Development of a risk-based tool for groundwater well rehabilitation and replacement decisions

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ABSTRACT

Groundwater wells are critical drinking water infrastructure elements that widely support basic system supply needs while also providing supply reliability, better water quality (in some cases), and comparatively lower operational costs. Well rehabilitation and replacement are thus an area where water utilities could benefit from rational decision support frameworks and quantitative tools that enable them to better navigate the complex trade-off relationship(s) that exist among a variety of environmental quality, public health, financial, regulatory, organizational, and technological dimensions. Consistent with these considerations, a business risk-based prioritization tool was developed for this study that augments/extends California Water Service (Cal Water)'s well rehabilitation and the replacement decision-making process. For this derivation, a business risk exposure methodology is combined with an analytical hierarchy process (AHP), with the AHP being utilized to determine the weights of the factors involved in the likelihood of failure and the consequence of failure calculation. It is expected that the new tool will assist in optimizing inspection and action plans and identify the wells requiring attention and/or additional work for water utilities.

Key words | analytical hierarchy process, asset management, business risk exposure, decision support system, groundwater well, risk-based prioritization

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INTRODUCTION

According to the most recent State of the Water Industry Report prepared by the American Water Works Association (AWWA), aging infrastructure is the most important challenge facing the US water industry, followed by financing for capital improvements, long-term water supply availability, and asset management (AWWA 2018). In 2015, the U.S. Environmental Protection Agency (EPA) conducted a Drinking Water Infrastructure Needs Survey, concluding that the nation's water systems need to invest $472.6 billion through 2034 if they are to continue to provide safe drinking water to the public. Of all the states and territories, California has the greatest share of this burden at $51 billion (EPA 2018a). This is a clear indication of California's increasingly urgent need for infrastructure rehabilitation and replacement. More generally, given that infrastructure solutions are expensive, and water resources are finite, water utilities must replace/renew their deteriorating infrastructure elements, while also managing their assets wisely, considering their financial situation and the health of their available water sources. As such, the implementation of asset management practices and tools to enable enhanced decision-making is critical for economically feasible water utility operation, maintenance, renewal, and replacement.

Wells are important elements of drinking water infrastructure, as groundwater is often considered to be a more reliable and generally higher quality water resource than surface water. This level of criticality and importance placed on groundwater has only increased with changing

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weather patterns and the evolving role of water in our society (Güngör-Demirci & Aksoy 2011a, 2011b; Schnieders & Marks 2014). Cal Water (California Water Service) – one of the largest water utilities in California – relies upon groundwater either partially or entirely in many areas, yet its portfolio of over 600 production wells have a median age of over 50 years. Given that replacing all of these facilities would cost over $1 billion (Harrison 2010), the utility clearly needs a rational, data-driven and criteria-based tool to support regular to urgent well rehabilitation and replacement decisions, while also helping system planners more broadly anticipate supply challenges linked to aging and at-risk wells.

The objective of this study is therefore to develop a risk-based prioritization tool for making well rehabilitation and replacement decisions that will help to maximize the value of the capital investment by extending asset life to its fullest cost-effective term. BRE (business risk exposure), criticality, and risk-based prioritization concepts have been in place for years to make well rehabilitation and replacement decisions (e.g., SSWD 2009; SEFC 2019). In addition to studies on economic well life expectancy and well efficiency (e.g., Helweg 1982), there are books designated to understand factors affecting well operation and maintenance and to develop methods for assessing well health (e.g., Houben & Treskatis 2007; Hanna *et al.* 2016). However, to the best of the authors' knowledge, there is no peer-reviewed journal article exploring the application of the BRE methodology based on the combination of attributes/criteria toward well rehabilitation and the replacement decision-making process. Thus, this study provides a unique contribution to the available literature.

The following sections describe Cal Water's well system, along with the overall methodological derivation. The results of the research, along with a discussion of their practical implications, are then presented. The paper concludes with a series of observations, remarks, and suggestions.

