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# Method for Assessment of Water Supply Diversification

**Krzysztof Boryczko *** and **Janusz Rak**

Department of Water Supply and Sewage Disposal, Faculty of Civil and Environmental Engineering and Architecture, Rzeszow University of Technology, 35-959 Rzeszow, Poland; rakjan@prz.edu.pl

* Correspondence: kb@prz.edu.pl; Tel.: +48-17-865-1427

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**Abstract:** The approaching prospect of obligatory implementation and pursuit of Water Safety Plans forces water companies to reflect on supplies in crisis situations that, for example, relate to the closure of a basic intake, or scarcity of water due to climates changes (droughts). Where supplies are diversified, there can be greater certainty as to the continuity of good quality supply, even in an emergency. As one of each country's systems of critical infrastructure, the collective water supply system (CWSS) should be protected, with the diversification of supply treated as a basic tool to raise levels of security among consumers. This article, therefore, presents a method from the authors' by which diversification may be assessed, including by reference to basic and key elements of the CWSS capable of affecting the continuity of water supply. Sample calculations using the proposed method are also presented here for selected Polish cities. In the event, as only one Polish CWSS can be assigned to the category representing excellent diversification, the suggestion is clearly that Poland's systems must still progress with the diversification of water supply, in order to further reduce the risk of water shortages.

**Keywords:** diversification; water supply; water tanks

## 1. Introduction

The term diversification comes from Latin and means variety. The concept of portfolio diversification, known in economics, is the most popular, and described as one of the most effective methods of reducing investment risk. This concept means the division of the portfolio into different types of investments, among others, in terms of the type of market (e.g., raw materials, currency, shares, bonds), trade (in the case of shares) or geographical coverage of given entities (e.g., shares, shares funds of enterprises from a specific region). In the 1940s, it was adopted by the economic and financial sciences, and in the 1950s, by the management sciences [1]. For example, in the field of finance, H. Markowitz applied it in describing a differential investment portfolio, allowing for the selection of such components, as this would reduce risk and maximise profits [2]. In turn, diversification is an increase in the number of industries in which a company operates. In the late 1950s, H. Ansoff stated explicitly that diversification was one of the main development strategies. In turn, applied to the value chain, diversification was presented by R. Grant as an extension of a company's activity with new products, new geographical areas or new activities. In the natural sciences, diversification is identified by the biodiversity of fauna and flora in different biosystems [3–8]. In the human environment, it is likewise an important issue where the supply of electricity, gas and heat to urban agglomerations is concerned [9–13]. If it is to function properly, each agglomeration requires a supply of water of good quality, in the necessary amount. This is particularly true of crisis or emergency situations. The possibility of water being supplied from several sources obviously represents a way in which the diversification of supply can be achieved [14]. However, if water intake is shut off, the volume of water stored in tanks assumes a key role [15,16]. Collective pressure pipelines associated with second-degree pumping stations, whose number and diameter affect the of water supply, are also of importance [17–22]. In turn, a reduced water supply, or total lack of water, can threaten the lives or health of water consumers, with financial losses among both recipients and water companies also possibly arising. The operator of a collective water supply system (CWSS) enjoying a high degree of diversification has greater room for manoeuvre in time of crisis, with decisions not then needing to be taken under severe time pressures [23,24].

Diversification of water supply has been a key issue for urban residents for centuries. Ancient Petra lay on a combination of trade routes connecting the Black Sea with Damascus and the Persian Gulf with Gaza. Today, the city is in the territory of Jordan and is on the UNESCO World Heritage List. Petra was created by the Nabateans as a city "carved in pink rock" in the 4th century BC. During its heyday, the city had 30,000 inhabitants, notwithstanding, annual rainfall in the area was just 150 mm. The city of Petra occupied an area of around 60 $km^2$ and its location in the semi-desert basin necessitated the construction of an advanced system of tanks and dams, allowing for the storage and distribution of water via clay pipes [25]. The designers of the city and its inhabitants did not waste water. The entire desert water system was supplied from eight sources, the largest of which were [25]:

- Siq—36 $m^3$/h;
- Wadi Shab Qais—30 $m^3$/h;
- Ain Braq—0.8 $m^3$/h;
- Ain Dabdabah—2.5 $m^3$/h;
- Ain Ammon i Ain Siyagh—<1.0 $m^3$/h.

The water supply system also consisted of 40 tanks with dams, 200 cisterns and 200 km of pipelines. In the city centre, there was a swimming pool measuring 45 × 20 m and, around that, a paradise garden. The Nabateans also used groundwater. Some tanks were dug so deep that they penetrated the aquifer and served as wells.

While it is usual for a small waterworks to have a single functioning intake, large metropolises are supplied from two or several independent intakes. The security of a CWSS can be considered from the point of view of protection against threats and vulnerabilities [26,27]. The issue of diversification is then seen to fall within the vulnerability research [28,29].

The only prerequisites for a diversified of water supply are those arising from reliability theory. By reference to the Bernoulli distribution, the functioning of the so-called threshold structure "m-k" with "m" can be considered. Probabilities associated with different operating states are determined, with the failure of k = 0.1, ..., m−1 water intake [30,31]. A limitation is that equal probabilities need to be accepted to describe the "m" of the water intakes. The method, taking account of the various probabilities that need to be accepted for individual water intakes, is called "analysis of the water shortage expected value" [32].

