Achieving cost-efficient diversification of water infrastructure system against uncertainty using modern portfolio theory

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ABSTRACT

Recent water-related disasters have shown that not all disrupted events are prevented with water infrastructure systems and current water systems are becoming more vulnerable to disruptions due to the high uncertainty of disrupted events. Many scholars in various fields suggest diversification in the system as a way to respond to the uncertainty. In the real world, however, it is difficult to maximize its use, especially with water infrastructure, due to high costs and incomplete assessment methods. Thus this study attempts to develop a method to quantify cost-effectiveness of diversification using a drought case study in Korea. Modern Portfolio Theory is used to find optimal combinations of water resources infrastructures in terms of diversification. First, expected return and risk of individual water resources for water supply are estimated. Then, expected return and risk of individual portfolios of the water resources are evaluated by varying their shares of 0 to 100%. Finally, non-inferior portfolios are identified and an optimal portfolio for an acceptable return or risk is selected as a solution. Consequently, a portfolio is selected as a desirable one to practically enhance diversification in water infrastructure systems against real world uncertainty in consideration of cost and budget.

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INTRODUCTION

Many countries suffer from water-related disasters, such as droughts and floods, of which frequency and intensity have increased since the last century. In particular, urban areas have become more vulnerable to the water-related disasters because of high concentrations of people, infrastructures and industrial activities. However, response actions, especially with water infrastructures, are difficult to be implemented due to high uncertainty from complicated impacts of various driving forces including climate change, population, economy, infrastructure, culture and policies (Quiggin 2008; Gallopín 2012). The conventional approaches that mostly focus on average or predictive estimates for water management without considering these uncertainties may yield more significant failures in

infrastructure systems and catastrophic consequences in urban communities when unexpected disrupted events occur. This is well supported by the concept of 'risk transference', which describes that inadequate response actions may make the system more vulnerable to a disruption that exceeds the expected, and transfer system risk to more catastrophic consequence (Etkin 1999). For example, a large dam as a water resource is designed and constructed to resist predicted future water scarcity and surrounding areas are accordingly developed. The potential damage will be, due to the development, much larger in case of a drought event, worse than the prediction. Moreover, due to climate change effects, significant changing trends in frequency, intensity, and variability of rainfall and increasing

extreme precipitation events have been investigated in worldwide urban areas (e.g. Brunetti et al. 2000; Sen Roy & Balling 2004; Fujibe et al. 2005; Groisman et al. 2005; Wang & Zhou 2005; Liuzzo & Freni 2015). The spatial and temporal pattern of the extreme precipitation changes has also been more complex and non-uniform (Manton et al. 2001). In this regard, the current water infrastructure systems under climate and hydrological conditions predicted in the past will face more risk and damage from climate-induced disasters, especially coupled with urban development (e.g. growing impervious surface and population) (Liuzzo & Freni 2015). As such, the rising trend of damage of such water-related disasters recently makes water engineers take the uncertainty into account more seriously in their engineering works.

In water management, there are a variety of uncertainty sources such as (1) inherent randomness and variability, (2) complicated and nonlinear behavior by complexity, (3) knowledge deficiency for system process, (4) incomplete models and incorrect parameters and (5) data error (Quiggin 2008; Wang & Huang 2015). Over the last few years, a variety of studies have been carried out dealing with uncertainties in water management. Wang & Huang (2015) developed a multi-level Taguchi-factorial two-stage stochastic programming (MTTSP) approach, which was improved by incorporating useful optimization methods such as Interval-parameter linear programming, two-stage stochastic programming and multi-level factorial design, for the analysis of parameter uncertainties and their interactions in optimization methods for water resources management. Wang et al. (2015) proposed a polynomial chaos ensemble hydrologic prediction system (PCEHPS) for analysis and quantification of parameter uncertainties of hydrologic models representing processes of water cycle. The PCEHPS provides more rapid and accurate analysis of parameter uncertainties of hydrologic models. Chang & Sayemuzzaman (2014) and Assumaning & Chang (2014) suggested the application of a stochastic data assimilation filtering method such as the Unscented Kalman Filter and Kalman Filter coupled with Monte Carlo sampling to subsurface contaminant transport models for improvement of the accuracy of groundwater contaminant prediction.

Meanwhile, scientific communities (e.g. Wilby et al. 2009) accept that technical advances, for example on prediction techniques and impact models, cannot completely eliminate uncertainties within several decades. Although climate change and its effects, which may largely affect urban water management, cannot be predicted with certainty, a variety of reports have shown consistent predictions on changing trends in climate and hydrological conditions. Thus, it is stressed that there is a need for more research focusing on reduction of current vulnerability or response and recovery to uncertain disturbances (Aerts et al. 2014). In this regard, many scholars in various fields (e.g. military, financial asset management, service system, energy security and urban management) have suggested diversification in a system to cope with unpredictable and variable impetus from surrounding environments (Bushey & Nissen 1999; Fabozzi et al. 2002; Godsiff 2010; Cohen et al. 2011; Mars et al. 2012). In reference to the unique role of 'keystone' species for ecosystem survival, Shin et al. (2011) suggested diversification of keystone infrastructure as an option to deal with the uncertainty. According to the previous research cited above, beneficial effects of diversification in a system are introduced as follows: (1) damaged part of a system can be partially compensated or replaced by others in the system; (2) resources mobilization can be improved to respond to a disruption; (3) combination of diversified options can create a variety of response actions and strategies to uncertain disturbances. In the field of cybernetics, it was quantitatively addressed that only variety in control forces can force down variety of the perturbations. This is the 'law of requisite variety' that is well known as 'only variety can destroy variety' (Ashby 1958). This all indicates that diversification can provide such variety to control various perturbations.

