The Evaluation of an Artificial Infiltration and Groundwater Recharge Project in the Well Field in Rožnov pod Radhoštěm (Czech Republic)

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Abstract

The article analyses the permeability of ground surface in order to implement artificial surface infiltration and groundwater recharge by means of surface spraying near the well field, from where groundwater is pumped using a collection gallery in the fluvial gravel terrace. The artificial groundwater recharge project was implemented in order to deal with the periods of drought and related lack of water to be pumped from the fluvial terrace. The area of interest was divided into quasi-homogeneous blocks of surface permeability. Surface spraying was applied in the permeable quasi-homogeneous block. The other low permeable quasi-homogeneous blocks were unsuitable for the application of spraying and groundwater recharge. In the research, two methods were applied to evaluate the ground surface permeability. The first method was in-situ measurements of surface permeability using a two-cylinder infiltrometer in a regular network of points near the collection gallery (drainage channel). The second method was used to evaluate the ground permeability based on soil grain-size curves, where the soil samples were drawn from the same network of points as in the first method. It showed that the majority of the area of interest is sufficiently permeable for the puposes of artificial groundwater recharge, except for three polygons, where the soils were low permeable and where ponds used to occur in the past. Based on the study, surface spraying using water from nearby ponds was applied via an irrigation system, which resulted in increased groundwater levels. In the future, artificial infiltration and groundwater recharge may be applied in analogous geological conditions.

Keywords: artificial infiltration, groundwater recharge, permeability, well field, Rožnov pod Radhoštěm (Czech Republic)

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Introduction

The risks of drought related to climatic changes and groundwater reserves have recently grown on importance. Artificial water infiltration and groundwater recharge have been reported in several studies (Abu-Taleb, 1999; Bouwer, H. 2002; Díaz-Cruz, M. S., Barceló, D. 2008; Al-Assa'd, T. A., Abdulla, F. A. 2010; Bhattacharya, A. K. 2010).

This study reports research carried out in a well field, where groundwater is obtained from a deep horizontal drainage channel situated in the collection gallery. It is 250 m long and is situated in the depth of 5.6 m in the fluvial gravel terrace of the Rožnovská Bečva River. The fluvial terrace bedrock is located in the rocks of flysch beds of predominant claystone and sandstone. The study was implemented to deal with the periods of drought to ensure sufficient yields of groundwater for pumping.

In the well field in Rožnov pod Radhoštěm, they aim for groundwater recharge using surface spraying of water by means of a system of irrigation, which leads to the recharge of the gravel terrace and increases the amounts of groundwater to be pumped from the collection gallery. However, it was first necessary to test the ground surface permeability.

Artificial groundwater recharge is not possible if the surface layer is impermeable or low permeable. For this reason, the soils in the area need to be tested and divided into permeable, low permeable and impermeable quasi-homogeneous blocks. Only the permeable quasi-homogeneous blocks may be used for the application of water spraying using a system of irrigation. Due to seepage through the geological environment of the fluvial terrace, this shall lead to an increase in the groundwater level and shall improve the situation thanks to higher groundwater resources.

Natural conditions of the area of interest and description of the well field

From the geomorphological point of view, the well field falls in the Rožnov groove that is an elongated intermontane depression. It is surrounded by Vsetín Highs in the south and Radhošť Upland in the north. As for geology, the well field is made up from the Quaternary fluvial terrace of the Rožnovská Bečva River (Fig. 1a). The bedrock is made by claystone and sand-