In practice, it is sometimes possible to combine local water supply systems, and to exclude one intake from operation, in a kind of anti-diversity. An example of this is provided by the waterworks in Niewiesz and Chropy (Poland), located in the commune of Lodz. Local authorities are considering the option of excluding the water intake at Chropy, which is located at an industrial plant. The basic argument underpinning a decision of this kind has been a major drop in water consumption, observable for several years now.

Scientific publications currently lack extensive research that determines the diversification of water supply numerically. Thus, while publications on the need to diversify sources of supply are plentiful, they are mostly not supported by calculations of the parameters describing diversification [33–35]. Analysis of the literature reports likewise reveals a lack of in-depth analyses of water-supply diversification in in developing countries.

Where an approach was taken, the main indices of diversification of water supply used by authors [36–38] are indices from ecology, like Shannon-Weaver [39], Pielou [7,40], Simpson [8,41] and Hurlbert [42].

Diversification strategies are the subject of intensive research in water, sewerage and heating, as well as many other industries [1,43–51]. Research in this area is still developing. What is more, there is a significant increase in research areas in this aspect [52–55], as well as broader empirical studies, covering several dozen national water supply systems [14,18,19,31,37,56,57]. To put things concisely, diversification means a more even distribution of risk relating to a lack of tap water or its poor quality.

The diversification strategy offers one method by which the reliable and safe operation of a CWSS can be supported. It is implemented primarily in systems of this kind, and is not homogeneous, given the way that various CWSS subsystems can be involved. The most effective diversification strategies relate to numbers of water intakes, network water tanks. Diversification strategies should be taken account of where the modernisation and development perspectives for a CWSS are under consideration [23,24,38,58–62].

Diversification means dispersal of the functioning of strategic subsystems of a CWSS, with the potential of water supply for consumption thus being separated out. This is a set of strategic activities that create new key factors of reliability and safety. Such a strategy almost always requires new investments that contribute to the growth in the development potential of a CWSS. A diversification strategy may prove attractive to a water supply company on account of the positive synergy effect that is created. Awareness of such a state of affairs should lead to a careful assessment of the diversification effect supported by appropriate calculations. Another advantage of diversification is a spreading of the risk associated with undesirable events in a CWSS.

Diversification can be pursued as part of the investment activity of a water supply company. Such a strategy reflects a market, legal or political situation. Factors also leading to diversification relate to the appearance on the market of other entities offering a supply of tap water to the population, and to industrial and service infrastructure. As a rule, this is related to the development of cities, when the existing source(s) of water supply are insufficient. Then, a decision is made to construct a new water intake. Recently, the local authorities in border areas' authorities have also decided to import tap water.

According to the authors, there are three types of diversification: horizontal, vertical and concentric. Horizontal diversification entails an extension of the offer of water, as regards both its quantity and quality, to a given city/commune within existing possibilities. In turn, vertical diversification may entail the extension of individual subsystems of water supply (of a groundwater intake with new wells, new network water tanks constructed, etc.). This kind of diversification leads to an improvement in water supply standards. Finally, concentric diversification is about the acquisition of new water recipients from neighboring towns. It usually leads to the connecting-up and expanding of the water supply networks in both of the towns involved.

The strategy pursued in the name of diversification depends on the situation an enterprise finds itself in (market position, price attractiveness of the water supply). The possible scenarios involve investment, support, survival and branching out.

While the first two scenarios are conducive to a strategy of water supply diversification, the next two fail to provide for diversification as part of a company's operations. Prior to a decision regarding a diversification strategy, the advantages and disadvantages will need to be considered. The advantages include a reduction in risk thanks to dispersion, the possibility of a synergistic effect being achieved, with consequent additional benefits as resources and skills are combined, avoidance of the negative effects where a water-supply system is decapitalised, the ensuring of stability and safety where a company's operations are concerned, and a forcing of creativity where the standards of service for recipients' of water are concerned.

The negatives include the more complicated management a diversified system requires, difficulties with the even distribution of diversification into individual subsystems for the supply and distribution of tap water as part of modernising investments in the system as a whole, increased costs per $m^3$ of water produced as a result of increased safety (reliability and safety cost) related to customer worries (awareness-raising action is needed in regards to the trade-off between the quality of the service and its cost).

Within a few years, all European water companies will be obliged to pursue supply-related risk analysis under the so-called Water Safety Plans (WSPs) developed by the World Health Organization (WHO). In turn, the proposal for a Directive of the European Parliament and the Council of 1 February 2018 on the quality of water intended for human consumption states that "(...) a risk-based approach should be progressively implemented by all water suppliers, including small entities". Among other things, this provision has ensured water companies' increased interest in methods of risk analysis and management, as well as the possibilities for implementation they offer [58,63].

The aim of the work described here has thus been to supply an auctorial method by which to assess the diversification of supplies, with an account taken of the basic and key elements of a CWSS affecting continuity of the water supply. Calculations for selected Polish cities are also presented in relation to the method proposed.

