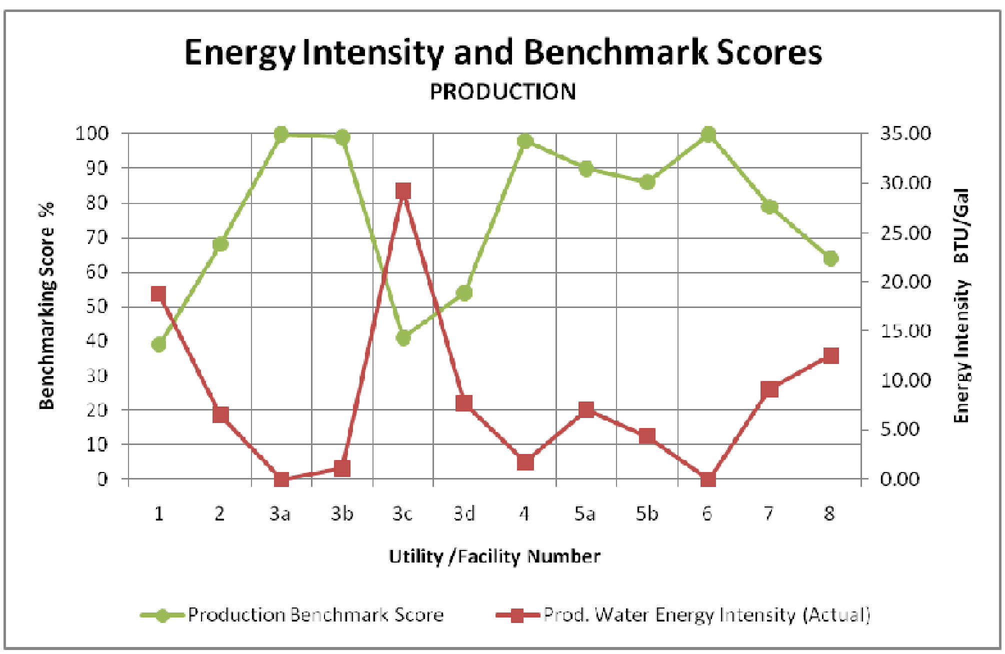


Fig.44.Energy Intensity and benchmarking scores for production

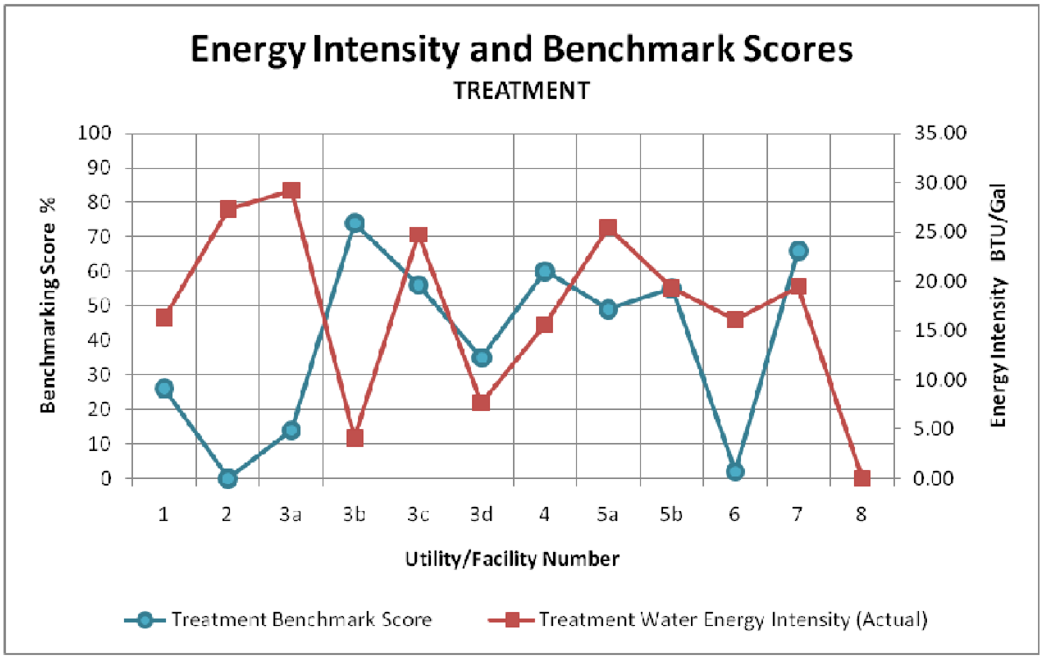


Fig.45. Energy intensity and benchmarking scores for treatment

In figs.44 and 45 we have the water energy intensities for all the utilities in the sample, and the benchmarking scores. The objective of these charts is to show that some correlation exists between the two energy efficiency measures, especially in the production phase of the process.

In fig.44 notice that actual energy intensity line (red) is almost a mirror image of the benchmarking score (green). Both lines have a good symmetry respect to a horizontal axis. This means that behavior of both indicators is in general consistent: Those utilities that reach high production benchmarking scores are likely to have low energy intensity of water; and conversely, low production benchmarking scores will be in general associated with higher energy intensities. Despite this general tendency, there is no determined correlation between production benchmarking score and energy intensity of water. Different utilities can have same energy intensity of water and very different benchmarking scores.

Next chart show the obtained benchmarking scores by the eight utilities for production and treatment.

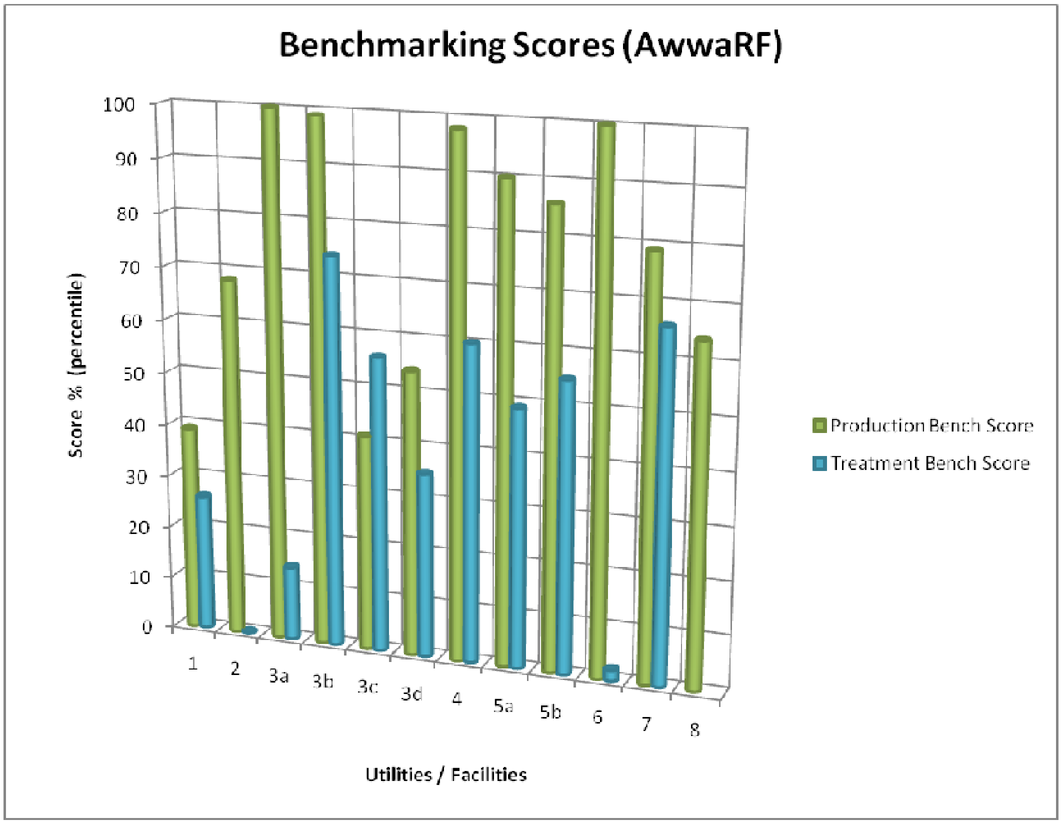


Fig.46. Production and treatment benchmarking scores for the eight utilities

In table 13 we have the production benchmarking scores (original and adjusted) and thermodynamic score for the eight utilities. We included the elevation differences between raw water and treatment plant. It is clear that those utilities with treatment elevation below the raw water level should be able to reach high benchmarking scores. The only exception to this is facility 3c, which despite having the biggest elevation difference on its favor still uses large quantities of energy because it is really a pumped storage. Despite the favorable elevation change, the pumped storage requires significant amounts of energy. In the other hand, to have a considerable static head to overcome, does not mean necessarily low benchmarking scores. Further analysis is always required. Some of the table 13 information is plotted in chart of fig.47.

Table 13. Production benchmarking actual and max scores

Utility	Region	Elevation Change Raw-WTP	Production Bench. Score	Max Production Benchmark Score	Adjusted Production Benchmark Score	Thermo dynamic Score
1	Mountain	288.00	**39**	**90**	**43**	**32.75**
2	Valley	15.00	**68**	**100**	**68**	**13.57**
3a	Valley	-38.00	**100**	**100**	**100**	**100**
3b	Valley	-8.00	**99**	**100**	**99**	**42.89**
3c	Valley	-62.10	**41**	**100**	**41**	**3.66**
3d	Valley	10.00	**54**	**100**	**54**	**9.99**
4	Central	-17.92	**98**	**100**	**98**	**17.45**
5a	Northern	178.50	**90**	**93**	**97**	**37.14**
5b	Northern	154.25	**86**	**90**	**95**	**85.58**
6	Northern	-17.50	**100**	**100**	**100**	**100**
7	Coastal	22.00	**79**	**100**	**79**	**14.3**
8	Coastal	121.00	**64**	**98**	**65**	**29.74**

The correlation shown in figs. 44 and 45 are expected since most of the energy consumption is directly related to the amount of water that is processed by the utility. In fact, the benchmarking models utilized in this research (production and treatment) have a coefficient of determination of about 85% , while a benchmarking model with just one parameter (total water flow) already had a coefficient of determination of 70% (Carlson, 2007). Amount of water processed explains most of energy use in any given utility. This is, of course, an energy intensity of water.