In the same context, diversification in water infrastructure systems is also necessary to resiliently cope with an uncertain environment in water management. Recent research related to water management (e.g. Beuhler 2006; Fane & Turner 2010; Aerts et al. 2014) also introduced the importance of diversification in response to uncertain surroundings. In the real world, however, it is difficult to cost-effectively utilize diversification of response options, especially with water infrastructure, due to the lack of quantification of uncertainty and high cost of construction. Thus, most of the current water infrastructure systems rely only on a limited number of response options, even if such

dynamic changes of surroundings as environmental conditions, climate change, urban development and policies increase the uncertainty imposed on them. The current infrastructure systems thus suffer from their incapability to deal with the sudden occurrence of unpredicted events. That is, despite various response options available, it is still a challenge to find an optimal set of the options against the high uncertainty of perturbation, especially within budget constraints of the real world. This indicates that diversification and cost should be considered together at the same time to deal with the uncertainty. Current evaluation methods such as benefit-cost analysis and probabilistic risk analysis have their own limits to deal with the challenge (Beuhler 2006; Aerts et al. 2014).

It is thus necessary to find an optimal and robust combination of response options to satisfy real world uncertain situations including budget and benefit. This can be considered as a selection problem where a combination of response options with infrastructures should be chosen such that investment returns are maximized under a given budget. In this study, the authors call it 'cost-efficient diversification'. In this regard, this study aims to develop a method to evaluate cost-efficient diversification and to quantitatively prove a hypothesis that under budget constraints it is more effective and applicable to carry out cost-efficient diversification of infrastructure systems, rather than simply to maximize diversification in a system with available response options. With an example of water infrastructure, this study will demonstrate that cost-efficient diversification can provide meaningful strategies to cope with future uncertainties in the real world.

With a drought case in Korea as an example, various combinations of response options in water supply are evaluated for cost-efficient diversification. For that, Modern Portfolio Theory (MPT) (Markowitz 1952) is adopted which is widely used for portfolio managers to develop investment strategies with various options against high uncertainty of finance and investment. The portfolio managers are primarily concerned about the development of combinations of assets in an investment portfolio to maximize return and to reduce the overall risk. The risk is defined as variation or standard deviation for average return. As such, this study organizes portfolios of water infrastructure options and analyzes them for a given acceptable risk. It then finds a portfolio of the largest return for the case study.

In this way, this study develops a method to obtain cost-efficient diversification of water infrastructure.

METHODS

Modern portfolio theory

MPT was established in the 1950s, mainly based on the work of Harry Markowitz (Markowitz 1952). The key concept of MPT is that a portfolio should not be constructed based on benefits of individual assets, but a combination of assets less correlated, i.e. more diversified. MPT describes quantitatively why a portfolio consisting of diversified assets works to reduce overall risk of investment and shows how different assets can be mixed in a portfolio with lower risk or higher return than that of the individual assets (Werners et al. 2011; Aerts et al. 2014). The key criteria for portfolio selection are expected return and risk on the portfolio. According to MPT (Elton et al. 2003), first expected return and risk on individual assets are established. The risk in MPT is statistically estimated by the variance or standard deviation since it is regarded as volatility, i.e. how much unfavorable return can be yielded or how much the outcomes differ from the expectation. The return is generally defined as 'the benefit associated with an investment'. Then, expected return and risk on a feasible portfolio are estimated along with shares (fractions of total investment) of the individual assets within the portfolio. Finally, an efficient set of assets in a portfolio is identified which generates the largest return for a given risk or lowest risk for a given return. The decision makers (investors) can select a portfolio among the efficient ones in accordance with risk and return preferences (Elton et al. 2003).

The expected return of an individual asset i can be estimated as follows:

$$\overline{R_i} = \sum_{k=1}^{n} p_{ik} R_{ik} \tag{1}$$

where $\overline{R_i}$ is the expected return on asset i, p_{ik} is the probability that the kth return on the asset i occurs, R_{ik} is the kth possible outcome for the return on asset i, and n is the total number of possible outcomes. The variance as risk of an individual asset i is calculated by:

$$\sigma_i^2 = \sum_{k=1}^{n} p_{ik}\left(R_{ik} - \overline{R_i}\right)^2 \qquad (2)$$

Instead of variance, when the returns above the expected return are regarded to be desirable, the semivariance which considers only deviations below the expected return can be used as another measure of risk. Accordingly, the standard deviation can be calculated as square root of the variance.

The expected return on a portfolio is a weighted average of the expected returns of the individual assets. Thus the expected return of a portfolio consisting of n assets is estimated as follows:

$$\overline{R_p} = \sum_{i=1}^{n} x_i \overline{R_i} \qquad (3)$$

where $\overline{R_p}$ is the expected return on a portfolio and x_i is the share or weighting of asset i in the portfolio. The x_i is a value between 0 and 1 and the sum of them is thus one. The variance as risk of a portfolio consisting of n assets can be evaluated as follows:

$$\sigma_p^2 = \sum_{i=1}^{n} x_i^2 \sigma_i^2 + \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} x_i x_j \sigma_{ij} \qquad (4)$$

where σ_p^2 is the portfolio variance, and σ_{ij} is the covariance between two assets i and j. The covariance shows how the returns of two assets move together and is calculated by:

$$\sigma_{ij} = \mathrm{E}\left\{\left(R_{ik} - \overline{R_i}\right)\left(R_{jk} - \overline{R_j}\right)\right\} \qquad (5)$$

If the returns of two assets move together or opposite to each other, the covariance between two assets is positive or negative, respectively. Instead of covariance, the correlation coefficient, which shows the same properties with the covariance but with a range from −1 to 1, can be used in Equation (4). The correlation coefficient ρ_{ij} between asset i and j is defined as follows:

$$\rho_{ij} = \frac{\sigma_{ij}}{\sigma_i \sigma_j} \qquad (6)$$

When the returns of two assets are perfectly positively or negatively correlated, the correlation coefficient is +1 or −1, respectively. If there is no correlation between the assets, the coefficient is 0. Equation (4) also indicates that total risk of a portfolio results from the risk of individual assets, as well as

from the relationships between the assets. It is noted that the total risk of a portfolio can be reduced as the correlation coefficient between the assets in the portfolio decreases, and the risk reduction is largest when the assets are perfectly negatively correlated. This means the diversification effect occurs only when the assets with lower correlation are combined in a portfolio. Conversely, when the assets are completely positively correlated, there is no risk reduction of the portfolio by diversification effects than the weighted sum of the risk of the individual assets.