BACKGROUND AND SYSTEM DESCRIPTION

As the largest subsidiary of the California Water Service Group, Cal Water provides high-quality regulated and non-regulated utility services to approximately 1.7 million people in 24 service areas across the state. The company's main service elements are the production, purchase, storage, treatment, testing, distribution, and sale of water for domestic, industrial, public, irrigation, and fire protection purposes (Keck & Lee 2015; Güngör-Demirci *et al.* 2018a, 2018b).

Groundwater is the sole source of water supply in eight Cal Water districts and a major source supplying approximately 70% of the water in three other districts. The groundwater system managed by Cal Water consists of 656 groundwater production wells, 420 of which are currently active. More than half of the active wells (51.2%) are now over 50 years old. There are a number of factors influencing the life expectancy of a well, such as geology and ambient groundwater quality, but in the water industry, it is commonly assumed that wells will have a useful life of around 50 years (Cal Water 2004; SSWD 2009). This suggests that many of Cal Water's active wells are on the cusp of their expected useful life. Some of Cal Water's wells are affected by additional concerns such as declining groundwater levels and a variety of water quality issues (Cal Water 2004). A data-driven, condition/performance-based tool that would assist in the development of optimized inspection and action plans for each well would therefore help Cal Water make these crucial decisions on a rational basis.

METHODOLOGY

The first step in this study was to compile available data on active wells from the company's files, then 'scrub' the resulting dataset based on missing entries and other inconsistencies. This overall process produced a 'clean' record for 334 active wells with sufficient data to be included in this study.

Next, BRE – the product of the likelihood of failure (LoF) and the consequence of failure (CoF) ($\mathrm{BRE} = \mathrm{LoF} \times \mathrm{CoF}$) – was determined by calculating LoF and CoF indices for each well. The LoF represents failure probability of a well, while the CoF represents the direct and indirect effects of such a failure or the loss of supply source. The analysis incorporated two different LoF indices in order to provide in-depth insights about the condition of each well. The criteria used to calculate the well-based LoF index ($\mathrm{LoF}_{\mathrm{well}}$) consisted of the well's specific capacity (SC), age, and water quality, while the pump's performance (electricity used per unit of water produced – energy density) was also taken into consideration for the well-and-pump-based LoF index ($\mathrm{LoF}_{\mathrm{well+pump}}$).

The CoF index was determined based on the maximum monthly water production and the number of critical connections estimated to be under the influence of a given well. For the purposes of this study, critical connections are defined to be schools, hospitals, medical centers, fire stations, police departments, day care centers, senior housing and retirement centers, hotels, and restaurants.

The subject weighting factors (i.e. relative importance measures) used to calculate each index were determined by consulting/surveying 11 experts in the field including Cal Water managers, supervisors, and staff along with the authors and applying the analytical hierarchy process (AHP). Including expert opinion in the BRE calculation ensured that appropriate expertise was included in the overall analysis, thus resulting in a better representation (or qualification) of real-life business and operating conditions. The framework of the methodology is presented in Figure 1.

LOF INDEX

The AHP, a multi-criteria decision-making technique for analyzing complicated problems (Saaty 1980), is a proven and widely used pairwise comparison and preference elicitation tool (Lee *et al.* 2009, 2013; Lee 2015; Güngör-Demirci *et al.* 2016). In this study, 11 experts were interviewed through a questionnaire to gather opinions on the relative importance of the various criteria affecting well failure or the determination of the end of well's useful life. The weights for each criterion were then determined by calculating normalized eigenvectors (Saaty 1980); these results are shown in Table 1.