In addition, energy intensity of the water is not considered an accurate indicator of energy efficiency when comparing utilities, since different utilities will have different imposed conditions such as topography, implying that they may require different energy intensities to perform.

Correlation shown in discussed figures 44 and 45 between energy intensity of water and benchmarking score for production can be explained by observing that in general, there is a tendency to have lower water energy intensities in those utilities with higher benchmarking scores. Low energy intensity does not imply necessarily a high benchmarking score *per se*, but makes it very likely since most of energy use relates to the amount of water being processed. It is not possible to establish a determined mathematical expression to exactly relate energy intensity and benchmarking scores in any given utility, but we can consider this general tendency of the two parameters to be related. This consideration refers only to a general tendency, and then a correlation of the same type under every circumstance should not be given for granted.

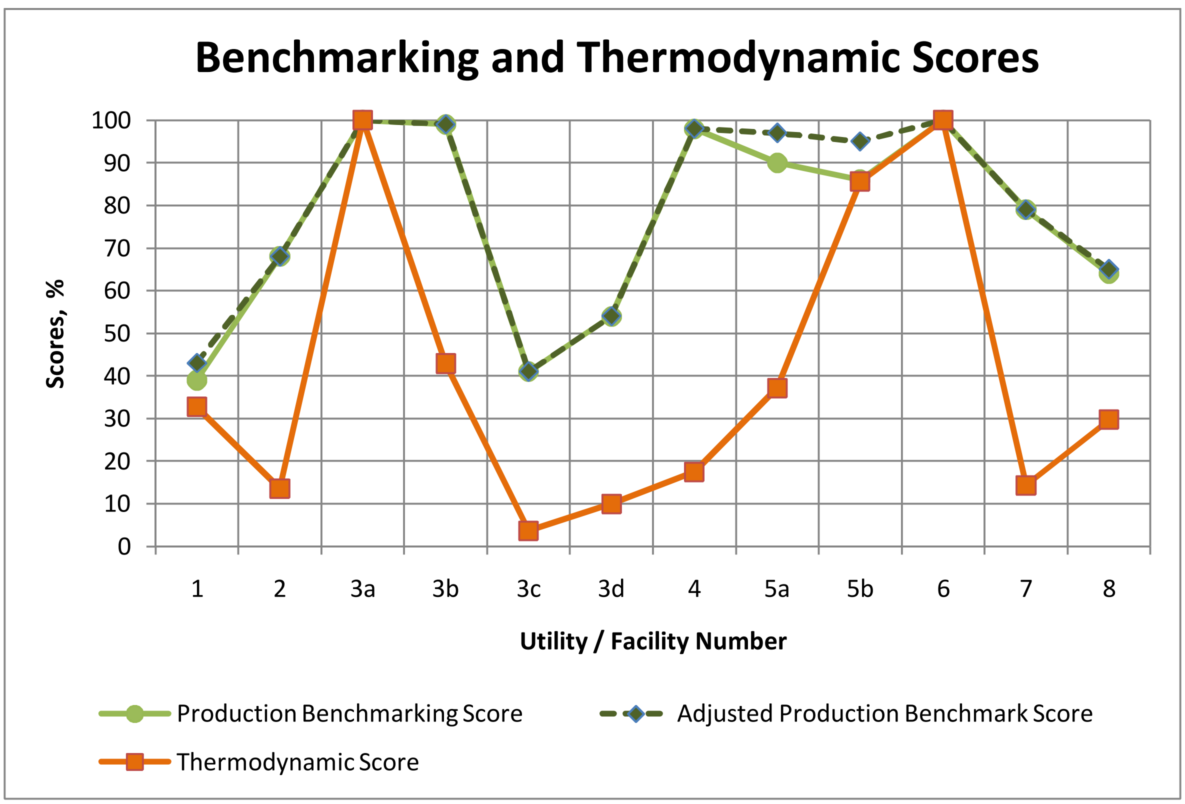


Fig. 47 Production benchmarking scores and thermodynamic score. Data is in table 13.

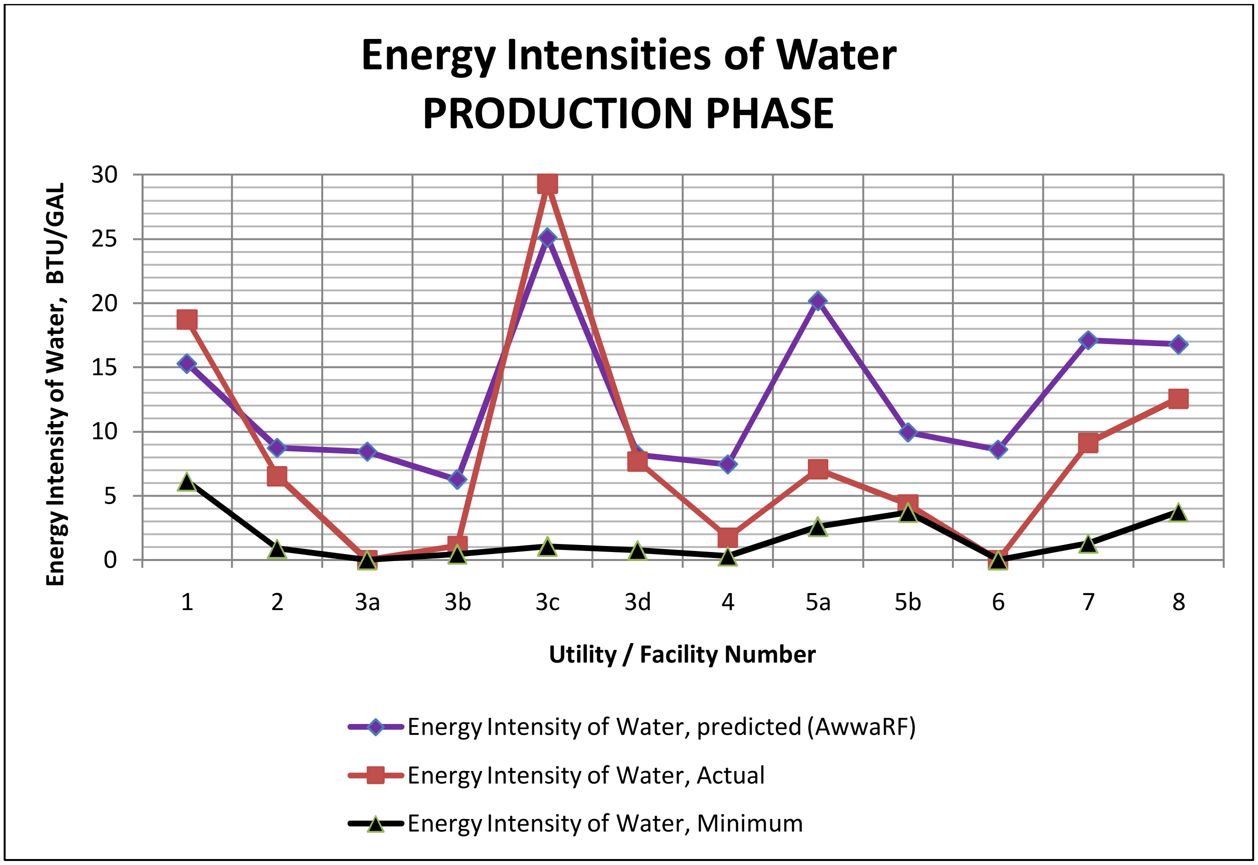


Fig. 48 Predicted, Actual and minimum energy intensities of water for the eight utilities

The thermodynamic score and the production benchmarking score proposed by AwwaRF (Carlson, 2007) are plotted for each utility in Fig.47. Notice that in this chart are also included the adjusted production benchmarking scores for each utility. Adjusted production benchmark scores are obtained by dividing the original benchmark scores by the maximum reachable score for each case. In addition, the actual, predicted and minimum energy intensities of water are plotted in Fig.48 for each utility also. By observing the charts, we notice the following characteristics (we will explain a little bit further utilities 1 and 5a):

1. **Utility 1.** In Fig.47 we observe that production benchmarking score and thermodynamic score are near each other. Although this is just a coincidence, the fact that both scores are located in the same area between 30 and 40 (Benchmarking: 39, Thermodynamic: 32.75) means that the utility can do better compared with peers and also in terms of the potential energy efficiency it can reach. Since the utility maximum reachable score is estimated at 90 (as explained in detail from page 108), the adjusted production benchmark score is

39/0.90 = 43 While the production benchmarking scores measure performance compared with peers, thermodynamic score measures the actual performance with the estimated best possible performance for that utility. Utility 1 has the potential to improve in both scales. In Fig.48 we notice that predicted energy intensity of water (15.298 BTU/Gal) is below the actual energy intensity (18.725 BTU/Gal) then resulting in a benchmarking score below 50. However, the minimum achievable energy intensity of water (6.132 BTU/Gal) is well below actual and predicted energy intensities.

The minimum energy intensity of water is resulting relatively low because the energy input they require consists mostly in overcoming the elevation change (see fig.49). Friction head loss was not particularly high since the utility has two ductile iron pipes conducting good quality water (according to the utility appraisal). The separation between plotted minimum and actual energy intensities of water (Fig.48) may indicate a problem with the interior diameter of pipe, as shown in the analysis starting on page 108.

