Journal of Materials and Environmental Sciences
ISSN : 2028-2508
CODEN : JMESCN

J. Mater. Environ. Sci., 2018, Volume 9, Issue 11, Page 3067-3074

http://www.jmaterenvironsci.com

Assessment of changes in the Water Quality Index followingthe establishment of a sewage system

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Received 18 Sept 2018
Revised 27 Jan 2019
Accepted 28 Jan 2019

Keywords
- *Water Quality Index,*
- Pollution,
- Wastewater,
- Sewage network,
- Groundwater contamination.

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Abstract

In the present Eastern-Hungarian case study the effects of the establishment of a sewage system on groundwater quality are evaluated using the Water Quality Index (WQI).The WQI was calculated via the weighted arithmetic index method using the following parameters: pH, EC, NH_4^+, NO_2^-, NO_3^-, PO_4^{3-},COD_{ps}, Na^+. The Water Quality Status (WQS) of the monitoring wells was determined according to the WQI values. In 2013 30%of the water samples were categorised as being in the poor (51<WQI<75) and very poor WQS categories (75<WQI<100),70% were unsuitable for any usage (WQI<100),and in none of the monitoring wells did the WQI range between25-50 (good WQS) and0-25 (excellent WQS). In 2017, 3 years after the establishment of a sewage network, there was a significant increase in the water quality. The average WQI values decreased from 147.8 to 78.9. The number of wells with a WQS which was unsuitable for any usage had dropped to one third, while the number of wells with good WQS had increased from 0 to12. However, in 201770% of the monitoring wells still had a WQS which was poor, very poor, or unsuitable for any usage, which can be explained by the fact that the cleaning process takes a long time, and by the existence of contaminant discharge of households not connected to the sewage system (approx. 10%), and other local contaminant sources which have not been eliminated.Based on the above, it can be concluded that the cleaning process has obviously started, but could take several years to complete, and further environmental measures may be necessary.

1. Introduction

The vulnerability of groundwater to pollution of anthropogenic origin is evidenced by several studies [1, 2]. The potential risk to groundwater pollution requires accurate monitoring and information about the quality of aquatic systems [3,4]. The water quality condition can be described by several physical, chemical and biological parameters [5], although the large quantity of data available makes evaluation and comparison difficult. To solve this problem Horton (1965) proposed the first Water Quality Index (WQI) [6]. The main advantage of the WQI is the aggregation of chemical, physical and biological information into a single number, which is a stable, reproducible unit of measurement and communicates information about water quality to the public and policy makers in an understandable form [7]. Therefore, WQI became a well-known method to describe the condition of surface and groundwater resources [8,9,10]. In the following decades, several index methods were developed, and various types of weighted averaging method are now used to aggregate monitoring data to obtain an overall quality index [5,11,12,13].

Waste disposal and landfill sites, as well as sewage and septic tanks, are considered one of the largest sources of waste and pollutant discharge to the environment, which is an unsolved problem not only in less-developed areas of the world, but in developed areas, as well [14, 15]. In the rural built-up areas of Eastern-central Europe, due to inadequate sewage management, and the lack of wastewater treatment systems sewage infiltration into the groundwater is a crucial issue [15,16,17]. As a consequence of this, the groundwater quality has significantly decreased in these areas.

Wastewater is characterized by high concentrations of organic and inorganic Nitrogen species and Phosphate, Na^+, and organic matter. The nitrogen flowing out from sewage tanks migrates into the groundwater primarily in the form of NH_4^+, NO_2^-, NO_3^-[14].
With its accession to the European Union in 2004, Hungary ratified the Water Framework Directive (2000/60/EC) and the Urban Wastewater Treatment Directive (271/91/EEC) which regulate the issue of contamination originating from agriculture and domestic wastewater. The latter requires the establishment of a sewage system in every settlement with a population over 2000. Thanks to resources provided by the European Union, the establishment of the sewage system in Hungary has accelerated over recent years; at the end of 2015 the national ratio of households connected to the sewage system was 78.8%, which, however, was still some way from the planned 90%. The ratio of households connected to the public water system, but not connected to the sewage system, was 14.5% at the end of 2016 [18]. In the Northern Great Plain region – where the investigated settlement is located – this ratio was approximately 24%. In the settlement under investigation, the operative works started in 2013, and the sewage system was completed in 2014. In 2017, more than 90% of households were connected to the sewage system; however, there were still households which had not fulfilled the legal requirements.
In the present study the effects of the establishment of the sewage system on groundwater quality were evaluated by using the Water Quality Index [11]. Our general assumption was that, following the establishment of a utility sewage water system, groundwater quality would improve, and three years after the elimination of the main sources of contamination the WQI of the groundwater wells would significantly improve. To verify our hypothesis, the groundwater investigation results from before and after the establishment of the sewage system were compared. Our study can contribute to creating a more accurate picture of the environmental impact of similar investments, and the cleaning processes of groundwater. The main purpose of monitoring and analysing water quality is to provide information on the groundwater purification process.