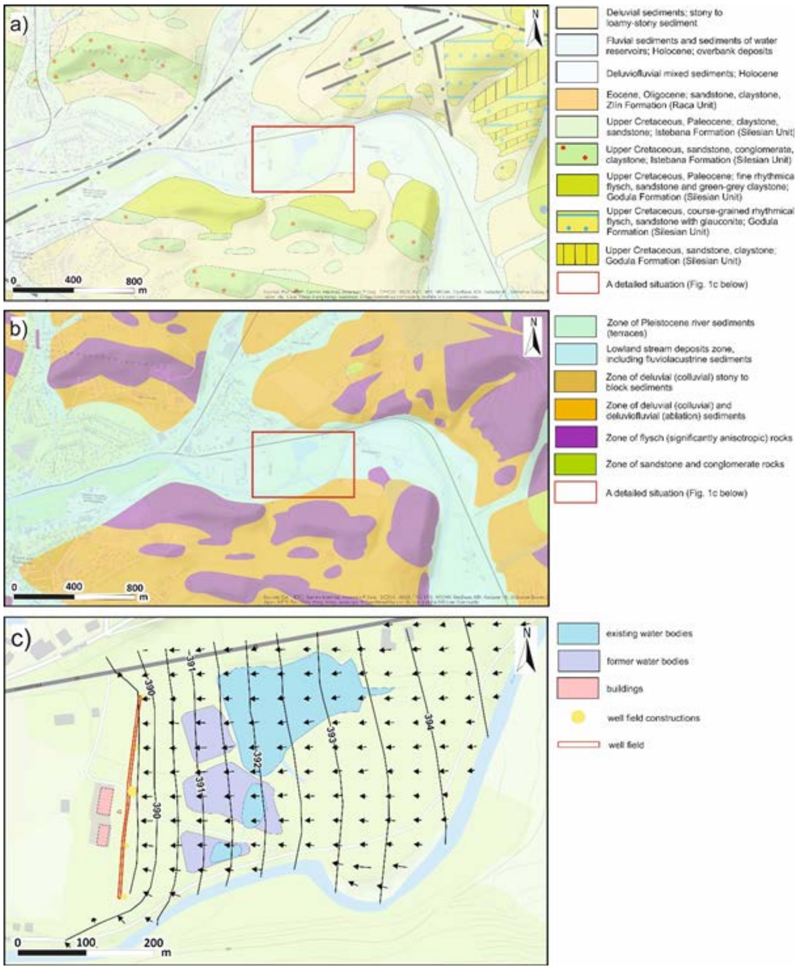

Fig. 1. Maps of the area of interest a) Geological map of wider surroundings; b) Map of engineering-geological zones; c) Map of groundwater hydroisohyps with marked groundwater flow

Rys. 1. Mapa badanego terenu a) Mapa geologiczna otoczenia; b) Mapa stref geologiczno-inżynierskich; c) Mapa hydrologii wód podziemnych z zaznaczonym przepływem wód gruntowych

stone sediments of flysch of the Godula Formation in the Silesian Unit (Pesl, 1972).

As for engineering geology, the area of interest is a zone of lowland stream deposits that constitutes of loose gravel and sand soils (Fig. 1b). In the surroundings of the studied well field there is a zone of deluvial and deluviofluvial sediments, made up by predominant colluvial loose sediments. The zone of flysch rocks outcrops in the surroundings of the area of interest with its claystone and sandstone rocks found in the fluvial teracce bedrock (Paleček, 2017). From the point of view of physical-mechanical properties, it is a varied environment of rocks. This also manifests in the hydrogeological conditions, where there are two completely different geological environments in the well field, i.e. a gravel terrace with a high pore permeability and the environment of flysch rocks, where water is mainly distributed through fissures (crevice permeability).

The well field is made up by a gravel terrace with pore permeability, thus constituting an aquifer with a free groundwater level. Besides other sources, this aquifer is saturated by water from the Rožnovská Bečva River. Other water doping is related to seepage through flysch rocks related to tectonic discontinuities and the crevice permeability. The course of hydroisohyps in the area of interest is in the north-south direction, and the groundwater flow heads westwards, which is primarily given by the course of the Rožnovská Bečva River (Fig. 1c). The groundwater level fluctuates around 390.9 m a.s.l. and is 1 m below the ground.

The well field constructions are three main objects: the linear collection gallery (1–1´), collection shaft in the middle of the collection gallery and four inspection shafts (Fig. 2).

The groundwater recharge is implemented using a collection gallery of 250 m in length (Fig. 3a). In the depth of 5.6 m there is perforated piping of 400 mm in diameter, which is packed with pebbles of 8–12 mm. Above this layer, the collection gallery is packed with gravel and fine-grained topsoil.

The most important construction is the collection shaft – for the cross-section see Fig. 3b. The collection shaft is situated in the centre of the collection gallery, which means that the drainage piping has 125 m in both

Fig. 2. A drone image of the area of interest with marked main constructions
Rys. 2. Widok z drona na badany obszar z zaznaczonymi głównymi konstrukcjami

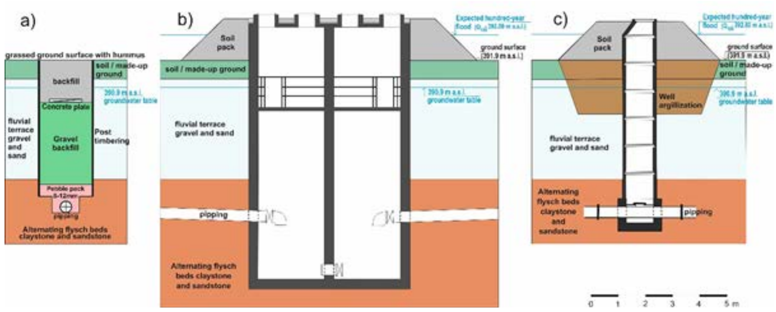

Fig. 3. Cross-sections of the well field constructions: a) collection gallery; b) collection shaft; c) inspection shaft
Rys.3. Przekrój przez onszar ochronny a. galeria nadawczy, b. szyb nadawczy, c. szyb inspekcyjny