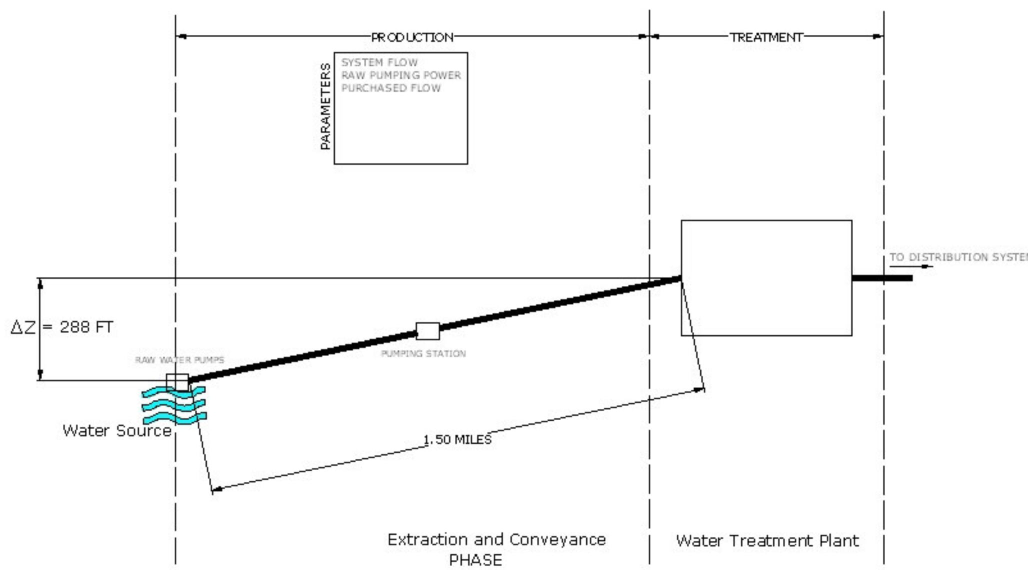


Fig.49. Utility 1 production system layout diagram

2. **Utility 2.** Production benchmarking score is in the ‘good’ bracket with a score of 68. However, thermodynamic score is 13.57 % (bracket ‘very poor’ in Fig.22 page 65). The meaning of this discrepancy is that while the utility performs well compared with other U.S. utilities, when compared with the energy efficiency it could reach is doing poorly. The utility has conditions to achieve higher energy efficiency, even when if compared

with the average U.S. utility is doing fine. From Fig. 48 we can see that although actual energy intensity is below predicted intensity, the minimum required value is even lower.

3. **Facility 3a.** This water treatment plant is gravity fed. They don't use energy for pumping raw water from source. For that reason, the facility has perfect scores of 100 in both cases: benchmarking and thermodynamic. We have the same case in utility 6. In Fig. 48 we observe that both energy intensities actual and minimum are zero. However, predicted energy intensity is not zero because the benchmarking model does not take into consideration the fact that the system is gravity fed. That is also the case with utility 6.

4. **Facility 3b.** This water treatment facility has a benchmarking score of 99, but thermodynamic score is 42.89 %.The reason is that the utility has a predicted energy usage much larger than the actual energy being used. The predicted energy use is based on three parameters: total water flow (MGD), Installed raw water pumping power (HP) and purchased water flow (MGD). In this case, the utility uses much less energy than predicted, obtaining a high benchmarking score. The utility has raw water level above treatment plant level, so is partially gravity fed. This allows reduced pumping usage. The utility uses around double of the calculated minimum energy it would have considering the system conditions. The result is a thermodynamic score of 42.89

5. **Facility 3c.** This is a special case. Production benchmarking score is 41, and thermodynamic score is 3.66 %.The raw water comes from a river and is lifted into a pumped storage reservoir that is much higher than the treatment facility. The raw water is then gravity fed into the plant. Gravity feeding the plant makes the minimum required energy appear very low, but the problem is actual energy usage is much greater because raw water pumping into the reservoir in first place. It is interesting to see in Fig.48 that actual and predicted energy uses are high, while the minimum energy intensity fails to capture that. The reason is that in the survey we asked for features of the system feeding raw water to treatment facility, while in this case the big energy impact comes before the pumped storage reservoir and not after that. We got information from the gravity fed part of system.

6. **Facility 3d.** This treatment plant has benchmarking score of 55 and thermodynamic score of 9.99%. As in other cases, the facility is doing well compared with peers but poorly when compared with the energy efficiency it could achieve. Actual and predicted energy intensities of water are close to each other, then resulting in a benchmark score near 50. The system characteristics allow reaching even lower energy intensity.

7. **Utility 4.** The case of utility 4 is very interesting. Benchmarking score is 98, while thermodynamic score is 17.45%. Compared with the average U.S. water utility is doing very good, but it still could reach higher energy efficiency. The problem here is that the plant is partially gravity fed, but they require pumping to provide pressure to the water for going through a filter. The minimum required energy approach considers that the system is "energy friendly", but they are still using energy. From Fig.48 we see that actual energy use is good, since it is lower than the predicted by AwwaRF, and somewhat closer to the minimum achievable. The low thermodynamic score is due to the effect of the ratio: Even when actual energy intensity is not bad, the system features are 'energy efficiency friendly' and then actual value appears high.

8. **Facility 5a.** Benchmarking score is 90 and thermodynamic score is 37.14. It is interesting to notice that (see Fig.48) predicted energy intensity of water is high due to large volume of water and large raw water pumping power installed. The utility is really doing fine in keeping a low actual energy use level despite those characteristics. In other words, energy intensity of water predicted by AwwaRF indicates that in average, a utility with the same installed pumping power, water flow and purchased water flow would have to use much more energy than this utility does. Probable causes of this are that this utility has very efficient pumps, or uses the pumps relatively little time. Finally, another probable cause is that they reported total installed pumping power but actually don't use all the pumps on a regular basis, then appearing to have high predicted energy use but actually operating on reduced electricity consumption. No system diagram was available for this facility.

9. **Facility 5b.** Benchmarking production score is 86 and thermodynamic score is 85.58. This case is analogous to the utility 1, in the sense that both scores coincide. We can say this utility is doing really good in energy efficiency, since it has very good scores when

compared with peers and also when compared with the efficiency it could reach considering its imposed system conditions. Beyond that, the coincidence of both scores is accidental.

10. **Utility 6.** This utility's case is like that of facility 3a. The facility is gravity fed, so they use no energy input at all, thus achieving production benchmark score of 100 and thermodynamic score of 100. Since actual energy use is zero, the thermodynamic score ratio E_{min} / E_{actual} would be undetermined. To avoid this problem, it is rational to assign a score of 100 to that utility that has zero actual energy use.

11. **Utility 7.** This utility has a system of reservoirs to store the raw water supply. Although the elevation changes to overcome are not important, the friction losses could be high because they have around 35 miles of raw water pipe. Actually friction head loss is kept low by using big diameter pipes. Production benchmarking score is 79, and thermodynamic score is 14.30 %.

12. **Utility 8.** This utility is doing well. They have production benchmarking score of 64 and thermodynamic score of 29.74%. This numbers are good considering the system: around 110 miles of raw water pipe with just one pumping station at the beginning. The system is designed to take advantage of the topographical features of the system to use gravity as much as possible. Besides one pumping station, they have a pressure sustaining station.

In the following pages we have the minimum required energy analyses performed for each utility in the case study. From those calculations we obtained the thermodynamic score for the utility, and the maximum achievable value of the production benchmarking score.

MINIMUM REQUIRED ENERGY (PRODUCTION)

Utility Number: **1**

Location Average Temp:	52	F
Kinematic Viscosity:	1.41E-05	ft^2/sec
Specific Weight:	62.38	lb/ft^3
Total Inflow:	6.86	MGD
Number of Pipelines:	2	
Diameter 1:	16	in
Diameter 2:	16	in
Flow 1:	3.43	MGD
Flow 2:	3.43	MGD
Pipelines Length:	7920	ft
Gravity Accel:	32.174	ft/sec^2
Elevation Change:	288	ft
Wire to water Efficiency:	62.47	%
Delivery Pressure:	15	psig
Water Loss:	0	%

E_{min}:	15,354,869.94	kBTU/yr
E_{actual}:	46,886,400.00	kBTU/yr
Thermodynamic Score:	32.75	%

Energy Intensities of Water in Production Phase		
E_{min}:	6.132	BTU/Gal
E_{actual}:	18.725	BTU/Gal

	Pipe 1	Pipe 2	
Flow rate Q:	5.307	5.307	ft^3/sec
Diameter:	1.333	1.333	ft
Area:	1.396	1.396	ft^2
Velocity:	3.801	3.801	ft/sec
Reynolds:	359,418.91	359,418.91	Turbulent
e:	0.00299	0.00455	ft
f:	0.0247	0.0276	
Friction Loss:	32.995	36.811	ft
Static Head:	288.000	288.000	ft
Total Head:	320.995	324.811	ft
Req Water Power:	106,265.366	107,528.852	lb-ft/sec
Total Req Power w:	213,794.219		lb-ft/sec
Energy, ideal:	8,663,190.296		kBTU/yr
Ln:	15.975		
Ea:	**15.864**		
Pressure Head:	34.626	34.626	ft
Total head, real:	355.621	359.438	ft
Req W Power:	117,728.475	118,991.961	
Total Req Power, p:	236,720.435		lb-ft/sec
Power, w2w:	378,934.585		lb-ft/sec
Power,Uw:	378,934.585		lb-ft/sec
Energy, min	15,354,869.941		kBTU/yr
Ln:	16.547		
Ea:	**16.432**	**90**	

MINIMUM REQUIRED ENERGY (PRODUCTION)

Utility Number:	2

Location Average Temp:	54	F
Kinematic Viscosity:	1.31E-05	ft^2/sec
Specific Weight:	62.38	lb/ft^3
Total Inflow:	1.4	MGD
Number of Pipelines:	1	
Diameter 1:	16	in
Flow 1:	1.4	MGD
Pipelines Length:	1320	ft
Gravity Accel:	32.174	ft/sec^2
Elevation Change:	15	ft
Wire to water Efficiency:	62.47	%
Delivery Pressure:	15	psig
Water Loss:	2	%

E_{min}:	451,628.64	kBTU/yr
E_{actual}:	3,328,392.46	kBTU/yr
Thermodynamic Score:	13.57	%