Thus, a variety of feasible portfolios with different return and risk can be evaluated through the parameters such as return, variance (or standard deviation) and shares of individual assets and correlation coefficient between them. Among the portfolios, the different sets of the efficient portfolios that generate the largest return for a given risk or lowest risk for a given return are called 'efficient frontier'. The shape of efficient frontier is dependent on the correlation coefficient between the assets in portfolios. The different efficient frontier of portfolios composed of two assets in accordance to the various correlation coefficients is illustrated in Figure 1. Figure 1 shows that the risk on the portfolios can be reduced when the correlation coefficient is smaller than unity, as described above. The lower the correlation coefficient between assets, the more bent is the curve of efficient frontier. The efficient frontier of portfolios with a correlation of unity (i.e. portfolios consisting of assets perfectly positively correlated) describes the straight line which indicates that there is no diversification effect. The point at the most left of the curve is the lowest risk, called the minimum variance portfolio. Intuitively, no investors want to hold a portfolio below the efficient frontier. Thus, among portfolios on efficient frontier, they can select the best combination of assets for an acceptable risk or return.

In the regard of the MPT, it is noted that diversification in water infrastructure systems, i.e. building portfolios of response options less correlated, is more effective to the investment of infrastructure systems for water-related disaster management. Water engineers are mainly concerned with investment benefits and costs in most water works related to infrastructure systems. Evaluation of the investment has been traditionally dependent on benefit-cost analysis or least-cost optimization, which include risk analysis using probabilistic information on future disasters and
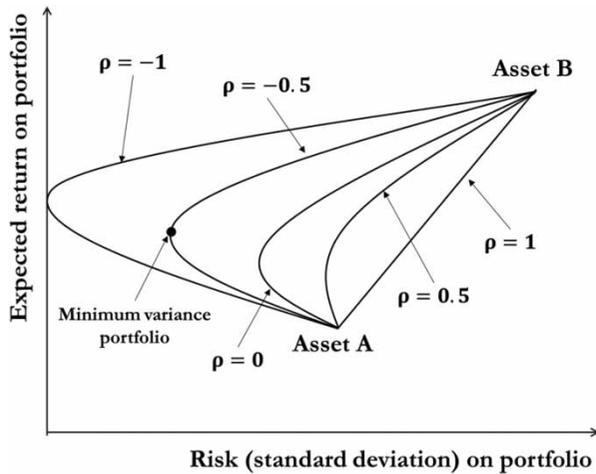
Figure 1 | Efficient frontier with different correlation coefficients (*Source:* Elton *et al.* 2003).

their impact (Beuhler 2006; Aerts *et al.* 2014). The risk is usually estimated by the product of occurrence probability of hazardous event and outcomes (e.g. damage cost) associated with the event. However, the risk analysis may be infeasible under high uncertainties in estimation of the probabilities, hazardous events, and their impacts, whereas the concept of MPT can provide new information on investment risk under uncertainty, as volatility or deviation from the expected performance of the asset. In addition, MPT demonstrates well the diversification effects of combinations of the assets quantitatively through interactive risk, as described in the second term of Equation (4), not simply summing the risk on individual assets. In particular, the efficient frontier in MPT makes portfolio managers identify various optimal combinations from the risk-return relationship, and thus the managers can examine feasible combinations of the assets for an acceptable return or risk. Therefore, analogous to financial portfolio selection, the authors believe that MPT analysis can provide information on the cost-efficient portfolios of water infrastructure options in the following case study section.

There are few applications of MPT to water management such as flood control, water quality management, and water resources management (e.g. Beuhler 2006; Marinoni *et al.* 2011; Werners *et al.* 2011; Aerts *et al.* 2014). In previous research, return on the water management options was mostly expressed as a monetary unit for investment benefit, e.g. avoided damage or economic profit. However, in order to find a cost-efficient portfolio of water infrastructure options, there is a need to evaluate cost-efficiency for investment of response options in portfolios. In this context, as a return on investment of water infrastructure system, the authors evaluate expected performance of infrastructure options for investment cost, e.g. unit production. For example, the performance of the options can be considered as follows: (1) peak discharge and discharge capacity for flood management, (2) Chlorophyll-a concentration in a dam reservoir for water quality management and (3) the amount of available water resources for water supply management. It is believed that the MPT analysis considering unit production as investment return helps decision makers compare the cost-efficiency of various infrastructure portfolios and establish optimal ones that meet cost-efficient diversification and water management goals together.

Meanwhile, portfolio risk in previous research was mainly estimated as variance or standard deviation, which considers all upside and downside volatility to expected return. In the area of water management, the risk is usually evaluated as expected damage or potential loss based on probabilistic information. In this study, the authors consider portfolio risk as downside volatility to expected return, since the invested response options are failed in coping with water-related disasters when the performance of them do not satisfy a design goal. Thus, the authors estimate the investment risk as a semivariance, which measures downside volatility relative to expected return. It is expected that estimation of the return and risk on infrastructure options suggested in this study helps decision makers apply MPT developed in financial asset management to water management and examine the diversification effect of portfolios with water infrastructure options.

