

## Article

# A Proposed Theoretical Approach for the Estimation of Seismic Structural Vulnerability of Wastewater Treatment Plants

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**Abstract:** The assessment of seismic vulnerability is critical for lifelines such as wastewater treatment plants (WTPs) because failures may result in environmental degradation, deterioration of water quality and human diseases development. The main scope of this research is the testing and application of a rapid, simple methodology for assessing the seismic structural vulnerability (SSV) of WTPs (according to the qualitative method Rapid Visual Screening), using structural variables as indices of these infrastructures. An original new method involving the assessment of the SSV of thirteen steps (four for a sample set of WTPs and nine for an individual one) is introduced following systematic literature retrieval. The analysis highlights twenty one factors that may determine the SSV of WTPs: three factors involving general characteristics, five factors involving seismicity and geotechnical data, six factors involving technical data (including structural data) and seven additional factors about WTPs' materials (concrete and the steel reinforcement of concrete frames). The structural data is analyzed to six additional factors. The implementation of the proposed methodology constitutes a simple, rapid methodological approach for assessing the SSV of WTPs using unique factors that were pinpointed and identified for the first time in this study.

**Keywords:** structural vulnerability; seismicity; Wastewater Treatment Plants; sustainability



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## 1. Introduction

The increased incidence of natural and technological disasters in recent years poses threats to infrastructures. Climate change, construction complexity, and urbanization can have more extended impacts on WTPs than earthquakes [1], especially if a multicriteria analysis related to urban geology and urban geomorphology is not included in proactive planning against natural hazards [2]. The vulnerability of sewage systems is increased if other factors (such as contamination of surface waters by organochlorine pesticides) exist in addition to potential fluid leakages [3]. Earthquakes affecting wastewater treatment plants (WTPs) may trigger other hazards such as liquefaction, landslides, tsunamis, fires, and odours, as well as karst collapse [4]. The effects of these hazards remain in the environment for many years, posing a risk to health and public safety and negatively influencing sustainability development. Wildfires caused by earthquakes or urban fires can release toxic elements into the soil and water resources [5].

The “Sendai Framework for Disaster Risk Reduction 2015–2030” established the principles of the prevention and mitigation of disasters through the Sendai World Conference [6]. Researchers in earthquake-prone countries such as Greece [7] have recorded earthquake events and construction assets during vulnerability assessments after significant [8,9] or catastrophic earthquakes [10]. HAZUS methods have been implemented to assess infrastructure in EU projects [11]. Methods of estimating the impacts of earthquakes have been raised [12]. Practically, the most important buildings and infrastructures must be checked

as a priority due to the created costs and huge effects of seismic disasters. Another priority is the health and safety of people and the protection of the environment.

According to the United Nations, Sustainability Development (SD) is one of society's main priorities. The goals of SD include "Good Health and Well-being", "Clean Water and Sanitation", "Sustainable Cities and Communities", and "Industry, Innovation, and Infrastructure" [13]. Earthquake damage to WTPs may influence infected individuals' health, because it may push infected people to maintain unsanitary practices, such as open defecation. Resilient infrastructure is an urgent need for sustainable cities to ensure human and environmental safety. Previous research highlights that "Novel sustainability concepts, approaches, methods and tools need to be developed" [14]. The European Union is committed to the implementation of SD, as documented in Agenda 2030 of the United Nations [15]. Previously conducted surveys have focused on environmental sustainability, aiming to minimize the economic cost of treatment. Tools for supporting management have been developed [16].

WTPs are a critical type of infrastructure that operates as a lifeline. The increase in the total development of the conduit length of pipelines in Japan has occurred due to an increase in the population and has resulted in considerable financial costs and extended periods of restoration (after seismic impacts) [17]. Sewage facilities such as sewers, pumping stations, and WTPs may be damaged by an earthquake [18]. The more vulnerable facilities are the worst designed [19]. The assessment of their vulnerability requires a disciplinary scientific approach [20]. The evaluation of the seismic structural vulnerability of WTPs in earthquake-prone countries or regions using concrete is fascinating. The impacts of an earthquake on WTPs may cause malfunctioning or non-operation, resulting in increased risks for both human health [21] and the environment [22]. In case of a disaster, the psychology of the citizens, families and children may also be affected at anywhere, e.g., at home and at work. Additional effects will be created as many other lifelines would be out of control.

The effects of seismic impacts have a direct relationship with sustainability principles. Following the Kobe earthquake in Japan (1995), many WTPs were quake-stricken. The restoration of these WTPs was part of the reconstruction actions [23]. Twenty out of the twenty-three pumping stations in the area were damaged and rendered useless, primarily due to power outages. The impacts of 15 great earthquakes from 1989 to 2011 have been recorded [24,25]. It is mentioned that WTPs were part of the affected areas. Many facilities, such as pumping stations, were destroyed during the New Zealand earthquake. Following the 1999 Taiwan and the 1995 Northridge earthquakes, a power outage involving pumping stations influenced the nonstructural vulnerability of WTPs. During the 1999 Turkey earthquake, heavy damage to mechanical equipment occurred. Similar damage to large-diameter interceptor pipes and small-diameter connection pipes was also observed during the Chile earthquake in 2010. The 2007 Gisborne earthquake caused minor damage to mechanical parts, and all the sewage systems collapsed due to the tsunami in Thailand in 2004. Changes in oceanographic characteristics near WTPs' outlets (such as ocean pollution in Izmit bay after the 1999 Turkey earthquake and the accumulation of sewage solids in the harbor during the 1931 New Zealand earthquake) can cause serious problems [26]. During the 1989 earthquake in Loma Prieta, California, liquefaction and damage to older buildings (in areas without antiseismic design) influenced steel tanks, a post-tensioned and pre-stressed concrete tank, and mechanical equipment. These seismic impacts led to the loss of commercial power [27]. According to the Oregon Resilience Plan for Water and Wastewater Systems, essential facilities (such as intakes, treatment plants, pump stations, and outfalls) are vulnerable to damage from liquefaction [28]. The sewage pipeline network is susceptible to failure from permanent ground deformations, causing an increasing degree of damage over time that also affects society [17,29]. Pipelines are prone to failure at connections with these essential facilities. In Des Moines, Iowa, due to the 1993 earthquake, floods led to a loss of water [30], which is useful for WTP facilities.

