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The Working Conditions and Optimisation of a Large Rainwater Harvesting and Treatment System in an Area at a Risk of Erosion

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Abstract
Rainwater harvesting and treatment systems (RHTS) are used in many places around the world as a part of sustainable water management. They decrease the risk of overloading the sewage network and environmental pollution. The efficiency and reasonableness of using such solutions in specific erosive conditions are not sufficiently understood. The aim of the study was to evaluate the operation of RHTS, receiving effluents from the wholesale market and fuel station (twenty years of observations). The studied system is located in an area endangered by water erosion. In the study period, due to the accumulation of erosive phenomena, it was necessary to optimise the system (including the installation of new devices and increasing the capacity of reservoirs). The analyses referred to the stability and work safety of the most important equipment and water treatment efficiency. The quality of water in the reservoirs was measured before and after the modernisation of the system. Selected physical, oxygen, biogenic and salinity indicators were determined in the water. During the study, RHTS had a positive effect on the quality of rainwater runoff – the values of many contaminants were reduced (RHTS 1: suspended solids, nitrogen, iron, potassium; RHTS 2: conductivity, suspended solids, nitrogen). Design and operational errors were noticed that in the long run may contribute to deteriorating the operational efficiency and even lead to a building collapse (intense erosive phenomena). This study clearly demonstrates that building a rainwater management system is a highly site-specific issue.

Keywords Rainwater · Pollutant · Treatment · Erosion · Modernisation

1 Introduction

The negative effects of progressing urbanisation include deterioration of the status of water resources. This is a result of levelling and sealing the surface of land and, as a consequence, deformation of the local hydrological cycle. A larger non-permeable area means an increase in the volume of rainwater that needs to be safely collected and disposed of

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into receiving bodies. Municipal sewerage systems show increasing flow rate irregularity and hydraulic overloading. Building development and sealing of the grounds additionally decreases the amount of water soaking into the soil, thereby reducing the possibility of natural self-purification and renewal of underground water resources (Geiger et al. 2009).

Rainwater and melt-water runoff in urbanised areas can contain considerable amounts of pollutants, and so they pose a risk to natural receiving bodies such as water and soil. Scientific literature points to a strong correlation between the method of development of the drained area and the quality of precipitation run-off. Increased migration of pollutants can be expected within road infrastructure, city centres, industrial grounds, and certain types of roofing material (Liu et al. 2014; Zhang et al. 2014a).

It is possible to decrease the risk of overloading the sewerage system and environmental pollution by reducing the volume of rainwater runoff and the load of pollutants it transports in an urban catchment. In areas where a lot of free space is available, simple solutions, such as retention ponds, wetlands, settling tanks and infiltration basins, are often the right choice. Dilution, sedimentation and biological reduction of pollutants takes place in those structures (Ivanovsky et al. 2018; Maniquiz-Redillas et al. 2014). There is still a deficit of research work documenting the efficiency and reasonableness of using such solutions in conditions of erosion. Incorrect selection, installation and use of the system may result in unsatisfactory operation and even a negative impact on the adjoining grounds.

This paper aims to assess the operation of the system of managing rainwater from the area of the Lublin Wholesale Market and fuel station located in the metropolitan area of Lublin (south-eastern Poland). The analysed rainwater harvesting and treatment system (RHTS) was commissioned in 1999. It is located within a loess area at considerable risk of water erosion. Many components comprise native soil, which in unfavourable hydraulic conditions can decrease the reliability and safety of work. The basic elements of a rainwater system are earthen reservoirs (reduction of rainwater run-off and reduction of the concentration of pollutants). Studies carried out in 2000-2020 determined, among other parameters, the quality of rainwater accumulated in the reservoirs and the water treatment efficiency. Based on field observations an evaluation of the basic technical and operating parameters of the facility at different stages of its operation was carried out.

