Compensating Water Service Interruptions to Implement a Safe-to-Fail Approach to Climate Change Adaptation in Urban Water Supply

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Abstract: A city resilient to climate change is characterized by effectively responding to and recovering from the negative impacts of climate hazards. In the city of Santiago, Chile, extreme weather that can be associated with a nascent manifestation of climate change has caused high-turbidity events, repeatedly forcing the main water company to interrupt the supply of drinking water, affecting millions of people. This study proposes a transformative response to reduce harm from extreme events due to climate change. The traditional approach of increasing resilience through large infrastructure works can be complemented by one-off reductions in water use during emergencies, in exchange for economic compensation. This alternative seeks to transfer the individual responsibility of water companies to a collective one, where the community is an active agent that reduces damage in the face of extreme events resulting from climate change. In the assessment of this response, we used a choice experiment to estimate the minimum amount users are willing to accept in compensation for water service interruptions. The results show that willingness to accept compensation is significant (close to 0.6 USD/hour) and decreases when users have experienced additional unplanned interruptions. The aggregate cost of the compensation is lower than infrastructure investments required to avoid service interruptions under various future hypothetical hydroclimatic scenarios associated with climate change impacts. Therefore, compensation-based instruments for water service interruptions could be a more flexible and cost-effective alternative to infrastructure-based measures to cope with future climate hazards.

Keywords: climate change; adaptation; willingness to accept compensation; choice experiment; unplanned water interruptions; safe-to-fail

1. Introduction

Climate change presents various scenarios that threaten the continuity of drinking water supply in cities. The Intergovernmental Panel on Climate Change (IPCC) projects that droughts, increased rainfall, rising temperatures, and natural hazards will become more frequent and more intense, affecting the availability and quality of drinking water [1]. Extreme weather events could increase in frequency and intensity because of climate change [2,3], leading to negative effects not only on water quality
but also on the availability of drinking water [4,5]. Risk identification and management are central elements of adaptation to the projected changes [6]. Water operators must be aware of the possibilities of unplanned infrastructure or operational failure, and therefore must have management procedures to ensure a rapid and adequate response [7].

As cities and urban populations continue to grow, people increasingly depend on the operation of complex water production and distribution systems. Water treatment plants are the cornerstone of these systems and must operate continuously to meet the demand. Traditionally, the focus of city infrastructure in relation to climate hazards has been on fail-safe design (i.e., designing to contain the hazard and thus avoid the corresponding damage). However, the fail-safe concept is considered a dangerous illusion, being unrealistic due to the uncertain and unpredictable nature of such hazards [8]. Given the possibility of the increasing intensity and frequency of extreme events due to climate change, authorities should question safety planning in cities based on mitigation efforts using the fail-safe approach.

In addition, planners must address the safe-development paradox [9], where infrastructure-based adaptation solutions tend to increase the number of people affected if the threat exceeds the infrastructure’s capacity to prevent damage. Similarly, using reservoirs to increase resilience during periods of water shortage can cause greater damage in the face of a failure due to increased demand and the resulting dependence on that infrastructure [10]. Resilience is defined as “the degree to which the system minimizes the level of service failure magnitude and duration over its design life when subject to exceptional conditions” [11] (p. 349). A city resilient to climate change is characterized by effectively responding to and recovering from the negative impacts of climate hazards.

Unlike the fail-safe approach, Ahern [12] proposes changing the mentality towards a safe-to-fail concept, that is, not to design the systems to avoid failures but to design them to be safe in case they happen. In this way, the damage would be controlled and minimized through multifunctionality, redundancy, and modularization strategies. According to the author, the concept of resilience relates to that of safe-to-fail, where the risk is spread over several interconnected systems so that if one fails, then a support network allows the system to resist, absorb and recover quickly from the negative effects of the corresponding threat. Resilience-based designs include adaptive measures, which are defined as “any action taken to modify specific properties of the water system to enhance its capability to maintain levels of service under varying conditions” [13] (p. 70). Adaptation measures are interventions that correspond to the relationship between the system and the impacts caused by failures that are a consequence of threats that cannot be mitigated [12,13]. Given the uncertainty regarding the frequency and magnitude of extreme weather events related to climate change, adaptation strategies can be implemented to reduce the corresponding impacts.

Policymakers often prefer demand-side management options to supply-side ones, for both economic and environmental reasons [14]. Conservation demand measures can significantly reduce the need for investments in supply infrastructure, especially if demand reductions are made firmly during periods of shortage. This demonstrates the great potential of demand management and points to the need for a more rigorous analysis of infrastructure expansion decisions along with demand management options [15]. To adapt to short-term events resulting from climate change, Vicuña et al. [16] propose demand reduction measures based on a water-savings option-contract. According to the authors, the objective of this instrument is to give the water utility the right to restrict water provision to some users in exchange for monetary compensation, which would extend the drinking water service. Therefore, water restrictions that impose prohibitive costs and costly investments in storage infrastructure are avoided. The possibility of reducing consumption in a short time could give flexibility to the system because it could adapt to events that exceed the design capacity of the storage works by increasing the autonomy of the system. However, this type of instrument could only be effective to the extent that it provides a cost-effective solution.

