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Restructuring a Water Distribution Network through the Reactivation of Decommissioned Water Tanks

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Abstract: Water resource management is a topic of great environmental and social relevance, since water must be preserved and managed to avoid waste, providing high quality service at fair tariffs for the consumer, as imposed by the European Water Directive (2000/CE). In the rehabilitation of a water distribution network, it may be suitable to recover decommissioned water tanks, if any, rather than afford high construction costs to build new ones. In this case, the assessment of the residual service life of these concrete structures affected by steel bar corrosion is the premise for the design of new pipeline routes, connecting them. For this aim, rather than carrying tests that can accurately determine mechanical properties of the dismissed water tanks, it is possible to empirically estimate their level of degradation. Their conditions infer on the expected life of the restructured water distribution network. However, they allow the aqueduct to be used for its technical duration, assumed to be equal to the decommissioned water tanks residual service life in the case they do not require maintenance. Here, a simplified model for the assessment of the residual service life of decommissioned water tanks is first proposed and then applied to a case study, consisting of a part of the water network managed by "Ausino S.p.A. Servizi Idrici Integrati", Cava de' Tirreni, Italy. Once the service life is assessed, the QEPANET plugin is used in QGIS to speed up the design of the new pipeline routes in the georeferenced space, thus overcoming the limits offered by the classic EPANET solver.

Keywords: water resource management; water distribution networks; residual service life; water tanks; georeferencing; EPANET; GIS

1. Introduction

Aging and consequent deteriorating of water distribution networks (WDNs) may yield leakage percentages up to 50% of the total input [1–3]. Control strategies, e.g., based on active pressure regulation and deployment of district metered areas, allow to reduce water losses while delaying asset deterioration [4–7]. A number of leakage estimation models have been proposed in recent decades (see for instance [8–10]). For decades, the Italian National Institute of Statistics (ISTAT), a public research organization main producer of official statistics for Italy, has periodically collected information on water resources for domestic use with the urban water census, at the aim of describing the state of urban water services in Italy. In 2015, total water losses amounted to 41.4% of the input water in the supply network, indicating a worsening compared to 2012, when the indicator reached a lower value of 37.4% [11]. The relatively applied low water tariffs together with the progressive decreasing of investments made it difficult to sustain service quality with the ageing of infrastructures [12]. According to Guerrini et al. [13], tariff growth represents a viable strategy to push investments in infrastructures. Customer engagement in the form of willingness to pay (WTP) is, therefore, highly desirable by water utilities to obtain social legitimization and support. The reliability of satisfying demands with desired pressure heads in WDNs can be endangered in the presence of water shortages as well, that is the condition of extended periods of hydrological drought or water disruption due to damages or maintenance operations. A water shortage emergency may result in the impossibility to operate WDNs continuously, making operators to meet demands intermittently [14–17], scheduling pump operations [18], regulating reservoirs [19].

The increasing availability of spatial data, monitoring and calculation tools has opened new horizons in the field of hydraulic engineering in which simulation models are now consolidated [20–22]. Concerning WDNs, simulation codes, to be either applied for design or verification purposes, increasingly require integrated tools involving GIS platforms and monitoring systems to support the search for losses, budget analysis, maintenance operations, and management in real time [23–26]. Gallina and Pasquale [27] introduced the GIS-based Smart Water System, serving 139 municipalities in the neighborhood of Novara and the Verbano-Cusio-Ossola area (Italy), allowing for the reduction of pipe leakages, and recovering six million m^3/year of water. The concept of Smart Water Network (SWN) technology has been recently introduced as a set of supporting strategies, helping utilities effectively manage critical infrastructure assets while maintaining the desired level of provided service at the lowest life cycle cost [28,29]. Grimaldi and co-workers [30] applied a Multi-Criteria Spatial Decision Support System (MC-SDSS) integrating three methodologies: GIS, Data Base Management Systems (DBMS), and Multi-Criteria Decision Analysis (MCDA) [31,32]. Piegdoń and co-workers [33] used a GIS framework for the analysis of risk of failure of water supply networks. Arrighi and co-workers [34] analyzed the exposure to floods with reference to the water supply system of the city of Florence, Italy, serving approximately 380,000 inhabitants. Direct and indirect damages were assessed by combining a semi-automated GIS procedure, a flood model, and an EPANET [35,36] based pipe network model with a pressure-driven demand approach [37].

