Household preferences for cyber-attack resilient water distribution networks: A latent class analysis of a discrete choice experiment in France

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1. Introduction

Recent events have raised alarm about the importance of protecting and ensuring the security of critical infrastructure against cyber-attacks: breach of the control system of a dam near New York City in 2013; malware attack of a power plant in Ukraine in 2015; attack meant to sabotage a petrochemical plant's operations and trigger an explosion in Saudi Arabia in 2018; malicious code hidden in updates to a US company that develops network management software and monitoring tools in 2020; massive power outage that may be the result of a malware attack in India in 2020; a hacker who tried to poison a US town's water supply in February 2021; ransomware attacks of two French hospitals that same month, to name just a few. Such attacks are designed to expose, alter and/or destroy data or enable industrial espionage and are likely to cause damage to the infrastructure itself [1]. Given the essential nature of the targeted facilities for the functioning of society [2] and of interdependencies between infrastructures [3], the effects may cascade and affect the capacity of other infrastructures and systems to operate normally [4] and have severe impacts for business and residential users [5].

Increasing concern over cyber-resilience has generated new research questions for policy and practice from both technical [6] and economic [7] viewpoints. As noted by Petersen et al. [8], the general public is rarely solicited to participate in the debate over crisis management and resilience, while Boin and McConnell [9] showed the importance of adaptive behaviour of citizens when confronted with unexpected events. However, the available literature on the central question of residents' willingness-to-pay (WTP) to improve the resilience of critical infrastructure remains largely under-developed. Regarding electricity distribution, one can quote studies by Maliszewski et al. [10] who used a two-stage hedonic approach to estimate the value of the reliability offered by electricity distribution infrastructures and their environmental conditions in Phoenix, Arizona, Thacker et al. [11] who relied on a risk-based approach to evaluate the benefits of adapting infrastructures facing a risk of flooding in England and Wales and Baik et al. [12] who proposed a multiple bounded discrete choice survey to estimate residential willingness-to-pay for back-up electricity services in the event of a large blackout during cold winter weather in northeast USA. Wang et al. [13] focused on the transportation system. They used a contingent valuation open question to estimate the New Yorkers willingness to support investments in making subway infrastructure more resilient and Discrete Choice Experiments (DCE) with scenarios described in terms of the percentage of their transportation system being operative several days/weeks after a highly disruptive extreme weather event. Based on a contingent valuation survey, Blythe et al. [14]

have estimated the WTP of UK consumers for the security of different Internet connected products and tested the influence of the percentage improvement in security proposed. Finally, Brozović et al. [5] and Price et al. [15] worked on the resilience of the water distribution network. Brozović et al. [5] demonstrate their methodology for estimating the economic losses to business and residential water users resulting from water supply disruption in the case of potential earthquake scenarios in one of the major water supply systems of the San Francisco Bay Area, California. Price et al. [15] used DCE to estimate household' WTP to reduce the likelihood of flood events and water service disruptions in Canada.

This paper aims to contribute to this growing body of research by elucidating residents' preferences for greater resilience of their water distribution system to cyber-attacks. In common with other critical infrastructure managers, water utilities are generally required to assess the vulnerability of their infrastructures [16, 17] and to secure their network and improve its resilience, for instance through the use of smart technologies [4, 18, 19]. However, as noted by the Environment Agency [20], the question of the economic efficiency of measures aimed at making water distribution networks more resilient remains open. Our work focuses on the inhabitants of the Eurometropolis of Strasbourg (France). Based on a DCE, it will help decision makers choose between a public protection policy that improves crisis response and one that promotes *ex-ante* measures aimed at reducing impacts. All of the above-cited studies focus on natural events such as hurricanes, earthquakes or flooding and none explicitly examines wilful human-induced risks (unauthorised access to a facility, accidental or intentional water contamination, cyber-attack, etc.). Furthermore, contrary to Brozović et al. [5] and Price et al. [15], we examine the resilience of water distribution networks by estimating residents' WTP for measures aimed at reducing damage when an event occurs rather than the likelihood of experiencing it.

The remainder of this article is structured as follows. In the second section, the DCE method, model specification and WTP calculation are introduced. The third section presents the survey design and data while the fourth section provides a brief outline of the descriptive statistics. The fifth section contains the econometric results and WTP estimates. The final section focusses on the discussion and conclusions.

2. Methodology

2.1. The Discrete Choice Experiment approach

This study is based on a DCE [21, 22]. The overall objective of this increasingly used survey approach is to elicit preferences and estimate economic values for multiple characteristics of an environmental good or service. DCE has roots in Lancaster's [23] characteristics theory of value which states that any good can be decomposed in a finite set of characteristics, referred to as "attributes". Consumers' utilities for goods can then be decomposed into utilities for composing characteristics. Thus, the first step in DCE is to describe the good in terms of its attributes and the levels that these take [24]. One of the attributes is usually price to permit the estimation of WTP [22]. Identification and selection of the attributes and their levels can be supported by various techniques such as literature review, expert advice and focus groups [25]. A limited number of attributes and levels is usually ensured due to concerns about task complexity and non-compensatory decision rules [26].

Once attributes and levels are determined, they are combined into "alternatives" and alternatives are combined into "choice sets", each respondent being presented with several choice sets [25]. As full factorial design, incorporating all possible combinations of the attributes' levels, is in general very large and impractical, fractional factorial designs are usually preferred. They can pursue no correlation between the attribute levels (i.e. be orthogonal) or the minimum predicted standard errors of the parameter estimates (i.e. be efficient). In order to reduce the number of choice sets per respondent, blocks of choice sets can also be identified and randomly assigned [21].