2. Material and Methods

2.1. Description of the study area

The settlement under investigation is located in the eastern part of the Great Hungarian Plain (Figure 1.).

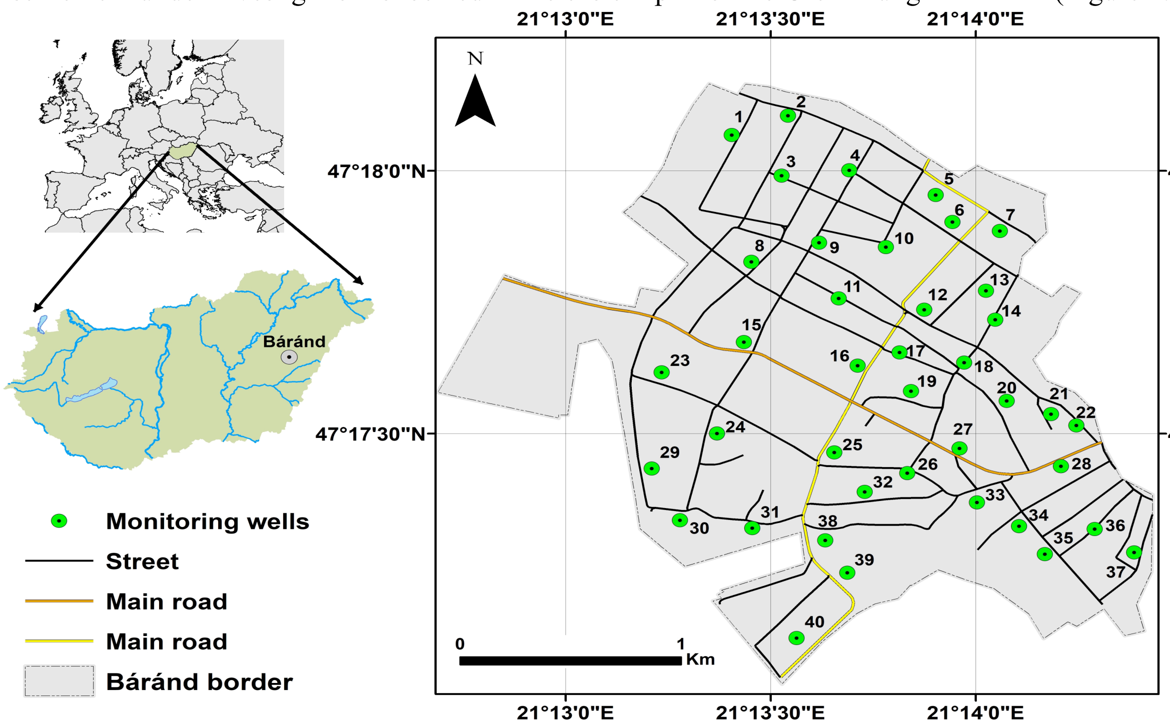

Figure 1: Location of the study area.

In the plain area, with an average elevation of 85-89 a.s.l, the groundwater level is 1-2 metres below the surface, as a result of which the characteristic soil types of the region were formed under the effect of water. The most frequent reference groups are Solonetz, Vertisol, Kastanozem and Chernozem. The average precipitation is 540 mm, and the climate is Cfb, according to the Köppen classification system [19].