Europe adopted rules (called Eurocodes) to construct structures, aiming to harmonize the Member States' other design traditions [31]. Nationally Determined Parameters (NDPs) are included in them. The Eurocodes consist of 10 European Standards (EN1990–1999) covering areas such as the basis of structural design (EN1990), the actions of structures (EN1991), the design of concrete structures (EN1992), the design of steel structures (EN1993), the design of composite steel and concrete frames (EN1994), geotechnical design (EN1997), and the creation of structures for earthquake resistance (EN1998). Each Code (except EN 1990) is divided into 58 Parts covering specific aspects in detail. In Greece, the Eurocodes were completed in 2007 and legislated in 2014, with implementation occurring in parallel with the implementation of the National building regulations (GGG 1457/B/2014). In the United States, the implementation of building codes such as the International Building Code (IBC) and the International Existing Building Code (IEBC) have helped to strengthen WTPs.

The United States has not adopted rules on the structural vulnerability of WTPs such as the “Water and Wastewater Systems Sector-Specific Plan” [32] or the “Roadmap to a Secure and Resilient Water and Wastewater Sector”. Assessments of the seismic risk of WTPs are not required by the Environment Protection Agency, but some WTPs prepare these without structural or nonstructural vulnerabilities [33]. Instead, the Federal Emergency Management Administration (FEMA) has tried to enhance resilience and SD by using fragility curves and new technologies (Geographical Information Systems, GIS) for seismic structural assessment, although this may result in many failures [34]. The project HAZUS, which operates under the above mentioned holistic view of structures, evaluates vulnerability in terms of losses and financial terms [35]. The European Union produced an overview of the existing methodologies used worldwide for practical risk assessment of critical infrastructures [36].

The European Programme for Critical Infrastructure Protection (EPCIP) and the US Critical Infrastructure Protection (CIP) operate with different views. These programs are based on SD in order to address the key factors of financial and human losses. The American Society of Civil Engineers (ASCE) specifies Guidelines for the seismic evaluation of water transmission facilities such as WTPs [37]. Structural failures are investigated according to the functions of WTP structures, the materials used (e.g., reinforced concrete, steel, PVC, HDPE, and GRP), and the pipeline network [28].

In Greece, the Syner-G Program named “Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks, and Infrastructures’ Safety Gain” was developed to estimate the seismic vulnerability of these structures [11,38]. Structural parameters were investigated by another Pan-Hellenic Project by the Earthquake Planning and Protection Organization (EPPO), which is currently active and is related to the seismic structural vulnerability of public buildings and public welfare institutions. It is a primary-stage pre-earthquake assessment and is based on rapid visual inspection using structural variables [39,40]. Table S1 in the Supplementary Material presents the abbreviations and definitions in this study.

## 2. Potential Threats to Water and Soil Quality

The importance of sustainability has been increasing [30]. Countries must implement governance for disaster risk management in parallel with environmental control [29]. The response and motivation of the authorities are essential, according to the rules of civil protection. Delays in these mechanisms may lead to the direct or indirect degradation of the environment. The planning of structures must follow the main principle “growth must meet today’s needs without jeopardizing the well-being of future generations”.

Structures must reduce their energy consumption (or produce energy from wastewater), and their materials must acquire increased strength to withstand increased seismic forces. Best practices advise stakeholders to mitigate against the impacts of disasters and preserve earth sources [30,41]. WTP planning must involve an increase in resilience, the reuse of effluent water, and the management of seismic impacts [42].

A high-intensity earthquake that occurs in an area containing WTPs may lead to disaster. Consequences may be immediate or long-term in terms of time and being local, national, or global. Damage to or malfunctions of infrastructure may trigger the contamination of soil, water, and air [43]. Fluid or air leakage may cause the ignition and explosion of flammable materials. Accidental discharge of wastewater into water resources may increase the contamination of a stressed area of society. Damaged sewer pipes can release sewage or waste, including toxic components.

Furthermore, a fire in petroleum refinery infrastructure that had broken out during the Turkey earthquake in 2000 caused the death of three inhabitants and the release of exhaust gases and particulate matter to the environment. During the 1995 Kobe (Japan) earthquake, asbestos fibers were released. Climate change may aggravate the situation, leading to more frequent fires and the release of dangerous materials [5,44]. Other disasters such as inundations or heavy rainfall may contribute to the dispersal of hazardous materials.

In case that the nutrients and elements concentration in untreated sewage of WTPs exceed the corresponding parametric values proposed by the Directive 91/271/EEC may have a serious impact on human health and ecosystems [45]. Chloride leakages from a WTP deposit occurred after the 1987 California earthquake [1]. The priority of countries regarding SD is to mitigate the impacts of disasters on the environment and human beings [46].

Disinfection byproducts, volatile organic compounds and other materials released from WTPs which contain heavy metals (e.g., Co, Cr, As, Ni, and Pb) may affect seriously ecology, ecosystems, and inhabitants' health [47,48]. Civil protection authorities should investigate areas immediately with increased concentrations of trace elements.

At present, the amount of pollution threatening soil and/or water is much more significant due to climate change, urbanization, and ageing structures [49]. The impacts of these events co-occurring are much more critical than the pollution of each of them independently.