In the case study analyzed here and presented next, the data collected from a survey of the hydraulic components of a water supply network, either operational or decommissioned, established the basis for the definition of the hydraulic model in the GIS environment [38,39]. The latter was set with the QEPANET, a free plugin [40] that allows communication between QGIS [41] and EPANET to simulate the water network which is automatically georeferenced by the use of either a Digital Elevation Model or Digital Terrain Model (DEM/DTM) raster basis.

In the rehabilitation of a WDN, it may be suitable to recover decommissioned water tanks, if any, rather than afford high construction costs to build new ones. This eventuality has been little explored among water utilities and academia. Water tanks typically consist of reinforced concrete (r.c.) structures. As they need maintenance, e.g., for preventing crack formation [42], many studies have been carried out over the last few decades to predict their vulnerability [43–45]. It is worth mentioning an environment information system developed in [46] that allows tank managers to assess the vulnerability to some natural hazards (snow, wind, and earthquakes), allowing to predict the level of degradation or ageing that may occur to a water tank. Here, a scale of classification of tanks in three levels—good, average, bad—based on a diagnostic method is proposed. In [47] it is stated that the water-related infrastructure in the USA is clearly aging, and investments were not able to keep up with the need. A predictive numerical Finite Element (FE) model describing the growth of water tank vulnerability with time by mean of a vulnerability index is proposed in [48]. Rehabilitation could therefore be a possible solution to extend service life and maintain safe water supply [49]. The literature is vast instead, in the general case of the rehabilitation of concrete structures. Due to the type, location, and conditions structures made of r.c., such as the water tanks considered here, carbonation and salt intrusion are the main causes of degradation [50]. Pan and Wang [51] assessed the service life of the facilities in three main phases: Chemical entry, steel corrosion, and concrete cracking. Balafas and Burgoyne [52], in the case study of a bridge, described the degradation through a model that identified two periods: A first phase, which begins when the chloride penetrates through the concrete cover, reaches the bars and begins to corrode them, and a second phase, which begins when the rust is formed and, as soon as the volume increases, puts pressure on the concrete cover and forms cracks. Wang and Liu [53] introduced a simplified method with which they estimated the residual life of corroded beams, bearing in mind the changed properties of the damaged materials, the corrosion depth, and the corrosion amount. Mitra and co-workers [54], through in-situ analysis for carbonation and chloride content, developed a method to get the corrosion index for the construction of r.c. buildings. Cheung and co-workers [55] developed a 2D (two-dimensional) FE combined approach to evaluate the chloride penetration process in a variable environment and thus the start of corrosion. Liang and co-workers [56] proposed a mathematical model based on Fick's second law of diffusion in order to study the service life of r.c. bridges. They divided the corrosion process, and therefore the service life of the existing r.c. structure, into three phases: The beginning, the depassivation, and the corrosion times. Song and co-workers [57] used the micromechanical corrosion model to predict the lifetime of r.c. structures and divided the service life into four parts: Start, propagation, acceleration, and deterioration phases. Masada and co-workers [58] proposed a risk assessment method giving an overall score to structural safety, between 0 and 9, from new to totally damaged, as will be discussed later in more detail. The concrete elements deterioration, due to the corrosion of the bars, was divided into two phases by Roelfstra and co-workers [59]: The start phase, from the construction until the steel bar depassivation, and the propagation phase, until the structural failure or the complete loss of bar section strength. Palazzo and co-workers [60] proposed a further prediction methodology, based on the modeling of the aging process induced by the structural element corrosion taking into account the axial bending mechanical behavior of the bar and the following effects: Steel cross section loss, bars ductility loss, local reduction of concrete strength, deterioration of coating, and chipping.