2.2. Water sampling and laboratory measurements

In the present study 40 groundwater wells were investigated (Figure 1). During the sampling - performed in the summers of 2013 and 2017 - the upper 1-metre water surface of the groundwater wells was sampled. The *pH, EC* was measured by WTW 315i handheld meter and the NH_4^+, NO_2^-, NO_3^-, PO_4^{3-} content of the collected water samples was determined by standard procedures for Hungarian Standards [20, 21].The Chemical Oxygen Demand COD was determined using the $KMnO_4$ method, and Na^+ was determined by using a PerkinElmer 3110 AAS.The evaluation and visualization of the results were made using SPSS 22 and ArcMap 10.4.1 software.

2.4. Calculation of Water Quality Index (WQI) and Water Quality Status (WQS)

Eight important parameters (*pH, EC,* NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, *COD*, Na^+) were selected to calculate the Water Quality Index [11]. Calculation of the WQI was carried out by following the 'weighted arithmetic index method' (Brown et al. 1970), using the equation:

$$\boldsymbol{WQI} = \sum \boldsymbol{Q_n W_n} \Big/ \sum \boldsymbol{W_n}$$

where $\boldsymbol{Q_n}$ is the quality rating of the n[th] water quality parameter, and $\boldsymbol{W_n}$ is the unit weight of the n[th] water quality parameter. The quality rating $\boldsymbol{Q_n}$ is calculated using the equation:

$$\boldsymbol{Q_n = 100[(V_n - V_i)/(V_s - V_i)]}$$

where $\boldsymbol{V_n}$ is the actual amount of the n[th] parameter present, $\boldsymbol{V_i}$is the ideal value of the parameter [$V_i = 0$, except for pH ($V_i = 7$)], and $\boldsymbol{V_s}$ is the standard permissible value for the n[th] water quality parameter. The unit weight ($\boldsymbol{W_n}$) is calculated using the formula:

$$\boldsymbol{W_n = k/V_s}$$

where $\boldsymbol{k}$is the constant of proportionality and is calculated using the equation:

$$\boldsymbol{k = \left[1/\sum 1/V_s = 1, 2, \ldots, n\right]}$$

The Water Quality Status (WQS) according to the WQI is shown in Table 1.

Table1: WQI range, WQS status and possible usage of the water sample [11].

WQI	Water Quality Status (WQS)	Possible usage
0–25	Excellent water quality	Drinking, irrigation and industrial
26–50	Good water quality	Irrigation and industrial
51–75	Poor water quality	Irrigation and industrial
76–100	Very poor water quality	Irrigation
Above 100	Unsuitable for any usage	Proper treatment required before use

2.4. Hypothesis testing

According to our hypothesis, the establishment of the sewage system affects the contamination level of the groundwater, and three years after construction the WQI of the water of the wells will be significantly reduced, and the WQS will be improved. To test our hypothesis, we performed statistical tests using the SPSS 22 software. Since, on the basis of the Shapiro-Wilks test, one of the data sets does not show normal distribution, evaluations of any positive or negative change in the two data sets are performed using the Wilcoxon Signed Ranks Test.

3. Results and discussion

The statistical summary of the parameters investigated in 2013 and 2017 are shown in Table 3, and in Figure 2.

Table 2: Descriptive statistics for the water quality parameters of the monitoring wells

Parameters	Standard	2013	2017
pH	6.5 - 8.5	8.25 ± 0.46 (7.23 - 9.42)	7.51 ± 0.3 (7.02 - 8.3)
EC (µS/cm)	300	3032.65 ± 1701.25 (340 - 7670)	2845.78 ± 1785.77 (876 - 9290)
NH_4^+ *(mg L^{-1}))*	0.5	0.69 ± 0.37 (0.225 - 1.885)	0.53 ± 0.55 (0.078 - 3.423)
NO_2^- *(mg L^{-1})*	0.5	0.31 ± 0.33 (0.017 - 1.284)	0.2 ± 0.4 (0.006 - 1.863)
NO_3^- *(mg L^{-1}))*	50	187.83 ± 164.38 (2.36 - 564.82)	142.65 ± 159.3 (4.46 - 616.64)
PO_4^{3-} *(mg L^{-1})*	0.5	1.22 ± 1.09 (0.07 - 4.065)	0.39 ± 0.39 (0.029 - 1.54)
COD (mg L^{-1})	4.5	6.85 ± 3.94 (2.4 - 18.2)	7.65 ± 3.23 (2.9 - 17.68)
Na^+ *(mg L^{-1})*	200	237.91 ± 141.72 (8.9 - 653.2)	377.94 ± 389.62 (75.8 - 2254.2)

The permissible limits of the *pH* value of drinking water are specified as 6.5 to 8.5, as per Hungarian standards. While in 2013 the average value was 8.25 (± 0.46) and in several monitoring wells it was measured above 8.5 pH, in 2017 a significant decrease was observed, with the maximum measured value reaching 8.3.