## 2. Materials and Methods

The authors have developed their own method of assessing diversification, which basically relates to a CWSS being safeguarded against the extreme threat that a supply of water will be lacking altogether. The impulse—drawing on experience and cooperation with managers of networks—was to find an index that does the most to promote a large number of water intakes. This is due to experience and cooperation with water network managers. The index developed is as follows

$$dQ = \sum_{i=1}^{n}\left(u_i - 2u_i^2 + u_i^3\right) \quad (1)$$

where:
n—number of water intakes;
$u_i$—share of the i-th intake maximum daily productivity in the total maximum daily productivity of water intakes.

Similarly, the equation was used to describe the water diversification in water supply tanks

$$dV = \sum_{j=1}^{m}\left(u_j - 2u_j^2 + u_j^3\right) \quad (2)$$

where:
m—number of water intakes/network water tanks;
$u_j$—share of the j-th tank in the total volume of network water tanks.

The method includes the tanks on the water supply network that collect treated water. Tanks upstream of the water treatment plant are not included. Tables 1–4 show the values of the indexes dQ, dV for m, n = 2–5.

**Table 1.** Values of the indexes d for m, n = 2.

| Shares | $u_1 = 0.5$ $u_2 = 0.5$ | $u_1 = 0.6$ $u_2 = 0.4$ | $u_1 = 0.7$ $u_2 = 0.3$ | $u_1 = 0.8$ $u_2 = 0.2$ | $u_1 = 0.9$ $u_2 = 0.1$ | $u_1 = 0.95$ $u_2 = 0.05$ | $u_1 = 0.99$ $u_2 = 0.01$ |
|---|---|---|---|---|---|---|---|
| dQ, dV | 0.25 | 0.24 | 0.21 | 0.16 | 0.09 | 0.0475 | 0.0099 |

**Table 2.** Values of the indexes d for m, n = 3.

| Shares | $u_1 = 0.33$<br>$u_2 = 0.33$<br>$u_3 = 0.33$ | $u_1 = 0.4$<br>$u_2 = 0.3$<br>$u_3 = 0.3$ | $u_1 = 0.5$<br>$u_2 = 0.3$<br>$u_3 = 0.2$ | $u_1 = 0.6$<br>$u_2 = 0.3$<br>$u_3 = 0.1$ | $u_1 = 0.6$<br>$u_2 = 0.2$<br>$u_3 = 0.2$ | $u_1 = 0.7$<br>$u_2 = 0.2$<br>$u_3 = 0.1$ | $u_1 = 0.8$<br>$u_2 = 0.1$<br>$u_3 = 0.1$ |
|---|---|---|---|---|---|---|---|
| dQ, dV | 0.444 | 0.438 | 0.4 | 0.324 | 0.352 | 0.272 | 0.194 |

**Table 3.** Values of the indexes d for m, n = 4.

| Shares | $u_1 = 0.25$<br>$u_2 = 0.25$<br>$u_3 = 0.25$<br>$u_4 = 0.25$ | $u_1 = 0.3$<br>$u_2 = 0.3$<br>$u_3 = 0.2$<br>$u_4 = 0.2$ | $u_1 = 0.4$<br>$u_2 = 0.3$<br>$u_3 = 0.15$<br>$u_4 = 0.15$ | $u_1 = 0.5$<br>$u_2 = 0.3$<br>$u_3 = 0.1$<br>$u_4 = 0.1$ | $u_1 = 0.6$<br>$u_2 = 0.2$<br>$u_3 = 0.1$<br>$u_4 = 0.1$ | $u_1 = 0.7$<br>$u_2 = 0.1$<br>$u_3 = 0.1$<br>$u_4 = 0.1$ |
|---|---|---|---|---|---|---|
| dQ, dV | 0.5625 | 0.55 | 0.508 | 0.434 | 0.386 | 0.306 |

**Table 4.** Values of the indexes d for m, n = 5.

| Shares | $u_1 = 0.2$<br>$u_2 = 0.2$<br>$u_3 = 0.2$<br>$u_4 = 0.2$<br>$u_5 = 0.2$ | $u_1 = 0.3$<br>$u_2 = 0.3$<br>$u_3 = 0.2$<br>$u_4 = 0.1$<br>$u_5 = 0.1$ | $u_1 = 0.4$<br>$u_2 = 0.3$<br>$u_3 = 0.1$<br>$u_4 = 0.1$<br>$u_5 = 0.1$ | $u_1 = 0.5$<br>$u_2 = 0.2$<br>$u_3 = 0.1$<br>$u_4 = 0.1$<br>$u_5 = 0.1$ | $u_1 = 0.6$<br>$u_2 = 0.1$<br>$u_3 = 0.1$<br>$u_4 = 0.1$<br>$u_5 = 0.1$ |
|---|---|---|---|---|---|
| dQ, dV | 0.64 | 0.584 | 0.534 | 0.496 | 0.42 |

The analysis of the indexes shows that:

- If there is limited (or a lack of) of unevenness shares, the index dQ/dV reach the approximate maximum values for a given number m/n;
- In the case of a significant unevenness in shares, the rule stating that the larger the m/n the higher the index dQ/dV does not apply.