A choice set typically contains two or more options [26, 27]. A common baseline alternative, corresponding to the status quo or "do nothing" situation, is usually added in each choice set. It ensures that respondents are not forced to choose only between hypothetical alternatives they might not actually want [25]. At the end, respondents are asked to consider all alternatives in a choice set and choose their most preferred. The debate remains open on the ideal number of choice sets per respondent [24]

2.2. The latent class logit model

The choice model is based on the Random Utility Theory [28] that expresses individual utility U_{ij} as the sum of a deterministic component (V_{ij}) and a random term (ε_{ij})

$$U_{ij} = V_{ij} + \varepsilon_{ij}$$

Given the principle of utility maximizing behaviour, an alternative j is chosen by individual i when the utility associated with it (i.e. U_{ij}) is higher than for all other alternatives $g \neq j$ proposed in the same choice set C. Hence, the probability that individual i chooses alternative j in a particular choice set C is written as:

$$P_{ij} = P\left(U_{ij} > U_{ig}, \forall j(\neq g) \in C\right) = P\left(V_{ij} - V_{ig} > \varepsilon_{ig} - \varepsilon_{ij}\right)$$

Converting the random utility model into a choice model requires certain assumption about the distribution of the random parameters. If they are assumed to follow the type I extreme value distribution and to be independently and identically distributed (iid) across alternatives and observations, the conditional logit [29] is obtained. In our case, we used a latent class model, an extension of the multinomial logit model that allows for capturing unobserved preference heterogeneity [30-32]. This model assumes that the population consists of a number of latent classes Q and that the class assignment probability is unknown to the researcher. The unobserved heterogeneity among individuals can be captured by these classes through estimating a different parameter vector in the corresponding utility function. The probability that individual i from class m chooses alternative j in a particular choice set C becomes:

$$P_{ij|m} = \frac{exp\left(\beta_m z_{ij}\right)}{\sum_{j=1}^{J} exp\left(\beta_m z_{ij}\right)}$$

where z denotes a vector of attributes of choice and β is the vector of the parameters to estimate. Then the probability that an individual i belongs to the class m is expressed as:

$$H_{im} = \frac{exp(\delta_m s_i)}{\sum_{m=1}^{M} exp(\delta_m s_i)}$$

where s_i is a set of individual i characteristics that enter the model for class-membership . Error distributions for H_{im} are assumed to be of type I so that the choice likelihood for individual i is expressed as the following joint-probability:

$$P_i = \sum_{m=1}^{M} H_{im} P_{ij|m}$$

This model addresses unobservable heterogeneity between classes; individuals who belong to the same class exhibit homogeneous preferences. The model estimates the membership probability in each class and the utility functions specific to each class [32].

2.3. Willingness-to-pay calculation

The marginal WTP for a change in one of the attributes is calculated as the marginal rate of substitution between the attribute and the price attribute in the indirect utility function [24]. Due to the linear-in-parameters utility specification of the latent class model, it is calculated as the ratio [33]:

$$mWTP = -\frac{\beta_a}{\beta_c}$$

where β_a and β_c are the corresponding parameters of the attribute of interest and the cost attribute, respectively.

3. Experimental design

This work aims to assess the preferences of Eurometropolis of Strasbourg inhabitants for the increased resilience of their water distribution network. Since 1 January 2017, the Eurometropolis of Strasbourg, a French metropolitan area located close to the German border in the north-east of France, has comprised 33 municipalities, covering a total area of 339.64 km^2. This public authority is responsible for public water and sanitation services for all the municipalities and shares the maintenance and operation of drinking water production and distribution equipment with the Alsace-Moselle Water Supply and Wastewater Authority (Syndicat des Eaux et de l'Assainissement Alsace-Moselle – SDEA). The Eurometropolis of Strasbourg itself supplies water to 499,357 inhabitants (48,920 customers) in 12 of the 33 municipalities which represent approximately 90% of the inhabitants of the territory (data from the Eurometropolis of Strasbourg [34]).

The total water distribution network is 1,563 km long, relying on four pumping stations to abstract water from the Alsace water table and supplying it without any complex treatment process using 14 production facilities and 11 tanks. There is very little water storage because the resource is readily available and storage only serves as a buffer for both pressure and peak demand. This simple configuration and the absence of independent network sub-units make the system easy to operate. On the other hand, a major failure may have severe consequences for the system.

3.1. Scenario, attributes and levels

The design of the valuation scenario is of crucial importance and must meet certain requirements [24, 35] as it is presented before the choice sets. In our DCE the valuation scenario assumes a malicious attack on the Polygone pumping station (which accounts for 80% of the supply, while also feeding a storage tank), coupled with false data being fed into the monitoring system. Consequently, the water utility is unaware of the drop in pressure until consumer complaints begin. Five attributes were selected after discussion with the Water and Sanitation Service of the Eurometropolis of Strasbourg to reflect the consequences of the cyber-attack:

1. The number of people affected by the malfunction (either 400,000, 100,000 or 10,000);
2. The duration of water service interruption (either four, three or two hours), the time to detect the cyber-attack and restore the water distribution network to normal operating conditions;
3. The duration of restrictions on water consumption (for drinking and cooking), the time to carry out drinking water potability tests (either six, five or four days). It is assumed that, in this case, bottled water would be distributed for free at different locations throughout the city;
4. The services for people regarded as "vulnerable", e.g. dialysis patients or the elderly and infirm, who cannot attend the water distribution points, or those unable able to read or understand safety instructions (either a partial, an exhaustive or an exhaustive service also taking individual needs into account). These services can rely on delivery of water to their homes or multilingual signs or booklets showing the steps to follow. This requires that such people be identified and mapped early in the process and that computer tablets be bought in order to gain immediate access to them and provide the necessary assistance;
5. The cost per household, paid as a lump-sum to the water utility (ranging from 0 to €50).