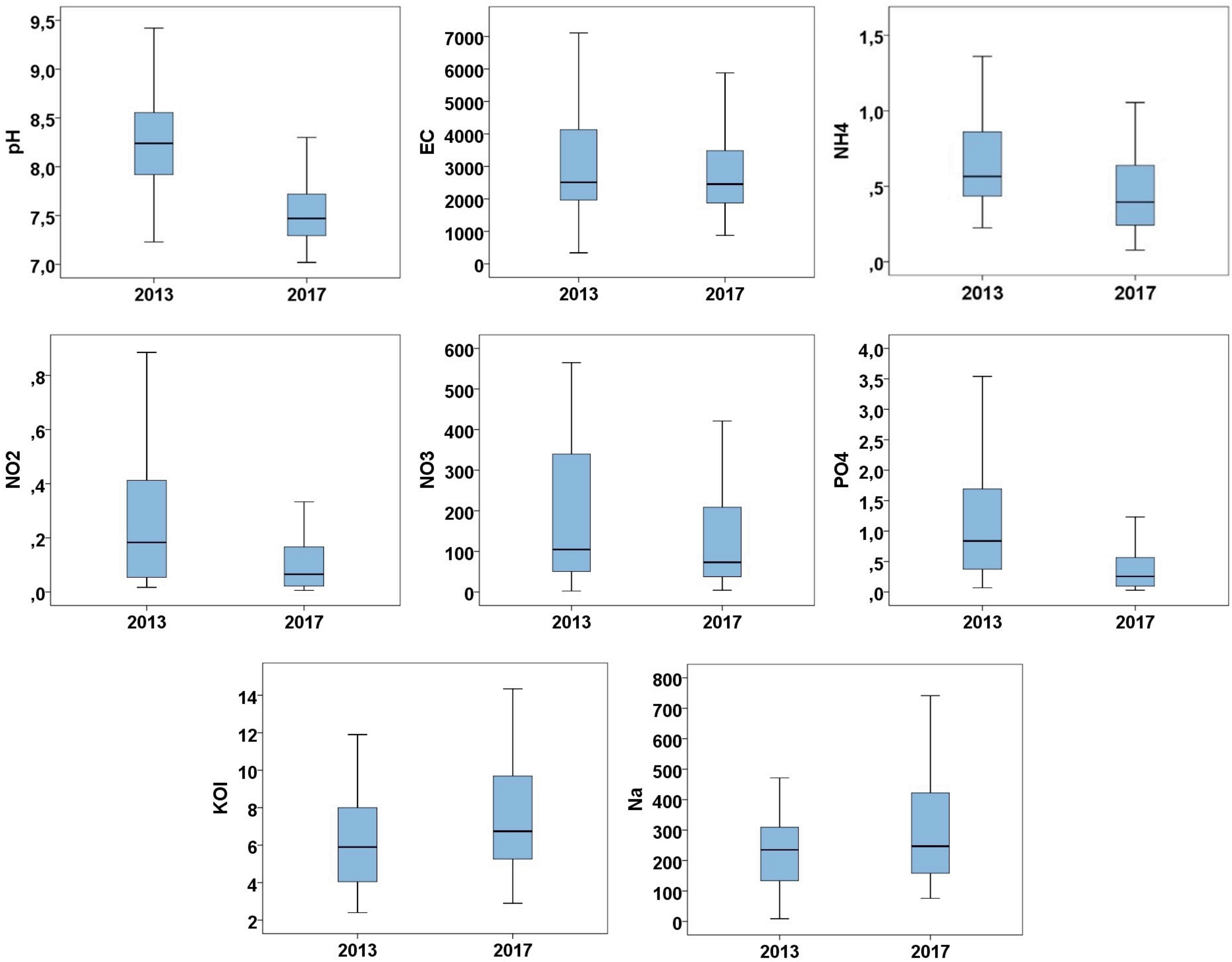

Figure 2: Box plot of investigated parameters in 2013 and 2017. The bottom and top of each box represent the lower and upper quartiles, and the line inside each box represents the median. The bottom and top bars represent the minimum and maximum concentrations.