APPLICATION OF MODERN PORTFOLIO THEORY TO WATER RESOURCES

Outline of case study area

In 2008, *T* city in Korea suffered from serious water scarcity due to severe drought in its major water resource, *G* dam reservoir. The *G* dam reservoir stores precipitation, usually

during the wet summer season, and supplies water until the following summer to three service regions including the T city. Inflow to the G dam reservoir over a short period from July to September occupies more than 65% of total annual inflow while approximately one-eighth of the total annual inflow is stored. It is often disputed that storage capacity of the reservoir should be expanded for securement of sufficient amounts of water over the wet summer season. However, precipitation in 2008 was much less than usual, and was reported to be approximately 21.6% of the average in September, and the storage rate of the G dam reservoir greatly dropped to lower than 80% of the average at the end of September. Afterward, water intake from the G dam reservoir was reduced to 50% of the contracts from the following January. People in the service regions suffered from serious water stress during this period, despite some emergency measures of the government such as water delivery by emergency water wagon. Particularly, most of the damage was concentrated in the T city because of its larger dependence on the G dam reservoir. In addition, the revenue water rate of the water supply system in T city was so low that the region was highly vulnerable to drought in G dam reservoir. The damage in T city was estimated to be more than 95% of the total damage in the service regions (Lee et al. 2011).

In this context, Lee & Park (2011) and Lee et al. (2011) have examined uncertainty of water supply circumstances and assessed vulnerability of water supply until the 2050s. They quantified the level of uncertainty on water inflow to the G dam reservoir and the water requirement in T city as a prediction range (i.e. difference between the predicted maximum and minimum values) with variation of coefficients and parameters in the prediction models. As a result, it was projected that by 2050s uncertainty of inflow to the G dam reservoir (I_w) and water requirement (Q_w) would increase approximately 1.5 times ($I_{w, 2050s}$: 7.5 million m^3/month) and five times ($Q_{w, 2050s}$: 54.5 million m^3/month) that in 2010s ($I_{w, 2010s}$: 5.2 million m^3/month, $Q_{w, 2010s}$: 10.2 million m^3/month) respectively. In addition, the damage by water scarcity during 2030–2050s was estimated to be more than two times that in 2008 (Cha et al. 2012). In this regard, the authors selected this case to examine diversification of water resources for water supply in T city against future water scarcity.

The aim of this MPT application to water resources is to provide an expository illustration of cost-efficient diversification in water management and quantitatively prove the hypothesis proposed in this study. Thus, the authors stress that the case study is conducted based on a variety of assumptions and investment returns of water resources options in this application are merely approximations.

Water resources options as assets

The T city primarily relies on G dam reservoir for water supply. In this study, four options that include dam water, reclaimed water, rain water and desalinated water are considered as available water resources in the T city. The reclaimed water is more reliable since a certain amount can be obtained, even during the dry season, by the treatment of daily generated wastewater (Beuhler 2006). It is assumed that the reclaimed water is produced from wastewater treatment plants in the T city and is used only for non-drinking water, which is generally consumed and is a substantial portion of the total water demand (Rijsberman 2004). Use of the rain water and desalinated water is also assumed for this study since it is difficult to obtain reliable information in the T city. The water quality as water resources may depend on the treatment process, but it is assumed to be treated for non-drinking water in this study. The desalinated water can only be an option if the service regions are adjacent to the sea. The desalinated water is considerably reliable due to abundant sea water, while being more expensive than other options.

As described in the outline of the case study area, the G dam water has high volatility during wet and dry seasons due to variation in upstream inflow. The rain water is also relatively much more volatile since it is much more impacted by hydrological cycles compared to other water resources (Beuhler 2006). The reclaimed water and desalinated water are relatively less volatile on the amount of available water since they consistently secure more than a certain amount required, even during the dry season. In this regard, in a drought, high dependence on the dam water or rain water as water resources may be unfavorable to the water supply system in the T city. However, it is believed that distributed dependence on diversified water resources, including reclaimed water and desalinated

water, is more desirable since the loss of water supply service in a drought season can be partially compensated by less volatile water resources in the hydrological cycle. In this regard, the authors believe that it is more desirable for examination of hypothesis of this study to consider four options to generate risks and returns of their combinations.

Return and risk of individual options

The return of individual options in this case study is defined as unit production, i.e. the amount of available water resource for investment cost of each option (m³/month/ USD).

Due to the inconsistency of water statistics data and hypothetical application of water resources options such as reclaimed water, rain water, and desalinated water for case study, the amounts of available water resources are merely approximations and assumed from the data for the last decade of the Water Management Information System (WAMIS) (Korean Ministry of Land, Infrastructure, and Transport (www.wamis.go.kr), statistics of water works in Korea (Korean Ministry of Environment (www.me.go.kr), and annual climatological report (Korea Meteorological Administration (www.kma.go.kr) and the data used in the previous research (e.g. Lee *et al.* 2011; Cha *et al.* 2012). The amount of dam water is estimated by multiplying the contracted amount of monthly supplied water to the *T* city from the *G* dam reservoir and the revenue water rates (39.4%) in the *T* city. The amount of reclaimed water is evaluated by multiplying the amount of monthly supplied water to the *T* city and the wastewater conversion coefficient (0.85). The available rain water is assumed as harvested rain water from residential, commercial, and industrial buildings. The amount of rain water is estimated by multiplying monthly rainfall intensity, building area, and runoff coefficient (0.9). It is also considered that the desalinated water can be produced and supplied enough to satisfy the monthly water demand (i.e. the contracted water amount from the *G* dam reservoir for water supply to the service areas) in the *T* city, with assumption of its production from abundant sea water.