In this research, rather than applying computational approaches that need direct testing detection of main mechanical and geometrical properties (e.g., [60]), an empirical procedure is proposed to establish if a decommissioned water tank can be reactivated. The developed methodology, described at the end of Section 2 and applied in Section 3 with reference to a case study, is actually useful to water networks operators. In facts, it is simple but efficient: First, the ten point (0–9) condition rating of Masada [58] is applied to obtain the present condition of decommissioned water tanks based on the measured values of concrete cover, carbonation depth, and chloride concentration. The obtained score then allows making the decision whether the water tank should be reactivated or not, as next explained in Section 3. In the positive case, remaining service life is derived making use of the Tuutti theory [61].

The article is organized as follows. Section 2 presents the context of the study and adopted methodology. Section 3 shows the obtained results, consisting of the residual service life of water tanks and pipeline routes to connect the rehabilitated ones. Finally, the discussion and conclusion sections provide interpretations of the results and their practical implications for water utilities, respectively.

2. Materials and Methods

The case study was the WDN of Cava de' Tirreni, in the province of Salerno (SA), southern Italy, serving about 50,000 inhabitants. The definition of the hydraulic GIS model of the WDN under investigation was based on the data provided by the "Ausino S.p.A. Servizi Idrici Integrati" as well as on those derived from a local survey [62]. Ausino is a joint stock company, publicly owned, responsible of the integrated water service of the Amalfi coast, Salerno main city and other nearby municipalities in southern Italy. The recognition allowed to identify the areas subject to local water shortages (red areas in Figure 1), which are addressed with two new routes, each of which in connection with a decommissioned water tank (San Cesareo and Crocelle, respectively, see Table 1).

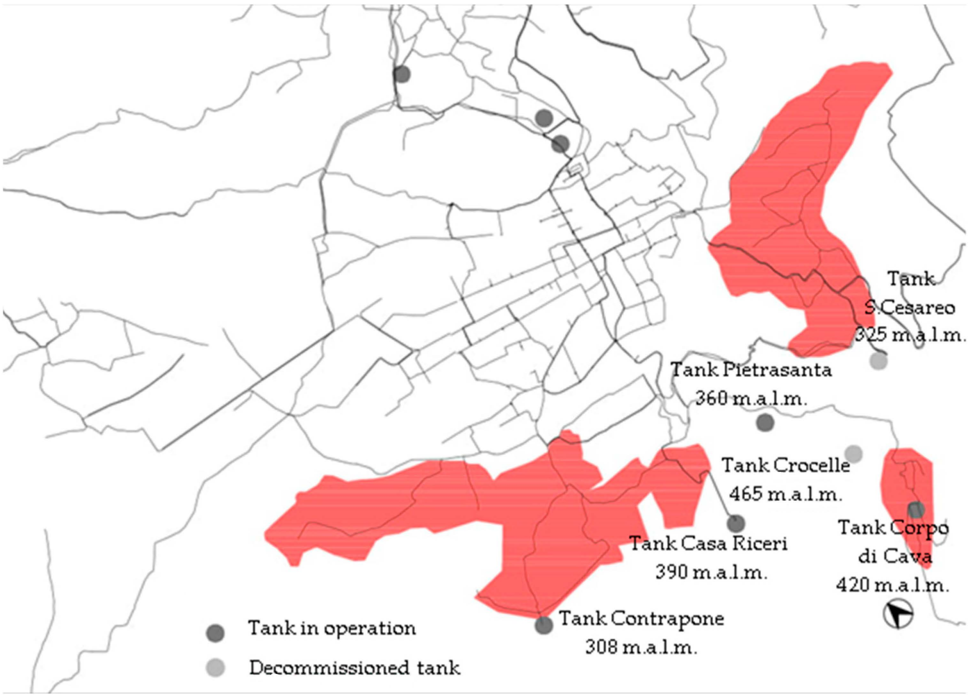

Figure 1. The water distribution network (WDN) object of the present study undergoes on seasonal water shortage (red coloured).

Table 1. Tanks survey and their classification [62].