Energy Intensities of Water in Production Phase		
E_{min}:	0.884	BTU/Gal
E_{actual}:	6.513	BTU/Gal

	Pipe 1		
Flow rate Q:	2.166		ft^3/sec
Diameter:	1.333		ft
Area:	1.396		ft^2
Velocity:	1.551		ft/sec
Reynolds:	157,900.19		Turbulent
e:	0.00212		ft
f:	0.0235		
Friction Loss:	0.871		ft
Static Head:	15.000		ft
Total Head:	15.871		ft
Req Water Power:	2,144.523		lb-ft/sec
Total Req Power w:	2,144.523		lb-ft/sec
Energy, ideal:	86,898.545		kBTU/yr
Ln:	11.372		
Ea:	**12.880**		
Pressure Head:	34.626		ft
Total head, real:	50.497		ft
Req W Power:	6,823.342		
Total Req Power, p:	6,823.342		lb-ft/sec
Power, w2w:	10,922.590		lb-ft/sec
Power,Uw:	11,145.500		lb-ft/sec
Energy, min	451,628.636		kBTU/yr
Ln:	13.021		
Ea:	**14.747**	**100**	

MINIMUM REQUIRED ENERGY (PRODUCTION)

Utility Number:	3a

Location Average Temp:	56	F
Kinematic Viscosity:	1.31E-05	ft^2/sec
Specific Weight:	62.38	lb/ft^3
Total Inflow:	0.5	MGD
Number of Pipelines:	2	
Diameter 1:	10	in
Diameter 2:	10	in
Flow 1:	0.250	MGD
Flow 2:	0.250	MGD
Pipelines Length:	422	ft
Gravity Accel:	32.174	ft/sec^2
Elevation Change:	-38.00	ft
Wire to water Efficiency:	62.47	%
Delivery Pressure:	15	psig
Water Loss:	0	%

Pressure Head provided:	16.461	psi
Difference to provide:	0.000	psi

E_{min}:	0.00	kBTU/yr
E_{actual}:	0.00	kBTU/yr
Thermodynamic Score:	100.00	%

Energy Intensities of Water in Production Phase		
E_{min}:	0.000	BTU/Gal
E_{actual}:	0.000	BTU/Gal

	Pipe 1	Pipe 2	
Flow rate Q:	0.387	0.387	ft^3/sec
Diameter:	0.833	0.833	ft
Area:	0.545	0.545	ft^2
Velocity:	0.709	0.709	ft/sec
Reynolds:	45,114.34	45,114.34	Turbulent
e:	0.01255	0.01255	ft
f:	0.0452	0.0452	
Friction Loss:	0.179	0.179	ft
Static Head:	0.000	0.000	ft
Total Head:	0.179	0.179	ft
Req Water Power:	4.317	4.317	lb-ft/sec
Total Req Power w:	8.634		lb-ft/sec
Energy, ideal:	349.868		kBTU/yr
Ln:	5.858		
Ea:	**7.129**		
Pressure Head:	0.000	0.000	ft
Total head, real:	0.000	0.000	ft
Req W Power:	0.000	0.000	
Total Req Power, p:	0.000		lb-ft/sec
Power, w2w:	0.000		lb-ft/sec
Power,Uw:	0.000		lb-ft/sec
Energy, min	0.000		kBTU/yr
Ln:			
Ea:	**0.000**	**100**	

MINIMUM REQUIRED ENERGY (PRODUCTION)

Utility Number:	**3b**

Location Average Temp:	56	F
Kinematic Viscosity:	1.31E-05	ft^2/sec
Specific Weight:	62.38	lb/ft^3
Total Inflow:	11	MGD
Number of Pipelines:	2	
Diameter 1:	36	in
Diameter 2:	36	in
Flow 1:	5.500	MGD
Flow 2:	5.500	MGD
Pipelines Length:	3,062	ft
Gravity Accel:	32.174	ft/sec^2
Elevation Change:	-8.00	ft
Wire to water Efficiency:	62.47	%
Delivery Pressure:	15	psig
Water Loss:	0	%

Pressure Head provided:	3.466	psi
Difference to provide:	11.534	psi

E_{min}:	1,877,187.95	kBTU/yr
E_{actual}:	4,376,552.19	kBTU/yr
Thermodynamic Score:	42.89	%

Energy Intensities of Water in Production Phase		
E_{min}:	0.468	BTU/Gal
E_{actual}:	1.090	BTU/Gal

	Pipe 1	Pipe 2	
Flow rate Q:	8.510	8.510	ft^3/sec
Diameter:	3.000	3.000	ft
Area:	7.069	7.069	ft^2
Velocity:	1.204	1.204	ft/sec
Reynolds:	275,698.74	275,698.74	Turbulent
e:	0.00992	0.00992	ft
f:	0.0275	0.0275	
Friction Loss:	0.632	0.632	ft
Static Head:	0.000	0.000	ft
Total Head:	0.632	0.632	ft
Req Water Power:	335.593	335.593	lb-ft/sec
Total Req Power w:	671.187		lb-ft/sec
Energy, ideal:	27,197.275		kBTU/yr
Ln:	10.211		
Ea:	**10.391**		
Pressure Head:	26.626	26.626	ft
Total head, real:	27.259	27.259	ft
Req W Power:	14,469.961	14,469.961	
Total Req Power, p:	28,939.923		lb-ft/sec
Power, w2w:	46,326.113		lb-ft/sec
Power,Uw:	46,326.113		lb-ft/sec
Energy, min	1,877,187.950		kBTU/yr
Ln:	14.445		
Ea:	**14.700**	**100**	

MINIMUM REQUIRED ENERGY (PRODUCTION)

Utility Number: **3c**

Location Average Temp:	56	F
Kinematic Viscosity:	1.31E-05	ft^2/sec
Specific Weight:	62.38	lb/ft^3
Total Inflow:	5	MGD
Number of Pipelines:	1	
Diameter 1:	36	in
Diameter 2:		in
Flow 1:	5.000	MGD
Flow 2:	0.000	MGD
Pipelines Length:	2,957	ft
Gravity Accel:	32.174	ft/sec^2
Elevation Change:	-62.10	ft
Wire to water Efficiency:	62.47	%
Delivery Pressure:	15	psig
Water Loss:	0	%

Pressure Head provided:	26.901	psi
Difference to provide:	0.000	psi

E_{min}:	1,955,043.91	kBTU/yr
E_{actual}:	53,470,283.02	kBTU/yr
Thermodynamic Score:	3.66	%

Energy Intensities of Water in Production Phase		
E_{min}:	1.071	BTU/Gal
E_{actual}:	29.299	BTU/Gal

	Pipe 1		
Flow rate Q:	7.736		ft^3/sec
Diameter:	3.000		ft
Area:	7.069		ft^2
Velocity:	1.094		ft/sec
Reynolds:	250,635.22		Turbulent
e:	0.00199		ft
f:	0.0194		
Friction Loss:	0.356		ft
Static Head:	62.100		ft
Total Head:	62.456		ft
Req Water Power:	30,140.200		lb-ft/sec
Total Req Power w:	30,140.200		lb-ft/sec
Energy, ideal:	1,221,315.928		kBTU/yr
Ln:	14.015		
Ea:	**13.776**		
Pressure Head:	0.000		ft
Total head, real:	62.456		ft
Req W Power:	30,140.200		
Total Req Power, p:	30,140.200		lb-ft/sec
Power, w2w:	48,247.478		lb-ft/sec
Power,Uw:	48,247.478		lb-ft/sec
Energy, min	1,955,043.907		kBTU/yr
Ln:	14.486		
Ea:	**14.239**	**100**	

MINIMUM REQUIRED ENERGY (PRODUCTION)

Utility Number:	**3d**

Location Average Temp:	56	F
Kinematic Viscosity:	1.31E-05	ft^2/sec
Specific Weight:	62.38	lb/ft^3
Total Inflow:	3.6	MGD
Number of Pipelines:	1	
Diameter 1:	20	in
Diameter 2:		in
Flow 1:	3.600	MGD
Flow 2:	0.000	MGD
Pipelines Length:	53	ft
Gravity Accel:	32.174	ft/sec^2
Elevation Change:	10	ft
Wire to water Efficiency:	62.47	%
Delivery Pressure:	15	psig
Water Loss:	0	%

E_{min}:	1,007,129.92	kBTU/yr
E_{actual}:	10,084,762.71	kBTU/yr
Thermodynamic Score:	9.99	%

Energy Intensities of Water in Production Phase		
E_{min}:	0.766	BTU/Gal
E_{actual}:	7.675	BTU/Gal

	Pipe 1		
Flow rate Q:	5.570		ft^3/sec
Diameter:	1.667		ft
Area:	2.182		ft^2
Velocity:	2.553		ft/sec
Reynolds:	324,823.25		Turbulent
e:	0.00094		ft
f:	0.0186		
Friction Loss:	0.060		ft
Static Head:	10.000		ft
Total Head:	10.060		ft
Req Water Power:	3,495.304		lb-ft/sec
Total Req Power W:	3,495.304		lb-ft/sec
Energy, ideal:	141,633.792		kBTU/yr
Ln:	11.861		
Ea:	**12.705**		
Pressure Head:	34.626		ft
Total head, real:	44.686		ft
Req W Power:	15,526.555		
Total Req Power, p:	15,526.555		lb-ft/sec
Power, w2w:	24,854.418		lb-ft/sec
Power,Uw:	24,854.418		lb-ft/sec
Energy, min	1,007,129.920		kBTU/yr
Ln:	13.823		
Ea:	**14.806**	**100**	

MINIMUM REQUIRED ENERGY (PRODUCTION)

Utility Number:	4

Location Average Temp:	58	F
Kinematic Viscosity:	1.21E-05	ft^2/sec
Specific Weight:	62.34	lb/ft^3
Total Inflow:	5.43	MGD
Number of Pipelines:	2	
Diameter 1:	24	in
Diameter 2:	24	in
Flow 1:	2.715	MGD
Flow 2:	2.715	MGD
Pipelines Length:	1320	ft
Gravity Accel:	32.174	ft/sec^2
Elevation Change:	-17.92	ft
Wire to water Efficiency:	62.47	%
Delivery Pressure:	15	psig
Water Loss:	1	%

