Quantifying Benefits of Adaptation Policies: Merging Water Management Performance with Cost-Benefit Analysis

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Abstract:
Adaptation policies are a major factor to achieve sustainable water resources systems. These strategies have three main elements: (1) provide a more reliable water supply under different hydroclimatic conditions, (2) reduce water allocation vulnerability for human and environment, and (3) improve resiliency of the system. The study integrates reliability, vulnerability, and resilience into cost-benefit analysis to improve the estimation of the net befits based on the system performance of previous years. Preliminary results show the Expected Annual Net Benefits (EANB) are overestimated when resilience is smaller than the reliability (Rel > Res); On the contrary, the EANB is underestimated when the resilience is bigger than the reliability (Rel < Res). This research gain knowledge in quantifying the economic benefits of adaptation policies.

Keywords: adaptation policies; resilience; reliability; vulnerability

Introduction

Redistribution of the water resources in a way that satisfies current and future water users needs while maintaining their ecological, environmental, and hydrological integrity is a major factor of adaptation policies. These strategies (1) provide a more reliable water supply under different hydroclimatic conditions (Brekke et al., 2009); (2) reduce the vulnerability for human and environmental water requirements (Bates, Kundzewicz, Wu, & Palutikof, 2008); and (3) improve resiliency when the system is in a deficit (Sandoval-Solis, 2011).

Time based *Reliability* is the frequency that an environmental or water demand is fully supplied during the simulation period; in other words, the probability of no-deficit along the period of analysis (McMahon, Adeloye, & Zhou, 2006). *Resilience* is the probability that the system recovers from a period of failure in the next period, which in this case is a deficit in environmental or water supply (Hashimoto, Stedinger, & Loucks, 1982; Loucks, van Beek, Stedinger, Dijkman, & Villars, 2005). *Vulnerability* is the expected value of the deficits, in other words, it is the average of the deficits experienced over the simulation period (Hashimoto et al., 1982). Vulnerability expresses the severity of the failures. These performance criteria are part of the results from water-planning models for two study sites: (1) Big Bend Reach of the Rio Grande/Bravo (Lane, Sandoval-Solis, & Porse, 2014), and (2) Apurimac River basin in Peru.

Gap

In water management, reliability, resilience, and vulnerability (RRV), are three water resources system performance criteria that have not been linked with an economic analysis. By matching the economic cost-benefit analysis with performance criteria, environmental and water users' objectives can be converted into economic benefits, and vice versa.

Objective

The main objectives of this research is to integrate the economic cost-benefit analysis with water management RRV performance criteria to provide an estimation of the net benefits, identify how adaptation policies improve the water management and the economic benefits, and determine how adaptation policies help decision making. There are three components of the main objective (**Error! Reference source not found.**): (1) perform a cost-benefit analysis using the performance criteria results from a water allocation model; (2) elaborate a risk analysis tree for the current economical quantification method (considering only reliability index), and the proposed quantification method (considering reliability and resilience); and (3) to evaluate and compare the economic outputs of both approaches.

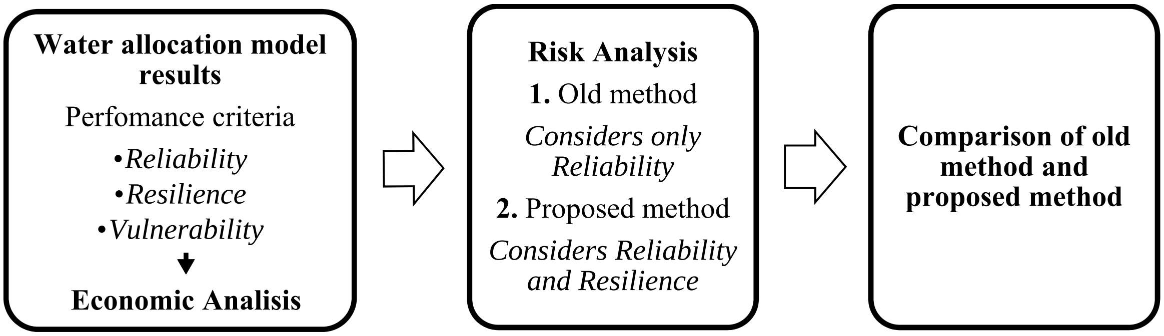


Figure 1 Research Design / Activities

When evaluating multiple scenarios, each of these activities must be performed for each alternative.