Table 5 presents the numerical values of the indexes d for a CWSS with equal shares of the intake/tank in the total capacity of water intakes/volume of network water tanks.

**Table 5.** Values of the indexes d for equal shares.

| m, n | 2 | 3 | 4 | 5 | 6 | 8 | 10 | 20 |
|---|---|---|---|---|---|---|---|---|
| $u_i$, $u_j$ | 0.5 | 0.33 | 0.25 | 0.20 | 0.167 | 0.125 | 0.10 | 0.05 |
| dQ, dV | 0.25 | 0.444 | 0.563 | 0.64 | 0.695 | 0.766 | 0.81 | 0.903 |

The two-parameter assessment of diversification for a CWSS was carried out in accordance with an additive model

$$d = dQ + \alpha\, dV \tag{3}$$

where:
d—a two-parameter index of diversification of water resources;
$\alpha$—the weight of the water volume allocation parameter in a network tank.

The allocation parameter $\alpha$ has been defined as the ratio of the sum of the volume of network water tanks to the sum of the production capacity of the water intakes

$$\alpha = \frac{\sum_{j=1}^{m} V_j}{\sum_{i=1}^{n} Q_i} \tag{4}$$

where:
$\alpha$—weight of the water volume allocation parameter in network tank;
$V_j$—volume of j-th tank;
m—number of tanks;
$Q_i$—water production of i-th intake;
n—number of intakes.

While the authors are aware of the possibility of grey water being reused. or rainwater harvested [64], what was adopted ultimately was a model based on two main aspects affecting the diversification of supply, i.e., water intake and tanks. The intention was to arrive at a universal method, utilisable for assessing diversification in both urban and rural CWSSs.

The categorisation and the scale of the assessment of the degree of diversification of water resources is presented below, with an account taken of the allocation parameter

In this part, the proposed method relies on experts on the security of water supply familiarising themselves with its assumptions, before brainstorming the following categories relating to diversification:

Lack of diversification $d = 0$

- Low diversification $0 < d \leq 0.200$
- Average diversification $0.200 < d \leq 0.400$
- Good diversification $0.400 < d \leq 0.600$
- Excellent diversification $d > 0.600$

The degree of diversification can be used to analyse situations of a lack of risk to the supply of water. Drawing on their professional practice (in analysing risk for water companies), the authors determined risk using the

$$r = \frac{P \times C}{S} \tag{5}$$

where:
P—point weight assigned to the probability of a water supply being lacking;
C—point weight associated with the negative effects of a failure of water supply;
S—point weight connected with the protection of a CWSS against lack of supply.

As parameters P and C have already been described in publications relating to lack of water supply risk, they have been omitted from this article [65]. These are usually determined on a 5-point scale, with descriptions of-very small, small, medium, large, and very large, and weightings in the 1–5 range.

The protection of a CWSS can be determined using the proposed assessment scale for diversification, where a lack is assigned a weighting of 1, while excellent diversification is allocated 5 points.

For the point weightings of parameters P, C and S adopted in this way, risk values may vary from 0.2 (for P = 1, C = 1, S = 5) to 25 (for P = 5, C = 5, S = 0).

Climate change is important when it comes to managing the diversification of supply. While the method proposed here takes no account of this in scenarios for the production capacity of each intake, it does consider the same change in capacity at each intake. This reflects $u_i$ shares being used in calculations rather than $m^3$/day.

Where climate change is selected for inclusion in analysis of the protection parameter, the production capacity of each intake should also be assessed. Climate change may necessitate changes in perception with regards to the diversification of water supply. A large number of intakes exposed to reduced production due to climate change may be linked to a lower point weighting for parameter S in Equation (5).

The case study of Poland's Rzeszow CWSS is presented below, with Figure 1 first offering basic data on its water intakes and tanks.

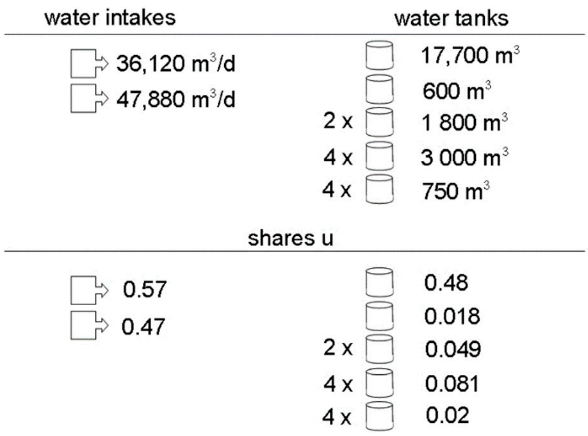


**Figure 1.** Production of water intakes and volumes of water tanks in CWSS Rzeszów.

Calculations of the proposed index for the city of Rzeszow are presented below.