To assess the costs and benefits of a measure such as the one proposed by Vicuña et al. [16], determining users’ willingness to accept compensation (WTAC) is key. Choice modeling is one of the
methods used to determine WTAC [17]. Under this approach, one of the most widely used techniques to determine willingness to pay for improved service attributes is the choice experiment [18–20]. Using the choice experiment method, these authors studied the variation in the preference for different water service attributes and the willingness to pay for improved services through a questionnaire. Few papers using the choice experiment have studied WTAC for a worsening of the water service. MacDonald et al. [21] determined Australian users’ WTAC if the water company is unable to provide a certain level of service. However, this technique has not been used to determine WTAC for voluntary interruptions, nor has it been used to evaluate the distribution of compensation based on the difference in cut-off experiences resulting from unforeseen interruptions of drinking water supply. In these papers, different econometric models were used to determine preference coefficients, namely, the multinomial probit model [21,22], the conditional logit model [19,20], and the mixed logit model [18,19], which captured the expected deviations in respondents’ preferences.

This study seeks to determine the costs associated with compensation for water service interruptions in the design of adaptation measures for unforeseen but potential disruptions in water production resulting from climate-change-related extreme turbidity events in the city of Santiago. Specifically, the study seeks to estimate the minimum amount of compensation people are willing to accept for water service interruptions through the choice experiment method and then compare the cost of the cut-off compensations with the cost of infrastructure under various potential scenarios of unforeseen interruptions in water production. In the second section, the description and background of the study area are presented in relation to unplanned interruptions in the production of drinking water. The third section details the methodology for estimating WTAC and the comparison of costs associated with compensation for cuts and infrastructure alternatives. The fourth section presents the main results, and finally, the fifth section discusses the results found and summarizes the major conclusions of this study.

2. Description and Background of the Study Area

The city of Santiago, Chile, has about 7 million inhabitants and produces about 40% of Chile’s GDP [16]. Three water companies, which are part of the Aguas Group, are responsible for supplying drinking water to 90% of the city’s population: Aguas Andinas S.A., which produces 80%, and Aguas Cordillera S.A. and Aguas Manquehue S.A., which produce 10%. Servicio Municipal de Agua Potable y Alcantarillado (SMAPA), a municipal service located in the western zone, is in charge of supplying water to the remaining 10% of the population. The study area corresponds to the Aguas Group’s concession area in the city of Santiago located in the Maipo basin (see Figure 1).

Since 2008, the city has been affected by high-turbidity events in the Maipo River, the main source of water, located in the southeast of Santiago. The Maipo contributes around 80% of all surface water resources. A possible cause of the high-turbidity events can be associated with high-temperature levels in the Andean zone where the Maipo River headwaters are located. The high-temperature levels are associated with a high 0° isotherm, which implies a greater area exposed to erosion when receiving liquid precipitation instead of snow precipitation. This phenomenon, known as warm storms, is plausibly associated with an early expression of climate change, especially as a result of increased temperatures [23,24]. As a result of the river’s high level of turbidity Aguas Andinas (from now on “the water company”) has had to temporarily interrupt the production of drinking water at its primary drinking water plants, Las Vizcachas and La Florida. In some events, water turbidity has reached more than 380,000 nephelometric turbidity units (NTU), with 3,000 NTU being the maximum possible turbidity treatable in their water production plants. Currently, the water company has storage infrastructure that gives it an average autonomy (duration of water supply without production) of 11 h; however, the duration and magnitude of the turbidity events have generated supply cuts affecting a large portion of the city.
Between April 2016 and April 2017, three high-turbidity events (April 2016, February 2017, and April 2017) caused several hours of service interruption. The duration of the February 2017 event exceeded 48 h, affecting more than 1,400,000 homes (customers). In the cases of April 2016 and April 2017, 1,000,000 and 1,400,000 customers were left without service, respectively. The affected zones are defined based on the average autonomy of each sector, the number of critical clients (e.g., hospitals), and the alternative supply capacity to the Maipo River. It should be noted that the Maipo River is the major supplier of the affected areas so that in the event of an interruption in water production due to extreme turbidity events, these areas are left without their main source of raw water, resulting in supply cuts. This dependence on the Maipo River largely explains the study area’s vulnerability to unplanned interruptions in water production due to high-turbidity events in the river.

Andean regions such as the headwaters of the Maipo basin are prone to a potential increase of such events due to climate change, as Pörtner et al. [25] described in depth. Specific scenarios involving the occurrence of such events in the Maipo basin are not available. According to studies in nearby basins that show a connection between extreme events such as floods and cryosphere effects of temperature-related climate change [26,27], it is likely that these types of events will occur more frequently in the future. However, we are uncertain of the likelihood of such events. It is in this context of deep uncertainty that city and water resource planners have to decide on the implementation of solutions that could cope with the current, but also the future, risk of the occurrence of such events.
3. Methodology

3.1. Choice Experiment

3.1.1. Choice Sample

In this study, 606 households in the city of Santiago were randomly selected and surveyed. A face-to-face questionnaire was applied, which is presented in the next section. Because 67 respondents did not finish the survey, the final number of completed questionnaires was 539. Figure 2 shows the spatial distribution of the surveyed households according to the number of service interruption events they faced between April 2016 and April 2017. Of the completed questionnaires, 387 corresponded to clients in areas that faced three service interruptions, 122 corresponded to clients in areas with only one service interruption, and 30 clients resided in an area without service interruptions in the aforementioned period. Figure 2 also presents the zones of the city that endured one and three service interruptions in the period. It can be seen that these events affected almost the entire city, except for the western zone, which is supplied by underground extractions of the municipal water company SMAPA (outside of the shaded polygon). Sectors of the northwest, north, and northeast zones were not affected since they have alternative sources of supply to the Maipo River, such as wells and the contributions of the Mapocho River.