Hypothesis

The main hypothesis is that the net benefits are being overestimated or underestimated depending on the conditions of the previous years because the current analyses considers that each year is statically independent from the previous years; meaning that the probability of success (having net benefits equal or higher than the expected) or failure (having lower net benefits than the expected) at the beginning of each year is the same of the previous year, despite the fact that the previous year was a successful (S) or unsuccessful ($\bar{S}$) year. If this hypothesis is true, this novel analysis will be very important during the decision making process because it makes possible to identify adaptation policies and quantify their benefits. This analysis will illustrates why adaptation policies that are more reliable and resilient, and less vulnerable are desired from an economic and water management point of view.

Data Sources

Performance criteria are obtained from a water allocation model simulated using the Water Evaluation and Planning System platform (WEAP). The study area is the Big Bend Reach of the Rio Grande/Bravo (BBR). The model is a one-dimension water routing model governed by the continuity equation on a monthly time step with a period of record of 55 years. The model includes inflows, outflows, change of storages of reservoirs, water demands, and returns flows. The distribution algorithm considers water allocation for agricultural and urban purposes and water rights. A comprehensive description of the BBR and the water-planning model can be found in the cited documents (Lane et al., 2014; Lane, 2014; Sandoval-Solis & McKinney, 2014).

Methods and Assumption

The methodology developed for this research is presented on Figure 1. Three main steps are required to quantify the benefit of an adaptation policy.

1) Water allocation model
The water-planning model is simulated using the Water Evaluation and Planning System platform (WEAP). The model is based on a monthly mass balance with a period of record of 55 years (Oct 1955-Sep 2009) that includes inflows, outflows, changes of storages of reservoirs, water demands, and returns flows. It is a one-dimension water routing model governed by the continuity equation on a monthly time step. The distribution algorithm considers water allocation for agricultural and urban purposes in United States and Mexico. It also contemplates the water division agreement establish by the Treaty of 1944 by both countries. A comprehensive description of the RGB, BBR, the water-planning model and the proposed EF policy can be found in the cited documents (Lane et al., 2014; Sandoval-Solis & McKinney, 2014).

2) Analysis of results
The analysis of results is divided in two categories:
    (i) Performance criteria based on the reliability, resilience and vulnerability of the system. These performance criteria will be analyzed from the water users and environmental requirements perspective.
    (ii) The economic analysis that will be used to determine the net benefit (NB) for each event. Whenever a decision is made, there is a chance of success (S) or failure ($\bar{S}$), which is determined based on if water was fully supplied or if there was deficit (Figure 2). The net benefit is obtained from the benefits and cost of each event. The benefits from either successful or unsuccessful events are obtained from the sum of the profits. On the other hand, the Cost considers the capital cost, operation and maintenance and the vulnerability cost, which represent the expected deficit.

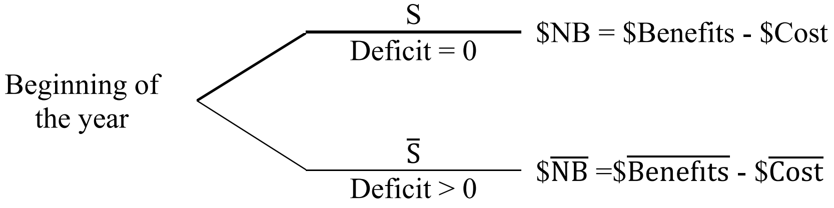


Figure 2 Economic analysis

3) Risk analysis
   The final step of this methodology considers the determination of the Expected Annual Net Benefit (EANB) for each quantification method. The results are compared to determine the benefits of adaptation policies.

