Economics of alternative water resources with an emphasis on aquifer storage and recovery
Jae-ho Choi, Miroslaw Skibniewski and Young-Gyoo Shim

ABSTRACT
This paper demonstrates a comprehensive methodology for assessing the comparison of unit water production cost (UWPC) between alternative water resources including desalination, freshwater reservoirs, single-purpose dams, underground dams and two indirect water in take technologies – riverbank filtration and aquifer storage and recovery (ASR). This study considers the Monte Carlo simulation as the only viable solution to tackle this critical question, which can be used to evaluate the economics of diverse water supply schemes incorporating those alternatives and prepare long-term water supply planning. Built upon actual and conceptual cost data for each alternative, total project cost and operation and management cost estimation models for each alternative were developed and used for generating mean UWPC information using the Monte Carlo simulation approach. The mean UWPC differences between alternative water supply schemes were found to be statistically significant and the simulation results revealed that ASR is the lowest-cost option to provide drinkable water for both cases when a conventional water treatment plant (WTP) and advanced WTP were used as a connected post-treatment process.

Key words | aquifer storage and recovery, economics, Monte Carlo, unit water production cost, water resource

INTRODUCTION
Alternative water resources are usually perceived as new water supply methods, particularly in islands and mountainous areas, where the direct in take of water through conventional methods such as dams, surface water, and direct use of groundwater is difficult to adopt (Park 2011). Despite no clear definition of alternative water resources, desalination (DES), underground dams (UGDs), and riverbank filtration (RBF) are classified as alternative water resource projects because they can secure water sources, increase the cost effectiveness of producing water, and meet other site-specific purposes (K-water 2013a). Another alternative method that is now gaining greater attention as a new source of water and under investigation in several countries including Korea, China, Qatar, and a few more Middle Eastern countries is aquifer storage and recovery (ASR). The escalating costs and environmental challenges of conventional water supplies that use mostly surface water have encouraged water professionals to explore ASR. ASR was defined by Pyne (1995) as ‘the storage of water in a suitable aquifer through a well during times when water is available, and recovery of the water from the same well during times when it is needed.’ The vadose zone plays a filtering, absorbing, and biologically mediated reacting role in removing or reducing the concentrations of suspended...
solids, biodegradable organic matter, nutrients, metals, and pathogenic microorganisms. The beneficial uses of ASR for coping with various water-related issues, such as securing drinking water resources, preparing water resources for disaster, preventing jurisdictional water disputes, preventing seawater intrusion in coastal regions, and so forth, are gradually being recognized throughout the world. More than 134 ASR well-fields (over 544 ASR wells) are operational in 22 states in the USA, and other countries, including England, Australia, The Netherlands, Namibia, South Africa, United Arab Emirates, India, Canada, and Israel, have either experimental or operational well-fields (Bloetscher et al. 2014; Pyne 2014).

The principal reason for the increased interest in ASR technology from many countries in the last decade can be attributed to its cost effectiveness. In almost all situations where the need exists for alternative or supplemental water supplies, ASR wells can provide this water at less than half the capital cost of alternative water sources. The operating costs are not well known but are believed to be similar to, and perhaps slightly higher than, typical production well-field operating costs (Pyne 2014). However, Maliva (2014) questioned the lesser degree of its adoption in the market and attributed the reason to a lack of sound economic cases for decision makers such as utility managers, water management agency officials, and political leaders.

In 2013, a 5-year-long national research project to develop technology packages for the practical use of large-scale ASR was funded by Korea’s Ministry of Land, Infrastructure, and Transport (Choi et al. 2015). One of the most sensitive and critical aspects of this project, particularly its market adoption, is its cost. This study serves to provide the economics of a drinkable water supply scheme using ASR by comparing its unit water production cost (UWPC) to those of other schemes using different water resources (hereinafter ‘alternatives’) such as RBF, freshwater reservoir (FWR), single-purpose dam (SPD), UGD, and DES. FWR and SPD are mainly used for drinkable water production purposes in Korea. The UWPCs of a water supply scheme using an alternative water resource project reflect all the capital and operation and management (O&M) costs from constructing and operating alternatives, in take facility, water transmission pipeline, and post-water-treatment utility. Therefore, building a thorough understanding of the water supply project schemes, water treatment processes, construction methods, and work scopes of an alternative water resource project is desirable to form the same baseline for the UWPC determination.