In order to choose the levels of the attributes, we assumed the implementation of *ex-ante* measures designed to achieve a rapid return to normal operating conditions, thus reducing the consequences of the cyber-attack on the water utility and its users. The intermediate levels rely on engineering tools such as the purchase of dedicated equipment, the development of hydraulic software, etc. and higher levels further assume training programs for staff and increasing population awareness (see Rulleau [36] for more details). All measures were assumed to be implemented and coordinated by The Prefect, the Mayor and the water utility. It was also assumed that all money raised will be dedicated to the resilience programs.

3.2. Survey design and data collection

Each choice set was a combination of two hypothetical alternatives and a status quo alternative corresponding to the way the water utility would deal with the cyber-attack given its current practices in terms of organisation, reaction capacity and effectiveness, knowledge of staff, communication aimed at customers, etc. (see Table 1 for an example of a choice set). This current situation (defined as Option C) was the one in which no extra protection measures against a cyber-attack were taken. Choice sets were created through a fractional factorial design [37] using the software NGene [38] and then split into three versions of the questionnaire [39] so that, in the end, each respondent was shown five choice sets and had to make five successive choices of their preferred scenario. Just before presenting the choice sets, the respondent was reminded of their budget constraint with a cheap-talk script [40].

Table 1: Example of a choice set

	Option A	Option B	Option C (without extra protection measures)
Number of people affected by the malfunction	10,000 people	200,000 people	400,000 people
Duration of water service interruption	3 hours	2 hours	4 hours
Duration of restrictions on water consumption (drinking and cooking)	6 days	4 days	6 days
Services for vulnerable people	Exhaustive and taking individual needs into account	Partial	Partial
Cost per household	€40	€10	€0
Which option do you prefer?	○	○	○

The questionnaire had the following six parts: 1/ respondents' attitudes towards the environment, 2/ water consumption habits, 3/ perception of water quality in the Eurometropolis of Strasbourg and associated health risks, 4/ assessment of the water supply service, 5/ choice sets and follow-up questions and 6/socio-economic characteristics of respondents. In order to elicit risk aversion, a lottery was included in this last part. Lotteries are sometimes used in DCE studies dealing with risk (e.g. Reynaud et al. [41], Bartczak et al. [42, 43], Glatt et al. [44]). Different methods are proposed in the literature; we chose that of Eckel and Grossman [45, 46] which has the advantage of being less complex and easier to understand [47] than that of Binswanger [48] popularised by Holt and Laury [49] for instance, in view of the high cognitive burden that a choice experiment questionnaire places on respondents [50]. This approach involves a choice between six gambles with a 50% chance of winning a low price and a 50% chance of winning a high price (Table 2). Gamble 1 implies a certain €28 payoff; the expected gain and the risk then increase gradually up to Gamble 5. Gamble 6 proposes the same expected gain as Gamble 5, but with a higher variance. Respondents are asked to choose the one they prefer. In other words, and contrary to Glatt et al. [44] and Bartczak et al. [43], all lottery choices we are proposing were in the gain domain, which is not uncommon [51] and allowed not to complicate the questionnaire. And the risk preferences are not determined based on switching points as in Bartczak et al. [43].

Table 2: Eckel and Grossman's [45, 46] lottery choice game

Choice (50/50 gambling)	Low payoff	High payoff
Gamble 1	€28	€28
Gamble 2	€24	€36
Gamble 3	€20	€44
Gamble 4	€16	€52
Gamble 5	€12	€60
Gamble 6	€2	€70

The questionnaire was pilot tested face-to-face and online in early 2018 and conducted face-to-face in May that same year in all 33 municipalities of the Eurometropolis of Strasbourg. It was administered in strategically chosen locations, such as shopping centres, railway stations, etc. by trained, skilled, and qualified personnel. A quota sampling technique was chosen (living area and household structure).

4. Statistical Analysis

A total of 485 people completed the valuation exercise and were included in the study sample. The majority (56%) of respondents were women. The average age of participants was 35 years and they tended to be highly-educated since 80% had obtained a high school diploma and 35% had completed at least three years of undergraduate studies. The mean income was €2,123 per household per month[1]. The majority of respondents were not familiar with survey topics: only 17% stated that they worked or had studied in the environmental field, 15% in risk management and 9% in water management. The proportion of people working in the health sector was slightly higher (27%). Finally, almost one third of respondents were members of associations, of which 14% of an environmental protection association; 28% had made donations to environmental protection associations in the last five years.

4.1. Water management and water consumption

For 41% of respondents, pollution control is the most important challenge facing water management, followed by the preservation of available water resources (22%) and the security of drinking water supply (11%)[2]. This last answer, directly related to the topic of our study, was quoted at least once by over two thirds of the respondents.

Regarding patterns of consumption, a majority of adults (53%) drink non-filtered tap water. Children's consumption is evenly spread between non-filtered tap water (45%) and bottled water (39%). In 35% and 41% of households respectively, the age or the health of one member makes them sensitive to water cuts and changes to water quality. The answers to these questions are correlated and, in both cases, adults and children drink significantly more bottled water and less tap water. Lastly, respondents with a household member sensitive to water quality came in significantly greater numbers from those working or studying in the environmental field and respondents with a household member sensitive to water cuts came more from the health sector.

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[1] This is comparable to the median disposable income per consumption unit in the area, which equals €1,730 per month.

[2] Other answer choices were flood prevention, groundwater protection, wetlands protection, disposal and treatment of wastewater…

4.2. *Perception of water quality*

For three-quarters of respondents, tap water poses “little” or “no” risk to human health in general and the proportion is the same when the question makes specific reference to their municipality. Those respondents who expressed concern were worried about the presence of chlorine-based disinfectant (despite it having no harmful effect on human health). Households sensitive to water quality variation were significantly more likely to estimate that tap water poses a risk to human health, both in general and in their municipality. As concerns tap water quality in their municipality, 17% of respondents do not know what source of information to trust and approximately 1% trust no one. Those respondents who were confident in water quality cited first the Eurometropolis of Strasbourg (37%), far ahead of SDEA (19%), Ministries of Health or of the Environment (10%), consumer associations (9%) or environmental protection associations (8%).