   (i) Typical approach to estimate Expected Annual Net Benefit (EANB)

   The expected net benefit for a given scenario is obtained from the product of the benefit of the outcome times its associated probability. On this approach, the probability of success (P(S)) is the reliability of the system. Correspondingly, the probability of failure is 1 – P(S). For any given year, or every time a decision is made, the probabilities will be the same. This is assumed to be true given that each year is statistically independent from the previous year. For one time step, the expected net benefit is represented by Eq. **1**:

$$\begin{aligned} \boldsymbol{E(\$NB|year)^{Sc.\text{"}X\text{"}}} &\boldsymbol{= P(S)x\$NB + P(\overline{S})x\$\overline{NB}} \\ &\boldsymbol{= Relx\$NB + (1 - Rel)x\$\overline{NB}} \end{aligned} \qquad \textbf{Eq. 1}$$

   When the analysis is done for more than one time step (t = n), a distinctive pattern is observed, which is represented by Eq. 2. Figure 3 displays a decision tree for a three steps risk analysis and their expected net benefit using the normal approach (P(S) = Reliability):

$$\boldsymbol{E(\$NB|year)^{Sc.\text{"}X\text{"}}} = \frac{\sum_{k=0}^{n}\binom{n}{k}P(S)^{n-k}\left(1-P(S)\right)^{k}\left((\mathrm{n}-\mathrm{k})\$NB+\mathrm{k}\$\overline{NB}\right)}{n} \qquad \textbf{Eq. 2}$$

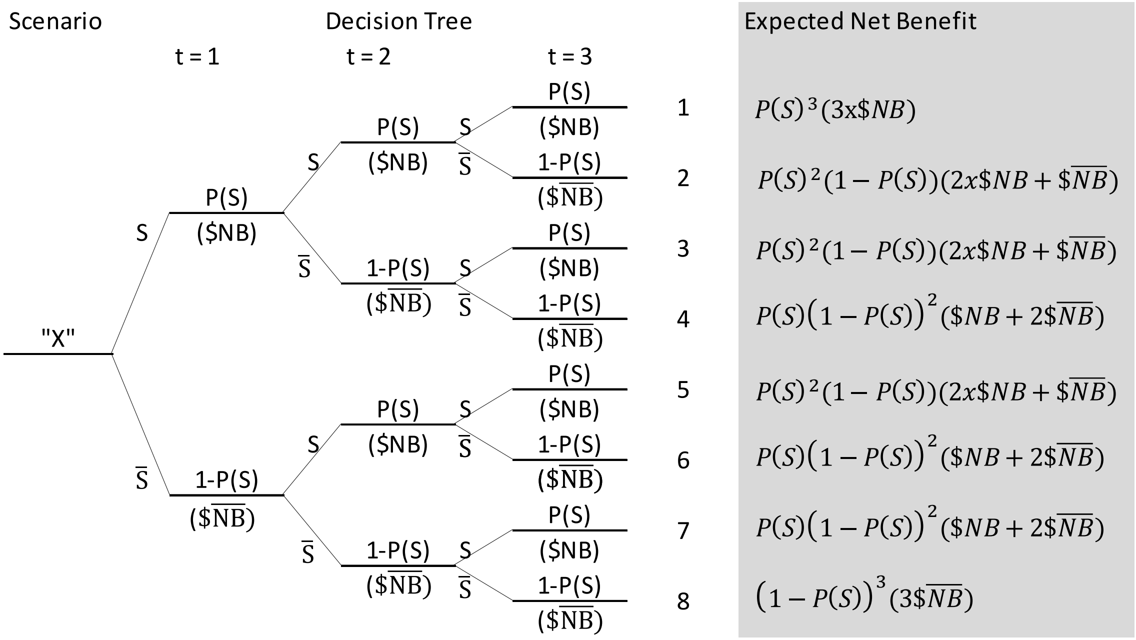


Figure 3 Decision tree for a three step Risk Analysis

Both Eq. **1** and Eq. 2 will have the same result, which demonstrate that there is no correlation between

(ii) Proposed approach to estimate Expected Annual Net Benefit (EANB)

The difference between the normal and the proposed approach is that resilience is used as the success probability given that the system has failed in the previous time step. This means that after a given failure, the success probability is equal to the recovery probability of the system, and as opposed to the normal approach, it will depend on the previous time step. In terms of water management policies, the probability of success on any given time step depends on the decisions implemented in the previous and current time steps. This is especially significant on water management policies that forecast hydrologic conditions or have to manage early responds for extreme conditions such as drought.