Tank Name	Classification	Construction Material	Construction Techniques	Volume (m^3)	State
1st S. Anna	Divider	r.c.	partly underground	1000	in operation
2nd S. Anna	Pumping station	r.c.	partly underground	80	in operation
Monte Castello Alto	Divider	masonry	Overground	430	in operation
Monte Castello Basso	Divider	masonry	overground	3500	in operation
Santi Quaranta	WDN	r.c.	underground	800	in operation
Pietrasanta	WDN	masonry	underground	10,000	in operation
Crocelle	Transmission	r.c.	partly underground	500	decommissioned
Casa Riceri	Divider	masonry	overground	1000	in operation
Contrapone	WDN	masonry	overground	50	in operation
Corpo di Cava	Pumping station	masonry	overground	80	in operation
Borrello	Pumping station	r.c.	partly underground	500	in operation
San Cesareo	Pumping station	r.c.	partly underground	500	decommissioned

2.1. The Water Distribution Network of Cava de' Tirreni

The municipality of Cava de' Tirreni extends mostly over mountain areas. The slopes were exploited so that the water network works mainly by gravity: Only in few cases the installation of pumping stations was necessary. Tanks serving the current network have been in operation since the 1970s (Figure 1). However, more tanks, actually decommissioned, were built over the districts of the municipality during the whole twentieth century. Some of them are placed at strategic elevations and, if exploited, could solve the water deficit that the network currently undergoes during the summer season. The causes of these disruptions can be attributed to the size of the area occupied by scattered residential units, the use of two pumping stations and the presence of housing units whose service is directly connected to the main supply pipe. The area object of investigation is actually served by the tanks of Pietrasanta, Contrapone, Corpo di Cava, and Casa Riceri. In Table 1, a list of the surveyed tanks serving the WDN managed by the "Ausino S.p.A. Servizi Idrici Integrati" in the municipality's neighborhood is given.

A previous investigation on the pipeline "New Aqueduct" managed by Ausino was carried out by Viccione et al. [63] to assess the expected hydropower potential.

2.2. The Hydraulic Model

The hydraulic model was implemented by means of the free add-on QEPANET, a plug-in linking QGIS software and EPANET solver, providing a set of editing tools to build a georeferenced supply water network. Firstly, the layout of the network was given as a set of 3D pipe branches and point nodes. Then, the DEM, covering the area of interest, was uploaded and georeferenced.

2.3. The Simplified Method for the Assessment of the Residual Service Life of Decommissioned Water Tanks

The determination of the residual life of the decommissioned water tanks was performed by combining the theory of Tuutti [61] and the Masada's Condition Ratings (CRs) [58], described in Table 2. These latter CRs describe the actual condition of the r.c. structure with an entire number between 0 and 9 (starting from safe condition and with increasing risk of failure), according to the chlorine concentration (cl) and the difference between concrete cover and carbonation depth (dccd). CR attribution can be generalized to cases comprehending decommissioned water tanks for which the values of cl and dccd are known. The rating scale allows itself to make the decision if a water tank can be reactivated or not: As one can see for 0 ≤ CR ≤ 3 no maintenance is required. In such cases, the residual service life of decommissioned tanks can be therefore assumed to be coincident with the WDN technical duration. For 4 ≤ CR ≤ 7 maintenance is required as the formation of cracks may yield water leakages to the point it is "mandatory for continuous use" (CR = 6) or the works need to be disconnected (CR = 7). For CR > 7, water tank cannot be reactivated.

Table 2. Ten-point Condition Rating system for reinforced concrete (r.c.) structures (redrawn from [64]).

Condition Rating (CR)	Failure Extent	Description (in Terms of cl [1] and dccd [2])	Action Required
0	safe	cl < 0.2, dccd > 0, age ≤ 10	excellent condition
1	good	cl < 0.2, dccd > 0, age > 10	no maintenance required
2	low risk but satisfactorily	cl < 0.2, dccd ≤ 0 or cl = 0.2, dccd ≥ 0	corrosion initiated, regular inspections required
3	fair	0.25 > cl > 0.2, dccd > 0	frequent inspections required
4	moderate risk	0.25 > cl > 0.25, dccd ≤ 0	no immediate maintenance, it may be delayed
5	poor	0.3 > cl ≥ 0.25, dccd > 0	maintenance is required to increase the service life
6	high risk	0.3 > cl ≥ 0.25, dccd < 0	maintenance is mandatory for continuous use, likely to repair
7	serious	0.4 > cl ≥ 0.3, dccd > 0	structure must be closed for maintenance
8	critical	0.4 > cl ≥ 0.3, dccd ≤ 0	poor condition not likely to be repaired
9	failure	cl ≥ 0.4	structures replacement

[1] cl = chlorine concentration, [2] dccd = difference between concrete cover and carbonation depth.