Pressure Head provided:	7.758	psi
Difference to provide:	7.242	psi

E_{min}:	598,604.98	kBTU/yr
E_{actual}:	3,429,500.56	kBTU/yr
Thermodynamic Score:	17.45	%

Energy Intensities of Water in Production Phase		
E_{min}:	0.302	BTU/Gal
E_{actual}:	1.730	BTU/Gal

	Pipe 1	Pipe 2	
Flow rate Q:	4.201	4.201	ft^3/sec
Diameter:	2.000	2.000	ft
Area:	3.142	3.142	ft^2
Velocity:	1.337	1.337	ft/sec
Reynolds:	221,013.66	221,013.66	Turbulent
e:	0.02708	0.01585	ft
f:	0.0425	0.0355	
Friction Loss:	0.779	0.652	ft
Static Head:	0.000	0.000	ft
Total Head:	0.779	0.652	ft
Req Water Power:	203.890	170.701	lb-ft/sec
Total Req Power W:	374.591		lb-ft/sec
Energy, ideal:	15,178.871		kBTU/yr
Ln:	9.628		
Ea:	**10.114**		
Pressure Head:	16.729	16.729	ft
Total head, real:	17.507	17.381	ft
Req W Power:	4,584.689	4,551.501	
Total Req Power, p:	9,136.190		lb-ft/sec
Power, w2w:	14,624.924		lb-ft/sec
Power,Uw:	14,772.651		lb-ft/sec
Energy, min	598,604.976		kBTU/yr
Ln:	13.302		
Ea:	**13.975**	**100**	

MINIMUM REQUIRED ENERGY (PRODUCTION)

Utility Number:	5a

Location Average Temp:	60	F
Kinematic Viscosity:	1.21E-05	ft^2/sec
Specific Weight:	62.34	lb/ft^3
Total Inflow:	87	MGD
Number of Pipelines:	2	
Diameter 1:	60	in
Diameter 2:	84	in
Flow 1:	29.392	MGD
Flow 2:	57.608	MGD
Pipelines Length:	27,667	ft
Gravity Accel:	32.174	ft/sec^2
Elevation Change:	178.5	ft
Wire to water Efficiency:	90	%
Delivery Pressure:	15	psig
Water Loss:	0	%

E_{min}:	83,028,381.66	kBTU/yr
E_{actual}:	223,576,210.40	kBTU/yr
Thermodynamic Score:	37.14	%

Energy Intensities of Water in Production Phase		
E_{min}:	2.615	BTU/Gal
E_{actual}:	7.041	BTU/Gal

	Pipe 1	Pipe 2	
Flow rate Q:	45.476	89.133	ft^3/sec
Diameter:	5.000	7.000	ft
Area:	19.635	38.485	ft^2
Velocity:	2.316	2.316	ft/sec
Reynolds:	957,054.82	1,339,876.74	Turbulent
e:	0.00427	0.00285	ft
f:	0.0193	0.0165	
Friction Loss:	8.924	5.430	ft
Static Head:	178.500	178.500	ft
Total Head:	187.424	183.930	ft
Req Water Power:	531,341.261	1,022,015.051	lb-ft/sec
Total Req Power w:	1,553,356.312		lb-ft/sec
Energy, ideal:	62,943,803.665		kBTU/yr
Ln:	17.958		
Ea:	**16.103**		
Pressure Head:	34.649	34.649	ft
Total head, real:	222.072	218.579	ft
Req W Power:	629,569.378	1,214,542.161	
Total Req Power, p:	1,844,111.539		lb-ft/sec
Power, w2w:	2,049,012.821		lb-ft/sec
Power,Uw:	2,049,012.821		lb-ft/sec
Energy, min	83,028,381.659		kBTU/yr
Ln:	18.235		
Ea:	**16.352**	**93**	

MINIMUM REQUIRED ENERGY (PRODUCTION)

Utility Number:	**5b**

Location Average Temp:	60	F
Kinematic Viscosity:	1.21E-05	ft^2/sec
Specific Weight:	62.34	lb/ft^3
Total Inflow:	66.3	MGD
Number of Pipelines:	2	
Diameter 1:	84	in
Diameter 2:	72	in
Flow 1:	66.300	MGD
Flow 2:	66.300	MGD
Pipelines Length (Series):	9,504	ft
Gravity Accel:	32.174	ft/sec^2
Elevation Change:	154.25	ft
Wire to water Efficiency:	90	%
Delivery Pressure:	0	psig
Water Loss:	0	%

E_{min}:	89,820,628.71	kBTU/yr
E_{actual}:	104,956,538.10	kBTU/yr
Thermodynamic Score:	85.58	%

Energy Intensities of Water in Production Phase		
E_{min}:	3.712	BTU/Gal
E_{actual}:	4.337	BTU/Gal

	Pipe 1	Pipe 2	
Flow rate Q:	102.581	102.581	ft^3/sec
Diameter:	7.000	6.000	ft
Area:	38.485	28.274	ft^2
Velocity:	2.666	3.628	ft/sec
Reynolds:	1,542,036.89	1,799,043.04	Turbulent
e:	0.00433	0.00089	ft
f:	0.0179	0.0137	
Friction Loss:	1.489	1.973	ft
Static Head:	154.250	154.250	ft
Total Head:	155.739	156.223	ft
Req Water Power:	995,939.847	999,031.685	lb-ft/sec
Total Req Power w:	1,994,971.533		lb-ft/sec
Energy, ideal:	80,838,565.843		kBTU/yr
Ln:	18.208		
Ea:	**16.328**		
Pressure Head:	0.000	0.000	ft
Total head, real:	155.739	156.223	ft
Req W Power:	995,939.847	999,031.685	
Total Req Power, p:	1,994,971.533		lb-ft/sec
Power, w2w:	2,216,635.036		lb-ft/sec
Power,Uw:	2,216,635.036		lb-ft/sec
Energy, min	89,820,628.715		kBTU/yr
Ln:	18.313		
Ea:	**16.422**	**90**	

MINIMUM REQUIRED ENERGY (PRODUCTION)

Utility Number:	6

Location Average Temp:	54	F
Kinematic Viscosity:	1.31E-05	ft^2/sec
Specific Weight:	62.38	lb/ft^3
Total Inflow:	13	MGD
Number of Pipelines:	1	
Flow, each:	13	MGD
Diameters:	30	in
Pipelines Length:	401.28	ft
Gravity Accel:	32.174	ft/sec^2
Elevation Change:	-17.5	ft
Wire to water Efficiency:	85	%
Delivery Pressure:	15	psig
Water Loss:	0	%

Pressure Head provided:	7.581	psi
Difference to provide:	7.419	psi

E_{min}:	0.00	kBTU/yr
E_{actual}:	0.00	kBTU/yr
Thermodynamic Score:	100.00	%

Energy Intensities of Water in Production Phase		
E_{min}:	0.000	BTU/Gal
E_{actual}:	0.000	BTU/Gal

	Pipe 1		
Flow rate Q:	20.114		ft^3/sec
Diameter:	2.500		ft
Area:	4.909		ft^2
Velocity:	4.098		ft/sec
Reynolds:	781,981.89		Turbulent
e:	0.00553		ft
f:	0.0244		
Friction Loss:	1.020		ft
Static Head:	0.000		ft
Total Head:	1.020		ft
Req Water Power:	1,279.949		lb-ft/sec
Total Req Power W:	1,279.949		lb-ft/sec
Energy, ideal:	51,865.031		kBTU/yr
Ln:	10.856		
Ea:	**10.743**		
Pressure Head:	17.126		ft
Total head, real:	18.147		ft
Req W Power:	22,768.713		
Total Req Power, p:	22,768.713		lb-ft/sec
Power, w2w:	26,786.721		lb-ft/sec
Power,Uw:	26,786.721		lb-ft/sec
Energy, min	1,085,429.090		kBTU/yr
Ln:	13.897		
Ea:	**13.752**	**100**	

MINIMUM REQUIRED ENERGY (PRODUCTION)

Utility Number:	7

Location Average Temp:	59	F
Kinematic Viscosity:	1.21E-05	ft^2/sec
Specific Weight:	62.34	lb/ft^3
Total Inflow:	40	MGD
Number of Pipelines:	3	
Flow, each:	13.333	MGD
Diameter 1:	42	in
Diameter 2:	42	in
Diameter 3:	42	in
Pipelines Length:	184,800	ft
Gravity Accel:	32.174	ft/sec^2
Elevation Change:	22	ft
Wire to water Efficiency:	85	%
Delivery Pressure:	15	psig
Water Loss:	1	%

E_{min}:	19,046,352.79	kBTU/yr
E_{actual}:	133,199,997.90	kBTU/yr
Thermodynamic Score:	14.30	%

Energy Intensities of Water in Production Phase		
E_{min}:	1.305	BTU/Gal
E_{actual}:	9.123	BTU/Gal

	Pipe 1	Pipe 2	Pipe 3	
Flow rate Q:	20.630	20.630	20.630	ft^3/sec
Diameter:	3.500	3.500	3.500	ft
Area:	9.621	9.621	9.621	ft^2
Velocity:	2.144	2.144	2.144	ft/sec
Reynolds:	620,226.00	620,226.00	620,226.00	Turbulent
e:	0.00947	0.00947	0.00947	ft
f:	0.0257	0.0257	0.0257	
Friction Loss:	97.129	97.129	97.129	ft
Static Head:	22.000	22.000	22.000	ft
Total Head:	119.129	119.129	119.129	ft
Req Water Power:	153,206.915	153,206.915	153,206.915	lb-ft/sec
Total Req Power W:	459,620.745			lb-ft/sec
Energy, ideal:	18,624,366.932			kBTU/yr
Ln:	16.740			
Ea:	**15.011**			
Pressure Head:	34.649	34.649		ft
Total head, real:	153.778	153.778		ft
Req W Power:	197,767.103	197,767.103		
Total Req Power, p:	395,534.206			lb-ft/sec
Power, w2w:	465,334.360			lb-ft/sec
Power,Uw:	470,034.707			lb-ft/sec
Energy, min	19,046,352.789			kBTU/yr
Ln:	16.762			
Ea:	**15.031**	**100**		