Figure 4 displays a decision tree for a three steps risk analysis and their expected net benefit using the proposed approach:

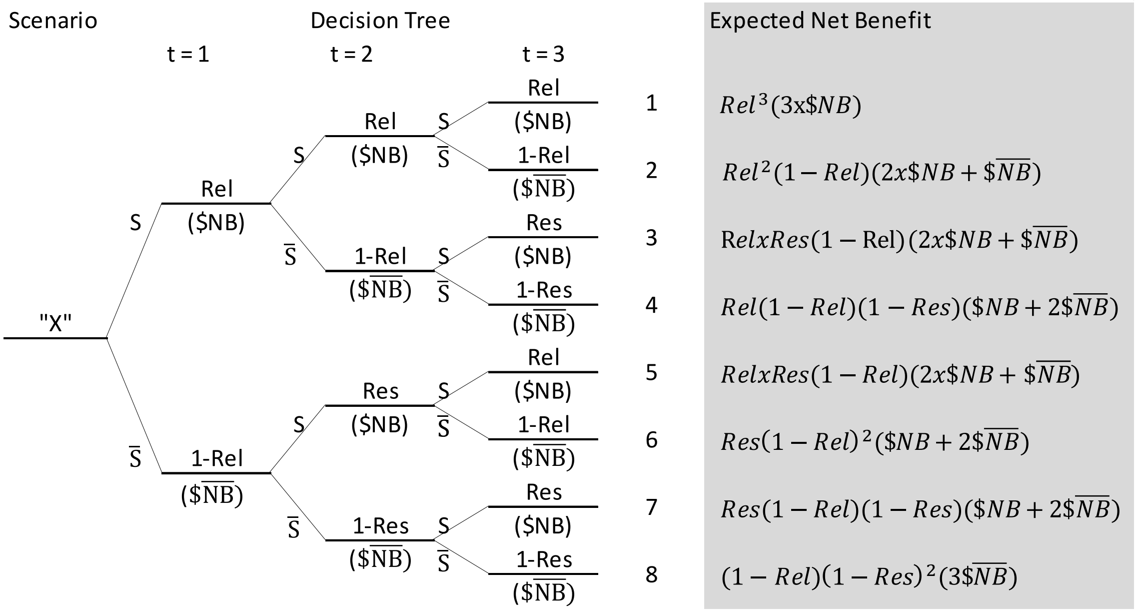


Figure 4 Decision tree for a three step Proposed Risk Analysis

Calculation/Results

The methodology described above is applied to the main agricultural (DR-90) area of the Big Bend Reach (BBR) of the Rio Grande/Bravo as the study site.

Big Bend Reach (BBR) of the Rio Grande Bravo (RGB)

The RGB is a transboundary river basin shared by the U.S. and Mexico. The BBR is selected for this study because of its binational recognized environmental and socioeconomic importance (Secretary, 2010), and because a water allocation model exists (Sandoval-Solis & McKinney, 2014) as well an economic analysis of the region (Ortiz-Partida, Sandoval-Solis, & Lane, 2015). Together, these researches constitute the inputs for the analysis. For a graphical description refer to Figure 5 where the considered irrigation district is shown in red color.