### 3. Estimation of WTPs' SSV—Future Needs

The assessment of the seismic vulnerability of structures has been researched using categorization methodologies to quantify the level of damage to structural elements [50]. Few surveys about the resilience of WTPs have been conducted due to the great effort and costs involved [42]. Many parameters, such as the vulnerability of materials used in these structures, their contribution to structural vulnerability, and the relationships among different elements of vulnerability, have not been assessed. New studies must identify the seismic vulnerability and resilience of WTPs (using a specific methodology), considering structural factors.

The planning and management of WTPs must meet two of the four fields that SD is focused on, i.e., water management—wastewater treatment and environmental engineering and management [51]. The creation of action plans on a large scale using innovative, practical solutions is required. These infrastructures focus on operational environmental performance but must increase the level of ecological thinking across the whole sector (including vulnerability factors coming from other scientific fields) [46].

Researchers have approached sustainability through the use of conceptual and mathematical assets [52] using indicators of the SD of WTPs [53] and investigating technical assets (such as the monitoring of pollutant removal) [16]. It has been observed that there is a lack of structural asset approaches for these infrastructures. Materials such as concrete are subject to building rules regarding their durability and corrosive exposure (such as carbonation or frost). The result of these is the changing of their sustainability degree [54]. This study investigates the criteria and variables that must be identified for the structural vulnerability assessment of WTPs. The structural requirements of factors that affect the structural vulnerability assessment of WTPs are the same as those used for standard structural buildings. Still, additional parameters, such as acid resistance, must be considered [55,56]. An approach focusing on structural vulnerability parameters (in addition to

existing methods) could aid in urban and rural planning using new technologies such as GIS [57].

In this study, a new methodology involving rapid visual inspection by technicians with the ultimate goal of sustainable development is proposed. Currently, there is no similar universal fast estimation method for these facilities. The methodology is categorized as an empirical assessment approach, and the next step must be to develop a questionnaire for Rapid Visual Screening [50]. Similar questionnaires have been used in Canada, Japan, Turkey, Greece, New Zealand, and India, as practical methods. An example of this approach used in Greece is a questionnaire about the variation in the individual seismic structural assessment standards of public and public-use buildings described by the EPPO [39]. A future questionnaire based on the proposed methodology would enrich previous research [57] that has attempted to adapt the EPPO's questionnaire and to make it appropriate for the needs of WTPs. The survey highlights the further enrichment and analysis of SSV factors in WTPs made from reinforced concrete, a material with many ambiguities compared with other standard materials used. Another attempt to focus on seismic vulnerability factors related to WTPs was then conducted for the whole infrastructure [58], especially for SSV [59]. The enriched categorization of these factors in a questionnaire that contributes to the investigation of the seismic vulnerability of WTPs is shown in this study.

Other researchers tried to introduce surveys using questionnaires about the variables related to the effects of WTPs as a method of rapid assessment, as time is a crucial factor in this type of assessment [60]. This method facilitated the formation of opinions by elected officials (technical specialists, decision-makers, stakeholders) through a multi-objective decision analysis of the questionnaires. The above approach involved six main questionnaires, including nine criteria for evaluating a WTP. According to local rules, the minimization of construction impacts included only the minimization of erosion and the insurance of operations.

#### 4. Proposed Method

The proposed method for the rapid assessment of SSV includes the following phases [61] and is similar to the planning of the "All-hazard Consequence Management Tool" that was proposed by the Water Environment Federation [62]. The sample set of WTPs involves several representative WTPs. The proposed methodology will be applied initially. The findings of this step will be used for possible revisions of a questionnaire sheet and as an input for Phase B. Phase A investigates the weighting factors of a sample set of WTPs, while the Phase B estimate the SSV score and compare the sample set of Phase A. A qualitative scale is used to visualize the results to protect individual WTPs.

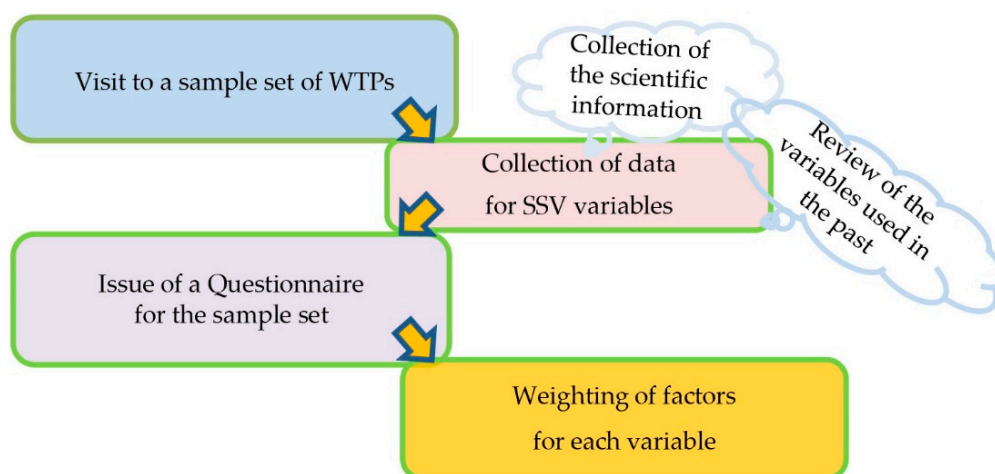
##### 4.1. Investigating the SSV of a Sample Set of WTPs

Phase A uses an obligatory step for the collection of SSV data. This is useful for future assessments of the SSV of an individual WTP, done using Phase B. The data must come from a representative sample set of WTPs using statistical methods. The means for conducting this assessment must be based on reliable and valid investigations. Figure 1 illustrates the steps required for the collection of SSV data of a WTP sample set.