Previous studies (K-water 2005; Carollo Engineers 2006; CDM 2007) that investigated the economics of alternative water supply systems have either used cost opinion information or focused on one specific alternative of interest, which was compared with a few other conventional water supply methods. Collectively, most of the related studies used cost opinions with a wide range of accuracy and focused on deterministic UWPC calculation, while no studies have examined the uncertainties and wide ranges of variables that affect the UWPC. Given the inherent uncertainty of input variables and estimates of UWPC, the only way to compare the UWPCs between alternatives is through the means of cost uncertainty analyses that are based on Monte Carlo simulation including the Latin hypercube sampling method (hereinafter ‘MCS’). In this regard, the major contribution of this study is a direct comparison of UWPCs between water supply schemes with different alternatives based on actual as-designed and as-built project cost data by using statistical simulation.

**METHODS**

The objective can be achieved by a four-step procedure based on an extensive compilation of total project costs (TPCs) and O&M costs in relation to the various water resources and water treatment projects in the context of Korea as follows. Step (1): identify alternative water supply schemes consisting of alternative water resource projects such as DES, SPD, FWR, UGD, RBF, and ASR, and post-water-treatment utilities such as conventional water treatment plant (WTP) and advanced WTP (hereinafter ‘AWTP’), and collect their TPC and O&M costs based on real project documents and conceptual feasibility reports.

Step (2): develop TPC and O&M estimation models for each alternative by using regression analysis with a single independent variable (water development capacity, m³/d). TPC estimation and O&M estimation models for conventional and advanced WTPs were also developed. Step (3):
set up variables that influence the UWPC estimation of different water supply schemes using each alternative as source water by using MCS, including the interest rate, service life, pipeline extension, pavement material cost, and post-treatment utility types. Step (4): compare UWPCs among these alternative water supply schemes by using different variable conditions, followed by a series of statistical methods to validate the mean difference between any pair of the schemes and the overall assessment of the comparison results.

**Database compilation for UWPC estimation**

All the alternatives produce source water that is transported to a standard WTP or an AWTP except DES, which mostly uses a simplified post-treatment process. The authors compiled all the data required for determining UWPC for each alternative water supply scheme by using real as-design and as-constructed project data and references (K-water 2005, 2013b; Lee 2013; Moon et al. 2010). Since ASR has not yet been implemented in Korea, cost information for a total of 11 ASR well-fields and four ASR O&M cost data reported by CDM (2007) were examined and applied for this study. This study only used four cases in which the aquifer was recharged with either the treated surface water or partly treated surface water, and the recovered water from the aquifer was used for public water systems.

**Figure 1** shows detailed information on the number of projects (4, 86, 17, 3, 18, 19 in the order of items on the X-axis) and the relative distributions of the capacity ranges and TPCs. The numbers of alternatives were not evenly distributed, and the capacity ranges and TPCs varied between alternatives. The largest proportion belonged to DES, followed by UGD, SPD, FWR, ASR, and RBF. The medians of DES and FWR in terms of the capacity range were much lower, whereas the medians of all the alternatives in terms of the TPC were not much different, except for SPD. These results imply that DES and FWR were planned and operated on relatively smaller scales, while SPDs demanded higher project costs. The base time-point for comparing the UWPCs between various water supply schemes using the selected alternatives was set to August 2006, which was

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![Figure 1](https://iwaponline.com/ws/article-pdf/18/2/612/206678/ws018020612.pdf)  
*Figure 1* | Box-and-whisker plots of alternatives: (a) Y = water intake capacity, m$^3$/d; (b) Y = TPC, 1,000 USD.
the date for the four ASR project cost data. The exchange rate (950) between the Korean currency unit ‘won’ and the US ‘dollar’ in August 2006 was used to convert dollar values into won values. The Construction Cost Index (CCI) from the water and sewage civil project that was published in Korea was used to adjust cost data to the same time-point (i.e., August 2006).