Almost eight respondents out of ten rated their current tap water quality as “Good” or “Very good”. However, they were less decisive about its quality over time: 73% were unable to compare it with that of five years ago. Households sensitive to water quality variation were significantly more likely to rate current tap water quality as “Poor” or “Very poor”, and to state that this quality has worsened over the past five years.

4.3. *Knowledge and assessment of the water supply service*

The majority of respondents (56%) knew that their tap water is extracted from groundwater. However, 25% could not answer this question, showing a lack of information in this respect. Furthermore, very few knew that no treatment (except by chlorination) is necessary before its distribution. A majority of respondents did not know which body supplies tap water and, as a logical consequence, 30% did not know to whom they paid their water bill. Three out of four did not know its amount, even when proposed classes of values.

These “don’t know” individuals differ in many ways. Regarding personal characteristics, they were significantly less educated and economically less active and regarding water uses, they were more likely to consume tap water. They were also less familiar with their water service: they were less likely to know their water supplier and to whom they pay their water bill or to be able to judge the quality of their present tap water or how it had changed over time. In other words, uncertainty can occur on many levels and may be cumulative.

Overall, the assessment of the service quality was very high: 16% rated it as “Very good” and 72% as “Good”; “Don’t know” answers were around 10%. Yet, when it comes to the information provided on service quality, opinions were split evenly between “Don’t know”, “Very good” and “Good”, and “Very poor” and “Poor”. Sensitive households were significantly more dissatisfied. Finally, those who knew their bill amount were more likely to appreciate the information provided on service quality.

When asked the three central criteria to offer high-quality service, respondents ranked first the sanitary quality of the water (47%), far ahead of maintenance and network renewal (27%) and water price (9%). More than 75% of respondents quoted at least once the sanitary quality of water and over 25% the price; fewer than 1% quoted security in the face of natural and human-induced hazards.

4.4. *Risk perception*

The majority of respondents thought that their water distribution network is not currently at risk of cyber-attack, water shortage, pumping station breakdown/failure or contamination of water (either accidental or deliberate). The only perceived risk stems from pipe burst (51% of positive answers). The relatively high percentage of uncertain respondents (from 14 to 21% depending on the risk) is noteworthy, as is the fact that respondents who knew their bill amount were significantly less likely to be uncertain. In addition, households sensitive to water cuts were more likely to state that their water distribution network is currently at risk of accidental contamination of water and of pumping station breakdown or failure.

When it comes to risk management 12% of respondents do not trust any institution. Among the remainder, the Eurometropolis of Strasbourg is quoted first (33%), followed by SDEA (26%), far ahead of other options such as the city council (16%) or the Department or the Region (7% each); residents and environmental protection associations did not garner much trust on these issues. Over 50% of respondents did not know whether the body they trust knows any of the risks. Yet, the percentage of "Poor" or "Very poor" knowledge remained relatively low whatever the risk. If an unexpected problem occurs, respondents were divided on how to be informed about safety arrangements and behaviour expected: among the three favourite solutions a phone call, an SMS, local newspapers, posters, local news on TV, local radio, emails and posting to social networks were all quoted at least once by 30 to 36% of respondents.

More than 80% of respondents felt "Rather not" or "Not at all" exposed to a risk of water distribution network malfunction (if this is the case, they quote a pipe burst) and 87% have never experienced a malfunction in their current home. The mean acceptable maximum duration for water cuts was 15 hours. Only three people answered "0" to this open-ended question, the mode being equal to "24 hours" (114 responses). Equivalently, the mean acceptable maximum duration for water usage restrictions (no drinking tap water or cooking with it) was 8 days and 15 hours; "0 day" answers were more frequent (22 responses), the mode being equal to "1 day" (100 responses). Both values seem extremely high.

4.5. Risk attitudes

In order to elicit risk aversion, a lottery choice game was included in the questionnaire. We used the Eckel-Grossman method [45, 46]. This method allows categorisation of respondents into risk categories [47]. It is expected that (i) risk averse respondents choose the least risky gambles but for lower expected gains, i.e. Gamble 1 to 4 (Table 2), (ii) risk neutral respondents pick Gambles 5 or 6 which offer the highest expected gain and (iii) risk seeking respondents select Gamble 6 since it proposes the same expected gain as Gamble 5, but with a higher variance [47]. It has been used in several DCE studies (e.g. Reynaud et al. [41]). However, we did not estimate individual risk preferences and a unique CRRA (Constant Relative Risk Aversion) coefficient for each household as proposed by Holt and Laury [49] and successively modified by Eckel and Grossman [46] and Reynaud and Couture [52]. Instead we created a dummy variable to distinguishe between risk averse and risk seeking respondents. As such, risks attitudes are not directly included into the utility model, as is the case in Glatt et al. [44]. Indeed, these authors evaluate and use individual risk attitudes combining individually perceived damages and probabilities of the threat occurring, one attribute of their DCE being the flood risk reduction.

In total, around 70% of respondents are risk averse. One respondents out of four chose the certain payoff that is to say Gamble 1 and Gamble 3, 9% selected Gamble 2 and 10% picked Gamble 4. Gamble 5 with higher expected gain was chosen by less than 5% of respondents. A chi-square test showed that women are more risk averse than men since they were significantly more numerous choosing Gamble 1 (22% against 35%). This result is in accordance with Eckel and Grossman's findings [46]. The proportion of risk seekers who picked Gamble 6 was also relatively high (20%). Risk-seeking respondents tended to have a higher level of education and were significantly more likely to be working or studying in either the water or risk management fields. Finally, risk aversion also influenced answers to a number of other questions. Risk-seeking respondents were, for instance, more likely to think that their water distribution network is currently "Rather" or "Very" exposed to a risk of cyberattack.