1. An inspectional visit to a sample set of WTPs to check the characteristics of their facilities: The impacts of flows on the structural components can only be investigated by contacting the facilities [63].
2. Collection of data: involves records, studies, interviews, and questionnaires. The assessment of SSV will be more accurate if many significant variables are collected.
  - Collection of the scientific information (seismological, geotechnical, and technical data about its parts): Any data associated with the processes of a WTP [64], the structure itself [9], and the seismic vulnerability, including geotechnical data [25], help assess the vulnerability. Structural variables can be used as indices, similar to empirical methods [50].



- Review of the variables used in the past. Any existing records about structural variables such as concrete tests conducted before or after the repair of seismic impacts and specific variables extracted from the Antiseismic Codes of construction times may be helpful. Geological or technical data (mentioned before) about the structure may be part of the set of data to be utilized.
3. Issue a questionnaire to the survey participants. The questionnaire must include all the SSV variables mentioned, and their validity and reliability must be investigated. The participants in the survey must have relevant education or training and great experience with WTPs.
  4. Weighting of factors for each of the above variables: Simple empirical values are often used to estimate structures (even at WTPs), such as equations used related to SD and cost issues [64]. In this study, the nomination of parameters must be followed by the weighting of these factors, because some parameters have more significant impacts (e.g., the foundation of the WTP) than others (e.g., the environmental temperature when the concrete was poured). A similar approach was implemented in another survey conducted by Keeney et al. [60] in WTPs of Seattle (USA).

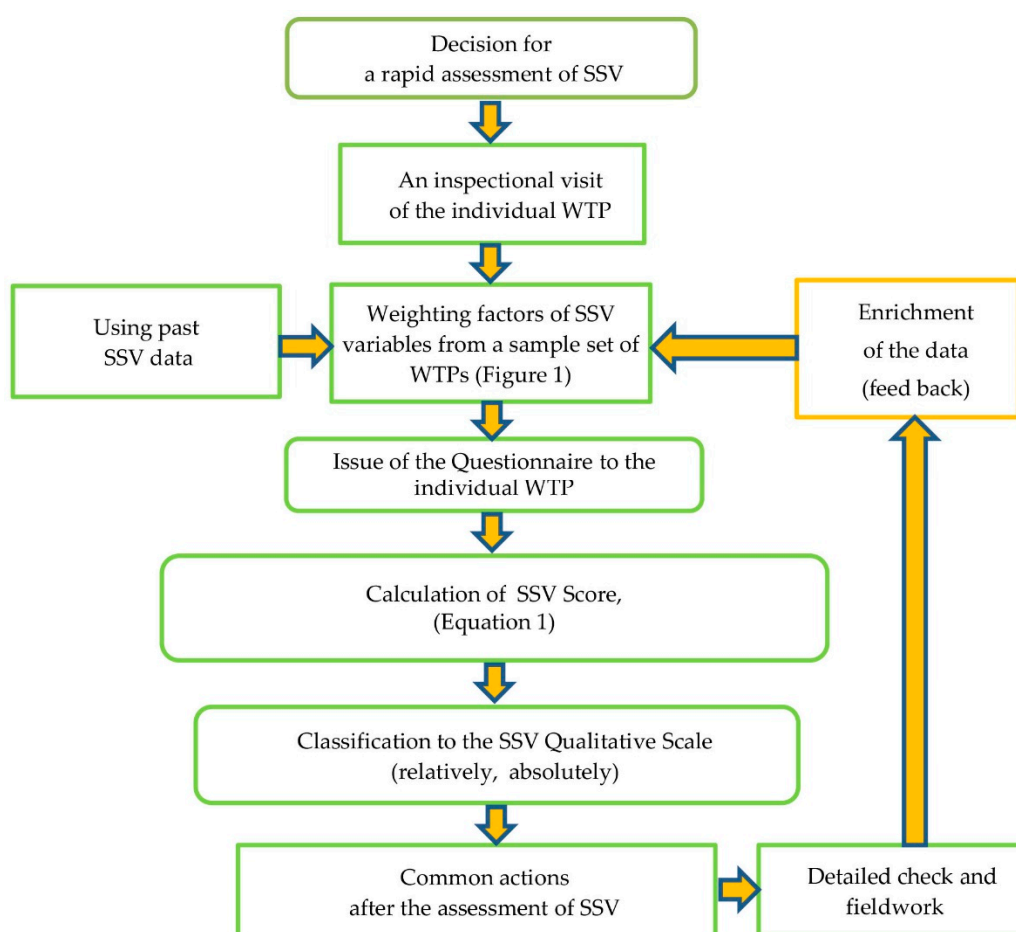


**Figure 1.** Investigating the SSV weighting factors from a sample set of WTPs (Phase A).

Weighting factors, such as the frequency of occurrence, related to the means of collecting data, e.g., the survey participants' answers to the SSV questionnaire, are calculated. The central tendency and variability of the SSV variables will assist in the definition of weighting factors. The determination of weighting factors completes Phase A.

#### 4.2. Investigating the SSV of an Individual WTP

Phase B follows the following nine steps that are suggested for the estimators for the evaluation of WTPs (Figure 2). First, the estimator decides against conducting a rapid assessment of SSV. The potential risk related to a decision depends on people's perception of risk, the time and means available, and the management of collected data as financial issues as well as the percentage of SD achieved. Economic, social, and environmental considerations may encourage a researcher to investigate the final structural values in a certain way [65]. An absence of qualitative scales or weighting factors for SSV variables from the past will trigger research (as described before) to investigate these weighting factors from a sample set of WTPs.