**TPC estimation and O&M cost estimation models**

TPC estimation models for each alternative were developed based on the compiled dataset from the previous section, as shown in Table 1. Each model produced a TPC for August 2006 and could be used only within the capacity range in the last column, from which the models were developed. The goal of this study is to determine the unit cost of producing drinking water that is treated by either conventional WTP or AWTP that sources water from an alternative, so the TPC models of the WTP and the AWTP are also required for the UWPC calculation. Cost data for a total of 25 rapid sand filter WTPs were compiled to develop a reliable TPC model (Equation (1)) by using regression analysis. Other types of WTPs that use slow sand filters and membranes were not considered because their numbers were very limited; in particular, they have been used on much smaller scales below 15,000 m$^3$/d development rates. In addition, most FWR, UGD, and SPD projects in our data were highly associated with rapid sand filter WTPs.

Total annual O&M cost estimation models for each alternative were based on O&M cost data from real projects or O&M cost determination criteria (K-water 2005; KDI 2012), as shown in Table 1. Annual ASR O&M costs were based on two real project data that were provided by CDM (2007), which explains why $R^2$ equals 1. The annual O&M costs of each alternative water supply scheme using FWR, UGD, and SPD are assumed to be a combination of the O&M cost of each alternative resource infrastructure and the O&M cost of the following conventional WTP. The annual total O&M cost, for example, of a WTP that used FWR as its primary source of water was the combination of $y_{WTP}$ and $y_{AWTP}$. This study also assumed that the annual O&M costs of UGD and SPD are 0.5% of the construction cost according to the guideline published by the Ministry of Construction and Transportation (MOCT 2006), while FWRs were set to 0.3% because this alternative has fewer ancillary structures than UGD and SPD. The annual O&M cost estimation model (i.e. $y_{WTP}$) of a conventional WTP that sources water from alternatives was developed based on 26 real project O&M cost data by using regression analysis (Equation (2)).

### Factors that affect the UWPC modelling

Once the TPC and annual O&M cost estimation models of each alternative and the TPC and O&M cost estimation models of WTPs were prepared, we could determine reasonable and commonly accepted values of factors that affect the

<table>
<thead>
<tr>
<th>Model</th>
<th>Alternatives</th>
<th>Linear regression model</th>
<th>Coefficient of determination (%)</th>
<th>Capacity range model applicable (m$^3$/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TPC estimation model</strong></td>
<td>FWR</td>
<td>$Y_{FWR} = 5,338.7 \times x + 7,243.3$</td>
<td>88.2</td>
<td>200–15,000</td>
</tr>
<tr>
<td></td>
<td>UGD</td>
<td>$Y_{UGD} = 6,596.9 \times x^{0.4868}$</td>
<td>88</td>
<td>50–77,000</td>
</tr>
<tr>
<td></td>
<td>SPD</td>
<td>$Y_{SPD} = 9,819.2 \times x^{0.7319}$</td>
<td>91.5</td>
<td>4,000–220,000</td>
</tr>
<tr>
<td></td>
<td>DES</td>
<td>$Y_{DES} = 5,054.6 \times x^{0.7434}$</td>
<td>99.7</td>
<td>1,100–50,000</td>
</tr>
<tr>
<td></td>
<td>RBF</td>
<td>$Y_{RBF} = 66,079 \times \ln(x) – 193,705$</td>
<td>100</td>
<td>20,000–60,000</td>
</tr>
<tr>
<td></td>
<td>ASR</td>
<td>$Y_{ASR} = 5,750.3 \times \ln(x) – 12,775$</td>
<td>83.2</td>
<td>10,000–45,000</td>
</tr>
<tr>
<td><strong>O&amp;M estimation model</strong></td>
<td>FWR</td>
<td>$Y_{FWR} = \text{Construction Cost} \times 0.3(%)$</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>UGD</td>
<td>$Y_{UGD} = \text{Construction Cost} \times 0.5(%)$</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>SPD</td>
<td>$Y_{SPD} = \text{Construction Cost} \times 0.5(%)$</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>DES</td>
<td>$Y_{DES} = 2,348.6 \times \ln(x) – 135.77$</td>
<td>88.2</td>
<td>1,100–50,000</td>
</tr>
<tr>
<td></td>
<td>RBF</td>
<td>$Y_{RBF} = 744.77 \times \ln(x) – 1,577.3$</td>
<td>99.9</td>
<td>20,000–60,000</td>
</tr>
<tr>
<td></td>
<td>ASR</td>
<td>$Y_{ASR} = 2,201.6 \times \ln(x) – 7208.5$</td>
<td>100</td>
<td>38,000–45,000</td>
</tr>
</tbody>
</table>