MINIMUM REQUIRED ENERGY (PRODUCTION)

Utility Number:	8

Location Average Temp:	60	F
Kinematic Viscosity:	1.21E-05	ft^2/sec
Specific Weight:	62.34	lb/ft^3
Total Inflow:	36.8	MGD
Number of Pipelines:	1	
Diameter 1:	60	in
Diameter 2	60	in
Flow 1:	36.8	MGD
Flow 2:	36.8	MGD
Pipelines Length:	401280	ft
Gravity Accel:	32.174	ft/sec^2
Elevation Change:	121	ft
Wire to water Efficiency:	85	%
Delivery Pressure:	0	psig
Water Loss:	0	%

E_{min}:	50,117,124.71	kBTU/yr
E_{actual}:	168,497,993.60	kBTU/yr
Thermodynamic Score:	29.74	%

Energy Intensities of Water in Production Phase		
E_{min}:	3.731	BTU/Gal
E_{actual}:	12.545	BTU/Gal

	Pipe 1	Pipe 2	
Flow rate Q:	56.938	56.938	ft^3/sec
Diameter:	5.000	5.000	ft
Area:	19.635	19.635	ft^2
Velocity:	2.900	2.900	ft/sec
Reynolds:	1,198,276.63	1,198,276.63	Turbulent
e:	0.00217	0.00212	ft
f:	0.0167	0.0167	
Friction Loss:	96.543	78.636	ft
Static Head:	0.000	121.000	ft
Total Head:	96.543	199.636	ft
Req Water Power:	342,679.836	708,611.718	lb-ft/sec
Total Req Power w:	1,051,291.554		lb-ft/sec
Energy, ideal:	42,599,556.000		kBTU/yr
Ln:	17.567		
Ea:	**15.838**		
Pressure Head:	0.000	0.000	ft
Total head, real:	96.543	199.636	ft
Req W Power:	342,679.836	708,611.718	
Total Req Power, p:	1,051,291.554		lb-ft/sec
Power, w2w:	1,236,813.593		lb-ft/sec
Power,Uw:	1,236,813.593		lb-ft/sec
Energy, min	50,117,124.706		kBTU/yr
Ln:	17.730		
Ea:	**15.984**	**98**	

Financial implications of the research

This section is intended to show the financial benefits of the minimum required energy approach and the thermodynamic score. The analysis will be performed over the utility 1 since we have the required information. The same analysis is possible for all the utilities as long as we have the information. This analysis will also clarify the methodology applied on the utilities that comprise the case study.

Diagram in fig.49 shows the production and treatment phases of utility 1. We will analyze only the production part of the system.

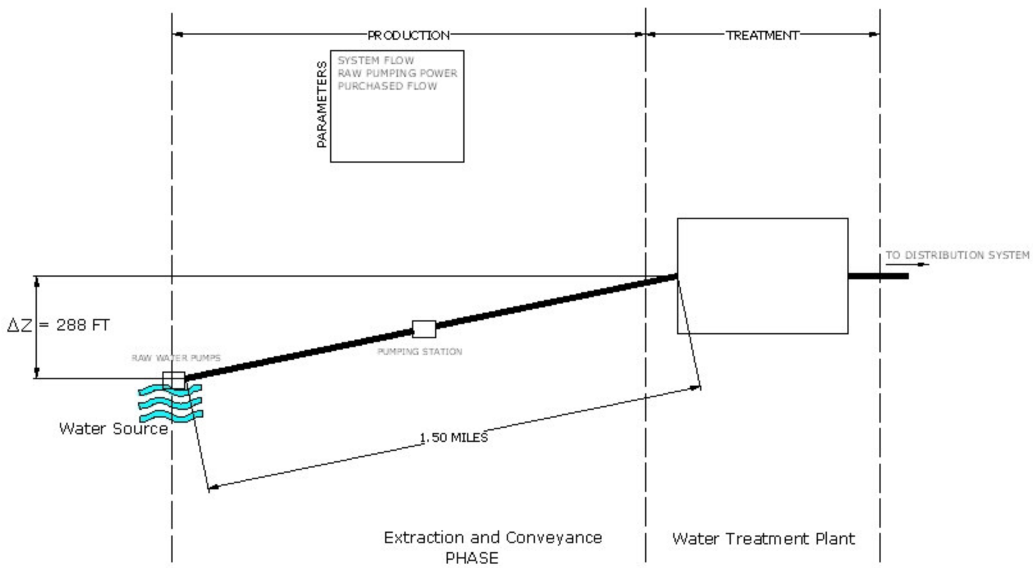


Fig.50 Utility 1 production system diagram

According to the parameters for calculating the production benchmarking score shown in fig.49, we have:

1. Total water flow: 6.86 MGD
2. Installed Raw pumping power: 1,625 HP
3. Purchased water flow: 0 MGD

Applying the benchmarking model shown in table 1 in page 21, we obtain the predicted natural logarithm for production energy use:

$$Ln(kBTU/yr) = 17.46106$$

Then

Predicted Energy Use = 38,303,812.80 kBTU/yr

From the utility information, we know they use only electricity at an actual average of 4,224,000 kWh. Converting this number to source energy at a rate of 11.1 kBTU/kWh (Carlson, 2007) we obtain the actual energy use for the average year as:

Actual Energy Use = 46,886,400 kBTU/yr

Ln(kBTU/yr) = 17.66324

From this information, we obtain the adjusted source energy use as 17.540 (For a detailed explanation see the sample calculation shown in page 45). Using table in fig.6 of page 24, the production benchmarking score is

Prod. Benchmark Score = 39

Dividing the predicted and actual energy uses by water flow at 6.86 MGD, we know the energy intensities of water at production stage:

Energy Intensity of water, predicted = 15.298 BTU/Gal

Energy Intensity of water, actual = 18.725 BTU/Gal

These energy intensities are shown for utility 1 in Fig.21 on page 64.

Now we need to use the minimum required energy approach. By looking fig.49, we know that the energy input required by the system to convey raw water to the treatment facility is comprised by two main issues: Overcome the elevation change (ΔZ) and the Friction Head Loss resulting from the conduction of water through two 16-inch ductile iron pipelines for the 1.50 mile that separate the raw water extraction point and the treatment facility.

Utility 1 has two pipelines of 16-inch diameter. Ages of the pipelines are 33 and 52 yrs old. To calculate the friction head loss in the pipes, we do the calculation shown in page 95. Parameters we are considering are (for detailed explanation of these results see also page 48):

1. Water flow rate Q = 5.307 ft3/sec for both pipes

2. Diameter of pipes D = 16 inch
3. Darcy friction factors are estimated at 0.0247 (33 yrs old pipe) and 0.0276 (52 yrs old pipe)
4. Pipe length: 1.50 miles; 7,920 ft

Using the Darcy-Weisbach equation, we have that friction head losses for these pipes are:

Friction head loss: 32.995 ft for 33 yrs old pipe and,

Friction head loss: 36.811 ft for 52 yrs old pipe.

Each pipeline has to overcome the same elevation change of 288 ft. Adding the friction head loss and the elevation change, we obtain the total head that pumps must provide to water in utility 1:

Total Head (33 yrs old pipe) = 320.995 ft

Total Head (52 yrs old pipe) = 324.811 ft

These total heads are added up and converted to power (see page 50) as:

Required energy under ideal conditions = 8,663,190.30 kBTU/yr

Finally we convert this number to an achievable minimum required energy applying the following factors:

a. Pumping efficiency (wire-to-water) = 62.47% (Provided by utility)
b. Pressure at delivery point = 15 psi
c. Water Loss between water source and treatment facility = 0%

Resulting:

Minimum Required Energy = 15,353,093.39 kBTU/yr

Dividing this energy amount by our water flow of 6.86 MGD, we obtain the energy intensity of water, minimum:

Energy Intensity of Water, Minimum: 6.132 BTU/Gal

This value is also shown in fig.21 on page 64.

Suppose that this minimum required energy is the actual energy consumption of the utility instead of the real value. Then:

$$Ln(kBTU/yr) = 16.5468$$

The adjusted energy use would be 16.432, and using again table of fig.6 on page 24 we have that the production benchmarking score would be 90. Conclusion is that if the calculations are correct, the utility could never reach a benchmarking score above 90.

As a summary so far, consider again fig.49. For utility 1 we have:

Production Benchmarking Score:	39
Energy Int. of water, predicted:	15.298 BTU/Gal
Energy Int. of water, actual:	18.725 BTU/Gal
Energy Int. of water, Minimum:	6.132 BTU/Gal
Maximum Prod. Bench. Score:	90

The parameters used to calculate the minimum required energy are, besides constants such as acceleration of gravity and specific weight of water:

1. Water flow
2. Pipe length
3. Pipe Diameter
4. Friction factor
5. Elevation change
6. Pumping efficiency
7. Water pressure at delivery point.

Observing these parameters, we notice that all of them are constant for practical purposes except pipe diameter and friction factor. We know that reduction of the pipe inside diameter from tuberculation and sediments has a greater impact on friction head loss than only roughness growth from age.

If we assume that the utility is using as less energy as it can, that would mean that somewhere in the 1.50 miles of pipe the interior diameter has been drastically reduced by tuberculation and deposits. Since we have two pipes with different ages and the same material conducting the same water, we estimate that the interior diameter reduction is distributed according to the age of each pipeline resulting interior diameters of **7 inches** for the 52 yr old pipe and **11 inches** for the 33 yr old pipe. These numbers were obtained by reverse-engineering the minimum required energy process to obtain as minimum required energy the same actual energy being used.