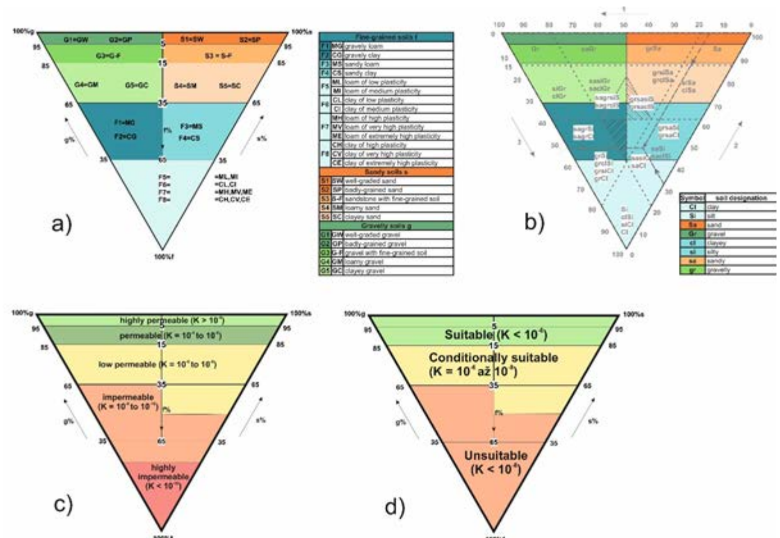

Fig. 4. Classification triangles to apply artififcial surface infiltration: a) ČSN 7310 01 classification triangle; b) ČSN EN ISO 14688-2 (721003) classification triangle; c) classification triangle of permeability; d) classification triangle of topsoil suitability for surface infiltration

Rys. 4. Trójkąty klasyfikacyjny do obliczania dodatku wody powierzchniowej : a) trójkąt klasyfikacyjny według ČSN 7310 01; b) trójkąt klasyfikacyjny według ČSN EN ISO 14688-2 (721003); c) trójkąt klasyfikacyjny dla przepuszczalności; d) trójkąt klasyfikacyjny przydatności warstwy wierzchniej do infiltracji powierzchni

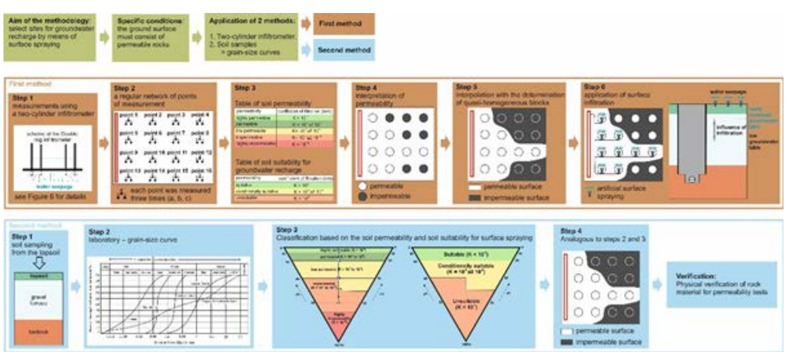

Fig. 5. Scheme of the two methods to implement artificial surface infiltration
Rys. 5. Schemat dwóch metod realizacji sztucznej infiltracji powierzchni