5. Econometric results

5.1. Estimation procedures

Both empirical and statistical considerations should be used to guide the determination of the number of classes to use in a latent class analysis and the literature recommends a number of information criteria (e.g. Louviere et al. [21], Boxall and Adamowicz [31], Greene and Hensher [53] or Nylund et al. [54]). We relied on the Akaike information criterion (AIC) and the Bayesian information criterion (BIC). These values gradually decrease as the number of latent classes increases up to 4. The AIC and BIC values increase again after the inclusion of 4 classes (Table 3). Since they do not vary much from one model to the other we opted for presenting and discussing the 2-class, the 3-class and the 4-class models. All estimations were done using the Apollo package software in R [55]. The models are estimated in preference-space [56][3].

Table 3: Goodness of fit measures for latent class models

Number of classes	Number of parameters	Log likelihood	AIC	BIC
2	21	-1,789.31	3,620.61	3,740.61
3	31	-1,728.13	3,518.27	3,695.41
4	41	-1,688.21	3,458.43	3,692.71
5	51	-1,679.24	3,460.49	3,751.91

Variables used in the latent class models are presented in Table 4. Except for COST and RESS_UC which are quantitative, all variables are qualitative and coded as binaries (0-1). RESS_UC represents the net monthly resources of the household per unit of consumption, where an adult is one unit and a child is a half-unit. This includes wages, tax revenues, benefits, rents and all other forms of income, and is measured in euros per month.

[3] This common procedure has been shown by some authors to better fit the data, while others found that estimations in WTP-space provide more reasonable WTP values [48]. Nonetheless, all agree that whereas estimations in preference-space may produce unrealistic results for mixed logit models, WTP measures are less affected by the assumptions made about the distribution of parameters in latent-class models [49].

Table 4: Variables used in the latent class model

Names	Description
ASC	Alternative Specific Constants
PERS2	200,000 people affected by the malfunction
PERS3	10,000 people affected by the malfunction
COUP2	3 hours of water service interruption
COUP3	2 hours of water service interruption
REST2	5 days of restrictions on water consumption
REST3	4 days of restrictions on water consumption
SENS2	Exhaustive services for vulnerable people
SENS3	Exhaustive and customised services for vulnerable people
COST	Cost per household
RESS_UC	Household resources per consumption unit
AVERSE	Risk-averse respondent
BILL	Water bill said to be paid to the trustee
RELIABILITY	Drinking water supply reliability quoted as one of the three biggest challenges in water resource management
QUALITY	Municipal/metropolis administration as the most trusted bodies regarding the quality of water supply in the municipality
ORIGIN	Ignorance about the origin of water distributed from the water system
INFORMATION	Information provided regarding the water supply service quality considered good or very good
EFFECTIVENESS	Cyber-attack protection measures proposed in the valuation scenario considered effective

It should be noted that AVERSE comes from answers to the lottery choice game proposed by Eckel and Grossman [45, 46] and takes the value 1 when the respondent chose Gambles 1, 2, 3 or 4; 0 otherwise. AVERSE is in consequence interrelated with other information contained in the questionnaire replies. Similarly, EFFECTIVENESS relates to other scale questions (e.g. assessment of the current risks of accidental or intentional contamination of water, of pipe burst, of pumping station breakdown/failure or of cyberattack, assessment of the current risk of malfunction of the water distribution network in the housing, assessment of the changes in water quality during the past five years). The purpose of this follow-up question was to test the relevance of the scenarios [35]. Over 60% of respondents were confident in the effectiveness of the proposed resilience measures to counter the impacts of a cyberattack.

Results of the models are presented in Table 5. Only 332 survey responses are included in the 2-class model (referred to as “Model 1”) and 344 in the 3-class model (referred to as “Model 2”) and in the 4-class model (referred to as “Model 3”) since not every question was answered by the respondents, in particular those relating to household income.