For estimating the investment cost of each option, the well-known power law rule is used as represented in Equation (7) (Wittholz *et al.* 2008). It can be derived from the known cost of other infrastructure by using the rule:

$$\left(\frac{Investment\ cost_{infra\ 1}}{Investment\ cost_{infra\ 2}}\right) = \left(\frac{Capacity_{infra\ 1}}{Capacity_{infra\ 2}}\right)^m \qquad (7)$$

In Equation (7), when there is no information on the exponent *m*, the value of *m* is normally assumed as 0.6 (this is well known as the 'sixth-tenths rule'). In this study, as described below, the exponent *m* for each infrastructure option is estimated with its investment cost and capacity data from a wide variety of sources including surveys, reports, and published journals (e.g. Karagiannis & Soldatos 2008; Chen & Wang 2009; Mun *et al.* 2012; Park 2012). The total investment cost is estimating by integrating the amortized construction costs and operation costs of the individual options. The average discount rate is assumed as 4.41% over the whole period of analysis. The power law model is readjusted to find the relationship between investment cost and capacity of the options (Wittholz *et al.* 2008). Simple linear regression is conducted to determine the exponent *m* and constant *k* for each option. Table 1 represents the parameters of Equation (8) and unit production cost:

$$\ln(investment\ cost) = m \times \ln(Capacity) + k \qquad (8)$$

where *ln* is the natural logarithm, *m* is the power law exponent, and *k* is a constant.

The unit production as the return of water resources options can therefore be evaluated as the amount of available water resource divided by the investment cost for each option. The authors stress again that this case study is an illustrative application of MPT for the examination of the hypothesis in this study.

In addition, the risk of each water resource is estimated by a semivariance, which measures downside volatility relative to its expected return. The upside volatility is not taken

Table 1 │ Unit production cost of individual water resources in *T* city

Water resource	Exponent, *m*	Constant, *k*	Unit production cost (USD/m³)
Dam water	0.7209	4.8324	0.364
Reclaimed water	0.7013	9.7547	0.632
Rain water	0.6238	8.1333	1.552
Desalinated water	0.6860	10.4120	3.050

into account since the returns above the expected return, i.e. more available amount of water than the expected, are beneficial for water supply and in turn do not contribute to the investment risk of the water resources options.

Return and risk of water resources portfolios

The return and risk of each option is used to get a best portfolio of the options using the MPT analysis. In general, MPT analysis can be applied when the following conditions are satisfied: (1) more than one available option exists; (2) all the options have volatility as risk; (3) information on the returns of individual options is available; (4) all options are not influenced equally by the same factor (Werners *et al.* 2011; Aerts *et al.* 2014). The authors consider that finding a best combination of the four options meets the four conditions and thus adapt the MPT analysis for it. For the MPT analysis, the returns and risks of individual water resources are first estimated and then portfolios are generated by combining individual options with their different ratios of 0–100%. The ratios are the percentages of the options satisfying water demand. Expected return and risk for each of the obtained portfolios are calculated using the expected returns and risks of individual options. Since numerous portfolios are possible with the four options and their different ratios and since it is impossible to evaluate all possible portfolios, the efficient frontier of the portfolios is obtained as explained below.

RESULTS AND DISCUSSION

Table 2 represents the expected return and risk of individual water resources options. It is analyzed that the expected return of dam reservoir for water supply is highest, but the risk is also relatively high for the investment. In this study, return and risk on an option are estimated as unit production for investment cost and downside volatility relative to its expected return (i.e. semivariance), respectively. An option generating high return can thus be considered as a cost-efficient one. This implies that cost-efficiency is high when the government decides to invest in heightening primary dam reservoirs. However, the drawback of this strategy is that risk is also high considering recent severe drought at the dam reservoir, since the dam

Table 2 │ Expected return and risk of individual water resources in *T* city

Water resource	Expected return	Risk (standard deviation)
Dam water	2.7481	0.2732
Reclaimed water	1.6005	0.0330
Rain water	0.5477	0.2865
Desalinated water	0.3277	0.0000

water is only a water resource for water supply to the *T* city. Therefore, the high dependence on the dam reservoir needs to be reduced by diversifying water resources.

Table 3 represents the correlation coefficient between dam water and the other options. As described in the MPT, especially Equation (4), a portfolio consisting of options with low correlation can reduce overall risk for investment. Therefore, the priority of investment order in a perspective of only diversification of water resources starts with desalinated water, rain water and reclaimed water, respectively, according to the low correlation with dam water. This implies that a portfolio consisting of the desalinated water and dam water could be a more beneficial combination of the diversified water resources for water supply among the portfolios with two water resource options.

However, as shown in Figure 2, it is considered that the combination of dam water and desalinated water is not desirable in terms of investment return. Figure 2 describes the efficient frontier of portfolios composed of two water resources including dam water. It is noted that the priority of investment order is changed to start with reclaimed water, desalinated water and rainwater, respectively, based on the higher return for a given risk. This implies that it is desirable to diversify water resources by adding reclaimed water in consideration of cost-efficiency, if a portfolio is constructed by two water resources only. The authors therefore believe that the optimal set of water resources can vary when cost-efficiency is reflected in diversification investment under budget constraints.