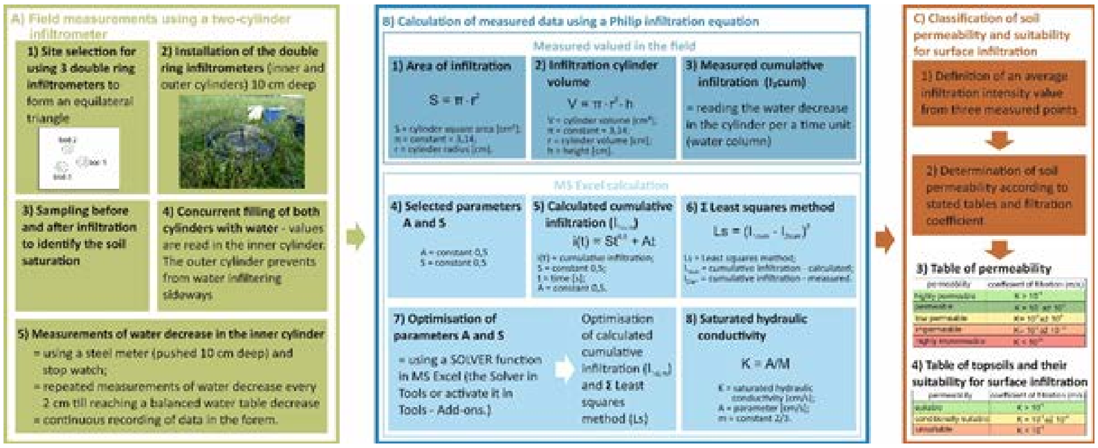

Fig. 6. Scheme of the two-cylinder infiltrometer method

Rys. 6. Schemat metody dwu-cylindrowej pomiaru infiltracji

directions. The collection shaft is divided by a wall into two separate parts, which have an operation-technical function and safety function. Piping into the collection gallery leads from each of the parts. It is possible to change the pump in one part, where the second part is independent and can continue to supply water.

The collection shaft is used to pump water into the water treatment plant. The diameter of the collection shaft is 5.8 m and it is 8.3 m deep. There are 4 inspection shafts in the well field – see Fig. 3c. The diameter of the inspection shaft is 1.2 m and it is 6 m deep. The inspection shaft provides access to the drainage piping. In the upper part, the construction is packed with impermeable clayey soil. The collection and inspections shafts end above the ground and are packed with soil to the expected hundred-year flood level Q100 (392.8 m a.s.l.).

Classification of soils and their suitability for surface infiltration

Permeability of soil has been studied, for example, by Romero et al., 1999; Xu and Sun, 2002; Iversen et al., 2003, where low permeable soils were described by Levy et al. (1993) and Tuli et al (2005) focused on disturbed and undisturbed soils.

The soils were classified into basic categories (Fig. 4d). The fist category are soils suitable for surface infiltration. It is the case of topsoil with permeable soils (filtration coefficient over 10-6 m.s-1). This category may be broken into 2 sub-categories (Fig. 4c). According to the relative permeability, the soils divide into permeable and highly permeable. The permeable soils are sand (S3=S-F) and gravel (G3=G-F) with fine-grained soil (5–15%) and soil classes according to ČSN 731001 Standard (Fig. 4a). Highly permeable soils are made up by well-graded (S1=SW, G1=GW) and badly-graded (S2=SP, G2=GP) sand and gravel, which are sand and gravel with a low amount of fine-grained soils (below 5%). According to the new European standard (Fig. 4b) ČSN EN ISO 14688-2 (721003), this category includes gravel (Gr), sandy gravel (saGr), gravelly sand (grSa) and sand (Sa).

The second category that is conditionally suitable for surface infiltration includes low permeable soils (filtration coefficient 10-6 to 10-8 m.s-1). From the point of view of foundation soils (according to ČSN 731001) there are sandy loam (F3=MS), loamy sand (S4=CS), clayey sand (S5=SC), loamy gravel (G4=GM) and clayey gravel (G5=GC). According to ČSN EN ISO 14688-2 these are silty gravel (siGr), clayey gravel (clGr), sandy-silty gravel (sasiGr), sandy-clayey gravel (saclGr), gravelly-silty sand (grsiSa), gravelly-clayey sand (grclSa), silty sand (siSa), clayey sand (clSa) and gravelly-sandy silt.

The third category are impermeable soils made up by fine-grained soils (filtration coefficient below 10-8 m.s-1) and thus unsuitable for surface infiltration. The category includes impermeable and highly impermeable soils (Fig. 4c). Highly impermeable soils have clay componets of low (F6=CL) and medium plasticity (F6=CI), clay with high (F8=CH), very high (F8=CV) and extremely high plasticity (F8=CE), loam with high (F7=MH), very high (F7=MV) and extremely high plasticity (F7=ME). According to ISO standards, highly impermeable soils are silt (Si), clayey silt (clSi), silty clay (siCl) and clay (Cl). The impermeable soils are gravelly loam (F1=MG), gravelly clay (F2=CG), sandy clay (F4=CS) as well as loam with low (F5=ML) and medium plasticity (F5=MI). According to ISO standards, impermeable soils are sandy-gravelly silt (sagrSi), sandy-gravelly clay (sagrCl), gravelly-sandy silt (grsaSi), gravelly-sandy clay (grsaCl), sandy silt (saSi), sandy-clayey silt (saclSi), sandy-silty clay (sasiCl), gravelly silt (grSi), gravelly-clayey silt (grclSi), gravelly-silty clay (grsiCl), gravelly clay (grCl) and sandy clay (saCl).