*x unit: 1,000 m$^3$/d, y unit: 1,000 USD (August 2006).*
UWPCs of various water supply schemes that incorporate each alternative. We subdivided the input factors into four groups – economic, construction, operation and utility system parameter groups – as shown in Table 2. MCS was utilized to accommodate the probabilistic distributions of input factors and different water supply schemes to mimic the real data conditions. Economic factors consider the time value when determining the equivalent uniform annualized cost (EUAC), which is defined by the cost per year of owning and operating an asset over its entire life-span. In particular, the EUAC is more effective to decision makers because organizations typically report their annual activities and need to compare alternatives with unequal lifespans with greater computational efficiency (Jones & Smith 1982).

\[ Y_{\text{WTP}} = 3648.5 \times x^{0.6375}, \quad R^2 = 95.5 \% \]

where

\[ x \text{ unit: 1,000 m}^3/\text{day (applicable development range: 1,000-1,000,000 m}^3/\text{d}), \]
\[ y \text{ unit: 1,000 USD (August 2006)}. \]

\[ Y_{\text{WTP}} = -0.0072 \times x^2 + 15.693 \times x + 141.44, \]
\[ R^2 = 98.5 \%(\text{2}) \]

where

\[ x \text{ unit: 1,000 m}^3/\text{day (applicable development range: 1,000-1,000,000 m}^3/\text{d}), \]
\[ y \text{ unit: 1,000 USD (August 2006)}. \]

This study applied the EUAC method to compare the cost effectiveness between different water supply schemes utilizing different water resource alternatives. The total EUAC of a water supply scheme is the sum of the EUAC of all the infrastructures comprising the water supply scheme including an alternative, transmission pipeline,

<table>
<thead>
<tr>
<th>Category</th>
<th>Factors</th>
<th>Mean</th>
<th>Std</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic parameter</td>
<td>Interest rate</td>
<td>6 (%)</td>
<td>0.5 (%)</td>
<td>KDI (2012)</td>
</tr>
<tr>
<td></td>
<td>Service life</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FWR</td>
<td>70 (years)</td>
<td>7 (years)</td>
<td>K-water (2012)</td>
</tr>
<tr>
<td></td>
<td>UGD</td>
<td>50 (years)</td>
<td>5 (years)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SPD</td>
<td>50 (years)</td>
<td>5 (years)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DES</td>
<td>20 (years)</td>
<td>2 (years)</td>
<td>MOCT (2006)</td>
</tr>
<tr>
<td></td>
<td>RBF</td>
<td>42.5 (years)</td>
<td>2.5 (years)</td>
<td>(45 years, KDI (2012)),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(40 years, Gapyeong Project)</td>
</tr>
<tr>
<td></td>
<td>ASR</td>
<td>40 (years)</td>
<td>4 (years)</td>
<td>Expert opinion</td>
</tr>
<tr>
<td></td>
<td>WTP</td>
<td>30 (years)</td>
<td>3 (years)</td>
<td>MOCT (2006)</td>
</tr>
<tr>
<td>Construction parameter</td>
<td>Water transmission pipeline extension</td>
<td>6.777 (km)</td>
<td>4.913 (km)</td>
<td>Various basic design report analyses</td>
</tr>
<tr>
<td></td>
<td>Unit construction cost for the pipeline(^a)</td>
<td>474.91 USD</td>
<td>94.17 USD</td>
<td>MOE (2015)</td>
</tr>
<tr>
<td></td>
<td>Unit material cost for the pipeline(^b)</td>
<td>500.94 USD</td>
<td>50.09 USD</td>
<td>MOE (2015)</td>
</tr>
<tr>
<td>Operation parameter</td>
<td>Advanced water treatment O&amp;M increase</td>
<td>6.15%</td>
<td>0.7%</td>
<td>MOE (2004) and related assumptions</td>
</tr>
<tr>
<td></td>
<td>Alternatives</td>
<td>Deterministic mean</td>
<td>MOCT (2006)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FWR</td>
<td>0.3 (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>UGD</td>
<td>0.5 (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SPD</td>
<td>0.5 (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Utility system parameter</td>
<td>Alternatives</td>
<td>Connected water treatment options</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FWR, UGD, SPD</td>
<td>Conventional WTP(^c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DES</td>
<td>Simplified post-treatment</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>RBF</td>
<td>1. Conventional WTP</td>
<td>2. Advanced WTP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASR</td>
<td>1. Conventional WTP</td>
<td>2. Advanced WTP</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Average and standard deviation based on three pavement types: asphalt, concrete, soil.