Specific capacity

SC is defined as the pumping rate divided by the drawdown at some time after pumping began (Lohman 1972). This is one of the most common methods used by practitioners for determining and tracking the productivity of a well. For most of Cal Water's wells, SC data were available for

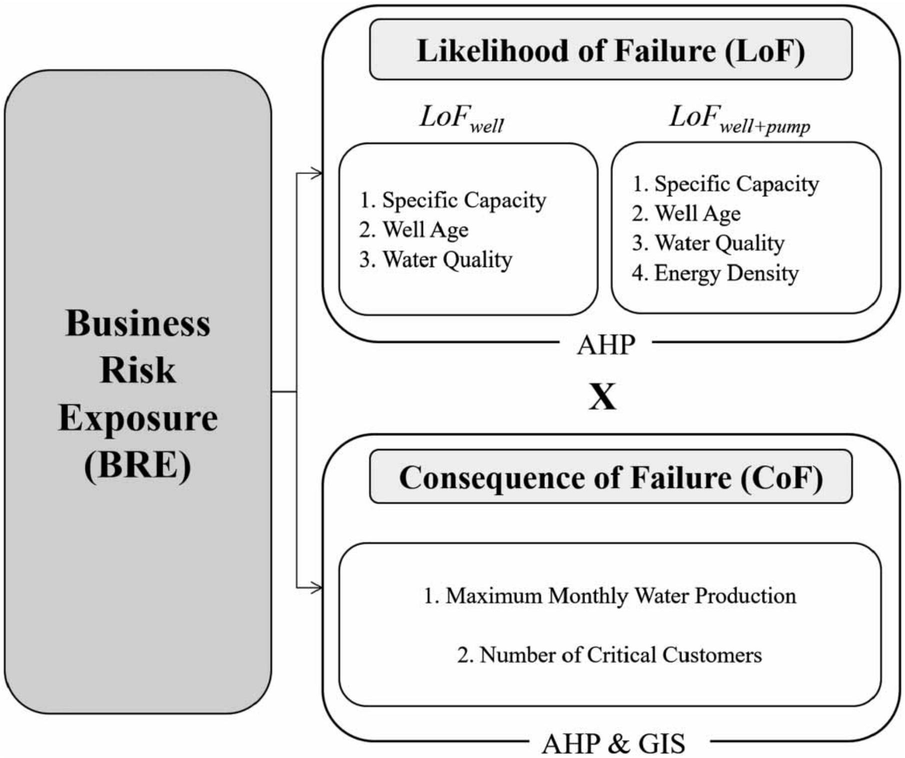


Figure 1 | General framework of the methodology used in this study.

Table 1 | Weights and scores applied for the LoF and CoF index calculations

	LoF index				CoF index	
Score	SC (–)	Age (years)	WQI (–)	Energy density (kWh/MG of pumped water)[a]	Maximum monthly water production (MG)[a]	Number of critical connections (–)
1	$0.80 < SC_{RATIO} \leq 1.00$	0–9	<50	<1,000	0–19.99	0–2
2	$0.60 < SC_{RATIO} \leq 0.80$	10–19	50–99.99	1,001–2,000	20–39.99	3–5
3	$0.40 < SC_{RATIO} \leq 0.60$	20–29	100–199.99	2,001–3,000	40–59.99	6–8
4	$0.20 < SC_{RATIO} \leq 0.40$	30–39	200–299.99	3,001–4,000	60–79.99	9–11
5	$0 < SC_{RATIO} \leq 0.20$	40+	≥300	>4,000	80+	12+
LoF_{well} AHP weights	*0.431*	*0.132*	*0.437*	–	*0.648*	*0.352*
$LoF_{well+pump}$ AHP weights	*0.347*	*0.117*	*0.369*	*0.167*	*0.648*	*0.352*

[a] 1 MG (Million Gallon) = 3,785.4 m^3.