Artificial surface infiltration and groundwater recharge

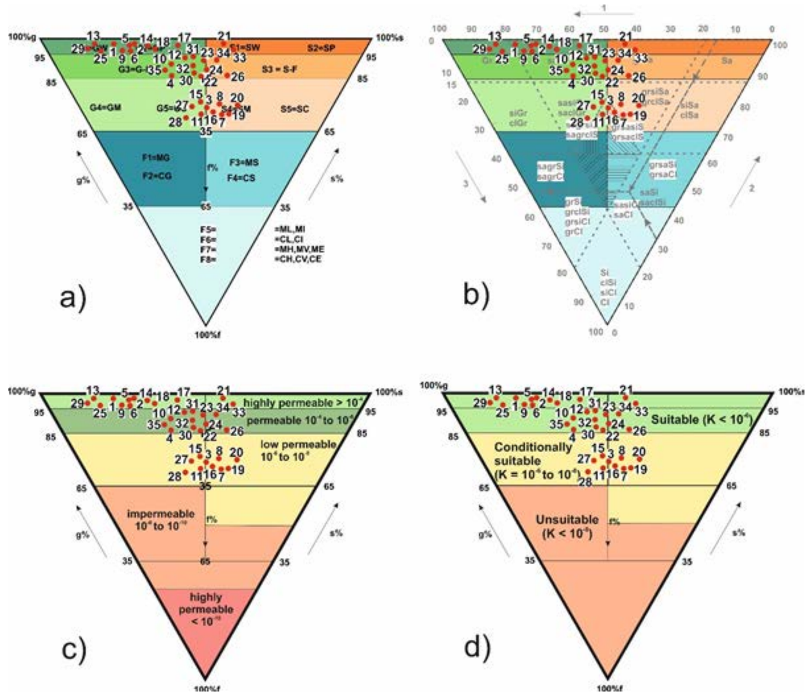

Fig. 7. Representation of 34 soil samples from the topsoil a) classification triangle of ČSN 731001; b) classification triangle of ČSN EN ISO 14688-2 (721003); c) classification triangle of permeability; d) classification triangle of topsoils marking the points falling into suitable areas for artificial surface infiltration

Rys. 7. Analiza 34 próbek z wierzchniej warstwy gleby a) trójkąt klasyfikacyjny ČSN 731001; b) trójkąt klasyfikacyjny ČSN EN ISO 14688-2 (721003); c) trójkąt klasyfikacyjny przepuszczalności; d) trójkąt klasyfikacyjny gleb ornych wyznaczający punkty sztucznej infiltracji powierzchni

Tab. 1. Evaluation of the filtration coefficient for 34 points measured by a two-cylinder infiltrometer

Tab. 1. Ocena współczynnika filtracji dla 34 punktów pomiarowych, pomiar infiltrometrem dwu-cylindrowym

Point number	Filtration coefficient K		Point number	Filtration coefficient K	
	cm.s^{-1}	m.s^{-1}		cm.s^{-1}	m.s^{-1}
1	0,019376	1,94E-04	18	0,043480	4,35E-04
2	0,010285	1,03E-04	19	0,000017	1,74E-07
3	0,000049	4,91E-07	20	0,000012	1,19E-07
4	0,000246	2,46E-06	21	0,013132	1,31E-04
5	0,087743	8,77E-04	22	0,000602	6,02E-06
6	0,077260	7,73E-04	23	0,000116	1,16E-06
7	0,000026	2,59E-07	24	0,000105	1,05E-06
8	0,000087	8,73E-07	25	0,011238	1,12E-04
9	0,019482	1,95E-04	26	0,000678	6,78E-06
10	0,000334	3,34E-06	27	0,000063	6,33E-07
11	0,000030	3,04E-07	28	0,000090	9,02E-07
12	0,000315	3,15E-06	29	0,018690	1,87E-04
13	0,038443	3,84E-04	30	0,000934	9,34E-06
14	0,018824	1,88E-04	31	0,000891	8,91E-06
15	0,000011	1,11E-07	32	0,000552	5,52E-06
16	0,000015	1,54E-07	33	0,010874	1,09E-04
17	0,011015	1,10E-04	34	0,000322	3,22E-06

The aim of the methodology was to select a site for artificial water infiltration using surface sprying in the period of drought. However, this is conditioned by the fact that the topsoil needs to be constituted by permeable rock material.

The permeable, low permeable and impermeable quasi-homogeneous blocks were determined using two methods (Fig. 5): a two-cylinder infiltrometer and soil sampling to analyse grain-size curves for permeability. The use of different types of infiltrometers in connection with soil properties were reported by Angulo-Jaramillo et al. (2000), Reynolds et al., (2000), Zimmermann et al., (2010).