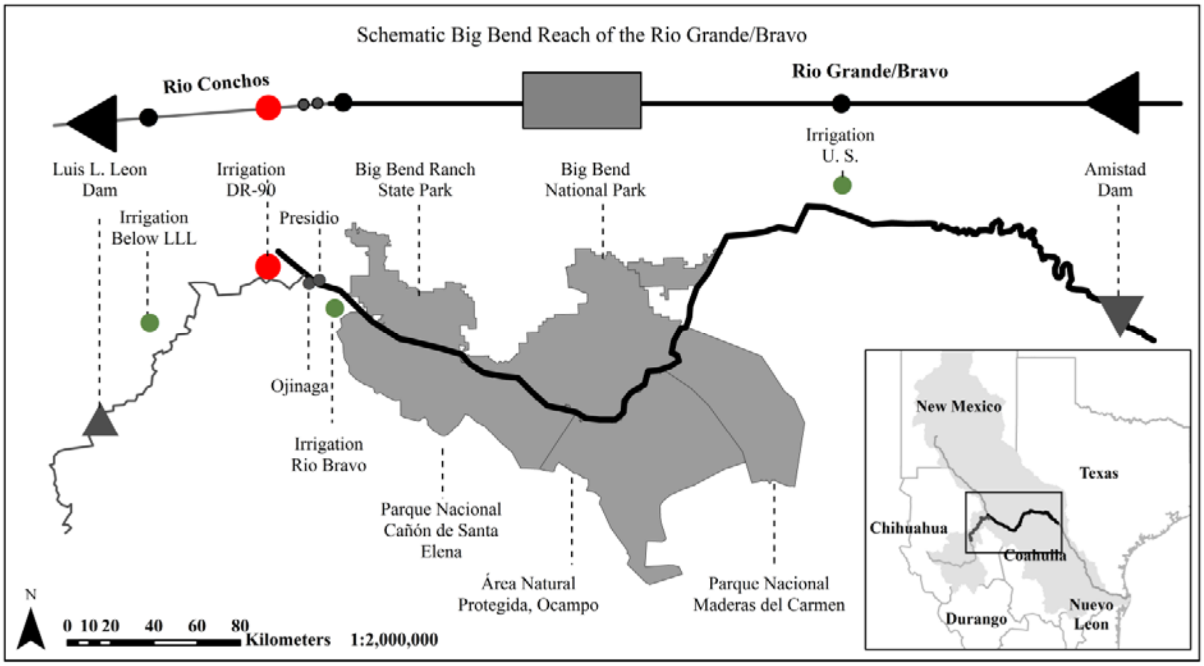


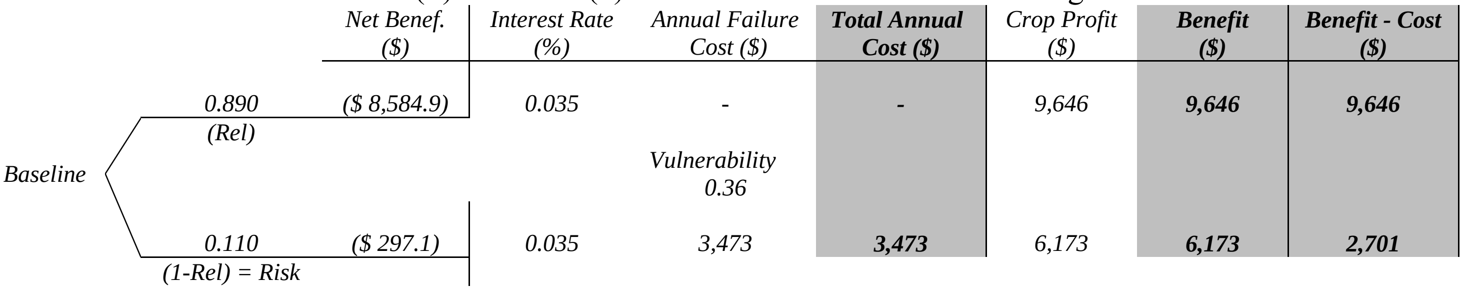
Figure 5. Schematic of Big Bend Reach.

Calculations include input data of performance criteria (RRV) from a water allocation model developed by Lane et al. (2014) and Sandoval-Solis, Reith, and McKinney (2010), and economic data from Ortiz-Partida et al. (2015). The information is adapted from these sources and presented in Table 1.

Table 1. Performance criteria and crop value from study site (BBR).