**Figure 2.** Investigating the SSV of an individual WTP (Phase B).

Additionally, an inspectional visit to the individual WTP is needed. Methods similar to questionnaires are used to collect scientific data about infrastructures. Each factor's weighted value is calculated as described in the previous stage (Phase A). Descriptive statistics assist in the determination of the weighting factors. It is considered that the weighting used for factors in the individual WTP questionnaire is the same as that used when assessing the sample set of WTPs. The score (total value) of a WTP's SSV is equal to the total value of each factor multiplied by its SSV weighting. This is done using Equation (1) as follows [66]:

$$\text{Score} = \sum (\text{Weight of factor} * \text{Factor}). \quad (1)$$

A qualitative scale for assessing SSV based on the above quantitative weighted variables of the WTP sample set is developed. The correlation of the scores of individual WTPs with the maximum and minimum values of similar products in the sample set of WTPs can assist in defining the relative qualitative scale for assessing SSV. The relative classification of the SSV of an individual WTP in question compares its score with similar scores in the sample set of WTPs. Scientists have stated that ordinal classification could benefit from the use of available relative information [67].

The final absolute classification is processed by constructing a whole qualitative scale, which includes the average individual WTP scores for the SSV factors compared with the ideal maximum and minimum scores expected for the sample set of WTPs.

This step in Phase B involves the classification of scores on the Qualitative Scale, which estimates SSV according to the SSV of the sample set of WTPs, in both relative (compared with each other) and absolute (corresponding to the desirability results accord-

ing to the rules) terms. The assessment of the SSV of an individual WTP is performed. The absolute and relative classification of any WTP in question can be achieved using the abovementioned SSV qualitative scales. These results offer inestimable value to SD planning and implementation.

After assessing the SSV of any WTP, another joint action conducted may be detailed checking and fieldwork if the level of vulnerability is significant (or if no structural factors can be evaluated). Depending on the circumstances, everyday actions conducted after assessing a WTP's SSV are the implementation of urgent/emergency protective meters on the structure (to prevent malfunctions or non-function). These situations will cause heavy consequences to the inhabitants of the affected area and the environment. Any detailed in situ check will provide valuable data about the seismic vulnerability of the structures [68].

Everyday actions conducted after the assessment of the SSV of any WTP may involve the enrichment of data using raw data related to the investigation's questionnaire with the results of the above calculation. Valuable data will be used for the restoration of existing problems. Feedback is necessary, as future estimates of SSV will use more updated data. The update of SD planning and actions is imperative.

## 5. Description of the Variables

After analyzing the collected data, as described previously (Figure 2, Phase B), we concluded that the method's variables must be in accordance with the nominated ones and the limits of the building rules. In Greece, these rules are the Eurocodes and the Greek Code for Seismic Resistant Structures (GCSRS) [69], Greek Code for Reinforced Concrete (GCRC), which are used for usual construction projects (or even the Greek Code of Structural Interventions). Remarkably, most countries' structures were built prior to the SD principles becoming part of the building rules.

Experience with impacts on WTPs should be incorporated into the countries' building rules. Other empirical approaches use a Seismic Priority Index consisting of variables that can estimate the levels of risk and vulnerability [50]. Similarly, a questionnaire may include the following elements that are important for assessing SSV.

Figure 3A–D shows the four main parts that are important for evaluating of SSV, including the general characteristics of WTPs, seismicity and geotechnical settings, technical factors and the material used for the construction of WTPs.

### 5.1. The General Characteristics of WTPs

#### 5.1.1. Year of Construction and Year of Last Intervention/Addition

This factor is directly related to the structural regulations at the time [28]. Researchers of the great earthquake that occurred in Bhuj in 2001 stated that reinforced concrete (RC) frames built in previous decades were more vulnerable than other structures built in recent years [70]. Sendai in Japan has sewage facilities that are more than 118 years old [18], and the process and auxiliary equipment in the WTP of the Sewer Authority Mid-Coastside have expired [33]. Earlier structure studies produce more safe conditions.

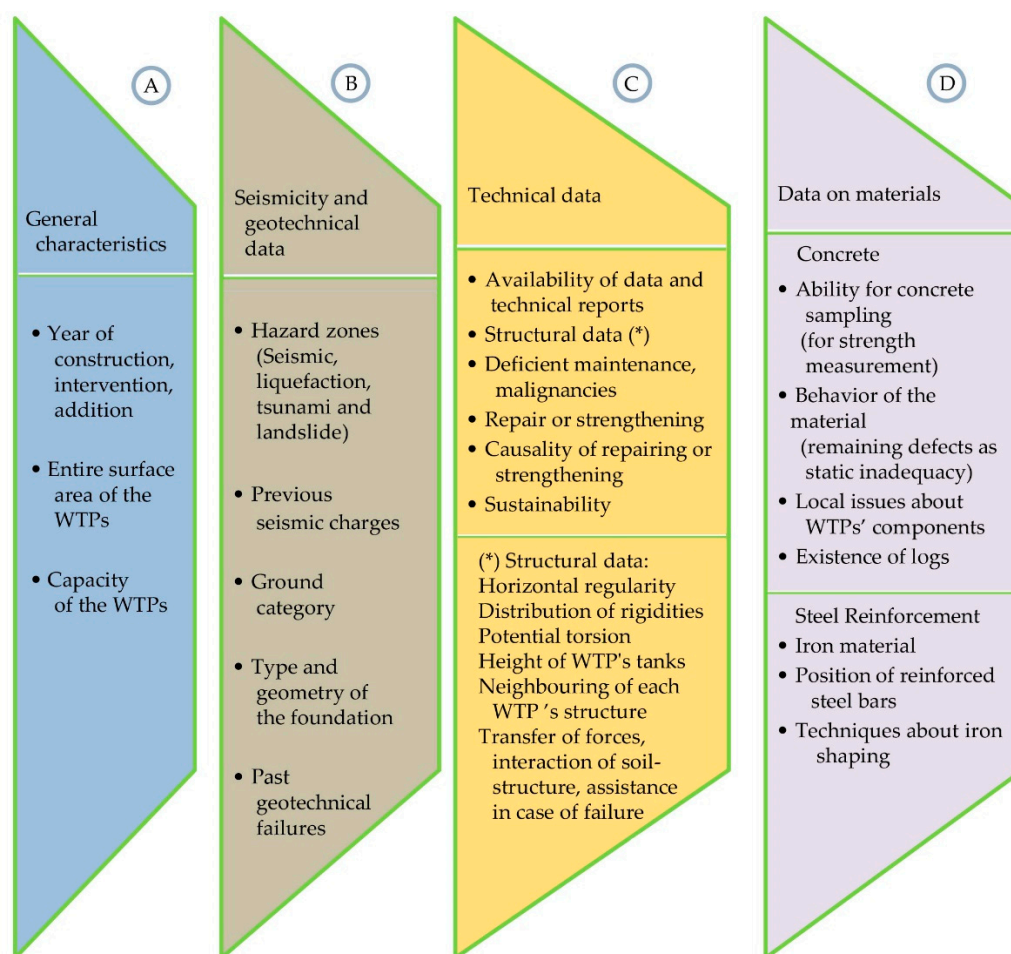
#### 5.1.2. Entire Surface Area of the WTPs