The first method uses a two-cylinder infiltrometer. At the beginning, the potential well field is divided into a regular network of points. In fact, each point consti-

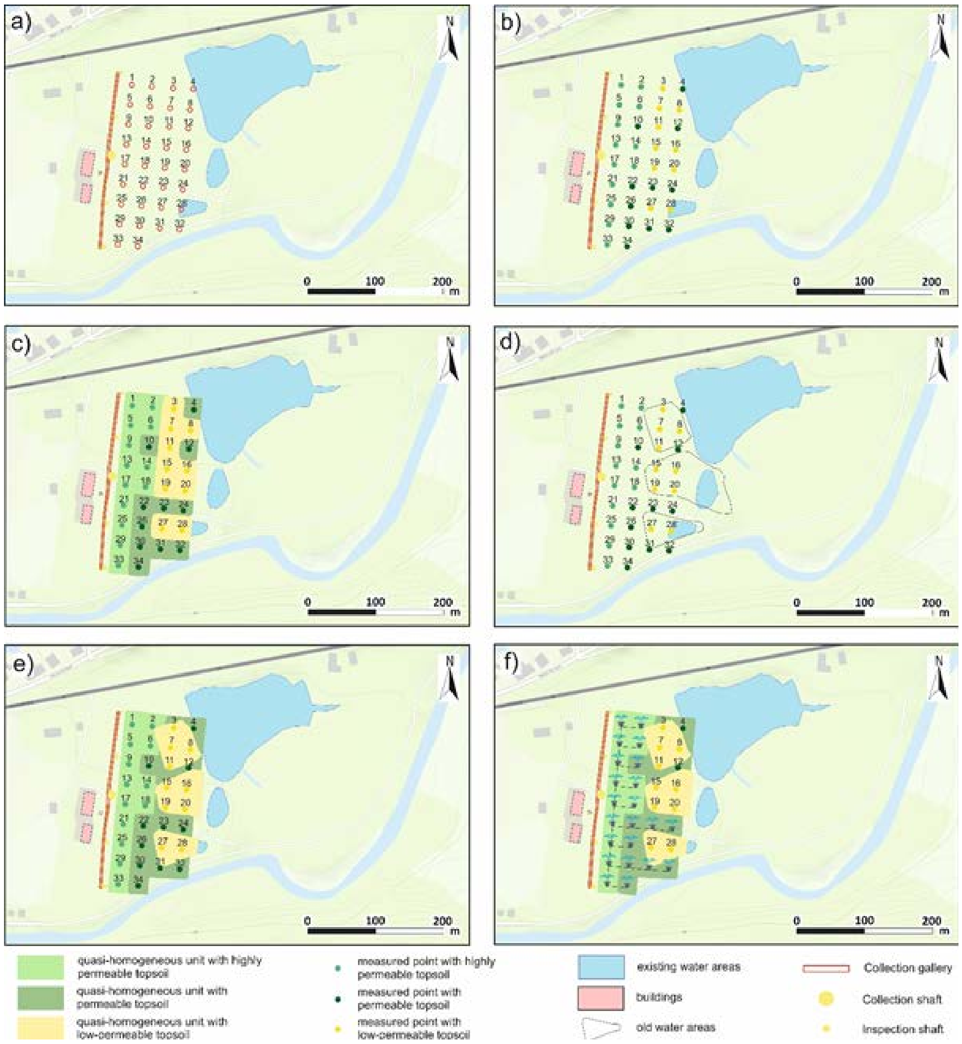

Fig. 8. Implementation of the casy study a) points of measurement; b) interpreted points of measurement based on permeability; c) interpretation based on measurement; d) corrected interpretation based on GIS records of former ponds; e) application of surface infiltration; f) application of surface infiltration by surface spraying

Rys. 8. Implementacja wyników a) punkty pomiarowe; b) wyliczone punkty pomiarowe oparte na przepuszczalności; c) wyliczenia oparte na pomiarze; d) korekta obliczeń oparta na zapisach GIS dla dawnych stawów; e) zastosowanie infiltracji powierzchni; f) zastosowanie infiltracji powierzchni poprzez natrysk powierzchniowy

tutes three points to measure. The three points form an equilateral triangle, where the two-cylinder infiltrometera are placed to measure the permeability for each point separately. The values are averaged from measuring the three points to provide the final value for the superior point, which includes the three points in the triangle (Fig. 5).

The method to use the two-cylinder infiltrometer (Fig. 6), to obtain the parameter of saturated hydraulic conductivity and filtration coefficient, has three main stages. The first stage is field measurements using the two-cylinder infiltrometer, the second is the calculation of the measured data, and the third is the classification of permeability and thus suitability for surface infiltration.