Final AHP weight values are shown in italics.

the years 1989–2016. Before performing any further operations, the outliers were removed. The lower bound of the outliers was taken as zero, as negative values indicate an error in the data, and the upper bound was selected as 100 gpm/ft (20.70 (L/s)/m) based on discussions with Cal Water engineers and hydrogeologists. After removing the outliers, the maximum value among all the available data points was found (SC_{MAX}), and the average of the most recent five data points was calculated (SC_{RECENT}) for each well. The aim of calculating the average rather than taking a single data point was to reduce the effect of possible uncertainty in the data. The ratio of SC_{RECENT} to SC_{MAX}, labeled the SC_{RATIO}, was used to score the wells in terms of their SC. The wells were then classified into five categories based on their SC_{RATIO}, as shown in Table 1.

Well age

Well age can be a useful indirect indicator of the condition and the remaining useful life expectancy (ULE) of a well as it is reasonable to assume an older well will be in a poorer condition than a new well under similar conditions (SSWD 2009) and will have a potentially less ULE. A linear relationship was therefore assumed between age and the well condition as well as the ULE for this study, with the age being calculated as the time from the well installation until November 2017. The scores assigned based on the age of a well are shown in Table 1.

Water quality

For the well classification, a single water quality identifier that combines the effects of multiple contaminants was used (e.g., the Water Quality Index, or WQI). The WQI method, originally developed by Brown *et al.* (1970) for surface water, is one of the most commonly used methods for performing water quality assessments. The method is also adapted to groundwater by many researchers in the literature (e.g., Sadat-Noori *et al.* 2014; Zahedi *et al.* 2017). Therefore, the methodology of Brown *et al.* (1970) was adapted for the current study's purposes.

Although Cal Water regularly monitors groundwater quality for compliance with federal and state regulations for both primary and secondary contaminants, the data used to derive and exercise current WQI framework were based on the monitoring results of specific secondary contaminants, namely total dissolved solids (TDS), and chloride (Cl), iron (Fe), manganese (Mn), sodium (Na), and sulfate (SO_4) ions. In the literature, the contaminants selected for the WQI calculation depend on the availability of suitable data, resulting in different contaminant sets being used in different studies. The six contaminants provided by Cal Water for this study are those generally used in other WQI-based studies (Sadat-Noori *et al.* 2014; Zahedi *et al.* 2017). The current drinking water standards set by both the World Health Organization (WHO 2011) and the EPA (EPA 2018b) for these six contaminants are shown in

Table 2. Based on an examination of the data, the standards set by the EPA were complied with except for Na; the EPA has not yet established a standard for Na, so the WHO's standard was used instead.

In the WQI methodology, weights are assigned to each contaminant based on their relative importance for the water quality assessment. In this study, the weights were assigned based on a review of the available literature (e.g., Sadat-Noori *et al.* 2014; Zahedi *et al.* 2017) in conjunction with our expert judgement (Table 2). Because of the criticality of the available contaminants, all but Na were awarded the maximum weight of five. The relative weights were then calculated using the following equation and are given in Table 2

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{1}$$

where W_i is the relative weight of the contaminant, w_i is the weight of the contaminant, and n is the number of contaminants.

Next, the quality rating of each contaminant (q_i) was calculated using Equation (2), where the concentration of each contaminant (C_i) was divided by its associated standard value (S_i). The concentration of each contaminant (C_i) was obtained from Cal Water's most recent water quality measurement records

$$q_i = \frac{C_i}{S_i} \times 100 \tag{2}$$

The sub-quality index for each contaminant (SI_i) was then calculated by multiplying its relative weight (W_i) by its quality rating (q_i), as shown in the following equation:

$$\mathrm{SI}_i = q_i \times W_i \tag{3}$$

Finally, the WQI for each Cal Water well was computed by summing all the sub-quality indices, as defined in the following equation:

$$\mathrm{WQI} = \sum_{i=1}^{n} \mathrm{SI}_i \tag{4}$$

The water quality could then be classified into categories according to the computed WQI, as shown in Table 1.