Now comes the financial part. For utility 1, we know the price of kWh was:

$0.06/kWh

Actual electricity usage of 4,224,000 kWh each year represents:

Average electricity cost for raw water pumping: $253,440 /yr

Thus, the energy cost in terms of BTU is:

Energy Cost of energy for utility 1: $ $5.4054\text{x}10^{-6}$ /BTU

(To check this number, if the utility uses 18.725 BTU/Gal and processes 6.86 MGD, we obtain the same dollar amount for energy on a year: $253,440)

If the energy intensity of water is reduced from 18.725 BTU/Gal to 6.132 BTU/Gal, under conditions of *ceteris paribus*, the electricity cost would be $82,995.68. The financial savings amount would be of around $170,445 each year. With this money the utility could replace both pipelines and recover the investment in an estimated time of around 5-7 years.

Relationship between energy intensity of water and the energy spending it implies for utility 1 is shown in fig.50

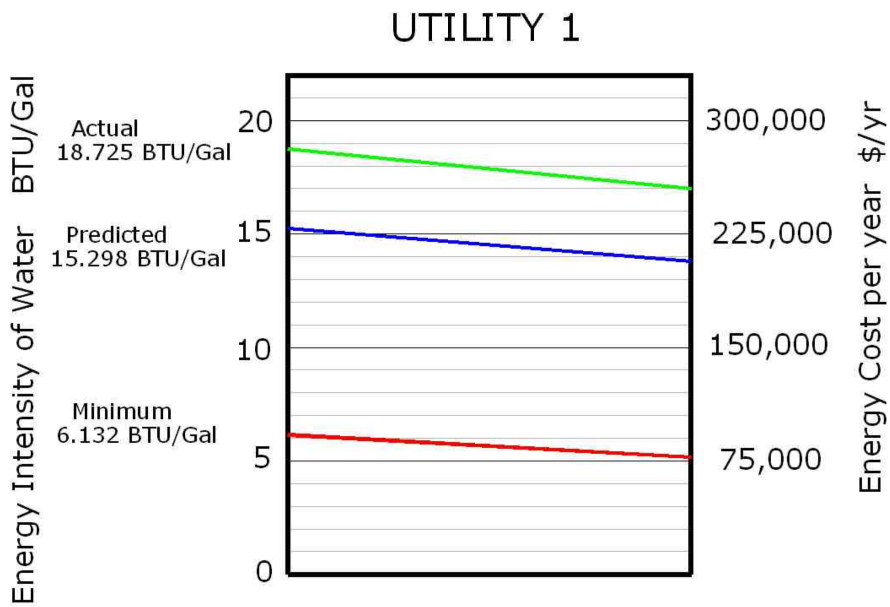


Fig.51 Financial savings from reducing energy intensity of water in production

The most important factor preventing the utility from saving 170 k yearly on electricity costs is likely to be the inside pipe diameter of pipes. The amount of potential financial savings is important enough to deserve serious consideration for pipe diameter study and pipe sections replacement, if necessary.

Another consequence of the minimum required energy analysis is that it has pointed out the need to inspect the interior of the pipelines. Since diameter is the most likely variation in real world from the minimum energy analysis, we can conclude that variations in the energy consumed for production in utility 1 are due mainly to variations in the interior diameter of pipe.

In this particular utility, we have all the information we need in order to consider all other parameters well defined and thus constant for practical purposes. In addition, the financial savings that would come from achieving a lower energy intensity of water in production phase are significant, then strongly suggesting the convenience of inspecting that pipe and replacing the required sections. If our analysis is correct, the investment will be recovered quickly.

Conclusions

We analyzed eight utilities from the State of Virginia. This analyses are comprised by:
a) Estimation of production and treatment benchmarking scores, applying the models and methodology proposed in the report “Energy Index Development for Benchmarking Water and Wastewater Utilities” published by the Water Research Foundation in 2007 (Carlson, 2007); b) Using the proposed Minimum Required Energy approach, for estimation of the production Thermodynamic Scores for each utility. This score is the ratio of minimum energy required by the utility to extract and convey raw water to a treatment plant divided by the actual energy usage. This score is expressed in percentage and constitutes a measure of how close is the actual energy consumption in relation with the thermo dynamic minimum energy required; and c) Calculation of some other ratios to provide context to the metrics: Energy intensity of water (BTU/Gal) and Installed pumping power ratio (HP/MG).

Having completed the analyses, we propose the following conclusions:

1. Benchmarking scores should never been used as a black box. Using segregated benchmarking scores for Production Energy Use and Treatment Energy Use as proposed, resulted in skewed scores in 50% of our studied facilities. Although this percentage of utilities cannot be generalized to every situation, we still consider it significant.

2. In consequence, benchmarking scores should not be applied without a context and a complete analysis of the energy-related issues of the utility, even if the metrics have sound methodologies like those used here.

3. The proposed Thermodynamic Score for Production energy efficiency has intuitive meaning and can greatly enhance the understanding of energy flows within the utility. However, it should be used cautiously since relies on some parameters that can have significant associated uncertainties, such as pipe roughness, pipe interior diameter, and pumping efficiency.

4. The gravity-fed utilities present the most skewed benchmarking scores for treatment, while those utilities that need to use a significant part of their energy consumption to overcome static head tend to have wrong production benchmarking scores.

5. In order to improve these benchmarking metrics while their methodologies are updated, we propose to use the production energy use benchmarking score always paired with the thermodynamic score. These metrics together provide a more holistic view of the energy efficiency within the raw water extraction and conveyance part of the system.

6. In relation with production benchmarking scores and thermodynamic scores, we can have three different cases:

    a. Both scores are very close to one another. This case is really just a coincidence. It would mean that the utility is ranked among its peers in the same bracket (from very poor to very good) of energy efficiency than compared with itself. For example, if the utility is doing as good as it can regarding energy efficiency (thus obtaining a good thermodynamic score), and is also well ranked among the national sample of utilities (good benchmarking)
    b. Benchmarking score is high and thermodynamic score is low. In this case, the utility is more energy efficient than the U.S. National average, but could do even better compared with itself. The utility has imposed conditions that allows better energy efficiency.
    c. Benchmarking score is low and thermodynamic score is high. This is the case where the utility is doing poorly compared to the national average, but a closer analysis of imposed conditions on the utility shows that the utility is doing almost as good as it can.

In all cases above, we call imposed conditions to those system characteristics that the utility cannot change, like elevation changes, raw water quality, and so on.

Future Research

Further research in the area of water-energy nexus applied to infrastructure systems is required. It is a promising area that is currently almost entirely comprised by the optimization of pumping operations. While this is understandable, given the fact that almost all of energy consumption in water utilities comes from pumping, there is also another vast, unexplored area. The flows of water and energy through networks, impact of climate change upon water and energy facilities, embedded energy-demanding features of water systems and the energy implications of current water availability trends are examples of areas that could greatly benefit from research.

Research is suggested in the following areas:

a) Measurement of parameters that have an effect over the energy consumption of water operations, such as:
    i. Roughness value change with pipe age, material and water quality
    ii. Inside diameter change in pipes, during service time
    iii. Wire-to-Water efficiencies of pumping systems,
    iv. Water leakage long term effects on the overall system efficiency

b) The effect of climate change over the energy efficiency of water utilities, and overall water-energy interdependent infrastructures.

c) Application of renewable energy sources to power water systems (Off-Grid Systems)

d) Analysis of Energy and water flows through pipe networks, and

e) Water systems design and operation for optimal energy efficiency.

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Appendix A

Survey Instrument

UTILITY SURVEY

Energy Use for Raw Water Extraction, Conveyance and Treatment

<u>Phase 2: Virginia's Utilities Survey</u>

"Energy Efficiency of Raw Water Operations in Water Utilities"

May 2009

VirginiaTech

Prepared by: Dr. Sunil Sinha and Mr. Leon Gay
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EXECUTIVE SUMMARY

Energy consumption is one of the largest expenditures of water utilities everywhere. In the U.S. is estimated that around 4% of national electricity consumption is for conveying and treating water and wastewater, and an estimated average of 80% of municipal water and wastewater services provision costs are just for electricity (Ghimire 2007).

Energy efficiency practices and technologies have the potential to bring important financial benefits for utilities, as well as increasing the overall sustainability and resiliency of these essential infrastructure systems. Research and advance on this topic is very important given the challenges that lie ahead such as climate change.

In order to encourage the energy efficiency of water utilities, a series of metrics have been developed to measure progress in this field. Among these metrics, benchmarking scores are widely used to perform comparisons among peers and thus promote energy efficiency leadership and continuous improvement on energy-related issues in the sector.

The objective of this project is to improve the benchmarking process accuracy and usefulness through parallel consideration of imposed characteristics of network and raw water quality, along with usual benchmarking parameters. Each water utility has to deal with different and fixed site conditions such as network topology, current system condition and source water quality. Although some of these factors are usually normalized into the benchmarking model, we feel that solely including them in a model is not enough to obtain accurate scores and full consideration of imposed system features is required.

The research project comprises the following phases:

1. Literature Review and State-of-the-art regarding measurement of energy efficiency in water utilities

2. Virginia's Utilities Survey

3. Data Analysis and Information summaries

4. Report preparation.

The information obtained from the surveys will be analyzed by calculating the applicable energy benchmarking scores as proposed by the Water Research Foundation (former AwwaRF) in 2007 using different models (Production, Treatment, Distribution and Overall) and then comparing these scores with the specific utility's network and water characteristics. The network characteristics and water quality data will be utilized to calculate the minimum energy required by the utility to perform its operations according to regulations. We believe that current benchmarking scores might be punishing utilities for characteristics that are externally imposed. Also, we have seen that some utilities have a 'ceiling score' which represents a maximum attainable score even under ideal operating conditions, and these utilities cannot go beyond that score on energy efficiency, no matter what improvements they implement. The benchmarking scores should allow every utility to reach top scores by taking the right decisions, with effort and a reasonable investment.