Figure 2. Spatial distribution of surveyed households by the number of water service interruptions.
3.1.2. Description of the Questionnaire

The survey gathered information about participants’ perceptions of climate (e.g., temperature, intensity, and amount of rain), the unplanned water service interruptions, and water service preferences. In addition, a discrete choice exercise was also included at the end of the questionnaire. More precisely, the exercise consisted of presenting the respondents with different contracts with the water company, renewable every three years, where the customer voluntarily accepts temporary water cuts in exchange for financial compensation. The compensation would translate into a monthly reduction of clients’ water bills during the three years from the start of the contract. The contract also specifies the duration and frequency of the proposed cuts. Respondents had the option of declining to accept the contract, maintaining their current household situation without compensation. The methodology used for the choice experiment follows [28], who proposed six stages for implementing the method (Table 1). The first stage is the selection of attributes to be included in the choice exercise. In this case, we selected the frequency and duration of the service interruptions, and compensation translated into a reduction of the water bill. These attributes were determined based on the existing literature [18,21] and then adapted to the study area and type of measure proposed. The frequency was presented as the number of service interruptions in the next three years, the duration referred to the duration of each service interruption, and the compensation was presented as monthly bill reduction for the next three years.

Table 1. Stages of the choice experiment methodology.

| N  | Stage                        | Description                                                                 |
|----|------------------------------|----------------------------------------------------------------------------|
| 1  | Attribute selection          | Identification of relevant attributes to be evaluated                      |
| 2  | Level assignment             | Assignment of levels for each attribute                                    |
| 3  | Choice of experimental design| Choice of theoretical statistical design to combine attribute levels in several scenarios with various choice alternatives |
| 4  | Construction of options      | Identification of the experimental design groups and selection of the number of choice scenarios to be presented to each respondent |
| 5  | Measurement of preferences   | Choice of survey procedure to measure individual preferences               |
| 6  | Estimation procedure         | Choice of the estimation procedure and corresponding model                 |

Note: Adapted from Hanley [28].

In the second stage, the levels of each attribute were constructed according to the characteristics and particularities of the turbidity-related service interruptions in recent years. Then, based on different pilot surveys carried out previously, the values of the levels were adjusted based on expert judgements, comments, and suggestions from the respondents (see Table 2).

Table 2. Attributes and levels of the exercise.

| Attributes     | Unit                        | Levels   |
|----------------|-----------------------------|----------|
| Frequency      | Cuts in three years         | 2 3 4    |
| Duration       | hour/cut                    | 12 24 36 |
| Compensation LC| USD/ month                  | 2.9 5.7 8.6 |
| Compensation HC| USD/month                   | 4.3 8.6 12.9 |

Note: 1 Approximate value of the dollar in June 2019 (1 USD = 700 CLP).

The levels of the frequency and duration attribute were common to all respondents, whereas the levels of compensation varied according to the average declared monthly water bill. Two types of users were distinguished: low consumption (LC), whose average monthly cost was less than 28.6 USD, and high consumption (HC), whose average monthly cost was greater than 28.6 USD. Based on these amounts, the compensation levels for LC users were set to 2.9, 5.7, and 8.6 USD per month, whereas for HC users, they were 4.3, 8.6, and 12.9 USD per month. The differentiation was intended to adjust the proposed compensation values to a significant percentage of the respondents’ monthly bills.
In the third stage, an orthogonal experimental design was created using Ngene software [29], with three attributes (three levels each), two choice alternatives, and 18 choice scenarios (divided into three blocks of six choice scenarios). One of the limitations of this design is that it does not maintain a balance of levels in each block, and, in certain choice scenarios, it delivers alternatives that are objectively superior to others (equal or better levels in each of the attributes). Levels were exchanged between the different blocks and alternatives to balance the levels at both the situation and block level. After such exchanges, the correlations between the attributes of the different alternatives were verified (Table 3), trying to maintain the correlations of the original orthogonal design and ensure they did not exceed the value of 0.5. Attribute A1 refers to the frequency of Alternative A, A2 refers to the duration attribute, and A3 refers to the compensation attribute, whereas the attributes of Alternative B are similar. Although there is an orthogonality loss, the correlations between attributes of the alternatives remained low (less than 0.5), so this design was used to construct the choice scenarios for the respondents.

Table 3. Correlation between attributes of the experimental design alternatives.

| Alternative | A1   | A2   | A3   | B1   | B2   | B3   |
|-------------|------|------|------|------|------|------|
| A1          | 1.000|      |      |      |      |      |
| A2          | 0.000| 1.000|      |      |      |      |
| A3          | 0.333| −0.167| 1.000|      |      |      |
| B1          | −0.333| −0.250| 0.083| 1.000|      |      |
| B2          | −0.250| −0.083| 0.250| 0.083| 1.000|      |
| B3          | −0.333| 0.000| 0.083| 0.250| 0.000| 1.000|

Note: Results derived from calculations using Ngene software.