Table 5: Latent class logit models results

	Model 1		Model 2			Model 3			
	Class 1	**Class 2**	**Class 1**	**Class 2**	**Class 3**	**Class 1**	**Class 2**	**Class 3**	**Class 4**
Utility function									
ASC1	1.4337*** (0.1900)		1.9900*** (0.2120)			1.8922*** (0,2664)			
ASC2	1.5456*** (0.1965)		2.1101*** (0.2222)			1.9119*** (0,2892)			
PERS2	-1.4967*** (0.5697)	0.1564 (0.1123)	-0.6529* (0.3840)	-15.4317*** (1.4314)	0.2033 (0.1241)	0.5625*** (0.1934)	-1.2899 (0.9643)	-15.4946*** (1.3146)	-0.7583** (0.3320)
PERS3	-0.5440 (0.3722)	0.0718 (0.1238)	-0.4597 (0.6139)	-6.9710*** (2.1552)	0.1470 (0.1567)	1.0666*** (0.3504)	-3.5529*** (1.2737)	-6.7690*** (2.2438)	-0.9543* (0.5752)
COUP2	-0.1622 (0.3653)	0.1129 (0.1152)	-0.0962 (0.2321)	-0.6768 (1.6710)	0.0976 (0.1266)	-0.4402** (0.1942)	2.2868 (1.5968)	-0.8103 (1.6611)	0.1214 (0.2777)
COUP3	-1.1862*** (0.3368)	0.0046 (0.1059)	-0.5249** (0.2221)	-18.8993*** (1.5511)	0.0539 (0.1153)	0.3142 (0.2084)	-0.2151 (0.8484)	-18.5128*** (1.6531)	-0.4418* (0.2627)
REST2	-1.0535*** (0.3651)	0.5538*** (0.1035)	-0.0394 (0.2327)	-4.5676** (1.8036)	0.5721*** (0.1181)	0.3843* (0.2276)	1.9276* (0.9892)	-4.2693** (1.8982)	0.1308 (0.3421)
REST3	-0.7095** (0.2967)	0.3801*** (0.0918)	0.0715 (0.4313)	-6.7631*** (1.0940)	0.4494*** (0.1397)	0.3051** (0.1526)	1.8505* (0.9651)	-6.5911*** (1.1830)	0.4004 (0.4611)
SENS2	-0.8634** (0.4292)	1.0283*** (0.1229)	0.3789 (0.3514)	-18.2730*** (2.0170)	1.0270*** (0.1776)	0.6207*** (0.2326)	4.5368*** (1.6297)	-18.5416*** (2.0733)	0.6176 (0.4626)
SENS3	-0.0308 (0.3316)	1.3748*** (0.1341)	0.7451 (0.6300)	0.1895 (0.3891)	1.4561*** (0.2216)	1.0196*** (0.2099)	6.0549** (2.6388)	0.1815 (0.4023)	1.1509** (0.4803)
COST	-0.0863*** (0.0186)	-0.0306*** (0.0043)	-0.0793*** (0.0177)	0.0346 (0.0393)	-0.0228*** (0.0050)	-0.0366*** (0.0080)	-0.0734 (0.0461)	0.0353 (0.0418)	-0.0931*** (0.0200)
Class-membership function									
Constant_class	-1.8371*** (0.3959)		-1.3195*** (0.4489)	-2.2186*** (0.4359)		0.7074 (0.5961)	0.6591 (0.5186)	-0.3542 (0.5154)	
RESS_UC	0.0002 (0.0001)		1.8910e-05 (0.0002)	5.9050e-06 (0.0001)		-0.0001 (0.0003)	3.996e-05 (0.0002)	-4.894e-05 (0.0002)	
AVERSE	0.5269*								

	(0.3172)								
BILL	0.8294** (0.3476)		-0.4633 (0.5757)	1.2841*** (0.3812)		0.6046 (0.7258)	0.5126 (0.7017)	1.8663*** (0.6372)	
RELIABILITY	-0.5876* (0.3556)								
QUALITY	0.5139* (0.3064)		-0.0131 (0.3954)	0.8731** (0.3467)		0.1855 (0.4857)	-0.4920 (0.4676)	1.0982** (0.4616)	
ORIGIN	0.8646*** (0.3252)		0.7891** (0.3571)	0.8653** (0.4073)					
INFORMATION	0.8458*** (0.3052)		0.1809 (0.3834)	1.1734*** (0.3452)					
EFFECTIVENESS	-0.5934** (0.2924)		0.0119 (0.3517)	-0.9876*** (0.3449)		0.1213 (0.5375)	-0.4630 (0.4592)	-1.0469** (0.4873)	
Number of individuals	332		344			344			
Log-likelihood	-1,294.72		-1,291.108			-1,265.41			
AIC	2,647.45		2,668.22			2,636.82			
BIC	2,804.47		2,902.57			2,925.68			
Class allocation	0.2440	0.7560	0.2102	0.1571	0.6327	0.4080	0.2541	0.1568	0.1811

Note: Variables are significant at the ***1%, **5% and *10% level. Robust standard errors are reported in parentheses.

The results of Model 1 show that respondents from the two classes do not have the same preferences for resilience attributes. While in both cases the monetary attribute has a negative coefficient, as expected by the theory, respondents in Class 2 do not take into account the number of people affected by the malfunction when making choices, while respondents in Class 1 do consider PERS2 and COUP3. On the contrary, the coefficient of SENS3 is not significant in Class 1. PERS3 and COUP2 are not significant in both classes, meaning that the number of people affected above a certain threshold and water service interruptions of short duration have no statistical difference with the base level. Above all, the remaining attribute levels have opposite signs: while the presence of REST2, REST3 and SENS2 in an alternative positively affects the probability of choosing this alternative in Class 2, it negatively affects it in Class 1.

All the variables involved in class-membership[4] relate to risk perception and information/knowledge, all the more so because, as noted above, both AVERSE and EFFECTIVENESS are highly linked to risk perception. Choosing drinking water supply reliability as one of the three biggest challenges in water resource management decreases the likelihood of Class 1 membership. This first class can also be explained by being more likely to choose the municipal/metropolis administration as the most trusted bodies regarding the quality of water supply in the municipality, to be unaware of the origin of water distributed from the water system and to rate the information provided regarding the water supply service quality as good or very good. And being risk-averse increases likelihood of Class 1 membership while considering the cyber-attack protection measures proposed in the valuation scenario as effective decreases this likelihood. Finally, the more people say they pay their water bill to a trustee (suggesting that they live in a flat rather than in a house), the more they are likely to belong to Class 1.

The results of Model 2 also highlight significant heterogeneity in preferences among respondents. Regarding the non-monetary attributes, Class 1-members only take into account PERS2 and COUP3 whose sign is negative. Class 3-members positively consider REST2 and 3 and SENS2 and 3. In Class 2, the coefficients suggest a negative relation between the medium and high levels of most attributes and the probability of choice. And these coefficients are very high compared to other classes. As in Model 1, no class is considering COUP2, i.e. water service interruptions of short duration. Finally, while negative for Classes 1 and 3, the coefficient of the cost attribute is not significant for Class 2. In other words, a small portion of the respondents (i.e. Class 2-members) strongly dislike most of proposed decrease in the consequences of cyber-attacks, without considering the cost.