Figure 3 illustrates an efficient (i.e. non-inferior) frontier of portfolios composed of four water resources, i.e. dam

Table 3 │ Correlation coefficient of water resources with dam water

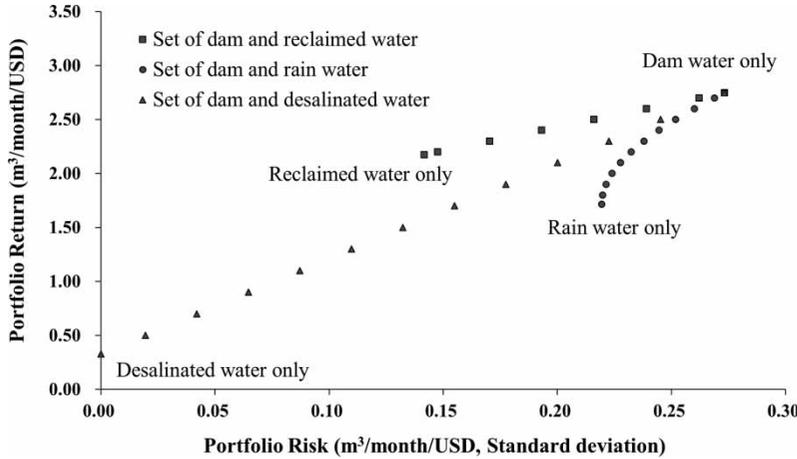|	Dam water	Reclaimed water	Rain water	Desalinated water
Dam water	1.000	0.253	0.232	0.000

Figure 2 | Efficient frontier of portfolios consisting of dam water and other resources.

water, reclaimed water, rain water, and desalinated water. The efficient frontier is obtained using a constraint method of multi-objective optimization, the non-inferior set of which is produced by finding solutions maximizing or minimizing one of the objectives (e.g. maximizing portfolio return) subject to limits on the rest of the objectives (e.g. minimizing portfolio risk) (Burke & Kendall 2005). The portfolios along the efficient frontier, such as point A, represent the combinations of all available water resources for enhancement of diversification. However, as noted from comparison of points A and B, the portfolios on the efficient frontier, which generate the largest return for a given risk, represent combinations of water resources (e.g. dam water and reclaimed water) that have relatively higher returns,

by reducing the share of lower return options (e.g. rain water and desalinated water). In other words, it is noted that a portfolio holding only high return options is closer to an efficient frontier, despite a lower level of diversification, than a portfolio including all four options for a larger level of diversification. Furthermore, shifting vertically from portfolios below to the one on the curve at the same risk level can increase investment return at no cost of risk. Thus decision makers can select portfolios that meet permissible design goals for investment return (or performance) for a given risk. In this regard, the authors believe that it is more desirable to construct portfolios with cost-efficient options to enhance diversification in a water infrastructure system, especially when budget is limited as
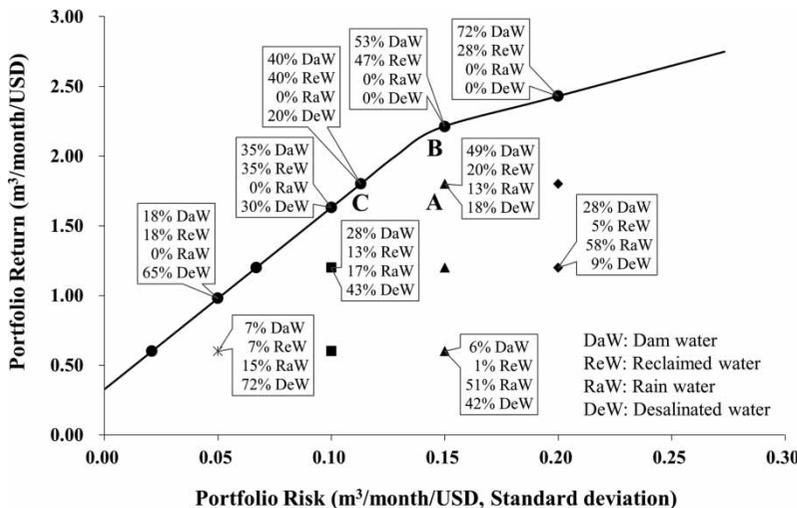

Figure 3 | Efficient frontier of portfolios consisting of all water resources.

is usual in the real world. MPT analysis in this study is also considered to well demonstrate cost-efficient diversification and be suited to quantitative evaluation of desirable portfolios of water infrastructure options in meeting cost-efficiency and water management goals.

Meanwhile, the portfolios on the efficient frontier also generate the lowest risk for a given expected return. It is shown that the risk on portfolios decreases as the share of relatively low risk options (e.g. desalinated water) increases. As described in Figure 3, the rain water option which has the highest variance is excluded in any portfolios on the efficient frontier, since optimal portfolios for a given return or risk can be explored by using other water resources than rain water. Furthermore, the horizontal move from portfolios below to the one on the curve at the same return can reduce portfolio risk without increasing investment cost. For example, although the share of desalinated water option (that generates higher unit production cost in this case study) increases, the portfolio at point C provides the same cost or return with the one at point A but less risk. The optimal combination of water resources in T city can thus be selected among the portfolios on the efficient frontier, considering budget constraints and expected return and risk preference. It is therefore believed that MPT analysis can quantitatively provide portfolios of infrastructure options reducing risk or increasing return, i.e. cost-efficient portfolios. It is stressed that this study has not implied at all that some water resources are the best or the most effective options for an uncertain situation, because they can be different according to local conditions such as climate, water resources capacity, water treatment process, and interest rate. This study is to develop a method to evaluate cost-efficient portfolios with water infrastructure systems in consideration of such factors using a case study.

CONCLUSIONS

Recent water-related disasters indicate that modern societies are becoming much more vulnerable due to high uncertainty of the hydrological extreme events and their complicated impact. There is a growing emphasis on shifting from a resistant approach (i.e. withstanding forces of disturbances without a system loss) to a resilient approach (i.e.

minimizing damage by a disturbance and rapidly recovering to system state in the pre-disruption condition). Many scholars (e.g. Ahern 2011) have announced that diversification is regarded as one of the representative strategies to enhance resilience in a system. However, the lack of a more quantitative approach to estimate diversification of a system, especially together with cost estimation, keeps most water engineers away from practicing it in their own real world projects. This leads the authors to develop a method of cost-efficient diversification with an example of water resources. The authors believe, however, that this method can be applied to cases of other infrastructures as long as their risk can be evaluated in connection with cost.