2 Materials and Methods

2.1 General Conditions

The studied facility is located within the Lublin Upland macroregion. The territory is characterised by varied loess relief. The presence of loess soil, terrain relief and method of its development are conducive to water and air erosion.

The Lublin Wholesale Market (LWM), the fuel station and the related sewerage system were commissioned in 1999. The activity of LWM is mainly based on trade, services and food processing. The fuel station sells motor fuel and retail products. These facilities are located on a national road, right behind the northern boundary of the city of Lublin. They cover an area of 23.6 ha (sealed surface 19.8 ha). The predominant structures are market squares and training yards, car parks, carriageways, pavements and roofs. The drained facility is located on the top part of the upland (Fig. 1).

A separate sewerage system is placed within the LWM and fuel station area. Rainwater is disposed of into the reservoirs which are the subject of the study. The rainwater sewerage

Fig. 1 Location of the rainwater harvesting and treatment system (2020) (www.geoportal.gov.pl)
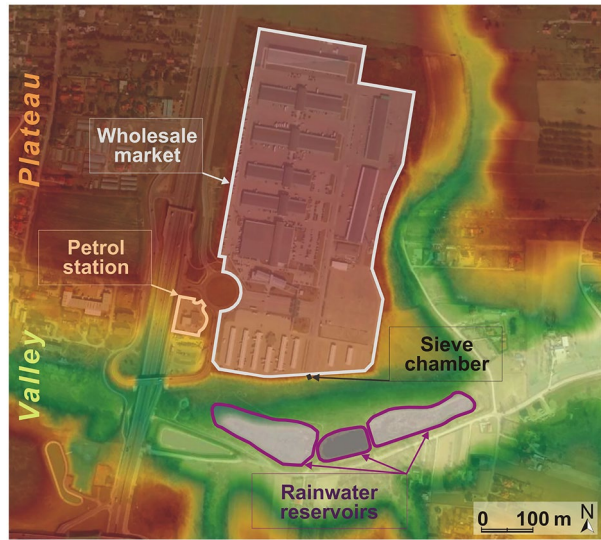
system consists of the main interceptor with a diameter of 1000 mm to which lateral sewers with a diameter of up to 400 mm are connected. The system is fitted with inspection chambers and street inlets with small settlers. Rainwater runoff from the area of the fuel station is pre-treated in a sand trap (HEK-EN 4000) and oil derivatives separator (SuperPEK NS 25) before it is transferred into the LWM sewerage system. The whole system is based on gravity flow. Reservoirs were built in the bottom of a dry erosion valley connecting to the valley of the Bystrzyca – the main river in Lublin city (Fig. 1). There are numerous small farms in the direct vicinity of the reservoirs.

The treatment technology was selected based on the availability of free space, relatively low costs of investment and operation, the possibility of using self-purification and gravity flows (energy savings) and the possibility of reusing the post-treatment water in the direct vicinity of the reservoirs (savings of tap water, reduced cost of transport).

2.2 RHTS–variant 1 (1999-2014)

In 1999-2014 the RHTS was made of an arc sieve and two earthen reservoirs – a sealed settler (area 0.43 ha, capacity 3,900 m^3) and infiltration reservoir (0.60 ha, 5,600 m^3) (Fig. 2). Active depths were about 1.0 m.