Measurement of the entire surface area is helpful as an estimator to calculate the "serving population". The maximum population that the infrastructure will serve is known as the "serving population". A proportional relationship exists between served populations and the surface area of each WTP [71].

#### 5.1.3. Capacity of the WTPs

The importance of WTPs is more significant than usual buildings and depends on the population served because of the potential seismic impacts on them. A large population needs more facilities for sewage treatment. Domestic sewage needs primary and/or secondary treatment, and wastewater from industries also requires tertiary treatment [72]. A low level of inclusion of SD principles may increase the vulnerability of WTPs.





**Figure 3.** SSV variables of WTPs: (A) General characteristics, (B) Seismicity and geotechnical data, (C) Technical data, (D) Data on construction materials.

### 5.2. Seismicity and Geotechnical Data

Earthquakes are an acute stressor of WTP facilities [42]. Seismic and geological data related to WTPs should be classified as critical vulnerability variables that must be recorded.

#### 5.2.1. Seismic Hazard Zone

The seismic data related to a country's areas determines which zones may be useful for vulnerability assessment [28]. Worldwide, in Europe, and in Greece, the formulation of these zones is based on peak ground acceleration (PGA) for a return period of 475 years [73–75]. In Greece, GCSRS categorizes the technical project areas in line with the expected acceleration of the soil [76].

Liquefaction, tsunamis, and landslide effects, as secondary phenomena, may influence structures. WTPs are usually established at lower heights (near rivers and/or near the sea) where alluvial deposits exist and liquefaction danger is serious. Using the wrong WTP settlement site may increase the seismic vulnerability, severely impacting the structure [77]. A possible tsunami may stress the structural framework [28]. Recorded data which include past events of liquefaction, tsunamis and landslides, is also valuable.

#### 5.2.2. Previous Seismic Charges

The existence of non-repaired damage to WTPs may change the structure, increasing its vulnerability. Records or testimonies may provide required data. Meanwhile, the

buildings' structural characteristics and ground-motion records following past earthquakes are used to export the fragility functions of typical buildings [78].

### 5.2.3. Ground Category

Additional information about the ground category may be collected from past data records and observations [79]. Data related to geological formations, water level, geomorphological relief and geological faults is crucial for estimating the related vulnerability factor [80]. Moreover, the ground categories used for common structures are categorized in Greece by GCSRS.

### 5.2.4. Type and Geometry of the Foundation

Data of seismic vulnerability factors is significant, because it is related to possible subsidence, seismic stress, fluctuation of water level and liquefaction [81].

### 5.2.5. Past Geotechnical Failures of the Broader Area

It is essential to develop a database record which include information related to past failures (e.g., landslides, liquefaction) in the region [82].

## 5.3. Technical Data

WTPs are critical infrastructures with special requirements regarding structural strength and sustainability, so special rules must be used to ensure maximum protection and safety for human and the environment. Remarkably, construction codes are used as the standard rules for usual buildings. The importance of introducing SSV parameters is necessary. Sustainability parameters are aggressively embedded in building rules.

In the United States, the IBC is one of the codes established by the International Code Council (ICC) based on its usage. It is the existing regulation for constructing buildings and structures. The IEBC sets out requirements for repairs, alterations, and additions to existing buildings and structures. WTPs are not subject to special building rules, as shown at the IBC, IEBC, and the Eurocodes of the European Union [31]. In Greece, structure laws like the Greek Codes for Reinforced Structures using Concrete [83] or the Code for Earthquake-Resistant Structures [69] (or even the Code of Structural Interventions 2012) do not refer to high-risk special constructions, e.g., WTPs, and their needs. As shown, no particular rules exist for building codes of structures (including WTPs) for the recording of structural values. Instead, these facilities are designed to have longer life cycles.

The technical variables for each part of a WTP are presented at the Section 5.3.1, Section 5.3.2, Section 5.3.3, Section 5.3.4, Section 5.3.5, Section 5.3.6 and should be examined, regardless of the type of treatment involved.

### 5.3.1. Availability of Data Records and Technical Reports

If the past technical reports are available, it is useful to compare them against the updated reports [84].

### 5.3.2. Structural Data

Structural data show similarities to the data required for standard buildings, as presented below:

- The horizontal regularity of each independent part of a WTP must be recorded. The shear walls of structures (as tanks) may experience failure after an earthquake [85];
- The distribution of its members' rigidity [86]: An earthquake may cause structural damage to sections with different levels of rigidity. After a strong earthquake, building damage mainly occurs because of the intense beams and weak columns of a building inside the WTP (such as the facilities' control building) [77].
- Potential torsion may affect the structure [87].