The example cases revealed that building a portfolio with options generating relatively higher investment return can be more desirable to enhance diversification in water infrastructure systems under budget constraints, despite a theoretically lower level of diversification. This may be a somewhat common-sense result to understand the cost-efficient diversification. However, in this study, the quantitative approach illustrated for investment with diversified water infrastructures within budget constraints will allow water engineers to efficiently plan diversification strategies for improving resilience and responding to water-related disasters, which will overall enhance the capability of coping with disasters and uncertainty in the coming years. It further advocates that improvement of response options requires cost-efficiency and functional innovation simultaneously for coping with future disasters in the real world.

The concept of MPT much used by portfolio managers in financial asset management well described the possible risk reduction of different portfolios together with the effect of diversification and also was useful to quantitatively find optimal combinations of water resources in the case study. Particularly, it is noteworthy that application of MPT developed for financial asset management to water resources for water supply was accomplished quantitatively in this case study. Though MPT application in case study was illustrative with a variety of assumptions, the authors believe that MPT is a useful method for planning of cost-efficient diversification in water infrastructure systems.

The authors also identified some challenges to incorporate the MPT approach into the decision making process for diversified infrastructure systems and propose the following

issues as future research. First, the authors considered the return on individual water resources as a unit production. However, in a decision making process, cost-efficiency can be characterized by multiple objectives because various stakeholders are involved in infrastructure system planning. Thus, there is a need to consider returns and volatility (risk) of the infrastructure options with various investment objectives. Second, the authors dealt only with hard options (i.e. water resources) of water infrastructure systems as assets in MPT analysis. However, there is a growing emphasis on soft options such as community participation, social insurance, and demand side management for enhancing resilience. In this regard, a variety of response actions including the soft options need to be quantified and standardized as investment return. Third, the concept of MPT addresses that diversification is efficient to reduce investment risk since low returns on some individual assets in some period can be partially compensated by higher returns from other assets (Fabozzi et al. 2002). In the infrastructure system this requires temporal and spatial connection in functionality between infrastructures. Thus, the connection needs to be evaluated in MPT analysis for examining a more practical diversification effect. Fourth, the MPT analysis can provide a decision making tool for engineering design and operation of water infrastructure systems in the perspective of cost-efficient diversification as a resilience strategy. In this regard, since the return and risk (i.e. volatility) in MPT analysis for water infrastructure systems can be greatly affected by future conditions of driving forces (e.g. change in temporal and spatial pattern of extreme rainfall due to climate change and water demand due to growing population), there is a need for more accurate and rigorous estimation of them. It is therefore believed that reliable analysis on the future conditions of driving forces needs to be incorporated into the MPT analysis. Finally, the efficient frontier in MPT is explored by the systematic analysis of relationship between return and risk of individual assets and portfolios. In this study, since the return of water resources options was defined as the amount of available water resource for investment cost, the relationship between the return and risk is obviously affected by variation in investment cost. In addition, the overall investment cost is also influenced by various factors such as discount rate, inflation rate, and economies of scale, water treatment method, and

expected years of operation. As highlighted above, the MPT application in this case study has the purpose of providing an expository illustration of cost-efficient diversification of water resources options and was conducted based on a variety of assumptions. In this regard, for practical planning of an optimal water resources portfolio in the case study area in terms of cost-efficient diversification, there is a need to improve reliability in cost estimation, for example through sensitivity analysis or a dynamic model for investment cost or Life Cycle Costing (LCC) model.

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REFERENCES

Aerts, J. C. J. H., Botzen, W. J. W. & Werners, S. E. 2014 Portfolios of adaptation investments in water management. Mitig. Adapt. Strateg. Glob. Change 20 (8), 1247–1265.

Ahern, J. 2011 From fail-safe to safe-to-fail: sustainability and resilience in the new urban world. Landsc. Urban Plan. 100, 341–343.

Ashby, W. R. 1958 Requisite variety and its implications for the control of complex systems. Cybernetica 1 (2), 83–99.

Assumaning, G. A. & Chang, S. Y. 2014 State and parameter estimation in three-dimensional subsurface contaminant transport modeling using Kalman filter coupled with Monte Carlo sampling. J. Environ. Inform. 24 (2), 80–89.

Beuhler, M. 2006 Application of modern financial portfolio theory to water resource portfolios. Water Sci. Technol. Water Supply 6 (5), 35–41.

Brunetti, M., Maugeri, M. & Nanni, T. 2000 Variations of temperature and precipitation in Italy from 1866 to 1995. Theor. Appl. Climatol. 65 (3), 165–174.

Burke, E. & Kendall, G. 2005 Search Methodologies. Introductory Tutorials in Optimization and Decision Support Techniques. Springer, Berlin.

Bushey, D. B. & Nissen, M. E. 1999 Systematic Approach to Prioritizing Weapon System Requirements and Military Operations Through Requisite Variety. Department of Defense, Washington, DC, USA.

Cha, D., Lee, S. & Park, H. 2012 Investigating the vulnerability of dry-season water supplies to climate change: a case study of the Gwangdong Reservoir drought management system, Korea. *Water Resour. Manage.* **26** (14), 4183–4201.

Chang, S. Y. & Sayemuzzaman, M. 2014 Using Unscented Kalman Filter in subsurface contaminant transport models. *J. Environ. Inform.* **23** (1), 14–22.

Chen, R. & Wang, X. C. 2009 Cost-benefit evaluation of a decentralized water system for wastewater reuse and environmental protection. *Water Sci. Technol.* **59** (8), 1515–1522.

Cohen, G., Joutz, F. & Loungani, P. 2011 Measuring energy security: trends in the diversification of oil and natural gas supplies. *Energy Policy* **39** (9), 4860–4869.

Elton, E. J., Gruber, M. J., Brown, S. J. & Goetzmann, W. N. 2003 *Modern Portfolio Theory and Investment Analysis*, 6th edn. John Wiley & Sons, Inc., NJ, USA.