EC is an indirect measure of total dissolved salts. The results showed very high values (3032.65 ±1701.2 in 2013), although the average value decreased somewhat after the establishment of the sewage system. The high conductivity is caused by anthropogenic sources, e.g. sewage effluent, agricultural pollution, and also through the natural weathering of the parent material. Significant differences between the minimum and maximum values were measured during the two periods (in 2013 340-7670 µS/cm, in 2017 876-9290 µS/cm).
Domestic wastewater contains a significant amount of phosphorus, which is mainly present in PO_4^{3-}in groundwater. In the 3 years following the establishment of a sewage system the mean value decreased from 1.22 (± 1.09) to 0.39 (± 0.39) mg L^{-1}. While in 2013 in 63% of the monitoring wells the level was above the limit value, this figure fell to 28% in 2017. The maximum value decreased from 4.065 to 1.54mg L^{-1}.
The nitrogen filtrating out from sewage tanks migrates into the groundwater primarily in the form ofNH_4^+**,** NO_2^- andNO_3^-. In 2013, NO_3^-varied between 2.4 and 564.8 mg L^{-1}, and in 2017,3 years after the establishment of the sewage system, it ranged between 4.5 and 616.6 mg L^{-1}(Fig. 2).The mean value, however, decreased from 187.8 mg L^{-1} to 142.7 mg L^{-1}. While in 2013, 22% of the monitoring wells recorded a concentration below 50 mg L^{-1}, in 2017 the figure was 37%. The mean values of NO_2^- in 2013(0.31 ± 0.33) had fallen to 0.2 (±0.4) mg $L^{-1}$by 2017.The concentration of NH_4^+ in 2013exceeded the 0.5 mg L^{-1} limit value in 63% of the investigated monitoring wells, but by 2017 this figure was 38%. The mean value decreased from0.69 (± 0.37) to 0.53 (± 0.55) mg L^{-1}. The fact that the average value was over the limit in 2017 can be explained, inter alia, by the fact that the degradation of organic matter accumulated in the soil over decades is still ongoing, providing for the generation of NH_4^+.
The average values of Na^+ were above the contamination limit in 2013 (237 mg L^{-1}), and also in 2017 (377 mg L^{-1}). The increase in concentration is also significant in this case, but it is also characteristic of alkaline soil conditions. The maximum value measured in 2017 (2254 mg L^{-1}) was nearly 3.5 times higher than the maximum value in 2013 (653 mg L^{-1}). A slight increase in average COD_{ps} values was detected, instead of the expected reduction. The 6.8 (± 3.9) mg L^{-1} value in 2013 increased to7.65 (± 3.2)mg L^{-1}in 2017.

Evaluation of WQI and WQS

The calculated constant and unit weights are shown in Table 3. The Water Quality Index (WQI) of the monitoring wells in 2013 and 2017 is shown in Table 4. The statistical summary of the WQI is presented in Figure 3.

Table 3: Unit weights (W_n) of the parameters used for WQI determination.

Parameter	*HU standard (V_s)*	*k*	*Unit weight (W_n)*
pH	6.5–8.5	0.15703	0.018474139
EC (µS/cm)	300	0.15703	0.000523434
NH_4^+ *(mg L^{-1})*	0.5	0.15703	0.314060359
NO_2^- *(mg L^{-1})*	0.5	0.15703	0.314060359
NO_3^- *(mg L^{-1})*	50	0.15703	0.003140604
PO_4^{3-} *(mg L^{-1})*	0.5	0.15703	0.314060359
COD (mg L^{-1})	4.5	0.15703	0.034895595
Na^+ *(mg L^{-1})*	200	0.15703	0.000785151

W_n= 1, k = 0.15703

The results showed that the groundwater is heavily contaminated. No water samples in 2013 and 2017 can be categorised as being excellent (WQI<25) or good WQS (26<WQI<50). In 2013 30% of the water samples were poor (51<WQI<75) or very poor WQS (75<WQI<100). The water in the majority (70%) of the monitoring wells was classified (WQS) as being unsuitable for any usage (WQI<100). The highest WQI value in 2013 was recorded in monitoring well no. 24 (WQI = 307.1), and in 2017 in monitoring well no. 3 (WQI=282.2). Comparing the WQI results in 2013 and 2017 significant positive changes were observed (Figure 3, Table 4). The average WQI values decreased from 147.76 to 78.9. The statistical tests concerning the two periods also showed a significant decrease in the WQI values (Figure 3).In the majority (93%) of the monitoring wells a decrease in WQI values was observed

Table 4: Water Quality Index (WQI) of the monitoring wells in 2013 and 2017.