The dQ index can be calculated according to Equation (6)

$$dQ = (0.57 - 2 \times 0.57^2 + 0.57^3) + (0.47 - 2 \times 0.47^2 + 0.53^3) = 0.245 \quad (6)$$

The dV index can be calculated according to Equation (7)

$$dV = (0.48 - 2 \times 0.48^2 + 0.48^3) + (0.018 - 2 \times 0.018^2 + 0.018^3) + 2 \times (0.049 - 2 \times 0.049^2 + 0.049^3) + 4 \times (0.081 - 2 \times 0.081^2 + 0.081^3) + 4 \times (0.02 - 2 \times 0.02^2 + 0.02^3) = 0.583 \quad (7)$$

The allocation parameter $\alpha$ is calculated as the ratio of the summary volume of network water tanks to the sum of maximum daily production capacities of intakes, in line with Equation (8)

$$\alpha = \frac{36900\text{m}^3}{84000\text{m}^3} = 0.44 \quad (8)$$

The two-parameter assessment of diversification in the Rzeszow CWSS was made by following the additive model in line with Equation (9)

$$D = 0.583 \times 0.44 + 0.245 = 0.50 \quad (9)$$

Rzeszow CWSS achieves listing under the "good" category of diversification.

Analyzed CWSSs were divided into four categories depending on the number of residents (NR):

- Category A—small <10,000 (6 CWSS);
- Category B—medium 10,000 < NR ≤ 25,000 (4 CWSS);
- Category C—large 25,000 < NR ≤ 100,000 (7 CWSS);
- Category D—very large NR ≤ 100,000 (6 CWSS).

Table 6 presents the number of residents in each city, analysed along with an expression of this number per intake.

**Table 6.** Numbers of residents overall and per intake.

| City (Number of Residents Category) | Number of Residents | Number of Water Intakes | Number of Residents Per Intake |
|---|---|---|---|
| Biecz (A) | 4629 | 5 | 926 |
| Blazowa (A) | 2148 | 1 | 2148 |
| Brzozow (A) | 7471 | 3 | 2490 |
| Czarna (B) | 11,177 | 3 | 3726 |
| Gloglow Mlp. (A) | 6431 | 3 | 2144 |
| Gorzow Wlkp. (D) | 122,141 | 3 | 40,714 |
| Jaslo (C) | 36,641 | 2 | 18,321 |
| Kolbuszowa (A) | 9158 | 2 | 4579 |
| Krosno (C) | 46,936 | 3 | 15,645 |
| Lancut (B) | 18,067 | 3 | 6022 |
| Majdan Krolewski (A) | 9858 | 1 | 9858 |
| Mielec (C) | 60,366 | 2 | 30,183 |
| Nowa Deba (B) | 11,215 | 1 | 11,215 |
| Olsztyn (D) | 173,125 | 6 | 28,854 |
| Poznan (D) | 536,438 | 2 | 268,219 |
| Raciborz (C) | 55,818 | 2 | 27,909 |
| Rzeszow (D) | 195,734 | 2 | 97,867 |
| Sanok (C) | 37,113 | 2 | 18,557 |
| Stalowa Wola (C) | 60,799 | 2 | 30,400 |
| Staszow (B) | 14, 762 | 3 | 4921 |
| Szczecin (D) | 402,100 | 2 | 201,050 |
| Tarnobrzeg (C) | 46,907 | 2 | 23,454 |
| Tarnów (D) | 107,954 | 3 | 35,985 |

As the analysis is performed, the size and type of CWSS need to be accounted for, as a small CWSS will usually have one intake, and maximum of a few tanks or none. Some CWSSs supply water to small areas that do not justify the construction of a large(r) number of tanks. On the other hand, large CWSSs will have more intakes and tanks, also in line with natural characteristics, such as location on a plain or among hilly, as well as large or small size.

## 3. Results and Discussion

Calculations have been made for 23 cities in Poland. The analysis required the collection of data on the number and maximum daily capacity of water intake as well as the number and volume of network water tanks. The analysis did not take account of the tanks of raw and treated water at a water treatment station.

Figure 2 presents numbers of residents per intake.

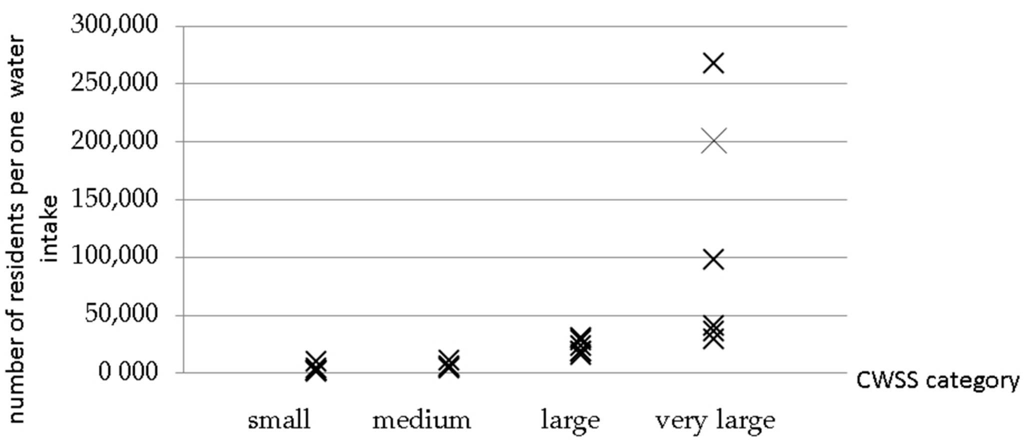


**Figure 2.** Numbers of residents per water intake.

Data in Figure 2 and Table 6, confirm that, within category D, four out of six CWSSs have two intakes, while one has three, and only one (the city of Olsztyn) has six. This leaves the number of residents per intake significantly higher than in categories A and B.