The Tuutti theory [61] (see Figure 2) divides the service life of r.c. structures into two phases, described in a chart in which depths of corrosion are plotted as a function of time. The first phase denotes the initiation phase, the time required for carbon dioxide and chloride ions, if present, to reach the inner steel bars. The second one is referred to the propagation phase, during which the carbonation causes the formation of cracks allowing the penetration of aggressive agents and, therefore, compromising both the concrete and the steel bars. The upper limit of the propagation phase corresponds to the threshold limit of corrosion, i.e., the maximum acceptable value of depth of corrosion. This step, once reached, is dangerous for r.c. structures as structural safety is undermined.

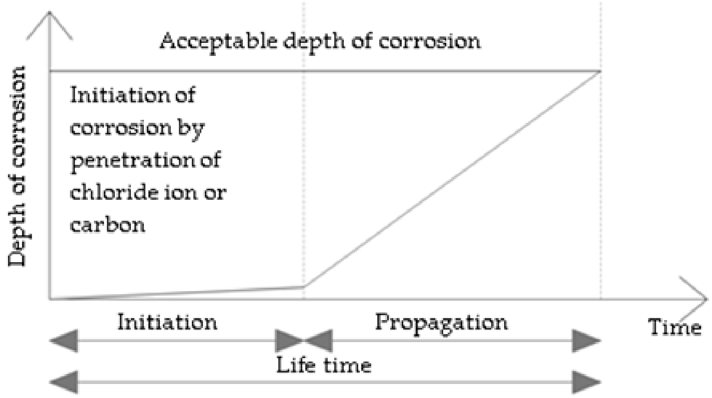

Figure 2. Service life model of Tuutti (redrawn from [64]).

The carbonation reaction starts on the concrete surface and penetrates with a progression that is approximately proportional to the square root of the physical time, according to Fick's first law of diffusion [64]:

$$Cd = K \times t^{0.50}, \quad (1)$$

where Cd (mm) is the depth of carbonation, t (years) is the physical time, and K (mm/$y^{0.50}$), slope of the chart, is the carbonation coefficient, which depends on both environmental factors and concrete features (concrete quality, aggregate types, exposure conditions, moisture content).

In the following, K is first of all evaluated as explained in Section 2.4. Then, the residual service life t_{rl} of the structure is derived from Equation (1).

2.4. Residual Service Life Assessment

The literature offers several contributions for the evaluation of K. Here, reference was made to the works of Pedeferri [65], El-Reedy et al. [66], Savoldi et al. [67], and Czarnecki and Woyciechowski [68] in relation to the following features. Water tanks were built using C25/30 class concrete (British standards), with the addition of pozzolana to increase the resistance to compression as well as to aggressive agents, reducing the permeability and hence increasing the durability. The water to binder ratio w/b was presumably less than 0.50 as the class of exposure is XC2 (wet conditions) [69]. The service life for which the water tanks were designed can be conservatively fixed in 70 years being the tanks of class I, consisting of works occasionally occupied (NTC 2018, par. 2.4.2 [70]). Corresponding K values are given in Table 3, from which the average value K = 1.97 mm/$year^{0.50}$ was adopted.

Table 3. Carbonation coefficient K derived from literature on the basis of environmental factors and concrete features of water tanks.