\(^b\)Steel pipeline (900 mm), topsoil depth: 1.5 m.

\(^c\)Rapid sand filter WTP.
and WTP, and the sum of the annual O&M cost of the infra-
structures. The construction parameter is related to the
material type and extension of water transmission pipelines
and the pavement type. This study used the cost information
from the research report (MOE 2018) in relation to materials
and construction of the pipeline, which are classified by
pavement type (i.e., soil, asphalt, concrete). The operation
parameter determines the O&M cost of each alternative.
Finally, the utility system parameter is related to the quality
of the source water and integration of alternatives into the
following water utility.

Post-water-treatment utility selection

The selection of a post-water-treatment utility for the two
representative indirect alternatives, RBF and ASR, are subject
to changes according to the amount, the location, and particu-
larly the quality of the source in take water. Determining the
UWPCs of water supply schemes that use these alternatives
therefore must reflect added project cost components and
O&M cost variations depending on the type of connected
post-water-treatment utility. The post-water-treatment utility
of the three RBF projects that were used to build our esti-
mation models used advanced water treatment processes.
Most of the advanced water treatment processes are added
to conventional WTPs, thus increasing capital and O&M
costs. This study analysed a total of 18 AWTP expansion pro-
jects, in which four cases added the powdered activated
carbon process, eight cases added the post-ozone and biologi-
cally activated carbon (BAC) processes, and the rest added
pre- and post-ozone and BAC processes to the conventional
water treatment processes. This study selected the project
expansion cost models that were built based on the first
four cases by using regression analysis because the cost
model was only applicable to the capacity range of interest
in this study, as shown in Equation (3).

\[
y_{\text{AWTP}} = 1381.3 \times x^{0.582}, \quad R^2 = 88.4 \% \quad (3)
\]

where

- \( x \) unit: 1,000 m\(^3\)/day (applicable development range: 28,000–85,000 m\(^3\)/d),
- \( y \) unit: 1,000 USD (August 2006).

RESULTS AND DISCUSSION

MCS was conducted to simulate real data conditions and
determine the means of UWPCs for each alternative based
on probabilistic and deterministic input variables. MCS
first needs to set up variables that influence the UWPC esti-
mation of different water supply schemes using each alterna-
tive as source water, including the interest rate, service
life, pipeline extension, pavement material cost, and
post-treatment utility types. Each variable is assumed to
follow a Gaussian distribution, and every random value is
generated through the Latin hypercube sampling. Figure 2
is the plot of the means of 10,000 simulations for different
water supply schemes using each alternative. This study
also performed two simulations by setting the post-water-
treatment utility of RBF and ASR to option 1 (conventional
WTP) and option 2 (AWTP), respectively. The other
alternatives are linked only to conventional WTPs, whereas DES was connected to the simplified post-treatment option. 

Figure 2 shows the simulated UWPC means of each alternative from the first MCS with 10,000 iterations over the water development capacity. Conventional water treatment processes were used for RBF and ASR in this simulation, and the UWPCs for each alternative were valid and drawn only within the capacity range, from which the O&M cost estimation models were developed.

All the UWPCs and the differences in the means between alternatives became smaller as the water development capacity increased as seen in Figure 2. The overall trends of the UWPCs are divided into higher UWPC alternatives and lower UWPC alternatives with a dark dotted line. Some points exist where the UWPCs of two different alternatives overlap (i.e., ⓐ–ⓑ), and the largest numbers of these alternatives including ASR can be compared (i.e., ⓒ). The first section, which has a development capacity of 1,000 m$^3$/d–5,000 m$^3$/d, illustrates that the lowest-cost alternative (i.e., DES) at 1,000 m$^3$/d becomes the highest-cost option at 5,000 m$^3$/d. The relative UWPC ranking orders from the 5,000 m$^3$/d and 15,000 m$^3$/d points until where the UWPCs of FWRs are available are DES, SPD, FWR, and UGD in descending order, although the UWPCs between SPD and FWR at point ⓒ are difficult to discern.