The fourth stage consisted of defining the number of choices of the experiment. In this case, each respondent was presented with six choices or scenarios. Each choice had three alternatives, two corresponding to new contract proposals and a third alternative corresponding to the current average situation of the study area. The current situation (status quo) was based on the average service interruptions in the study area between 2016 and 2018, which was one water service interruption in three years for the frequency, 24 h per service interruption for the duration, and compensation of 0 USD, since the water company has not compensated users for unexpected interruptions. A respondent could select only one alternative for each scenario. An example of a choice exercise is presented in Figure 3, where the respondent had the choice between two new contracts (Alternative A or Alternative B) or remaining in the current average situation (Alternative C).

Figure 3. Example of choice scenarios.
3.1.3. Description of the Econometric Model

The econometric model used to determine the WTAC corresponds to the mixed logit model, which captures the expected deviations in respondents’ preferences \[18,19\]. According to the theory of random utility \[30\], the utility function \( U_{ij} \) associated with individual \( i \) choosing alternative \( j \) is given by Equation (1):

\[
U_{ij} = V(X_{ij}) + \varepsilon_{ij}
\]  

The vector of the attributes \( (X_{ij}) \) varies for each individual \( i \) and alternative \( j \), \( V(*) \) represents the indirect utility function, and \( \varepsilon_{ij} \) represents the error component that varies for each individual \( i \) and alternative \( j \). Since the mixed logit model considers the heterogeneity between individuals, the utility function is modified according to Equation (2):

\[
U_{ij} = V(X_{ij} * \beta_i) + \varepsilon_{ij}
\]  

\( \beta_i = \beta + \delta_i \)  

The term \( (\beta_i) \) is the vector of preferences coefficients associated with attributes that vary for each individual \( i \), \( \beta \) represents the vector of the preference coefficients of the attributes, invariant between individuals, and \( \delta_i \) corresponds to the preference deviations that vary for each individual \( i \) (3). The utility function can then be written according to Equation (4):

\[
U_{ij} = V(X_{ij} * \beta + X_{ij} * \delta_i) + \varepsilon_{ij}
\]  

The probability of individual \( i \) selecting alternative \( j \) from a set of \( K \) alternatives can be written according to Equation (5):

\[
Pr_{ij} = \frac{\exp \left[ X_{ij} \ast \beta + X_{ij} \ast \delta_i \right]}{\sum_{k=1}^{K} \exp \left[ X_{ik} \ast \beta + X_{ik} \ast \delta_i \right]}
\]  

The parameters of the mixed logit model were estimated using the statistical software Stata 12 \[31\]. The implemented routine is based on the examples of the mixed logit model developed by \[32\]. Deviations in preferences between individuals are assumed for the three selected attributes. WTAC for a marginal change in duration for the different groups can be calculated using Equation (6), which is derived from the marginal replacement rate \[18\]. The coefficients of the vector \( \beta \) (\( \beta_{\text{duration}} \) and \( \beta_{\text{compensation}} \)) stand for the attributes of duration and compensation, respectively.

\[
WTAC = \frac{-\beta_{\text{duration}}}{\beta_{\text{compensation}}}
\]  

3.2. Comparison of Infrastructure and Compensation Costs

This study proposes the use of net present value (NPV) to compare the value of future flows of different alternatives in the present. The expression of NPV (USD) is presented in Equation (7):

\[
NPV = \sum_{t=0}^{T} \frac{C_t}{(1 + r)^t}
\]  

where \( C_t \) (USD) is the cost at time \( t \), \( r \) is the discount rate, and \( T \) (years) is the study period. The expression of the cost \( C_t \) (USD) is presented in Equation (8):

\[
C_t = C_c \ast N_{ct} \ast D_{ft}
\]
where \( C_c \ (\text{USD} / \text{hr} \times \text{Cl}) \) is the hourly compensation cost for each client, \( N_{\text{clients}} \ (\text{Cl}) \) is the number of customers to be compensated, and \( DE_{ft} \ (\text{hr}) \) is the effective duration of the cut at time \( t \). The expression of the effective duration \( DE_{ft} \ (\text{hr}) \) is presented in Equation (9):

\[
DE_{ft} = D_t - A_t
\]

(9)

where \( D_t \ (\text{hr}) \) is the potential duration of the cutting event without autonomy at time \( t \), and \( A_t \ (\text{hr}) \) is the autonomy of the system at time \( t \). Only investment cost is considered for the infrastructure alternatives \( I_n \) at \( t = 0 \). Operating and maintenance costs are not contemplated due to the lack of information.

4. Results

4.1. Sample Description

Regarding the respondents’ characteristics, 61% have an educational level of middle school or lower, 73% declared monthly income of less than or equal to USD 1143, and 90% represents a socioeconomic level observed by the surveyors as medium or low. In addition, 88% of respondents lived in houses and 12% lived in apartments; 74% of the houses were owned and 20% were rented. Furthermore, 86% of the respondents paid less than 43 USD per month for drinking water service, with 47% paying between USD 16 and 26. Eighty-two percent of the respondents considered the amount they paid per month to be regular or very high (above 3 on a scale of 1 to 5). Overall, respondents perceive that in the last 10 years, the climate has permanently changed, with a higher average temperature, less (but more intense) rain, and an increase in the number of alluviums. It is worth mentioning that 94% of the respondents considered that the climate will change in the next 10 years, following the same trend as in the last 10 years.