	Performance criteria			Crop Value		
	Reliability	**Resilience**	**Vulnerability**	**2010**	**2011**	**2012**
Baseline	0.89	0.35	0.36	8,536	9,646	10,656

The information is used to perform the cost-benefit analysis to obtain the net benefits of the baseline under success (S) or failure ($\bar{S}$) scenarios. Results are shown in Figure 6



	Net Benef. ($)	*Interest Rate (%)*	*Annual Failure Cost ($)*	***Total Annual Cost ($)***	*Crop Profit ($)*	***Benefit ($)***	***Benefit - Cost ($)***
0.890 *(Rel)*	*($ 8,584.9)*	*0.035*	*-*	***-***	*9,646*	***9,646***	***9,646***
0.110 *(1-Rel) = Risk*	*($ 297.1)*	*0.035*	*3,473*	***3,473***	*6,173*	***6,173***	***2,701***

Figure 6. Baseline net benefits from agriculture (DR-90) in the BBR.

The system performance criteria and the net benefits of the baseline are plugged into the risk analysis tree to calculate the expected annual net benefits (EANB) under the typical and the proposed approach. Under the typical approach the EANB stays steady (Figure 7), while under the proposed approach the EANB decreases over time (Figure 8).

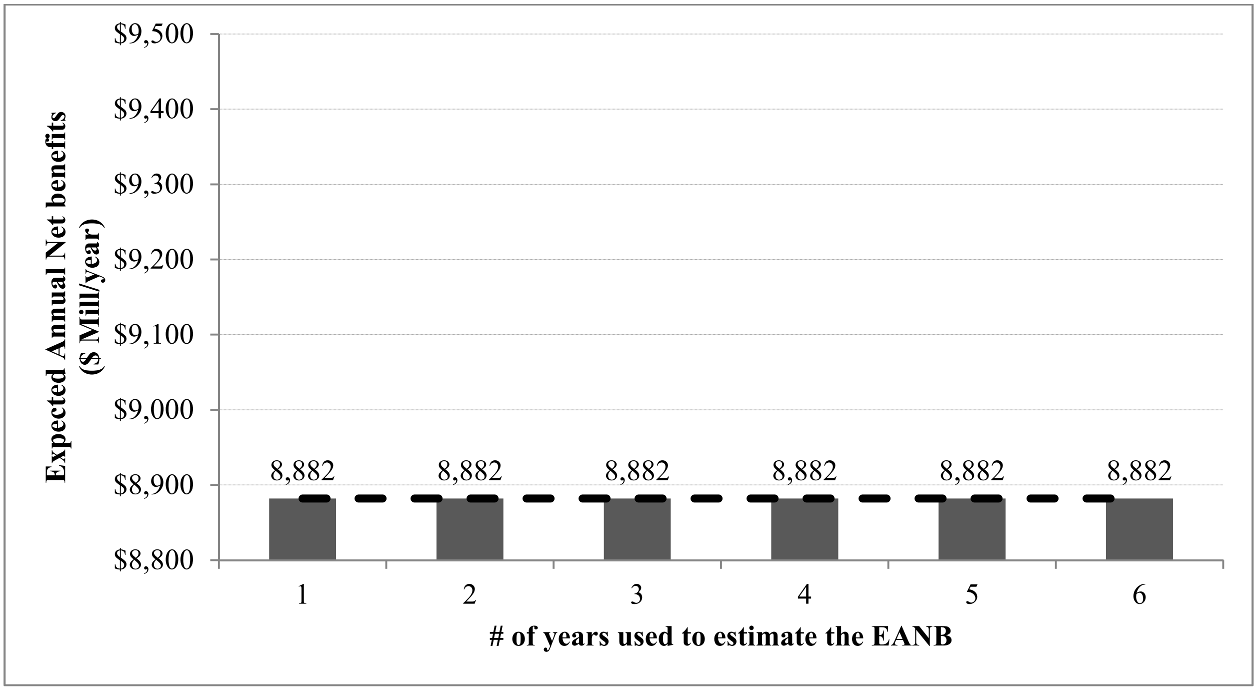


Figure 7. Expected annual net benefits under typical approach.