The situation is different with water supply tanks, whose average numbers in each category are as follows:

- Category A 0.5 tank;
- Category B 0.8 tank;
- Category C 2.3 tank;
- Category D 8.3 tank.

From the above data, it is clear that the larger the CWSS, the greater the number of water tanks.

The$\alpha$ index proposed in this paper (in line with Equation (4)) compares the total volume of network water tanks with the total production capacity of water intakes. Of the 23 CSWWs analyzed, 13 have tanks, while the average $\alpha$ index is:

- Category A $\alpha = 0.07$;
- Category B $\alpha = 0.14$;
- Category C $\alpha = 0.19$;
- Category D $\alpha = 0.36$.

The values of the $\alpha$ index point to the great importance of network water tanks within CWSSs, especially in categories C and D. As regards the average number of tanks, category D came last and it should be considered as rational in regard to the $\alpha$.

The proposed method for assessing the diversification of water supply takes no account of number of residents, and may not, therefore, be useful in comparing very different CWSSs.

Table 7 presents results for calculated water supply diversification, in line with the authors' d index.

**Table 7.** Calculated diversification of water supply.

| City (Number of Residents Category) | Number of Intakes | Number of Tanks | $\alpha$ | dQ | dV | d | Diversification Category |
|---|---|---|---|---|---|---|---|
| Biecz (A) | 5 | 0 | 0 | 0.584 | 0 | 0.58 | good |
| Blazowa (A) | 1 | 0 | 0 | 0 | 0 | 0 | lack |
| Brzozow (A) | 3 | 0 | 0 | 0.276 | 0 | 0.28 | average |
| Czarna (B) | 3 | 0 | 0 | 0.406 | 0 | 0.41 | good |
| Gloglow Mlp. (A) | 3 | 0 | 0 | 0.397 | 0 | 0.4 | average |
| Gorzow Wlkp. (D) | 3 | 3 | 0.23 | 0.403 | 0.296 | 0.47 | good |
| Jaslo (C) | 2 | 2 | 0.39 | 0.019 | 0.192 | 0.09 | low |
| Kolbuszowa (A) | 2 | 2 | 0.43 | 0.121 | 0.25 | 0.23 | average |
| Krosno (C) | 3 | 2 | 0.05 | 0.258 | 0.25 | 0.27 | average |
| Lancut (B) | 3 | 3 | 0.55 | 0.327 | 0.444 | 0.57 | good |
| Majdan Krolewski (A) | 1 | 1 | 0 | 0 | 0 | 0 | lack |
| Mielec (C) | 2 | 0 | 0 | 0.166 | 0 | 0.17 | low |
| Nowa Deba (B) | 1 | 0 | 0 | 0 | 0 | 0 | lack |
| Olsztyn (D) | 6 | 14 | 0.33 | 0.345 | 0.656 | 0.56 | good |
| Poznan (D) | 2 | 2 | 0.39 | 0.227 | 0.222 | 0.31 | average |
| Raciborz (C) | 2 | 3 | 0.31 | 0.188 | 0.444 | 0.33 | average |
| Rzeszow (D) | 2 | 12 | 0.44 | 0.245 | 0.583 | 0.5 | good |
| Sanok (C) | 2 | 4 | 0.33 | 0.248 | 0.322 | 0.35 | average |
| Stalowa Wola (C) | 2 | 0 | 0 | 0.166 | 0 | 0.17 | low |
| Staszow (B) | 3 | 0 | 0 | 0.371 | 0 | 0.37 | average |
| Szczecin (D) | 2 | 8 | 0.23 | 0.083 | 0.296 | 0.15 | low |
| Tarnobrzeg (C) | 2 | 5 | 0.23 | 0.146 | 0.571 | 0.28 | average |
| Tarnów (D) | 3 | 14 | 0.56 | 0.237 | 0.656 | 0.61 | excellent |

Three of the CWSSs—Blazowa (A), Majdan Krolewski (A), and Nowa Deba (B)—lacked diversification d. Each has one water intake only.

However, in six of the CWSSs, the diversification index is good:

- Biecz (A)—has the highest dQ;
- Czarna (B)—the second highest dQ;
- Gorzow Wlkp (D)—the third highest dQ and three tanks;
- Lancut (B)—has three intakes and three tanks, and the second highest $\alpha$ index;
- Olsztyn (D)—has the highest dV (with 14 tanks), as well as six intakes;
- Rzeszow (D)—has two intakes and 12, achieving the third highest dV.

Biecz (A) should be treated as an exception to the rule, having five intakes despite its small population.

Tarnow (D) achieves a diversification index classified as excellent, and thus exemplifies good management of the water supply network. Three water intakes ($u_1 = 0.168$, $u_2 = 0.634$, $u_3 = 0.198$) cooperating with 14 tanks generate an $\alpha$ index value of 0.56—the highest observed among any of the CWSSs analysed.