The results of Model 3 confirm the existence of preference heterogeneity. Class-1 members take into account all attribute levels except COUP3, while Class-2 members do not consider PERS2, COUP2 and COUP3. Class-3 members do not consider COUP2 and SENS3 and Class-4 members do not base their choices on COUP2, REST2, REST3 and SENS2. While the two levels of the number of people affected by the malfunction have a positive coefficient in Class-1, they are negative in the three other classes. The same applies to the duration of restrictions on water consumption and services for vulnerable people whose coefficients are positive in Classes 1 and 2 but negative in Class-3. Most importantly, while negative for Classes 1 and 4, the coefficient of the cost attribute is not significant for Classes 2 and 3. As in Model 2, a small share of the respondents (i.e. Class 3-members) strongly dislikes most of

[4] These variables have an influence on an individuals' assignment to the classes. Class 2, Class 3 and Class 4 represent the reference group in Model 1, Model 2 and Model 3, respectively.

the proposed attribute levels, without considering the cost. Approximately one quarter gives a more nuanced view, but still disregards the cost (i.e. Class 2-members).

For the purpose of calculating WTP for greater resilience of the water distribution system, the remainder of this article will in consequence focus on results of Model 1. We can however note that Model 2 contains all class-membership variables involved in Model 1 except AVERSE and RELIABILITY. When BILL, QUALITY, ORIGIN and INFORMATION equal 1, the likelihood of Class 2 membership increases; EFFECTIVENESS taking a value of 1 decreases this likelihood. The first class on the other hand is only explained by being unaware of the origin of water distributed from the water system. Very few variables play a role in explaining class-membership in Model 3. Only BILL, QUALITY and EFFECTIVENESS influence the likelihood of Class 3 membership, the first two positively and the last one negatively.

In conclusion with regards to Model 1, the two subgroups present noteworthy differences in terms of preferences for resilience attributes (different variables are significant and when this happens the coefficients are of opposite sign). Class-membership depends on: (i) being risk averse, (ii) being unaware of the origin of supplied water and, at the same time, trusting the municipal/metropolis administration when it comes to water service quality and considering the information provided regarding this quality good or very good, or (iii) not choosing drinking water supply reliability as one of the three biggest challenges in water resource management and, at the same time, considering the cyber-attack protection measures proposed in the valuation scenario to be effective. It would thus be interesting to know more about the characteristics of the individuals in each class.

5.2. Class characterisation

To identify and characterize the two classes, we assigned each individual to the class to which they had the greatest probability of belonging. Only a few characteristics are significantly different between classes when we have tested a large number of variables (Table 6). People in Class 2 are younger and the number of adults in their household is higher. There is also a larger proportion of people who think that public spending should be targeted at environmental protection but a smaller proportion of people who state that the water price is one of the three most important criteria for a high-quality water supply service. Other than that, the two classes are very similar in terms of water consumption habits, risk perception, assessment of their water supply service and the socio-economic characteristics of respondents.

Table 6: Descriptive statistics for select variables by class

	Class 1 (n=81)	**Class 2 (n=251)**
Mean		
Age*	59	34
Number of adults in the household**	0.65	0.92
Number of children in the household	0.25	0.32
Mean acceptable maximum duration for water cuts (in hours) / for restriction of water uses (in days)	18.6 / 4.41	16.6 / 13.98
%		
Is a Strasbourg resident	56.8	65.3
Is a woman	48.1	55.8
Is retired	11.2	7.3
Holds at least a Master degree	16.2	15.5
Pursues a professional activity or studies relating to environment / water / risks / health	15.8 / 6.7 / 11.8 / 20.8	17.6 / 10.5 / 16.8 / 27.9
Is a member of an association	34.2	27.4
Says that most of the time adult members / children of the household drink bottled water	33.3 / 11.6	29.1 /11.6
Says that the age or the health of one member of the household makes them sensitive to water cuts / to changes to water quality	41.4 / 39.3	36.4 / 32.2
Thinks that public spending should be targeted at environmental protection**	35.4	50.8
Does not know the amount of their water bill	76.5	74.9
Thinks that drinking tap water poses a health risk generally speaking / in their municipality	19.0 / 18.8	28.8 / 24.2
Thinks that the quality of their tap water is good or very good	75.3	77.7
Thinks that the tap water will be of better or really better quality in 5 years in their municipality	12.3	12.4
Does not know who manages the drinking water distribution in their municipality	34.6	28.3
Chooses the water price as one of the three most important criteria for a high-quality water supply service***	41.8	20.7
Thinks that their water utility is currently at risk of a cyber-attack	13.6	14.7
Does not trust any institution when it comes to risk management	9.5	10.5
Feels at (high) risk of a malfunction in their drinking water supply system	8.6	11.2
Has already experienced a malfunction in their drinking water supply system	12.3	16.0

Note: ***, **, * mean that the characteristics are significantly different between the two classes on the basis of a mean comparison or a chi-square test resp. at the ***1%, **5% and *10% level

5.3. Willingness-to-pay estimates

Marginal WTP were calculated for each attribute and for each class and confidence intervals were estimated using the delta method [33, 58] (Table 7). Results show that respondents from Class 2 display high WTP to benefit from a lower duration of restrictions on water consumption for drinking and cooking (be it 5 days or 4 days) and for services for vulnerable people (be they exhaustive or exhaustive and customised). Class 1-members exhibit diametrically opposed opinions regarding the two duration levels for water consumption restrictions and the exhaustive services for vulnerable people since they experience disutility from these attributes. On average, they are also not willing to pay for a decrease in the duration of the water service interruption from four to two hours and for a decrease in the number of people affected by the malfunction from 400,000 to 200,000. In other words, they are willing to pay €17.35 less per household for a reduction of the number of people affected should the resilience programs be implemented.