It is important to note that the present WQI framework is purely based on secondary contaminants, which may ultimately underestimate the true business risk (by virtue of underestimating the LoF). More specifically, true water quality-based operational and management decisions will be framed around primary constituents in a vast number of cases. This arises from the highly regulatory nature of water quality, including considerations that even flow down to operational state classifications for specific wells defined by the State of California, e.g., standby or inactive. Overall, internal (business) or external (regulatory) mandates to shut down wells or implement treatment based on primary constituents (as compared to secondary constituents) will generally have the effect of increasing the LoF, thus leading to a larger associated BRE measure (for a given CoF). A general acknowledgement of this overall landscape (relationships) is paramount relative to interpreting the results of this current framework, as well as for future

Table 2 | Standards, weights and relative weights for each water quality parameter

Contaminant	WHO standard (mg/L)[a]	EPA standard (mg/L)[b]	Standard used in the study (S_i)	Weight (w_i)	Relative weights (W_i)
TDS	600	500	500	5	0.1724
Cl	250	250	250	5	0.1724
Fe	0.3	0.3	0.3	5	0.1724
Mn	0.1	0.05	0.05	5	0.1724
Na	200	–	200	4	0.1379
SO_4	250	250	250	5	0.1724
				$\sum_{i=1}^{6} w_i = 29$	$\sum_{i=1}^{6} W_i = 1$

[a] No health-based guideline value is set for these parameters except Mn. For Mn, the health-based value is 0.4 mg/L.

[b] All standards presented here are secondary standards.

expansion of this BRE methodology to include more (primary) water quality constituents.

Energy density

The amount of electricity used per volume of water pumped (i.e. energy density) is a convenient measure of the efficiency of a pump (SSWD 2009) and was added as an extra criterion for the $\mathrm{LoF}_{\mathrm{well+pump}}$ calculations. Energy density values were computed based on data for the most recent year (12 months) of well operation. A pump with a lower energy density is clearly superior to the one with a higher energy density value, so the scoring metric used here assigned lower scores to wells with lower overall energy density (Table 1).

COF INDEX

Similar to the LoF index, the weighting factors used to calculate the CoF index were determined by interviewing Cal Water managers, supervisors, and staff as well as the authors and evaluating the results using the AHP.

Maximum monthly water production

The maximum monthly water production was taken as one proxy of the CoF given its overall linkage to a number of important system performance considerations, e.g., support for high demand periods, storage recovery, and fire flow. This is based on the general reasoning that the supply and customer service consequences of a failure will be comparatively more severe for a well providing large amounts of water than another well providing less water. Using a similar timeframe as above, the maximum value from the most recent year of water production data for each well was extracted for this criterion, and the assigned scores are shown in Table 1.

Number of critical connections

The number of critical connections was estimated using ArcGIS Version 10.4 (Esri 2016). The first step in this process was to establish a series of buffer regions around each well at distances of 152.4 m (=500 ft), 304.8 m (=1,000 ft), 457.2 m (=1,500 ft), 609.6 m (=2,000 ft), 914.4 m (=3,000 ft), and 1,524 m (=5,000 ft). Next, the number of connections of all types (i.e. critical and non-critical) for each buffer diameter was estimated within ArcGIS. After finding the average number of connections (of all types) for each buffer diameter, a regression analysis was performed to create the following model that links the average number of connections and the buffer diameter with an R^2 value of 0.9994.

$$C = 0.0049 \times D^{1.8717} \tag{5}$$

where C is the number of connections of all types and D is the buffer diameter (m). The available dataset contains the monthly pumping rate in gallons per minute (gpm) for each well. The maximum pumping rate for each well during the most recent 12 months was found and the number of connections served by each well was estimated based on the assumption that each connection used 5.45 $\mathrm{m^3/day}$ (=1 gpm) water (i.e. 1 gpm = 1 connection). The buffer distance representing the service area for each well could then be estimated using the following equation. Data about the locations of the premises in all Cal Water's districts were obtained, and the number of critical connections (i.e. schools, hospitals, medical centers, fire stations, police departments, day care centers, senior housing and retirement centers, hotels, and restaurants) could then be estimated. The scores resulting from this exercise are presented in Table 1.