The results show that most of the respondents understand the effects of climate change on climate variables and the threats affecting the continuity of the drinking water supply in the study area. The results may be relevant when analyzing the percentage of respondents who are willing to accept compensation for cuts. Given this, by perceiving a change in the future climate, the relevance of the proposed exercise could increase since these future events would be perceived as more intense and frequent than those that have occurred recently. Of the 539 valid responses, 81% of households were willing to accept service interruption compensation (i.e., at least one choice of Alternative A or B within the six choice scenarios presented to each respondent). Factoring in 67 discarded surveys, the percentage of respondents who were willing to accept compensation drops to 72%. Of the remaining 19%, 12% considered the proposed service interruptions to be too long, 4% considered the service interruption frequency to be too high, and 3% considered the proposed compensation amounts to be too low. With respect to the distribution of responses between alternatives, 31% chose Alternative C, the status quo. In contrast, when respondents were asked if they would be willing to pay to avoid supply cuts, 79% answered that they would not be willing, whereas 12% would be.

Table 4 presents a description of the sample for the different subsamples analyzed. Sample A represents the respondents with the most experience in water service interruptions against turbidity events, Sample B incorporates those of Sample A plus the clients with one service interruption, Sample C contains only the respondents with one service interruption, and Sample D contains all the respondents (zero, one, and three service interruptions). We did not select a sample with only the zero service interruption respondents because it was too small (\( N = 30 \)).
Table 4. Subsample description.

| Subsample | Description       | N   |
|-----------|-------------------|-----|
| A         | Three cuts zone   | 387 |
| B         | One or three cuts zone | 509 |
| C         | One cut zone      | 122 |
| D         | All the zones     | 539 |

Note: N = the number of households surveyed.

4.2. Estimated Results of Willingness to Accept Compensation (WTAC)

Table 5 presents the results of the mixed logit model estimation for the different subsamples. We see that in all subsamples, the frequency and duration have a negative coefficient (i.e., the higher the frequency or duration of a choice alternative, the lower the probability that the respondent will select it). Conversely, the compensation coefficient has a positive sign (i.e., the greater the compensation of a choice alternative, the greater the probability that the respondent will select it). The signs of the attribute coefficients are consistent and in line with those found in the literature. Most coefficients are significant at the 1% level, except for the frequency for Samples A and C and the compensation for Sample C (significant at 5%). With respect to standard deviation, all coefficients show 1% significance, which demonstrates deviations in respondent preferences for each of the attributes studied.

Table 5. Mixed logit model results.

| Attributes | Coef.  | z     | P > | Coef.  | z     | P > |
|------------|--------|-------|-----|--------|-------|-----|
|            | Mean   |       | Standard Deviation |       |       |
| Sample A   |        |       |                |        |       |
| Frequency  | -0.1328462 | -2.21 * | 0.027 | 0.394129 | 2.84 ** | 0.005 |
| Duration   | -0.0364866 | -6.10 ** | 0.000 | 0.0744567 | 10.78 ** | 0.000 |
| Compensation | 0.0001064 | 2.89 ** | 0.004 | -0.0005028 | -11.33 ** | 0.000 |
| Sample B   |        |       |                |        |       |
| Frequency  | -0.148164 | -2.80 ** | 0.005 | -0.4711221 | -6.17 ** | 0.000 |
| Duration   | -0.0376577 | -7.41 ** | 0.000 | 0.0699749 | 11.76 ** | 0.000 |
| Compensation | 0.0001052 | 3.52 ** | 0.000 | 0.0004669 | 14.50 ** | 0.000 |
| Sample C   |        |       |                |        |       |
| Frequency  | -0.1369232 | -1.30 | 0.193 | 0.4440935 | 2.75 ** | 0.006 |
| Duration   | -0.0424213 | -4.42 ** | 0.000 | 0.0586499 | 5.34 ** | 0.000 |
| Compensation | 0.0001136 | 1.97 * | 0.049 | 0.0004342 | 7.11 ** | 0.000 |
| Sample D   |        |       |                |        |       |
| Frequency  | -0.1408596 | -2.83 ** | 0.005 | -0.3491639 | -3.25 ** | 0.001 |
| Duration   | -0.0400017 | -8.08 ** | 0.000 | 0.0712369 | 12.46 ** | 0.000 |
| Compensation | 0.0000978 | 3.25 ** | 0.001 | -0.000507 | -14.36 ** | 0.000 |

Note: * significant at 5%, ** significant at 1%.

WTAC is assumed to be linear within the range of proposed durations. Similarly, for the compensation values available in [33], linearity is assumed in the compensation up to 24 h of service interruption. The WTAC for each subsample is presented in Table 6, and they all have values close to 0.55 USD/hour. Compared to Subsample A, which represents the WTAC from respondents with greater experience of water service interruptions due to turbidity events, the other subsamples (B and C) and the full sample (D) have higher average WTAC. Subsample C (one cut zone) has an 8.9% higher WTAC than Subsample A (three cuts zone). Thus, as respondents with fewer experiences of cuts are incorporated into a sample, the WTAC increases as in the sequence of Samples A, B and D with a variation of +0, +4.4, and +19.3%, respectively. As stated above, it was not feasible to have a sample with only the zero interruption zone because the sample was not large enough (N = 30).
Table 6. Willingness to accept compensation results.

| Sample | USD/hour | Variation ¹ |
|--------|----------|-------------|
| A      | 0.49     | 0%          |
| B      | 0.51     | +4.4%       |
| C      | 0.53     | +8.9%       |
| D      | 0.58     | +19.3%      |

Note: ¹ Variation relative to sample A.