- The considerable height of a WTP's tanks may be a significant factor [88]. The large size of tanks leads to a great degree of shaking of the sewage, producing forces beyond its design capacity and increasing its seismic vulnerability [28].
- The close neighboring of each WTP part with another. Mutual collisions or the pounding between parts may be factors that increase seismic vulnerability [89].
- The transferability of forces (in general), soil–structure interactions, and assistance following construction failure [90,91] or associations with geotechnical problems [92]: A possible reason for changing the route of forces to the ground is an earthquake. Knowledge about the existence of other methods of force transfer is valuable for the estimation of this factor.

### 5.3.3. Deficient Maintenance/Malignancies

It is possible for these situations to decrease the infrastructure's resilience and increase its vulnerability [93], while estimation is mandatory. Due to deficient maintenance, steel oxidation and concrete carbonation might be presented. Subsidence might produce malignancies to the structure.

### 5.3.4. Repair or Strengthening of Infrastructure

In this case, resilience increases and vulnerability decreases, although there are barriers, including a lack of design, the installation guidelines, and long-term durability studies [94].

### 5.3.5. Causality of Repairing or Strengthening of WTPs

Another factor is the investigation of the reasons that led restoration scholars to undergo improvements or strengthening. Such reasons may include the presence of soil subsidence or even a fire near the WTPs [95]. The causes must be separated in static and shock-dynamic loads (such as earthquakes) and time damage.

### 5.3.6. Sustainability

Technical issues should be according the sustainability principles. Researchers examined the relationship among the disaster and the seismic hazard, exposure of population and fragile buildings [20]. Each of these determinants is directly related with WTPs, posed to strong earthquakes.

## 5.4. Data on Materials

A complete qualitative study must include additional factors such as indices [50] related to the construction materials (RC, Steel, PVC, HDPE, and GRP). Materials often have specific standards, but reinforced concrete has many uncertainties regarding its composition, its method of construction, and its maintenance. The role of materials is essential to provide the strength of the frame [28,96]. Complementary data are primarily technical issues related to reinforced concrete, the primary material used in WTPs, as shown below [97].

- Data related to the concrete frame.
  - (a) Ability for concrete sampling. To measure the strength of the construction's structural frame, concrete sampling (where and when it is possible) and measurement of their values must be performed. An existing evaluation of damage caused by earthquakes may be useful [98]. Additional methods may be used to calibrate the concrete strength, including nondestructive methods such as ultrasound measurements, percussion methods, and a nail extractor [99].
  - (b) The behavior of the material. Defects can be influenced by static inadequacies from the past. Previous exposure to seismic stress may have caused residual faults (including sloping and sedimentation of structural elements) [100].
  - (c) Local issues about WTPs' components. Knowledge on local issues with WTP components may be valuable. Possibly, the presence of holes in piping con-

struction [101] or the permeability of components may affect the structural vulnerability.

- (d) Existence of logs. Concrete samples' logs taken by the owner (during construction) are valuable for assessing a structure's vulnerability [102]. Information about the substantial quality can be obtained from logs, for example, the quality of sand used, the place of concrete production (in situ or industrial), the existence of a sieve analysis and proper gradation of aggregates, and the appropriate vibration and curing of concrete and use of low cement values in the creation of structural elements [77]. In recent times, it has been mandatory (e.g., in environmental legislation) for SD parameters to be introduced in studies about vulnerability evaluation.
- Data related to steel reinforcement (of the concrete frame).
  - (a) Iron material. Any subject related to the material used in WTPs, such as iron-shaped memory alloys [103], must be checked. Characteristics of these steel bars (e.g., diameters, anchorage, and overlapping) may influence the resistance of structures.
  - (b) The positions of reinforced steel bars. Technical studies predict the position of steel bars inside the concrete, according to building codes [83].
  - (c) Techniques about iron shaping. Data on the "closure of fasteners" at the columns or walls are valuable, as these factors may decrease the strength of materials in WTPs [104,105]. Structural details, such as the absence of 135° seismic hooks and a lack of transverse ties, may be the causes of an increase in seismic vulnerability [77].

There is a contractual obligation regarding these critical infrastructures because this secures the WTP quality. The only way to investigate potential construction failures is to identify structures with high SSV. Other conditions such as the temperature of the environment, concrete construction, and the corrosion or carbonation of concrete [106] are essential because they may influence the strength of the WTP. Extreme temperature conditions caused by climate change over time may be a significant factor, too.

A sustainable WTP structure, characterized by its ability to act as a green building, mitigates against negative impacts and decreases the respective lifecycle of substances discharged to the natural environment. The wastewater treatment processes require significant energy resources, resulting in elevated emission levels [51,107]. The integration of all the parameters should provide planners for vulnerability with a holistic view, as shown by similar surveys [108,109].

## 6. Initial Evaluation of the Proposed Method

The origin methodology introduced herein is based on two main sets of actions conducted on totally 13 steps to achieve the objective—determining the SSV of WTPs. For the first set of four steps, previously collected SSV data from a sample set of WTPs is used (Figure 1) to perform the second steps (Figure 2). Proper implementation is based on onsite checking of twenty-seven critical structural variables in the WTP sample set (described by this study) and weighting to view their impacts on vulnerability (Figure 3). The parameters of the valuable structural data serving the SD principles are categorized into general characteristics, seismicity, geotechnical, and technical data (including related materials such as concrete and steel reinforcement).

The three variables that refer to the general characteristics are the following: (a) the year of construction and the year of last intervention/addition, (b) the surface area of the whole WTP, and (c) the WTP capacity. Similarly, there are five factors related to seismicity and geotechnical data: (a) the seismic hazard zone (including the hazard zones for liquefaction, tsunamis, and landslides), (b) damages related to past earthquakes, (c) the ground category, (d) information about the type and geometry of the foundation, and (e) past geotechnical failures.