The example of the city of Tarnów (D) shows a comprehensive approach to risk management. The expansion of water tanks in recent years is reflected in a significantly increased value for the d index and therefore in reduced risk.

Diversification indexes in relation to the category of CWSS were also analysed, with Figure 3 presenting the values for dQ indexes in each.

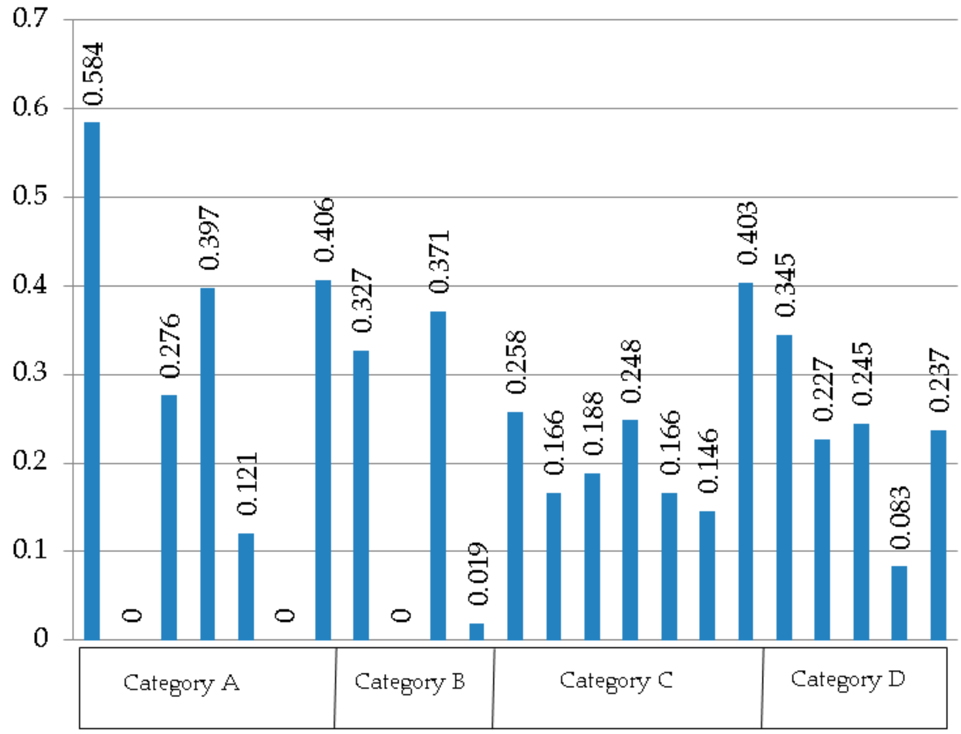


**Figure 3.** Values of the dQ index for each category of CWSS.

While CWSSs in categories A and B are characterised by high values for the dQ index, three out of 11 lack diversification in intakes. The lowest dQ values (0.17 on average) relate to category C, while category D can be seen as the most stable, given the presence of at least two water intakes, and a mean value equal to 0.26 for the dQ index. Figure 4 presents dV index values for the different CWSS categories.

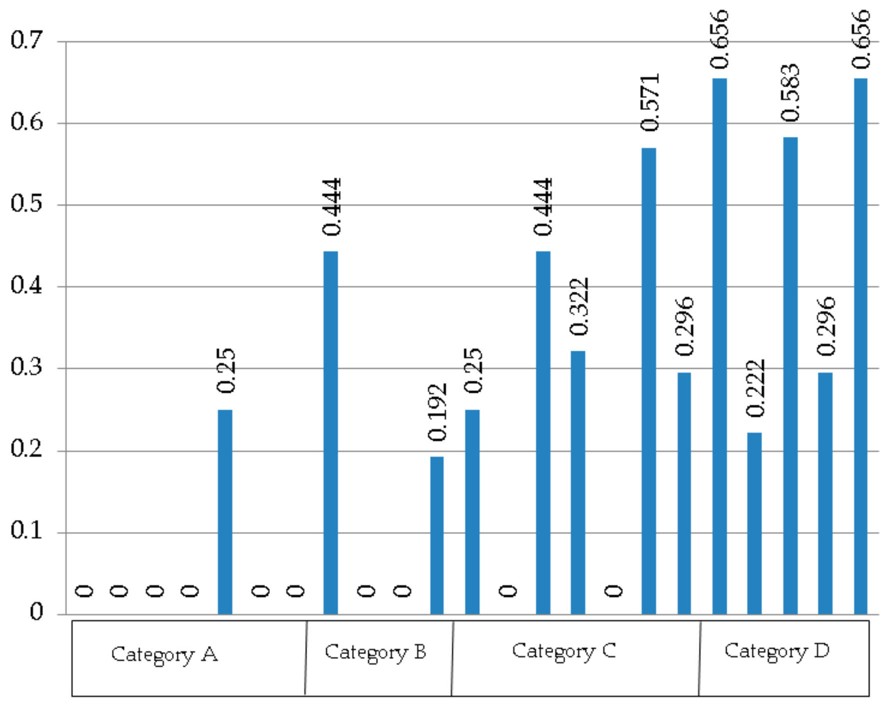


**Figure 4.** Values for the dV indexes in each CWSS category.

The values for the dV index are highest in relation to category D, in which all CWSSs have at least two water tanks. Categories B and C, in turn, include CWSSs with no diversification at the water tank level. In category A, only one CWSS has at least two water tanks.