Well	WQI		Well	WQI		Well	WQI		Well	WQI	
	2013	2017		2013	2017		2013	2017		2013	2017
1.	57.3	66.9	**11.**	122.4	53.6	**21.**	292.5	58.7	**31.**	132.4	70.9
2.	99.4	33.1	**12.**	198.0	89.5	**22.**	137.5	113.6	**32.**	158.4	44.4
3.	190.6	282.7	**13.**	135.2	174.5	**23.**	181.7	110.9	**33.**	86.4	72.3
4.	96.4	85.4	**14.**	290.1	26.2	**24.**	307.1	139.7	**34.**	106.3	47.5
5.	124.8	45.4	**15.**	178.6	54.7	**25.**	249.9	108.7	**35.**	145.6	60.4
6.	118.2	86.1	**16.**	166.0	116.8	**26.**	146.1	204.4	**36.**	117.5	41.9
7.	83.4	42.9	**17.**	201.8	93.0	**27.**	266.7	55.6	**37.**	139.6	68.3
8.	105.1	136.7	**18.**	305.2	36.5	**28.**	80.6	34.1	**38.**	63.7	26.4
9.	76.5	73.0	**19.**	53.1	66.8	**29.**	86.4	37.1	**39.**	125.1	63.2
10.	90.6	88.6	**20.**	155.6	64.3	**30.**	67.9	52.8	**40.**	170.7	27.6

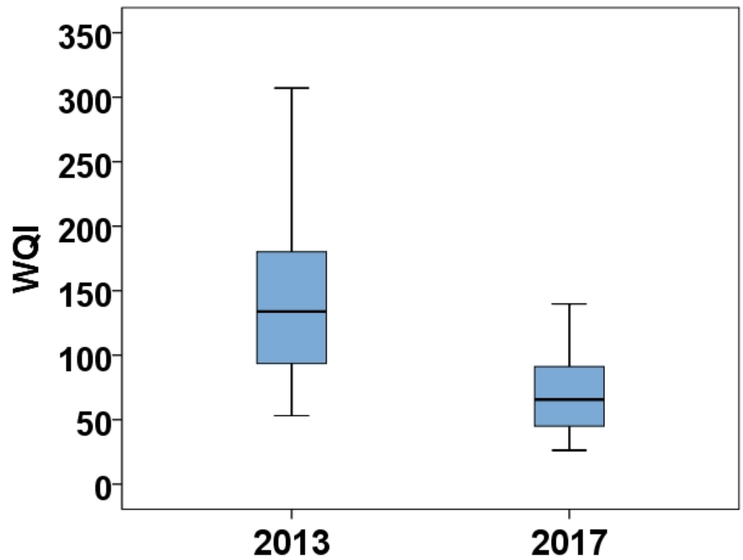

Figure 3: Box plot of the WQI in 2013 and 2017. The bottom and top of each box represent the lower and upper quartiles, and the line inside each box represents the median. The bottom and top bars represent the minimum and maximum concentrations

Based on the WQI values, the water quality of the monitoring wells was categorized for 2013 and 2017 (Table 5). The number of wells with unsuitable WQS had dropped by a third, while the number of monitoring wells with good WQS had increased from 0 to 12 (Table 5).

Evaluating the map regarding the spatial distribution of the WQS in 2013 and 2017, it can be stated that the most polluted area is the central part of the settlement (Figure 4). Three years after the establishment of the sewage system, the area was characterized by significantly better WQS rankings.

By performing the Wilcoxon test on the two investigation periods, the significance level was determined. Given that p=0.001, the significance level is 99.9 %. It can be therefore concluded that following the establishment of the sewage system the WQI values of the groundwater wells did not improve by accident; the main reason for this was the significant reduction in wastewater discharge, which led to the decrease in the concentrations.