The results suggest that a difference exists in the WTAC based on the experience of unplanned interruptions in drinking water production due to turbidity events: the greater the experience, the lower the amount respondents are willing to accept as compensation. This result is akin to the one found by Hensher et al. [18] with respect to the difference in willingness to pay to avoid outages, where willingness to pay was lower when respondents had experienced more outages. The authors explain this difference as follows: if clients face more frequent disruptions, then they are more likely to adapt by taking measures to reduce their impact. Additionally, the WTAC was calculated for samples with different educational and income levels. The WTAC for respondents who have an educational level up to elementary school or lower (N = 330) was 0.54 USD/hour, and it was 0.70 USD/hour for those with higher education (N = 209). Similarly, the WTAC for the respondents whose declared monthly income was 714 USD or less (N = 169) was 1.19 USD/hour, and it was 2.68 USD/hour for those whose declared monthly income was more than USD 714 (N = 222). The results for the educational variable were significant at 10%, whilst for income, they were not significant, and a considerable number of interviewees did not declare their monthly income (N = 148). The results suggest that respondents with higher educational levels or incomes were willing to accept higher amounts of compensation.

The values presented in Table 6 are close to values identified in the literature and used as a reference for user compensation. Table 7 compares the WTAC from Sample D (average sample WTAC) with reference values for various countries. Table 7 also presents the combined drinking water and wastewater tariff based on a consumption of 15 m³/month, as well as the ratio between the compensation and the tariff. The compensation amounts presented in the studies of Australia and England are higher than the ones in Chile. However, the current study, as well as [21], presents the two highest compensation amounts when the relationship between compensation and the combined rate is compared. This variation may be explained by the different methods used to determine the amount. The methodology implemented in [21] and this study is choice modeling, whereas a technique based on shadow price is used in [34]. Additionally, the value presented in [34] was estimated for a balanced panel from the 23 main Chilean water companies over the period of 2010–2014. The compensation presented in [33] was fixed by the English government according to its “guaranteed standards scheme,” which is paid when the water and sewerage companies do not meet its service standards. It is worth mentioning that this compensation may not apply “when severe or exceptional weather has prevented them (water and sewerage companies) from meeting their standards” [33].

Table 7. References for compensation and combined rate relationship.

| Compensation (USD/hour) | Country of Study | Combined Rate ¹ (USD/m³) | Compensation/Combined Rate | Reference |
|-------------------------|------------------|--------------------------|----------------------------|-----------|
| 2.86                    | Australia        | 4.84                     | 0.59                       | [21]      |
| 0.89                    | England          | 3.35                     | 0.27                       | [33]      |
| 0.15                    | Chile            | 1.31                     | 0.11                       | [34]      |
| 0.58                    | Chile            | 1.31                     | 0.42                       | This study|

Note: ¹ Combined rate for drinking water and wastewater based on the consumption of 15 m³/month for the city of the country of study: Sydney, Australia; London, England; Santiago, Chile [35].
4.3. Cost Comparison Results

The following are the results of the cost comparison between the use of cut-off compensation and infrastructure alternatives. Starting their operation in 2020, the Pirque Ponds provide the capacity to store about 1.5 million cubic meters of water, which would increase the city’s basic autonomy ($A_t$) from 11 to 34 h in the event of unplanned interruptions in the production of drinking water. As previously mentioned, since it is likely that climate change could increase the likelihood and magnitude of such events, the company is assessing various infrastructure alternatives with the aim of achieving autonomy ($A_t$) of 48 h (14 additional hours). Four alternatives, which were evaluated in early considerations, are presented in Table 8. The additional hours of autonomy are calculated for demand of approximately 1.5 million clients corresponding to the water company’s concession area in the city.

| Table 8. Alternative infrastructure evaluated by the water company. |
|------------------------------------------------|----------------|
| ID | Additional Autonomy (hours) | Estimated Investment (M USD) |
|-----------------|-----------------|----------------|
| I1 | 14 | 115 |
| I2 | 14 | 238 |
| I3 | 14 | 410 |
| I4 | 14 | 500 |

Note: Estimated investment does not include maintenance data. Modified from Aguas Andinas [36].

For the NPV calculation (Equation (7)) of cut-off compensation costs, it is assumed that the period $T$ is equal to the useful life of hydraulic works (e.g., dam embankments); in this case, equal to 50 years [37], therefore $T = 50$ years. The social discount rate considered is $r = 6\%$, proposed by the Ministry of Social Development and the Family of the Government of Chile [38]. Additionally, it is assumed that the hourly compensation cost per customer ($C_c$) is equal to the average WTAC estimated above at a cost of $C_c = 0.58$ USD/hour *Cl and that for each cutting event 1.5 million customers are affected, $N_{cl} = 1.5$ M Cl. Finally, because Pirque Ponds were available for use at $t = 0$, the basic autonomy ($A_t$) equals 34 h, $A_t = 34$ h, and there is no compensation at $t = 0$, so $C_0 = 0$. The parameters of the compensation NPV are presented in Table 9.

| Table 9. NPV parameters compensation. |
|---------------------------------|-----|
| Parameter | Unit | Value |
| $r$ | percentage | 6 |
| $T$ | years | 50 |
| $C_c$ | USD/hour/Cl | 0.58 |
| $N_{cl}$ | M Cl | 1.5 |
| $A_t$ | hours | 34 |
| $C_0$ | USD | 0 |