The field measurements using a two-cylinder infiltrometer is described in 5 steps. First, it is important to select a suitable location to position the three two-cylinder infiltrometers (Fig. 6–A1) in the shape of an equilateral triangle. It is necessary to avoid undesirable roughness and small obstacles, such as stones, branches and plant and shrub root systems. Both (inner and outer) cylinders are hammered down (Fig. 6–A2) 10 cm into the ground. Before starting infiltration, soil samples are drawn (Fig. 6–A3) to observe soil saturation. A steel meter is hammered down (10 cm into the ground) in the inner cylinder and both the cylinders are filled with water (Fig. 6–A4) to reach the same level (5–10 cm). The water level decrease in the inner cylinder is marked into a form (Fig. 6–A5) in mm and time is measured to mark each decrease of 20 mm. Each 20-mm-decrease, measurements are repeated and water refilled till the seepage levels off (after five consecutive measurements with identical time interval, water is not added any longer and measurements are finished).

The second stage focuses on the calculation of the measured data. The field measurements yield an infiltration square area, infiltration cylinder volume and measured cumulative infiltration (Fig. 6–B1, B2, B3), on the basis of which we may evaluate the data using the Philip infiltration equation. Using the selected infiltration parameters A and S, and constant of 0.5, we calculate the cumulative infiltration and the sum of variations (Fig. 6–B4, B5, B6). Next, using the sum of variation we optimise the infiltration parameters A and S using a “resolver” function in MS Excel. The function serves to optimise the calculation of parameter S (sorptivity) and A (parameter of Philip’s model of filtration) so that the cumulative infiltration correlated with the measured cumulative infiltration (Fig. 6–B7). Thus, we look for such a line that shall interline the measured data and shall least differ. Finally, we obtain the saturated hydraulic conductivity from the formula K = A/M, where A is an optimised parameter, and M is characterised by a 2/3 constant (Fig. 6–B8).

In the third stage, the site is classified for permeability and thus suitability for surface infiltration. The three final values of saturated hydraulic conductivity (filtration coefficient) of each measured point were averaged (Fig. 6–C1). The values are subsequently classified according to the suitability for artificial surface infiltration into suitable, conditionally suitable, and unsuitable – see Fig. 6–C2, C3, C4. The literature reports a number of methods applied to measure soil permeability (Luthin and Kirkham, 1949, Domenico and Schwartz, 1998, Iversen et al., 2001).

Next, using interpolation the area is divided into permeable, low permeable and impermeable quasi-homogeeous blocks. This means that the well field is divied into polygons based on permeability to identify where surface spraying may be applied. The demarcation of the impermeable area was verified by means of overlay analysis in GIS and older vectorised aerial photos. This way, former water bodies (ponds) with impermeable sediments were identified.

Surface water sprays were mounted in the permeable polygons to form a regular network of points, where measurements were earlier carried out. Water spraying lasted to reach the desired groundwater level, which had decreased due to longer periods of drought.

The second method is based on the principle of sampling in a regular network of points in the potential well field. Samples of foundation soils are drawn from the topsoil, where the network of points is identical to the previous method (two-cylinder infiltrometer) to be able to contrast the results.

The soil samples were analysed for grain-size in the laboratory. Grain-size analysis serves to identify the percentages of fine-grained, sandy and gravelly fractions. In sandy and gravelly soils, the soils may be classified based on the soil classification triangle. In fine-grained soils, it is also necessary to study the liquid limit (WL) and plasticity index (IP) to be able to distinguish between loam and clay of particular plasticity.

Projecting the points in the classification triangles, we obtain foundation soil classes according to ČSN 731001 (Fig. 7a) and ČSN EN ISO 14688-2 (Fig. 7b) standards. Next, the measured data are projected into the triangle classifying soil permeability (Fig. 7c). The last triangle (Fig. 7d) shows the distribution of points and classifies the areas as for suitability for the application of artificial surface infiltration, such as suitable due to permeable soils, conditionally suitable due to low permeable soils, and unsuitable due to impermeable soils.

Case study in the locality Rožnov pod Radhoštěm

First, the area of interest was divided into a regular network of 34 points eastwards from the collection gallery (Fig. 8a). In the east, the boundary is represented by the collection gallery and in the west by the existing ponds, where water spraying cannot be applied. In the north and south, the boundary is represented by the length of the collection gallery. The north-south distance is about 250 m and the west-east distance is about 110 m. The measured points were located eastwards from the collection gallery because of the direction of the groundwater flow (east-west).