The authors are aware that the above-described methodology involves a simplified assumption that a customer who is proximal to a well is served water from that well. A future enhancement of this determination (derivation of source contribution footprints or boundaries) would make use of source tracing techniques within a water distribution system model (e.g., EPANET). Such an approach would yield more system-specific results that are also more faithful to numerous physical, hydraulic, and operational nuances captured by the network model (e.g., actual customer demand allocation and timing, network topology and transmissivity, and control scheme influence).

CALCULATION OF LOF AND COF INDICES

After assigning scores for each of the above-mentioned criteria, the LoF_{well}, $\text{LoF}_{\text{well+pump}}$, and CoF indices were calculated using the weights previously determined for each criterion as follows:

$$\text{LoF}_{\text{well},j} = (0.431 \times \text{SC}_j) + (0.132 \times A_j) + (0.437 \times \text{WQI}_j) \tag{6}$$

$$\text{LoF}_{\text{well+pump},j} = (0.347 \times \text{SC}_j) + (0.117 \times A_j) + (0.369 \times \text{WQI}_j) + (0.167 \times \text{ED}_j) \tag{7}$$

$$\text{CoF}_j = (0.648 \times \text{WP}_j) + (0.352 \times \text{CC}_j) \tag{8}$$

where j is the well number, SC_j the SC score for well j, A_j the age score for well j, WQI_j the WQI score for well j, ED_j the energy density score for well j, WP_j the maximum monthly water production score for well j, and CC_j the score for the number of critical connections for well j. After calculating each index, they were classified into their final forms in order to construct the BRE map. The classification was based on a form of 'center rounding' of the decimal places to accurately locate each (LoF, CoF) coordinate (cell) within the BRE matrix, while simultaneously not being too conservative by the use of the following equations:

$$\text{LoF}_{\text{well\_final},j} = \text{INTEGER}\ (\text{LoF}_{\text{well},j} + 0.5) \tag{9}$$

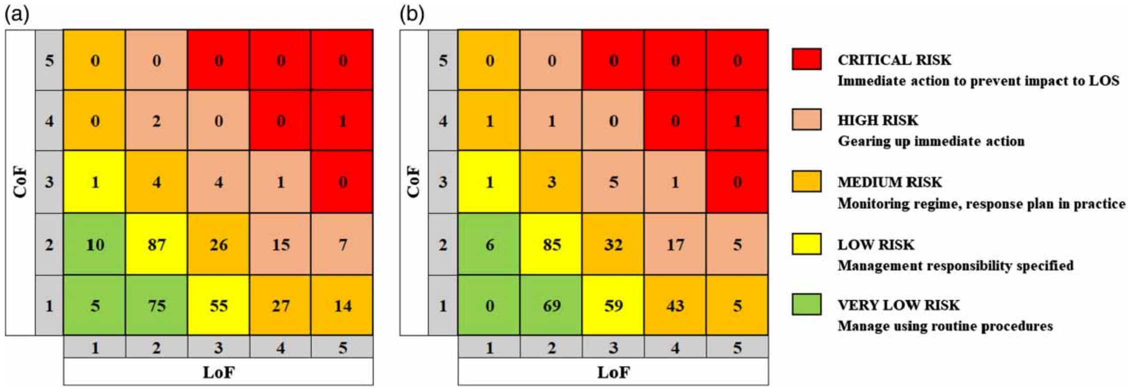
$$\text{LoF}_{\text{well+pump\_final},j} = \text{INTEGER}\ (\text{LoF}_{\text{well+pump},j} + 0.5) \tag{10}$$