Note: 1 ∀ $t = [0, T]$

For the calculation of NPV (7) of infrastructure costs, it is assumed that $T = 50$ years is the lifetime of the four infrastructures. Additionally, it is assumed that the investment of the N alternatives ($I_n$) is counted at $t = 0$, so $C_0 = I_n$. Moreover, there is no cost of maintenance or operation in the works, $C_t = 0$ USD, for all $t$ from $t = 1$. Finally, the infrastructure alternatives are in normal operation from year $t = 0$ (strong assumption due to the time of construction and start-up), with which the base autonomy would be $A_t = 48$ h from $t = 0$. The NPV parameters of the infrastructure alternatives are presented in Table 10.
Table 10. Infrastructure NPV parameters.

| Parameter | Unit | I1 | I2 | I3 | I4 |
|-----------|------|----|----|----|----|
| $A_t^1$   | hours | 48 | 48 | 48 | 48 |
| $C_0$     | M USD | 115| 238| 410| 500|
| $C_t^2$   | M USD | 0  | 0  | 0  | 0  |
| $T$       | years | 50 | 50 | 50 | 50 |

Note: $^1 \mathcal{U} = [0, T]$,$^2 \mathcal{U} = (1, T)$.

Figure 4 shows the comparison of the NPV of the four infrastructure alternatives and the compensation during the study period $T = 50$ years. It should be noted that in this case, the NPV is negative because the flows correspond to costs; however, they are presented as positive for better visualization. In the case of compensation, cost estimates that represent different potential scenarios of the occurrence of extreme events are considered. These scenarios combine the magnitude with the likelihood of such events. In terms of frequency, the scenarios consider that the events occur annually (one event every 1 year), biennially (one event every 2 years), triennially (one event every 3 years), and quadrennially (one event every 4 years). In terms of magnitude, different scenarios of effective length cut (measured in hours) were considered, ranging from 4 to 23 h. The effective duration of each cutting event is shown on the x-axis, $DE_{f_t}$ (9) in hours, in addition to the 9 h of autonomy $A_t$ for compensation. That is, a potential cutting event $D_t$ of 42 h corresponds to 8 h of effective cut, $DE_{f_t}$, and likewise, potential events of 48 and 57 h correspond to 14 and 23 h, respectively. The effective duration values represent reference values for upcoming hypothetical events. The 23 h effective duration corresponds approximately to the magnitude of the event of February 2017, which meant a cut $DE_{f_t}$ of 48 h considering the 9 h of autonomy $A_t$ to date (potential cut $D_t$ of 57 h). On the other hand, 14 effective hours represent the goal of 48 h of autonomy through the infrastructure options presented earlier, and finally, 4, 8, and 17 effective hours correspond to events of intermediate magnitude between basal autonomy, additional autonomy through infrastructure, and the largest event of the last 10 years. Although the likely magnitude and frequency of these events in the future are mediated by the potential impacts of climate change, such information is not currently available. In this regard, the study does not expect to show the expected cost of implementing different measures but rather compares the costs given the occurrence of hypothetical but plausible future extreme events. On the y-axis of Figure 4, the NPV of the different alternatives is presented in millions of USD, represented by the rhombuses, while the compensation values are represented by circles according to the frequency of the events.

It can be noted that, for events with a duration, $DE_{f_t}$, of 4 and 8 effective hours, the NPV is below the infrastructure investments for all frequency scenarios. That is, the use of compensation for events less than 8 effective hours for annual to quadrennial frequencies represents a lower cost than the infrastructure alternatives for the 50-year study period. As reference values, the investment of the four alternatives, $I_n$ (i.e., 115, 238, 410, and 500 million USD), corresponds approximately to the NPV in $T = 50$ years of annual events lasting 8, 17, 30, and 36 effective hours, respectively. For example, the investment of $I_3 = 410$ million USD is equivalent in present value to the cost of compensating 1.5 million customers for an event of 30 effective hours (potential cut of $34 + 30 = 64$ h) that occurs once a year for the next 50 years. With respect to events of duration, $DE_{f_t}$, of 14 effective hours, which would be fully covered by the infrastructure alternatives, it is observed that the compensation cost for the biennial, triennial and quadrennial frequency is less than $I_1 = 115$ million USD. However, for the annual frequency, the infrastructure investment is less than the compensation cost.
Finally, for events of duration, $DE f_t$, of 17 effective hours, it is observed that the cost of compensating for the annual frequency is close to the investment of $1 = 115$ million USD and the cost for the biennial frequency is close to the $1 = 238$ million USD. However, since 17 and 23 effective hours exceed the capacity of the infrastructure (14 h), the infrastructure is not able to respond for the entire duration of the event. Therefore, the cost of compensating for the remaining 3 and 9 effective hours, respectively, should be considered, returning to the same cost ratio as for the 14-hour effective event. Thus, the use of compensation for cuts can be a complement to the infrastructure by giving it the flexibility to respond to events that exceed the design capacity of the works. It should be noted that in a case where no event exceeds 34 h of base autonomy during the study period, the compensation cost would be zero while the infrastructure works would maintain their investment cost since this is independent of the duration and frequency of future events.