Second, permeability was measured in 34 points using 2 methods. As mentioned above, the first method was a two-cylinder infiltrometer, where each point was interpreted from 3 auxiliary points. The results are stated in Table 1. The final points were classified into very permeable, permeable, and low permeable areas. There were no impermeable soils.

Permeability was also analysed using grain-size curves. Soil samples had been drawn at the measured points, grain-sizes determined in the laboratory, and soils were classified into foundation soil classes – see Fig. 7a, 7b, 7c and the results of soil suitability for artificial surface infiltration Fig. 7d. There were clear correlations between the soil types identified by the grain-size curves and using the two-cylinder infiltrometer.

Third, the point measurements were interpolated with the maps to mark quasi-homogeneous blocks. The first is a very permeable and permable quasi-homogeneous block, which is suitable for the application of artificial surface infiltration. The second is a low permeable quasi-homogeneous block, which is conditionally suitable and we decided to avoid the low permeable soils – see Table 1 and Fig. 8b. There were no impermeable soils. The spatial distribution of the quasi-homogenous blocks is shown in Fig. 8c. The borders between the very permeable, permeable and low permeable areas were drawn in the half distance between the measured points.

Fourth, the determination of low permeable areas was more closely specified and corrected using GIS. We managed to identify former ponds with low permeable soils thanks to the vectorization of older maps (Fig. 8d). The borders of quasi-homogeneous blocks were corrected based on overlay analyses using GIS Fig. 8e.

Finally, surface infiltration was implemented using water spray in the well field. Water sprays were placed in the suitable quasi-homogeneous block and water infiltered through the well field – see Fig. 8f.

Conclusion

In conclusion, the implemented case study may be applied under the following limiting conditions. The first limiting condition is the need to apply artificial groundwater recharge to improve the pumped yields of groundwater in the dry periods. The second limiting condition is the need for seepage into the acquifer through the topsoil. The third is the type of permeability in the aquifer, i.e. surface spraying is suitable only for acquifers with pore permeability.

The key factor in implementing this type of groundwater recharge was the division of the area of interest into permeable, low permeable and impermeable quasi-homogeneous blocks to identify suitable, conditionally suitable and unsuitable areas for water spraying respectively. It showed that the most permeable area was the east of the well field. The less suitable area with low permeable soils was in the west. This was confirmed using two methods, i.e. a two-cylinder infiltrometer and grain-size analysis of soil samples. Plus, overlay analysis in GIS was also applied. The GIS analysis showed there used to be ponds in the past in the area of interest with low permeable topsoil. Surface spraying was applied only in suitable areas. The proposed methodology may be applied in other localities in the Czech Republic and world-wide supposing the limiting conditions are met.

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Ocena infiltracja wód i wód gruntowych w strefie ochronnej wód obszaru Rožnov pod Radhoštěm (Czechy)

W artykule przedstawiono analizę wpływu oprysków rolniczych na wody powierzchniowę i infiltrację do gruntów w strefie ochronnej wód obszaru Rožnov pod Radhoštěm (Czechy), gdzie wody są odprowadzane do rzeki. Projekt sztucznego dostarczania wód do wód gruntowych został wdrożony, aby rozwiązać problem małej ilośi wód w okresach suszy. Obszar zainteresowania podzielono na quasi-homogeniczne bloki o okreslonej przepuszczalności powierzchni. Natryskiwanie powierzchniowe zastosowano w przepuszczalnym quasi-homogenicznym bloku. W badaniach zastosowano dwie metody oceny przepuszczalności powierzchni gleby. Pierwszą metodą były pomiary percepcji powierzchniowej in-situ za pomocą dwu-cylindrycznego infiltrometru w regularnej sieci punktów w pobliżu miejsca nawadniania (kanał odwadniający). Drugi sposób zastosowano do oceny przepuszczalności gruntu w oparciu o krzywe wielkości ziarna gleby, gdzie próbki gleby pobrano z tej samej sieci punktów jak w pierwszej metodzie. Wykazano, że większość badanego obszaru jest dostatecznie przepuszczalna dla sztucznegouzupełniania wód podziemnych, z wyjątkiem trzech wielokątów, gdzie gleba była słabo przepuszczalna i gdzie kiedyś występowały stawy. Na podstawie przeprowadzonych badań zastosowano natryskiwanie powierzchniowe przy użyciu wody z pobliskich stawów za pomocą systemu nawadniającego, co spowodowało zwiększenie poziomu wód gruntowych. W przyszłości sztuczne infiltracje i uzupełnianie wód gruntowych mogą być stosowane w analogicznych warunkach geologicznych.

Słowa kluczowe: sztuczna infiltracja, uzupełnianie wód podziemnych, przepuszczalność, pole dołkowe, Rožnov pod Radhoštěm (Czechy)