Required network characteristics include the infrastructure and processes from raw water extraction and conveyance, to end of treatment. After the drinking water plant, drinking water transmission and distribution networks are not currently being considered due to project's time constraints to analyze these sometimes huge and complex networks, and also because some of the utilities do not own that part of the system. Nevertheless, every utility have raw water operations, from extraction to treatment.

All information is considered confidential and will be used solely for the purpose of this study. Credit will be given to participant utilities for their contributions that make this research project possible.

Case-Study Questionnaire

This questionnaire is designed to obtain the information on the utility's current practice about energy usage for raw water extraction, conveyance and treatment. Some information on the distribution system will allow calculations of distribution and overall benchmarking scores, if applicable.

Utility Information

Utility Name: ____

Location:____

Private/Public:____

Population Served:____

Contact for Follow-Up Information

Name: ____

Address: ____

Email: ____

Phone: ____

1. **To calculate Production Energy Use Benchmarking Score:**

Number of Water Sources:________________________________

Total Average Inflow (MGD):______________________________

Total installed raw water pumping power (HP):____________________

Total Average purchased water inflow (MGD):____________________

Average Energy consumption for raw water pumping operations (at the source)

i. Electricity (kWh/mo):________________________

ii. Natural Gas (Therms/mo):________________________

iii. Fuel Oil or Diesel (Gal/mo):________________________

iv. Propane (Gal/mo):________________________

v. Other ________________________

2. **To calculate Treatment Energy Use Benchmarking Score:**

Please mark Y/N whether the water treatment operations have the following objectives and processes:

Oxidation:________________________________

Direct Filtration:________________________________

Sand Drying Bed:________________________________

Iron Removal:________________________________

Ozonation:________________________________

Average Energy consumption for Water Treatment operations (at the plant)

i. Electricity (kWh/mo):____

ii. Natural Gas (Therms/mo):____________________________________

iii. Fuel Oil or Diesel (Gal/mo):__________________________________

iv. Propane (Gal/mo):____

v. Other ____

3. To calculate Distribution Energy Use and Overall Benchmarking Scores:

Distribution system installed pumping power (HP):______________________________

Maximum, Minimum Elevations of Distribution System (ft):________________________

Lagoon Dewatering Thickening (y/n):____

Pressure Filtration (y/n):____

Residual Gravity Thickening (y/n):____

Total Distribution Mains Length (mi):_______________________________________

Average Energy consumption for water distribution pumping operations:

Electricity (kWh/mo):______________________________________

Natural Gas (Therms/mo):___________________________________

Fuel Oil or Diesel (Gal/mo):_________________________________

Propane (Gal/mo):____

4. **Network Characteristics from Extraction to Treatment.**

Normal Average Elevation of water source (ft):________________________________

Water Treatment Facility Elevation (ft):______________________________________

Distance between Raw Water Source and Treatment (mi):________________________

If there is one or more pumping stations between water source and treatment facility, indicate for each one distance from source, elevation and other features:

Distance (mi)	Elevation (ft)	Installed Power (hp)	Energy Cons (kWh/mo)
__________	__________	________________	________________
__________	__________	________________	________________
__________	__________	________________	________________
__________	__________	________________	________________
__________	__________	________________	________________

Number of pipelines between source and treatment facility:______________________

Material of pipelines _____________________________, age (s):______________ yrs

Diameter of pipeline(s), (in):____

Estimated Water loss between source and treatment, % _________________________

5. How would you describe the overall raw water quality in relation with drinking water standards in a scale from 1 to 4, where: 1.Poor, 2. Fair, 3.Good, 4.Very Good?

____

6. Do you have some other information on the system layout from raw water extraction to the treatment process, such as drawings?

7. Please provide other information that you think would be useful for this study (in the back side or add pages as needed).

We appreciate your participation in this research project.

Appendix B

Summary of Information obtained from Surveys

CONSOLIDATED INFORMATION FROM UTILITIES FOR RESEARCH PROJECT

	1	2	3a	3b	3c	3d	4	5a	5b	6	7	8
Utility Nr.	**1**	**3**		**4**			**6**	**7**		**8**	**9**	**10**
Region	Mountain	Valley		Valley			Central	Northern		Northern	Coastal	Coastal
Private/Public	public	public	public	public	public	public		public	public	public	public	public
Population Served	65,000	10,000	3,900	85,000	38,600	27,500	47,000	900,000	600,000	134,000	406,000	450,000
Production Energy Use Benchmarking Score												
Number of Water Sources	1	1	1	1	1	1	1	1	1	2	4	1
Total Average Inflow (MGD)	6.86	1.4	0.5	11	5	3.6	5.43	87	66.3	13	40	36.8
Installed Raw Water Pumping Power (HP)	1625	150		300	4000	250	270	18,000	3,000		7,200	6,500
Total Average Purchased Water Inflow (MGD)	0	0	0	0	0	0	0	0	0	0.25	0	0
Average Energy consumption for raw water pumping operations (at the source)												
Electricity (kWh/mo)	352,000	25,000	1	32,857	401,428.57	75,711.43	25,747	1,678,500	787,962	1	1,000,000	1,265,000
Natural Gas (therms/mo)	0	0	0	0	0	0	0	0	0	0	0	0
Fuel Oil or Diesel (Gal/mo)	0	0	0	0	0	0	0	0	0	0	0	0
Propane (Gal/mo)	0	0	0	0	0	0	0	0	0	0	0	0
Other	0	0	0	0	0	-	-	-	-	-	-	-
Treatment Energy Use Benchmarking Score												N/A
Oxidation	1	0	1	1	1	0	1	1	1	1	1	-
Direct Filtration	0	1	1	1	0	1	0	0	0	1	0	-
Sand Drying Bed	0	1	0	0	0	0	0	0	0	0	0	-
Iron Removal	1	0	0	0	0	0	0	0	0	0	0	-
Ozonation	0	0	0	0	0	0	0	1	1	0	1	-
Treatment Pumping Power (HP)	0	0	0	0	0	0	0					-
Average Energy consumption for Treatment processes (at the plant, offices not included)												
Electricity (kWh/mo)	298,152	95,000	14,457	112,871.43	339,000	75,711.43	232,533	6,064,625	3,501,159	574,404	2,100,000	-
Natural Gas (therms/mo)	973.92	1066	0	1,119.01	0	0	0	0	0	0	0	-
Fuel Oil or Diesel (Gal/mo)	0	0	0	0	0	0	0	0	0	0	2,500	-
Propane (Gal/mo)	0	0	3,112.30	0	0	0	0	0	0	0	0	-
Other	0	0	0	0	0	0	0	0	0	0	-	-
Distribution Energy Use Benchmarking Score	N/A		N/A	N/A	N/A	N/A	N/A					
Dist System installed pumping power (HP)	-	500	-	-	-	-	-	-	-	1,500	2,500	8,750
Distribution System Max Elevation (ft)	-	1320	-	-	-	-	-	-	-	320	100	330
Distribution System Min Elevation (ft)	-	1000	-	-	-	-	-	-	-	170	0	199
Lagoon Dewatering Thickening	-	1	-	-	-	-	-	0	0	0	0	
Pressure Filtration	-	0	-	-	-	-	-	0	0	0	0	
Residual Gravity Thickening	-	1	-	-	-	-	-	0	0	1	1	
Total Distribution Mains Length (mi)	-	20	-	-	-	-	-	3,363	3,363	165	1,800	76
Average Energy consumption for Distribution												
Electricity (kWh/mo)	-		-	-	-	-	-	-			100,000	
Natural Gas (therms/mo)	-		-	-	-	-	-	-			0	
Fuel Oil or Diesel (Gal/mo)	-		-	-	-	-	-	-			0	
Propane (Gal/mo)	-		-	-	-	-	-	-			0	
Other	-		-	-	-	-	-	-			-	
Raw Water Network Characteristics												
Normal Average Elevation Raw Water (ft)	1694	0	1663	1163	1392.1	935	455	181.5	122	290	18	199
Water Treatment Facility Elevation (ft)	1982	15	1625	1155	1330	945	437.08	360	276.25	272.5	40	15
Distance Raw Water - Treatment (ft)	7,920.00	1,320.00	422.40	3,062.40	2,956.80	52.8	1,320	27,667	9,504	401.28	184,800	580,800
Pumping Stations in Between	1	1	0	0	0	0	0	0	0	1	-	
Distance from Source (mi)	-	528	-	-	-		0	0	0	0.06	-	
Elevation (ft)	-	20	-	-	-		0	0	0	256	-	
Installed Raw Pumping Power (HP)	-	150	-	-	-		0	0	0	90	-	
Energy Consumption (kWh/mo)	-	25000	-	-	-		0	0	0	0	-	
Number of Pipelines Raw - Treatment	2	1	2	2	1	1	2	2	1	1	3	1
Material of Pipelines												
Line 1	Ductile Iron	Ductile Iron	Cast Iron	Cast Iron	Ductile Iron	Ductile Iron	Cast Iron	ISO-250 PCCP	lded Carbon Steel (p	Ductile Iron	Ductile Iron	PCCP (55%)
Line 2	Ductile Iron		Cast Iron	Cast Iron			Cast Iron	Vrapped Welded Ste	lded Carbon Steel (p	-	-	Ductile Iron (45%)
Age of Pipelines (yrs)												
Line 1	52	8	80	60	13	8	109	30	50	40	70	14
Line 2	33		80	60			69	20	8	-	-	14
Diameter of Pipelines (in)												
Line 1	16	16	10	36	36	20	24	60	84 (5280)	30	42	60
Line 2	16	-	10	36			24	84	72 (4224)	-	-	
Estimated Water Loss Raw - Treatment (%)	0	2	0	0	0	0	1	0.1	0	0	1	0
Other Issues												
Overall Raw Water Quality	very good	Fair	Good	Good	Good	Very Good	Fair	Good	Very Good water	Good	n/a	Good
Drawings	yes									yes	yes	
Extra Info:	0											