Table 7: Marginal WTP estimates

	Class 1		**Class 2**	
PERS2	-17.35**	(-32,77; -1,93)	5.11	(-2,14; 12,36)
PERS3	-6.31	(-15,44; 2,83)	2.35	(-5,60; 10,29)
COUP2	-1.88	(-10,30; 6,54)	3.69	(-3,63; 11,01)
COUP3	-13.75***	(-23,70; -3,80)	0.15	(-6,63; 6,93)
REST2	-12.21**	(-22,69; -1,73)	18.10***	(9,82; 26,38)
REST3	-8.23*	(-16,47; 0,01)	12.42***	(5,54; 19,30)
SENS2	-10.01*	(-21,06; 1,04)	33.61***	(22,32; 44,89)
SENS3	-0.36	(-7,90; 7,18)	44.93***	(31,09; 58,77)

Note: Variables are significant at the ***1%, **5% and *10% level. Confidence intervals at a 95% level are reported in parentheses.

These figures must be compared with the reference water bill which, using the average annual French consumption of 120 m^3 and the Eurometropolis of Strasbourg water price[5], was calculated to be €193 in 2018. The highest WTP, that is to say the willingness to pay of respondents from Class 2 for exhaustive services for vulnerable people that take individual needs into account rather than partial services, represents less than one quarter of that amount. It is worth recalling that the estimated WTP are assumed to be lump-sum payments.

6. Discussion and conclusion

This article presents an assessment of the preferences of residents with regard to the resilience of a drinking water distribution network subject to a cyber-attack, based on a survey of the Eurometropolis of Strasbourg in France. Our research contributes to the scarce body of studies on the economic efficiency of measures aimed at making critical infrastructure, water distribution networks in our case, more resilient. Several conclusions can be drawn from it.

First, our descriptive statistics highlight the importance of knowledge. We observed on several occasions that answering "Does not know" to a question increases the probability of giving the same answer elsewhere in the survey. Knowledge and information also help explain the heterogeneous nature of preferences. Quality of the information provided regarding the water supply service quality and ignorance of the origin of the water distributed by the system are among the variables that explain the class-membership in the latent class model. This result may be linked to the general public's lack of familiarity with the resilience of the drinking water distribution network [59] and, more generally, with water infrastructure

[5] We only consider here the price of drinking water, i.e. €1.60 per m^3. When treating waste water is taken into account, the reference bill amounts €343.20 (€2.86 per m^3).

management. Tailored and targeted communication campaigns could therefore prove useful to increase users' awareness and understanding of the underlying issues and thereby the public commitment to resilience policies and their acceptability, leading to their successful implementation [60].

Second, we have seen that in terms of personal characteristics, the choice determinants chiefly concern risk perception: statement that a member of the household is sensitive to water quality variation or water cuts, assessment of water quality in general or in the municipality, assessment of current exposure of the WDN to risks, etc. Variables linked to risk perception are also the ones that play a role in the class-membership in the 2-class latent class model. This finding is in accordance with Rulleau and Rey-Valette [61] who showed that risk perception has more influence on choices than the socio-economic characteristics traditionally used in econometric modelling.

Finally, the results of our 2-class latent class model highlight the desirability, for a large proportion of the Eurometropolis of Strasbourg respondents (i.e. those belonging to Class 2), of water distribution network resilience measures aimed at mitigating some effects of a cyber-attack. More precisely, these younger and more environmentally conscious residents (who say that public spending should be targeted at environmental protection) value: (i) a reduction of the duration of restrictions on water consumption for drinking and cooking, while drinking water potability tests are carried out and (ii) the providing of services for people regarded as "vulnerable", i.e. the elderly and infirm, who cannot attend the water distribution points, or those who are not able to read or understand safety instructions.

However, this does not apply to the population as a whole since about one quarter of our sample exhibit completely opposite preferences (i.e. respondents belonging to Class 1): they do not value the same attributes and, when this happens, their WTP has a negative coefficient. As the only distinctive characteristics of these residents are their age and that they chose water price as one of the three most important criteria for a high-quality water supply service, the underlying reasons for such differences are not obvious, all more so given that, like Class 2-members, three quarters of them did not know the amount of their water bill. This figure echoes that of other studies conducted at national level in France [62] and further reinforces the need for more accurate information on the drinking-water sector: French water utilities are required by Law to send at least once a year information about the name and address of the operator, the water price, the water quality etc. together with the water bill. Possibly, these particular preferences may be linked to some form of free-riding. If so, the fact that WTP of Class 2-members is much lower than the current reference water bill and that WTP are assumed to be lump-sum payments may help water utilities in developing relevant policies and financing plans for resilience policies, especially since the implementation of such policies may generate economies of scale and efficiency gains [63].

Finally, it may be noted that the number of people affected by the malfunctions and hours of water service interruption are not valued by Class 2-members and that respondents in Class 1 exhibit a significant and negative WTP for PERS2 and COUP3. This result is, however, not surprising given the high figures given in response to the open-ended questions concerning the acceptable maximum duration for water cuts (15 hours on average) and for water usage restrictions (8 days and 15 hours on average). It can also be explained by Powe et al.'s [64] finding that households are reluctant to pay for any improvement when they feel that the current level of service is already sufficient.

Our work is not directly comparable to other published results since it is the first of its kind. However, it provides important information for the decision-makers, given that it is reasonable to assume that damage, disruption, and reconstruction costs in the case of a crisis would be very high and greatly outweigh the investment costs in resilience programs [17]. This calls for further research on other types of human-induced risks (e.g. intentional contamination of water) and on the potential “domino effect”, whereby malfunctions to one infrastructure cascade to a myriad of other infrastructures [3, 4].

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