The six factors related to technical data are the following: (a) the availability of data and technical reports, (b) structural data (such as the horizontal regularity, the distribution of rigidity to its members, potential torsion, the considerable height of the WTP's tanks, the too-close neighboring of WTP parts, and the transfer of forces), (c) deficiencies in maintenance, malignancies (due to the presence of subsidence), (d) repair or strengthening conducted, (e) the reasons provoked repairing or strengthening, and (f) the sustainability of a WTP's structure.

From the point of view of sustainability, an investigation about the materials of which a WTP is made is necessary. When reinforced concrete is used as a material for a WTP, four issues arise: the ability to undergo concrete sampling (proof of concrete samples, use of additional methods to calibrate the concrete strength), the behavior of the material including remaining defects as a past static inadequacy, local issues about WTP components, and the existence of logs of concrete tests conducted on the set of concrete samples during or after construction.

Three issues about the steel reinforcement of a concrete frame include the use of materials such as iron-shaped memory alloys, the positions of reinforced steel bars and techniques about iron shaping (diameters, anchorage, overlapping, and data about the "closure of fasteners" at columns or walls).

Phase A of the methodology suggests that the variables' weightings may be estimated via methods such as descriptive statistics (Figure 1). Historical data, interviews and questionnaires (extracting from experienced estimators), and bibliographies can provide data about SSV. These data are organized through a questionnaire given to participants of the survey. The calculation of the weighting factors of SSV for the sample set of WTPs consists of the collection of the data analyzed previously, e.g., from the answers given by the questionnaire's participants. The sorting of them and discovery of the proportions and frequency relations in the WTPs sample data is the next step in the methodology.

Phase B of the methodology suggests that the estimation of the SSV of an individual WTP requires a set of actions (nine steps; Figure 2). As there are many methodologies regarding the assessment of a structure's vulnerability (which are unreliable according to some researchers) [50], the decision to perform a rapid, qualitative, empirical analysis survey must be adopted (Figure 2). In the first case, an estimation is performed using briefing records, questionnaires, and interviews. A qualitative assessment is conducted by comparing the SSV of an individual WTP with the SSV of the previously calculated WTP sample set. The results are produced by constructing relative and absolute qualitative scales to categorize the SSV of the individual WTP at the survey time. Two qualitative scale categories exist: (a) a relative scale, which uses the values of the sample set, and (b) an absolute scale, which uses ideal maximum and minimum values.

Verification of the results and the relations among elements of vulnerability may be achieved through onsite checks, and protective measures may prevent post-seismic damage related to sustainability issues. Enrichment of the primary data in the sample set is necessary as a type of feedback. Correlations among specific variables and the classification of absolute and relative findings are based on imported data, the time at which the survey is completed, and the people involved, including their perceptions. Very distant future assessments of SSV require renewed study with new rules and restrictions set by the state.

## 7. Concluding Remarks

WTPs are usually old-structured establishments constructed applying old building codes. Damages in the structure of WTPs are very often in seismic-prone countries, resulting in serious problems. Nowadays, SSV is assessed by applications, such as GIS, and scenarios that produce virtual results about losses and financial assets. As resilience and sustainability are priorities for modern societies, the rapid implementation of a universal program requires the application of a method to examine the values of variables that affect the SSV of these constructions. There is a need for the rapid assessment of SSV following an earthquake, although the empirical approaches which use Rapid Visual



Screening seem to be ineffective tools. This approach needs qualitative analysis. Additionally, earthquakes themselves involve many uncertainties that necessitate the use of qualitative methodological approaches.

A new qualitative, rapid, and comprehensive methodology is available to assess the SSV of WTPs, as well as satisfying the principles of SD. The proposed method involves totally 13 steps to investigate the SSV of WTPs using twenty-one critical variables (where structural data is analyzed to six more variables) and examines the WTP characteristics. There is a need to implement two sets of actions (one for assessing the SSV of the WTP sample set and one for evaluating the SSV of an individual WTP). The investigation takes place through the assessment of general characteristics, seismicity, geotechnical, technical aspects, and factors related to the materials used at the WTPs.

The method used is an empirical methodology due to a lack of time in earthquake-prone areas. It involves using questionnaires containing SSV variables and compares the relative and absolute scores of an individual WTP with a sample set of WTPs. The proposed method by the present study is a qualitative approach with advantages and disadvantages, and it follows the SD principles. The most significant advantage of the method is the time and cost saved in assessing the SSV of an individual WTP; while the Phase A is time-consuming and should be improved. The weighting factors of the variables should be subjected to extensive and thorough research based on various research methods. Many factors may change the results, e.g., the technicians involved, the timing of the survey, and the society's rules and regulatory constraints at the time of the study. The vulnerability assessors using the proposed method must be specialized officers of these facilities with relevant education and experience. There is a need for accurate implementation of the descriptive statistical methods for the sample set of WTPs, such as using the occurrence percentage of each SSV variable. After the SSV assessment of an individual WTP, an update of data is required.

Similar studies about estimating of the structural resilience of WTPs have investigated past failures of pipelines, their lateral spread, the percentage of maintenance hole replacements, a comparison of the age distribution of the existing facilities with the building code requirements, and parameters such as the seismic hazard zone, liquefaction zones, landslide zones, tsunami inundation, and extra forces produced by the shaking of liquids inside the tanks. In contrast, the proposed coherent method introduces and qualitatively handles more parameters related to seismic structural vulnerability. The total number of SSV-evaluating parameters are parallel to the sustainability goals.

The main aim of each type of vulnerability classification is to protect human life and the environment. Beyond that, there are more issues, such as the social and economic values involved in decisions that need to be made following the assessment of a WTP's structural vulnerability. Future investigation may discover other criteria, such as the operators' perceptions of vulnerability, SSV assessment mechanisms, and the importance of used factors. Modern threats such as natural hazards and climate change should be considered seriously using the appropriate evaluation of WTPs' structures, using a total review of SSV.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/article/10.3390/su13094835/s1>, Table S1: Abbreviations and definitions.

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