Figure 5 shows the sensitivity analysis of NPV with respect to the discount rate $r$. It should be recalled that the reference rate corresponds to the current social discount rate of $r = 6\%$. Results are presented for lower rates ($r = 4\%$ and 5\%) and for higher rates ($r = 7\%$ and 8\%), where the higher the rate, the higher the discount of the compensation flows, and therefore the lower the absolute value of the NPV. It can be seen that for shorter effective durations (4 and 8 h), NPV does not change considerably in the face of changes in the discount rate, whereas for longer effective durations (17 and 23 h), NPV is more sensitive given the magnitude of the discount of the compensation flows. In turn, the scenarios with the highest frequencies are those that change the most due to the number of discounted flows. For example, at an annual and biennial frequency, 50 (one per year) and 25 (every 2 years) flows are discounted, respectively. The value of the discount rate is relevant when comparing compensation and infrastructure costs in different scenarios.
Figure 5 shows the sensitivity analysis of NPV with respect to the discount rate $r$. It should be recalled that the reference rate corresponds to the current social discount rate of $r = 6\%$. Results are presented for lower rates ($r = 4\%$ and $5\%$) and for higher rates ($r = 7\%$ and $8\%$), where the higher the rate, the higher the discount of the compensation flows, and therefore the lower the absolute value of the NPV. It can be seen that for shorter effective durations (4 and 8 hours), NPV does not change considerably in the face of changes in the discount rate, whereas for longer effective durations (17 and 23 hours), NPV is more sensitive given the magnitude of the discount of the compensation flows. In turn, the scenarios with the highest frequencies are those that change the most due to the number of discounted flows. For example, at an annual and biennial frequency, 50 (one per year) and 25 (every 2 years) flows are discounted, respectively. The value of the discount rate is relevant when comparing compensation and infrastructure costs in different scenarios.

Figure 5. NPV sensitivity analysis of discount rate (a) $r = 4\%$; (b) $r = 5\%$; (c) $r = 7\%$; (d) $r = 8\%$.

5. Discussion

From the empirical results, it can be concluded that surveyed users in the city of Santiago are willing to accept compensation for emergency drinking water supply interruptions resulting from turbidity events. The WTAC varies among the different users depending on the experience of outages due to unplanned interruptions in drinking water production. The more outages they experience from these events, the lower the amount of compensation they are willing to accept. This result is similar to the difference in the willingness to pay for improved drinking water attributes studied by Vicuña et al. [18], where the greater the experience of outages, the lower the willingness to pay. The average amount of compensation per hour of cut was approximately 0.58 USD/hour, which is in the range found in previous studies.

The compensation cost can be compared to the infrastructure alternatives proposed by the water company to increase the autonomy of the drinking water system in the face of risks of high-turbidity events that could occur due to climate change. As Fletcher et al. [15] point out, demand management can significantly reduce the need for infrastructure investment. The results of the cost comparison show that the design of adaptation instruments based on cut-off compensation could be a more flexible and cost-effective alternative to the infrastructure-based measures proposed by the water company to deal with future climate threats, while the investment cost of infrastructure alternatives is fixed since it does not depend on the magnitude or frequency of future events. The design of this infrastructure needs to make commitments to assessing the likelihood of very uncertain events. In turn, instruments based on the use of compensation for service interruptions could complement the infrastructure in cases where its design capacity is exceeded.
The results show that the design of instruments based on service interruption compensation could be a cost-effective and flexible adaptation measure to interruptions in drinking water production. This result supports Vicuña et al. [16] statement about the cost-effectiveness of “water savings option contracts” as a measure of adaptation to climate change. A compensation instrument could add flexibility to the drinking water supply system, given the possibility of reducing demand in a short time, thus being able to balance supply and demand quickly during unplanned interruptions in drinking water production.

This proposal seeks to modify the traditional approach to address natural threats to the drinking water supply. Authorities and companies are currently responsible for building infrastructure to ensure the operational continuity of the service. However, by means of instruments based on service interruption compensation, the aim is to change this paradigm so that network users can actively take charge of adaptation in the face of the possibility of increasingly intense and frequent events resulting from climate change. This type of approach indirectly encourages users to implement their own measures to reduce the effects of supply interruptions. A possible individual initiative could be the prioritization of water use during emergencies, where the water reserves of each household would be used for priority consumption (drinking, hygiene, or cooking) and not for use in secondary consumption (watering gardens, filling swimming pools or washing cars). Another possible measure could be the organization and cooperation between members of the same residential community, where they collectively finance some type of local storage (e.g., medium-sized pond) from the same compensation provided by the water company. This could increase the resilience of the system because redundancy and distribution of multiple local alternative supplies would replace current centralized solutions.

Although this study compares the cost-effectiveness of instruments based on compensation for interruptions and that of alternative infrastructure in the face of different scenarios of unplanned interruptions in drinking water production, we have not projected or incorporated uncertainty regarding the magnitude and frequency of these events in the future. At the same time, the design of instruments based on compensation for cuts and the corresponding contingency plans for different simulations of water-production interruption based on projections of the magnitude and frequency of events is proposed for future studies.

Finally, another aspect to be considered in future research is the applicability and political acceptance of this type of instrument based on compensation for water cuts. The implementation of these instruments could be evaluated in conjunction with awareness campaigns to increase their political and social acceptability during emergencies. These campaigns have been widely used during droughts and periods of scarcity [39,40]. The main objective of these measures is to make the population aware of the reasonable use of the resource and the importance of saving water before and during periods of limited availability. Diversification and implementation of new adaptation measures to increase resilience could be a necessity in the future in view of the possibility of increased extreme events due to climate change.

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