$$\text{CoF}_{\text{final},j} = \text{INTEGER}\ (\text{CoF}_j + 0.5) \tag{11}$$

RESULTS AND DISCUSSION

The final LoF_{well} and CoF indices (i.e. $\text{LoF}_{\text{well\_final}}$ and $\text{CoF}_{\text{final}}$) were calculated and plotted for all 334 of the active wells for which data were available, leading to the BRE map shown in Figure 2(a). If only well conditions are considered, namely LoF_{well}, only a single well falls into the critical risk region requiring an immediate corrective action to avert any potential adverse impact on the level of service provided. This well falls into the intolerable risk region and should be urgently considered for rehabilitation and replacement. Twenty-nine wells are in the high-risk region where the utility should conduct aggressive monitoring and plan for an immediate action. A further 71 wells (21%) are in the medium-risk region, where a program of routine monitoring and inspections and a response plan should be in place. The majority of the wells, 143 wells (43%), are in the low-risk region, where management responsibility should be specified, but a more relaxed management posture relative to rehabilitation and replacement is (comparatively) warranted. The wells in this region should be monitored regularly to capture relevant data for future use. Lastly, 90 wells (27%) are in the very low-risk region and can be safely managed with only routine inspections.

When the pump performance was incorporated (Figure 2(b)), the analysis revealed that – once again – a single well was located in the critical risk region, while the number of wells in the high-risk region was 29. The medium-risk region consisted of 84 wells. As shown in Figure 2(a), the majority of the wells (in this case, 145



(a)

CoF \ LoF	1	2	3	4	5
5	0	0	0	0	0
4	0	2	0	0	1
3	1	4	4	1	0
2	10	87	26	15	7
1	5	75	55	27	14

(b)

CoF \ LoF	1	2	3	4	5
5	0	0	0	0	0
4	1	1	0	0	1
3	1	3	5	1	0
2	6	85	32	17	5
1	0	69	59	43	5

Figure 2 | BRE map based on (a) $\text{LoF}_{\text{well\_final}}$ and $\text{CoF}_{\text{final}}$ indices, (b) $\text{LoF}_{\text{well+pump\_final}}$ and $\text{CoF}_{\text{final}}$ indices.

wells (43%)) were situated in the low-risk region, while 75 wells (22%) were in the very low-risk region. These results indicate that the addition of the pump criterion decreased the total number of wells in the low- and very low-risk regions and shifted 13 wells to the medium-risk region from low- and very low-risk regions.

CONCLUSIONS

In this study, a business risk-based prioritization tool was developed to support Cal Water's well inspection, rehabilitation, and replacement decisions. The BRE methodology, combined with the AHP, was used to rank the wells and identify those requiring a higher priority for rehabilitation and replacement. Two different approaches to calculate LoF indices were applied, and the results showed slight variations between these two approaches. These results showed that although the overall risk of Cal Water's wells is low, with a majority of the wells being classified as low risk, the company still requires aggressive monitoring and maintenance. A total of 30 wells were assessed as having a high (29 wells) or critical risk (one well); thus, they need urgent attention.

For rehabilitation and replacement, Cal Water should first target the wells assessed as having a critical or high business risk. The wells under medium and low risk should continue to be aggressively monitored, and a well-structured management plan should be in place as soon as possible, as the BRE factors of these wells tend to increase with increasing well age and decreasing SC. This type of risk-based prioritization scheme provides a rational guide for inspection and rehabilitation efforts, taking into account financial constraints. The information collected during the early inspections will provide a valuable baseline for later efforts to optimize ongoing inspections and rehabilitation and replacement schedules.

A formalized and effective risk management methodology will help Cal Water (or any water retailer company for that matter) improve the decision-making process by balancing the level and the cost of the service provided, thus making best use of the available resources. This study should be considered a key ingredient in Cal Water's well asset management program. In addition, this is not intended to be a one-time analysis, but is expected to be ongoing, with the rankings being regularly updated through the use of the company's Enterprise Asset Management tools along with monitoring and assessing new and additional information.

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