Figure 5 presents the categories of diversification for all CWSSs.

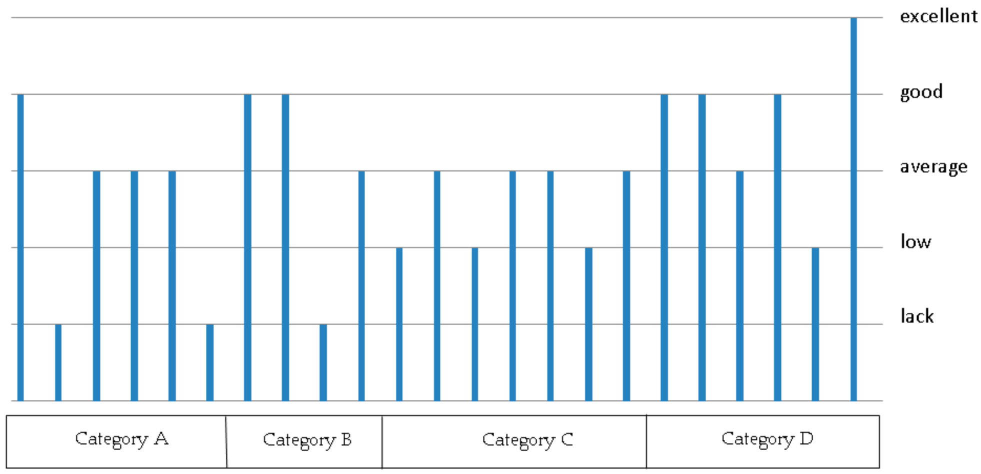


**Figure 5.** Categories of diversification for all CWSS.

Analysing the categories of diversification applying to 23 CWSSs, it can be stated that:

- The largest CWSSs (in category D) support the highest values for d diversification indexes;
- Categories A and B are characterised by very varied diversification (from lacking through to good);
- Only low or average diversification is present among the CWSSs of category C.

When interpreting the results, the possible underestimated dQ and dV indices of small CWSSs should be remembered (as explained at the end of Section 2).

The results of diversification assessment may influence the decision of CWSS operators. If a risk is to be managed, it must be identified, measured, controlled for, monitored and re-controlled. As part of risk control, decisions that increase diversification of water supply may be considered. The presented method promotes larger numbers of water intakes and water tanks. Attention should be paid to even maximum daily production capacities. On the other hand, the proposed allocation parameter $\alpha$ rewards those CWSSs in which the total volume of water in the tanks is able to cover maximally for the production capacity of water intakes, for example, in the event of shutdown (failure).

Small- and medium-sized CWSSs (of categories A and B) should strive to connect with other CWSSs to diversify at the level of intake. Basically, as they do not have water tanks, connection to another CWSS is the easiest way to reduce the risk of lack of supply, e.g., through drought or contamination at the source.

## 4. Conclusions

The proposed method seeks to achieve the rapid and easy assessment of water supply diversification. It can serve as an element of CWSS risk assessment under Water Safety Plans and does not require a large amount of input data. This implies independent implementation, by water supply companies whose managers draw conclusions for CWSSs that affect the security of local residents. The diversification of water supply raises the level of the CWSS protection parameter and is very relevant to risk analysis relating to lack of water supply.

Should the diversification of a water supply prove insufficient, the response to analysis might consider remedies such as:

- The construction of new water intakes or tanks;
- The modernisation of selected water intakes or water tanks;
- The closure of intakes whose maintenance costs are high and whose impact on the diversification of supply is insufficient;
- Connection with the CWSSs of other local authorities or cities;
- The development of procedures for alternative water supply (e.g., involving bottled water or private wells).

Dimensionless values for the component indices allow for the comparison and assessment of all types of CWSS, regardless of their construction, size or the number of residents supplied.

The results may then serve as additional prompts for managers of water supply network to consider the ongoing diversification of water supply. In turn, the use of the allocation parameter $\alpha$ underlines the importance of the volume of water in network water tanks, encouraging the consideration of emergency volumes of water tanks are designed.

Compared with the diversification indices adopted previously, the one proposed here attaches enhanced importance to numbers of water intakes and tanks. A balanced share of intake production in total water production remains important and, in fact, the roles played by intake production and tank volume should be almost equal.

The proposed method takes partial account of climate change, which may operate to reduce the production capacity of water intakes. In risk assessment, the parameter related to CWSS protection may take in threats relating to climate change as well as diversifying supplies. Climate change may reduce the protection parameter.

The authors are aware of imperfections in the presented method reflecting the over-dependence of the diversification category on CWSS size. Our discussion with experts therefore prompted the setting of common criteria, irrespective of size. This helps draw to the attention of the small CWSS to the problem of security of water supply. Size needs recalling the results are interpreted, but the overarching goal is to raise managers' awareness of all CWSS divisions needed to diversify supply. Following the aforementioned consultations with experts, the authors conclude that the possible underrating of results among small CWSSs will contribute to decisions to combine small CWSSs into larger ones.

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