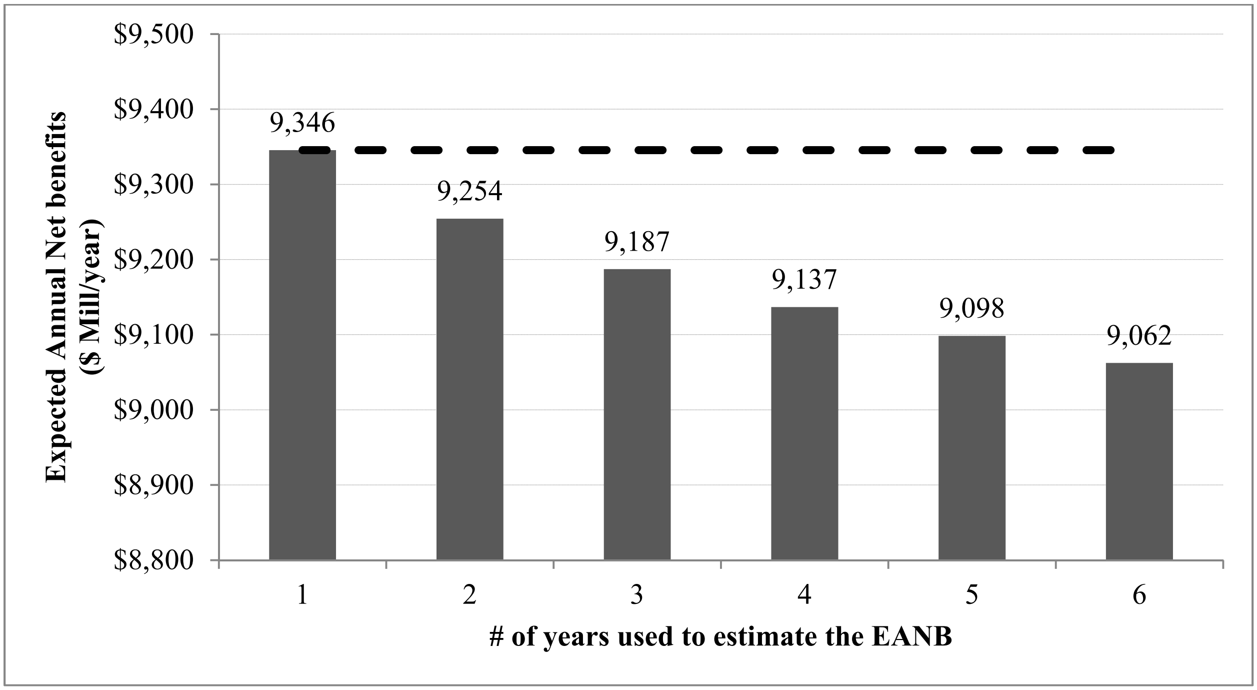


Figure 8. Expected annual net benefits under proposed approach.

Recommendation/Limitations

The analysis was performed in only one study site, and at only one unit of the agriculture economic sector (DR-90). It involves uncertainties, such as when the reliability and resilience values are the same, it is uncertain whether it will converge or not. What if it does not converge? Then how can we make a decision? This study is performed using Excel and it is hard to evaluate complicated scenario, so using different software (i.e. matlab, R) to calibrate or validate the model will improve uncertainties.

Different study sites with a variety of performance criteria are needed. It is going to be necessary to incorporate more elements within the selected economic sector (i.e. consider all agricultural units areas of the BBR, not only the DR-90).

Conclusions

EANB are overestimated when resilience is smaller than the reliability (Rel > Res); in this case the system does not recover as fast as it is expressed by the reliability. On the contrary, the EANB is underestimated when the resilience is bigger than the reliability (Rel < Res); in this case the system recovers faster than what is considered with the reliability. Benefits from this research are matching the economic cost-benefit analysis with performance criteria that have been widely used in water management. Environmental and water users objectives can be converted into economic benefits, and vice versa. This research gain knowledge in quantifying the economic benefits of adaptation policies. This research is aimed to help the plan selection during the decision making process. The methodology proposed can be easily and meaningfully explained to water users, policy makers and people in general; making the selection of adaptation policies more transparent.