Etkin, D. 1999 Risk transference and related trends: driving forces towards more mega-disasters. *Environ. Hazards* **1** (2), 69–75.

Fabozzi, F. J., Gupta, F. & Markowitz, H. M. 2002 The legacy of modern portfolio theory. *J. Invest.* **11** (3), 7–22.

Fane, S. & Turner, A. 2010 Integrated water resource planning in the context of climate uncertainty. *Water Sci. Technol. Water Supply* **10** (4), 487–494.

Fujibe, F., Yamazaki, N., Katsuyama, M. & Kobayashi, K. 2005 The increasing trend of intense precipitation in Japan based on four-hourly data for a hundred years. *Sci. Online Lett. Atmos.* **1**, 41–44.

Gallopín, G. C. 2012 *Five Stylized Scenarios*. Global Water Future 2050. United Nations Educational, Scientific and Cultural Organization, Paris, France.

Godsiff, P. 2010 Service systems and requisite variety. *Service Sci.* **2**, 92–101.

Groisman, P. Y., Knight, R. W., Easterling, D. R., Karl, T. R. & Hegerl, G. C. 2005 Trends in intense precipitation in the climate record. *J. Clim.* **18** (9), 1326–1350.

Karagiannis, I. C. & Soldatos, P. G. 2008 Water desalination cost literature: review and assessment. *Desalination* **223**, 448–456.

Lee, S. & Park, H. 2011 Understanding uncertainties in projecting water demand and effects of climate change for adaptive management of water supply risk of the water resources system. *J. Korean Soc. Water Wastewater* **25** (3), 293–305 (in Korean).

Lee, S., Abdul-Talib, S. & Park, H. 2011 Lessons from water scarcity of the 2008–2009 Gwangdong reservoir: needs to address drought management with the adaptiveness concept. *Aquat. Sci.* **74** (2), 213–227.

Liuzzo, L. & Freni, G. 2015 Analysis of extreme rainfall trends in Sicily for the evaluation of Depth-Duration-Frequency curves in climate change scenarios. *J. Hydrol. Eng.* **20** (12), 04015036.

Manton, M. J., Della-Marta, P. M., Haylock, M. R., Hennessy, K. J., Nicholls, N., Chambers, L. E., Collins, D. A., Daw, G., Finet, A., Gunawan, D., Inape, K., Isobe, H., Kestin, T. S., Lefale, P., Leyu, C. H., Lwin, T., Maitrepierre, L., Ouprasitwong, N., Page, C. M., Pahalad, J., Plummer, N., Salinger, M. J.,

Suppiah, R., Tran, V. L., Trewin, B., Tibig, I. & Yee, D. 2001 Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961–1998. *Int. J. Climatol.* **21** (3), 269–284.

Marinoni, O., Adkins, P. & Hajkowicz, S. 2011 Water planning in a changing climate: joint application of cost utility analysis and modern portfolio theory. *Environ. Model. Softw.* **26**, 18–29.

Markowitz, H. 1952 Portfolio selection. *J. Finance* **7** (1), 77–91.

Mars, M. M., Bronstein, J. L. & Lusch, R. F. 2012 The value of a metaphor: organizations and ecosystems. *Organ. Dyn.* **41**, 271–280.

Mun, J., Kim, H., Park, J., Lee, J. & Kim, R. 2012 Evaluation of tank capacity of rainwater harvesting system to secure economic feasibility and sensitivity analysis. *J. Korean Soc. Water Wastewater* **26** (2), 191–199 (in Korean).

Park, S. 2012 *Study on the Water Reuse Improvement in Gwangju*. MS Thesis, Honam University, Gwangju, Republic of Korea (in Korean).

Quiggin, J. 2008 Uncertainty and climate change policy. *Econ. Anal. Policy* **38** (2), 203–210.

Rijsberman, F. R. 2004 Water scarcity: fact or fiction? *Agric. Water Manage.* **80**, 5–22.

Sen Roy, S. & Balling, R. C. 2004 Trends in extreme daily precipitation indices in India. *Int. J. Climatol.* **24** (4), 457–466.

Shin, J., Lee, S. & Park, H. 2011 An ecological perspective for environmental infrastructure evaluation to achieve urban sustainability. *2011 Proceedings of the 5th IEEE International Conference on Digital Ecosystems and Technologies*. Daejeon, Republic of Korea.

Wang, S. & Huang, G. H. 2015 A multi-level Taguchi-factorial two-stage stochastic programming approach for characterization of parameter uncertainties and their interactions: an application to water resources management. *Eur. J. Oper. Res.* **240**, 572–581.

Wang, Y. & Zhou, L. 2005 Observed trends in extreme precipitation events in China during 1961–2001 and the associated changes in large-scale circulation. *Geophys. Res. Lett.* **32** (17), L09707.

Wang, S., Huang, G. H., Baetz, B. W. & Huang, W. 2015 A polynomial chaos ensemble hydrologic prediction system for efficient parameter inference and robust uncertainty assessment. *J. Hydrol.* **530**, 716–733.

Werners, S. E., Erdelyi, E. & Supit, I. 2011 Use of modern portfolio theory to evaluate diversification of agricultural land use as an adaptation to climate risks in the Tisza River Basin. *Clim. Change Adapt. Dev. Nations Adv. Glob. Change Res.* **42**, 371–383.

Wilby, R. L., Troni, J., Biot, Y., Tedd, L., Hewitson, B. C., Smith, D. M. & Sutton, R. T. 2009 A review of climate risk information for adaptation and development planning. *Int. J. Climatol.* **29** (9), 1193–1215.

Wittholz, M. K., O'Neill, B. K., Colby, C. B. & Lewis, D. 2008 Estimating the cost of desalination plants using a cost database. *Desalination* **229**, 10–20.