Authors	K
Pedeferri [65]	2.82
Shiessl [66]	1.06
Salvoldi et al. [67]	1.50
Czarnecki and Woyciechowski [68]	2.50

3. Results

3.1. Condition Rating CR and Residual Service Lifetime t_{rl} Definition

The application of Equation (1) with the current age of the tank (50 years) gives back Cd = 13.94 mm. The difference between the concrete cover and the carbonation depth is therefore dccd = (25 − 13.94) mm = 11.06 mm, which, as derived from the same Equation (1), needs 20 years more to be depleted. As the percentage of chlorides in the area in which the decommissioned tanks are located is lower than the threshold value cl = 0.2 and dccd > 0, the corresponding condition rating is CR = 1 (see Table 2). This value is also confirmed from the visual inspection during the tank survey (decommissioned water tanks in Table 1). Therefore, the tanks do not need any particular intervention and the residual service lifetime can be therefore fixed in t_{rl} = 20 years within the initiation phase (Figure 3) of Tuutti service life model.

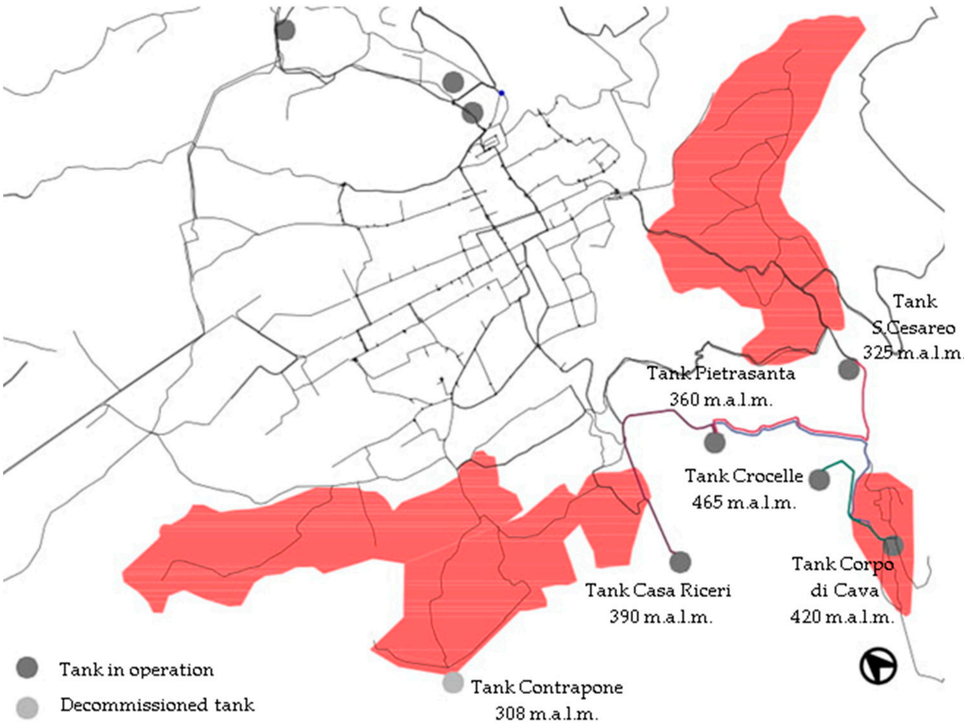

Figure 3. The new route proposal (in red Pietrasanta-San Cesareo pipeline, in green Crocelle-Corpo di Cava pipeline, in purple Pietrasanta-Casa Riceri pipeline).