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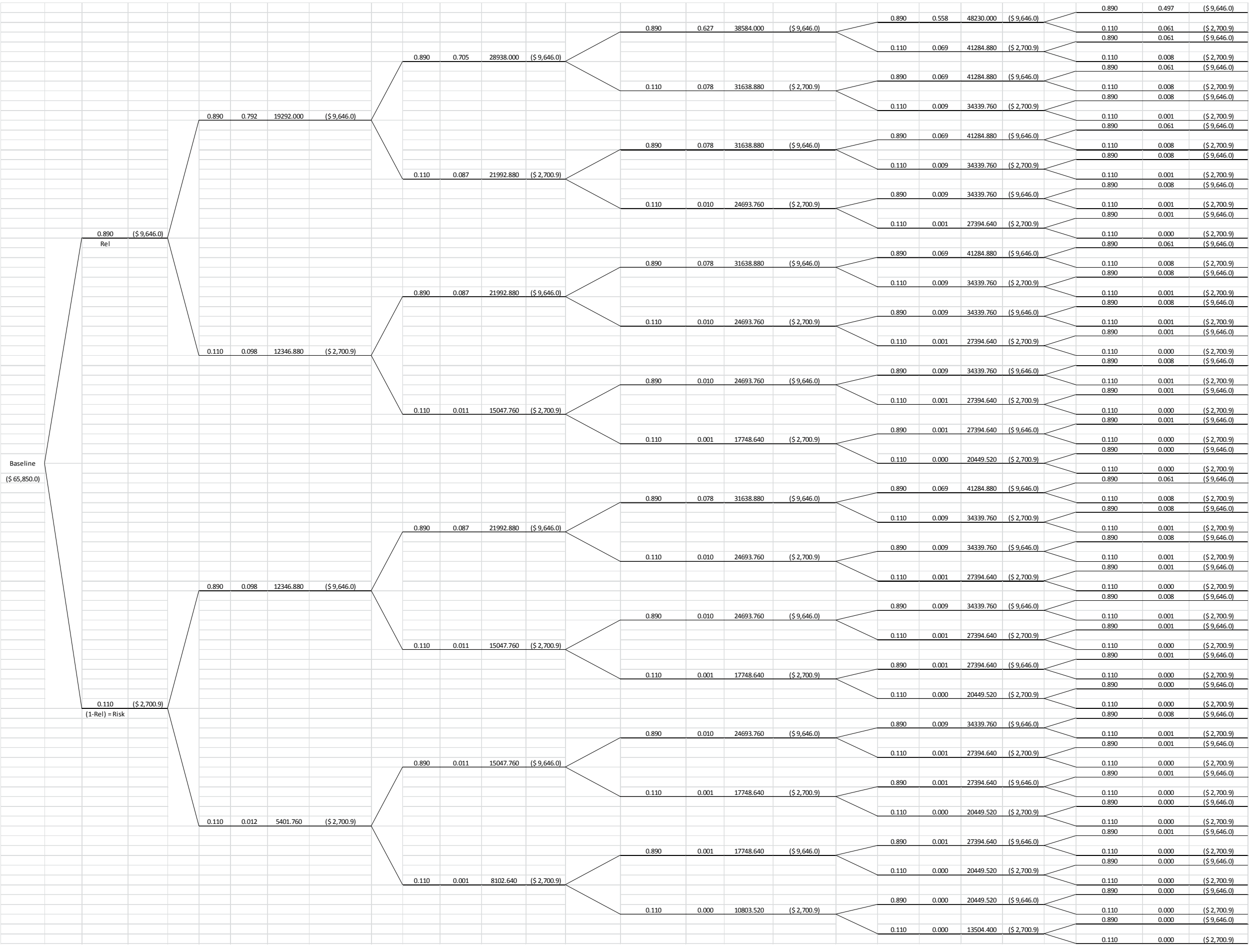
Appendix 1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