Table 5: Water Quality Status (WQS) of the monitoring wells in 2013 and 2017

WQS	2013	2017
Excellent	0	0
Good	0	12
Poor	4	14
Very Poor	8	5
Unsuitable	28	9
Total	40	40

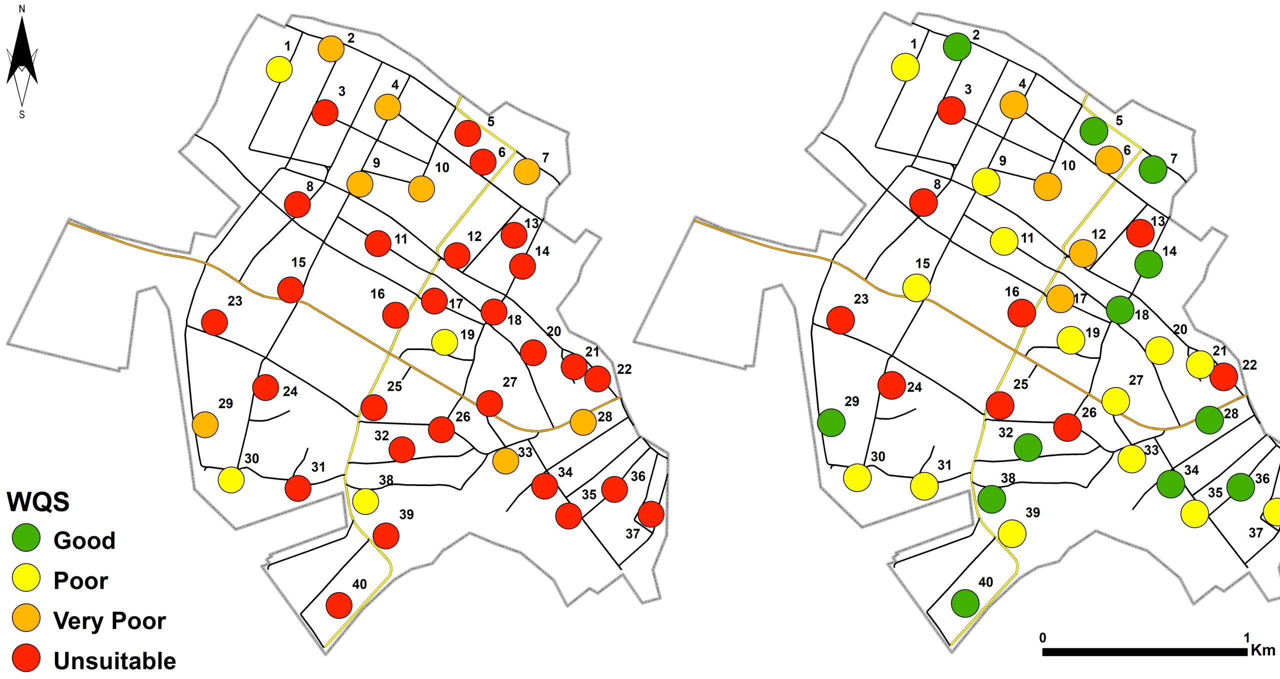

Figure 4: WQS distribution of investigated monitoring wells in 2013 and 2017.

Conclusion

The present case study, conducted with help of the Water Quality Index, provides a valuable insight into the cleaning process of groundwater after the establishment of the sewage system. The investigation clearly showed that the groundwater quality of the settlements without established sewage systems significantly decreased as a result of the contamination effects experienced over several decades.WQI values ranged from 53.1 to 307.1.In 2013, 30% of monitoring wells had a poor or very poor, and 70% an unsuitable, Water Quality Status. After investigating the effects on groundwater quality of the sewage system which was set up to protect the underground water resources, it was concluded that three years after the establishment of the sewage system the WQI and WQS showed a positive change, with the average WQI values decreasing from 147.76to 78.9by2017. By performing the Wilcoxon test (p=0.003) it was confirmed with a probability of 99.7% that the decrease in WQI values was not accidental but was the result of the establishment of the sewage system. However, more than 50% of the monitoring wells already had a poor, very poor, or unsuitable WQS (WQI>50). Based on the above, it can be concluded that the cleaning process has obviously started, but could take several years to complete, and further environmental measures may be necessary.

Acknowledgement-The research was financed by the Higher Education Institutional Excellence Programme of the Ministry of Human Capacities in Hungary, within the framework of the 4. thematic programme of the University of Debrecen.

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