3.2. The New Pipeline Routes

The demographic trend of the resident population of Cava de' Tirreni municipality over the last twenty years was derived from the Italian National Institute of Statistics (ISTAT) data and then projected over the next 20 years, in accordance with the evaluation of the residual life t_{rl} (see previous Section 3.1). The forecast yielded a population decrease of 1%, a negligible percentage of the same order of the seasonal population. The new pipeline sizing, therefore, was carried out according to Peters et al. [71], on the basis of the constant flow rates given in Table 4. The decommissioned water tanks of Crocelle and San Cesareo (see Table 1) are comprehended in two new routes, "Pietrasanta-San Cesareo" and "Crocelle-Corpo di Cava", solving the critical areas depicted in Figure 1 in terms of computed piezometric heads (with the QEPANET solver) as next specified, satisfying water demand with an adequate service level. These pipelines work by gravity and are mainly laid over existing roads. The elevation of San Cesareo and Corpo di Cava tanks allow to serve the local distrubution networks (nearby red areas in Figure 1) with piezometric heads measured from ground between 42 m and 72 m. The Contrapone tank, actually served by two pumping stations, each operating for $n_1 = 20 \times 365 = 7300$ h per year and a total installed power $P_{cr,1}$ = 78 kW (source Ausino) was replaced by the higher Casa Riceri tank, served by the "Pietrasanta-Casa Riceri" new designed lifting pipeline. The basic principle was indeed to prefer gravity systems. The Casa Riceri tank then served the larger red area depicted in Figure 3 by gravity, with piezometric heads between 35 m and 78 m. The new pipelines required the insertion of adjustable pressure reduction valves for the introduction of a minor head loss ΔH, whose maximum values are shown in Table 4.

Table 4. Parameters' values of Crocelle-Corpo di Cava, Pietrasanta-S. Cesareo new pipelines working by gravity and Pietrasanta-Casa Riceri new lifting line. Q is the design flow-rate, L is the pipeline's length, D is the design diameter, and ΔH is the maximum minor head loss of the pressure reduction valves.

Parameter	Crocelle-Corpo di Cava	Pietrasanta-San Cesareo	Pietrasanta-Casa Riceri
Q (m^3/s)	0.007	0.010	0.0375
L (m)	710	1560	2380
D (mm)	80	125	200
ΔH (m)	24.3	27.5	-

The Pietrasanta-Casa Riceri pumping line was sized considering the best efficiency among nine operating scenarios (between $\delta = 8$ h and $\delta = 24$ h per day, stepped by 2 h). Corresponding average flow rate was assessed by

$$Q_\delta = V_d/(3600\ \delta)\ (l/s), \tag{2}$$

being $V_d = 2160$ m^3 the required daily volume. The best solution corresponded to a pumping station, inverter provided to control the pump speed to meet with the exact demand, operating for 16 h a day ($n_2 = 16 \times 365 = 5840$ h), with a design flow-rate of 135 m^3/h and a diameter D = 200 mm. A maximum efficiency of 73% was attained. In this case, the installed power is $P_{cr,2} = 49.9$ kW. Assuming the electricity price $C_e = 0.20$ Eur/kWh [72], the annual saving S would then be:

$$S = (P_{cr,1} \times n_1 - P_{cr,2} \times n_2) \times C_e \approx 55{,}000 \text{ Eur}. \tag{3}$$

4. Concluding Remarks

A WDN restoration with the rehabilitation of decommissioned water tanks was presented here with reference to a case study, specifically the water supply system of Cava de' Tirreni (SA), Italy. The WDN under investigation suffers of seasonal water shortages (read areas in Figure 1) which solution was found making use of the decommissioned water tanks of Crocelle and San Cesareo (Table 1). Tank recovery implied the definition of the corresponding residual service life, assessed with the simplified methodology obtained by combining the Masada's Condition Ratings [58] and the theory of Tuutti [61]. The rating scale allows to make the decision if a decommissioned water tank can be reactivated or not. The rating attribution is generalizable to cases with dismissed tanks. Since it just needs the knowledge of the concrete cover, carbonation depth, and chloride concentration are known, the related procedure can be easily applied by water network operators. In the case of $0 \le CR \le 3$, no maintenance is required, hence the residual service life of decommissioned tanks can be assumed to be coincident with the WDN technical duration. Since the condition rating of decommissioned water tanks for the case at hand was CR = 1, they were included in two new pipeline routes, working by gravity, allowing piezometric heads between 42 m and 72 m over the served areas. The "Pietrasanta-Casa Riceri" new designed lifting pipeline now replaces two pumping stations, allowing piezometric heads between 35 m and 78 m over the served areas and an annual saving of the order of 55,000 Euros, in terms of energy costs for lifting. The new pipelines resolved the critical areas depicted in Figure 1 in terms of QEPANET computed piezometric heads, proving that the restoration of WDNs with the rehabilitation of decommissioned water tanks is a practical solution.

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