Before and after point ⓐ, where RBF and UGD have similar UWPCs, their relative orders are reversed and the UWPC of RBF becomes higher than that of UGD because the RBF cost estimation model was developed based on the low-cost vertical well option, which is usually used with lower development capacities (e.g., 20,000 m$^3$/d), and the high-cost collection well option, which is usually required for higher development capacities (e.g., 60,000 m$^3$/d). The relative
UWPC ranking in descending order from 40,000 to 45,000 m³/d was DES, SPD, RBF, UGD, and ASR although the mean differences between alternatives could not be statistically proven. At point Ⓝ, similar to points ⓐ and ⓑ, the mean difference between two alternatives (i.e., DES and SPD) was also very close and thus needed to be validated with statistical follow-up procedures.

The recommended approach to find statistical mean differences between more than two groups (i.e., alternatives) is to use analysis of variance, or ANOVA. This approach tests all the means simultaneously while considering within-group variability to determine whether at least one reliable difference exists between any of the group means or a linear combination of group means in the set of means. However, this method requires follow-up procedures, which are called multiple comparisons, to precisely pinpoint sources of significant differences (Carlberg 2015). Point Ⓞ was tested to determine whether any significant difference existed between the mean values for both cases: CASE 1 had a difference at 40,000 m³/d with a conventional water treatment utility, and CASE 2 had a difference at 45,000 m³/d with an advanced water treatment utility. Figure 3 shows the probability density results from the MCS for both cases. DES shows a narrower density distribution because no water transmission pipelines and connected water treatment utilities were present.

One well-regarded multiple comparison procedure for controlling Type I error, or the incorrect rejection of a true null hypothesis, is Bonferroni’s adjustment. The Bonferroni adjustment is often considered to be overly conservative because this method simply divides the Type I error rate (0.05) by the number of tests (15 for 40,000 m³/d, 10 for 45,000 m³/d). Table 3 shows the pairwise T-test comparison with the Bonferroni adjustment for both cases (i.e., CASE 1 and CASE 2) indicating that all the comparison pairs appear to be significantly different and the UWPCs of alternative water supply schemes at 45,000 m³/d were, in descending order, DES, SPD, RBF, UGD, and ASR. For conventional water treatment utilities that were connected to RBF, the p-values at points ⓐ, ⓑ, and Ⓝ were 0, 0.00046 and 0, respectively, which all indicate a significant difference in the mean values for those pairs of alternatives at a significance level of 0.01.
CONCLUSIONS

The MCS results practically demonstrate that DES, SPD, and FWR are considered higher UWPC alternatives, whereas UGD, RBF, and ASR are considered lower UWPC alternatives. DES costs less than FWR and UGD at a development capacity of 1,000 m$^3$/d but is the most expensive alternative over all the development capacities mainly because of higher O&M costs. FWR is the best option for lower development capacities from 5,000 to 15,000 m$^3$/d among the higher UWPC alternatives. RBF is a highly competitive option at relatively small water development capacities; for instance, RBF is the cheapest option at 20,000 m$^3$/d, but its position is overtaken by UGD over 25,000 m$^3$/d.

However, these findings must be carefully adjusted and used in reality by considering the availability, quality, and recovery capacity of injected source water into an aquifer and by projecting the outer environment, such as the availability of a nearby WTP and transmission pipeline extension. As was indicated by two articles written by Bloetscher et al. (2014) and Pyne (2014), ASR projects have a higher operational risk mainly due to clogging issues resulting in an earlier closure of operation wells than planned. If the risk of failure in satisfying the life expectancy of ASR is reflected in the UWPC simulation, the statistical result could be changed. It also needs to address the limitation of applying the findings produced in the previous section because the results are based on a limited number of projects, particularly related to ASR and RBF. For a complete uncertainty analysis of UWPC estimation for the alternatives, not only the variabilities of the input factors summarized in Table 2, but also the types and confidence levels of the developed regression models need to be considered in a hybrid approach combining both sensitivity analysis and Monte Carlo analysis for a future research direction. Considering the level of water availability particularly for RBF in the simulation process may lead to a different result since RBF is highly dependent on river flow rates, which are susceptible to future climate change.

UWPC information that considers various input variables and water supply schemes could be used for policy or decision makers to swiftly measure the viability of selected water resource options in a specific project environment. Future studies should include incorporating the operational risk and water security issues into the UWPC simulation of alternative water supply systems and monetizing the benefits of ASR to conduct benefit–cost analyses.

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