The equipment was designed for rainfall $p = 50\%$ (probability of occurrence) lasting for 180 minutes with an intensity of 18 $dm^3 \cdot ha^{-1} \cdot s^{-1}$ and single-time influx volume of about 3,750 m^3. The US-910z type arc sieve was placed in the escarpment, inside a reinforced concrete chamber. The cascade solution allows bringing rainwater down from the elevation of 196.8 to 192.7 m asl. During the straining process the sieve retains large particles (e.g. packaging, leaves, residues of fruits and vegetables). Afterwards, rainwater was transported via pipelines to the weir chamber and then to the settler. In emergency situations water could be transferred directly to the infiltration reservoir (such an event did not occur during the study period). The bottom and slopes of the settler were lined with a bentomat and reinforced with strengthened concrete slabs. The settler was connected with the infiltration reservoir by downpipes with gate valves and a safety overflow in the levee crown
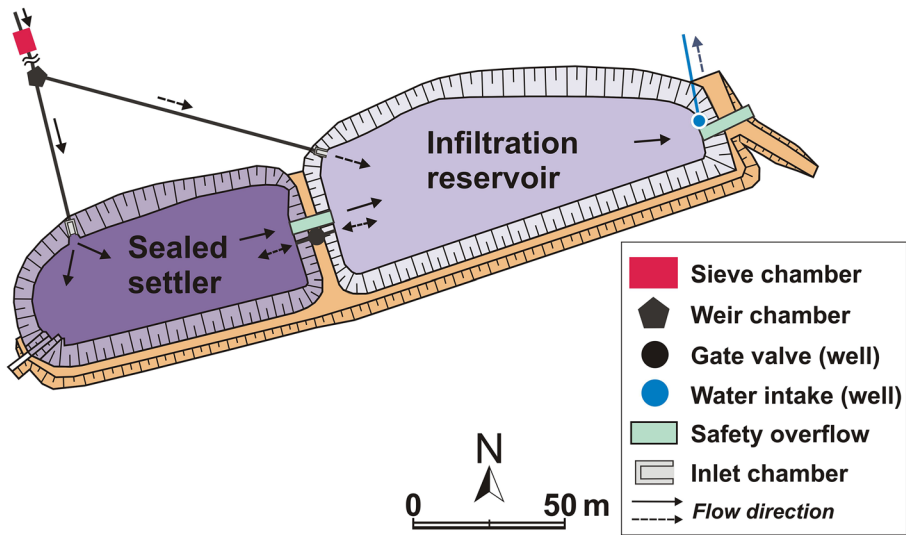
Fig. 2 Rainwater harvesting and treatment system – variant 1 (1999-2014)

(Fig. 2). The overflow was automatic after the settler was overfilled. The infiltration reservoir was not equipped with seals. Its levees were comprised of native soil and covered with turf. Pre-treated rainwater was introduced into the soil through the bottom of the reservoir. The slopes of both reservoirs and the bottom of the infiltration reservoir were covered with aquatic plants supporting the treatment process. Behind the infiltration reservoir an additional absorptive surface was separated (grassland), to collect rainwater in the event the reservoirs are overfilled. Water flowed through the safety overflow at the end of the reservoir (Fig. 2). In the initial period of the RHTS operation, rainwater pre-treated in the infiltration reservoir was reused for washing the squares and roads within the market. This solution contributed to saving tap water in the metropolitan area of Lublin that is deficient in this respect. Due to devastation of the intake, return pumping of water was abandoned, which increased the risk of overfilling the reservoirs.

2.3 RHTS–variant 2 (2014-2020)

In connection with the increasing level of water in the reservoirs, deteriorating technical condition of respective facilities and the planned increase of the sealed surface of the LWM (increase in inflow), in 2014 the RHTS was comprehensively modernised and expanded. A new large infiltration reservoir was built on the western side of the settler and a number of new reinforcing elements were added (Fig. 3). Only in the arc sieve chamber were no changes made.

In the case of the existing infiltration reservoir (eastern side) the bottom area was increased by 0.25 ha and the capacity by 2,200 m³ (after the expansion: 0.85 ha, 7,800 m³). The new infiltration reservoir (western side) has an area of 1.00 ha and capacity of 9,000 m³. Active depths of the reservoirs did not change and are about 1.0 m. The infiltration reservoirs have no technical reinforcement and are not sealed. The levees and bottoms were made from local soil. During the modernisation new safety overflows were built between the settler and the infiltration reservoirs (Fig. 3). They were reinforced with concrete slabs.
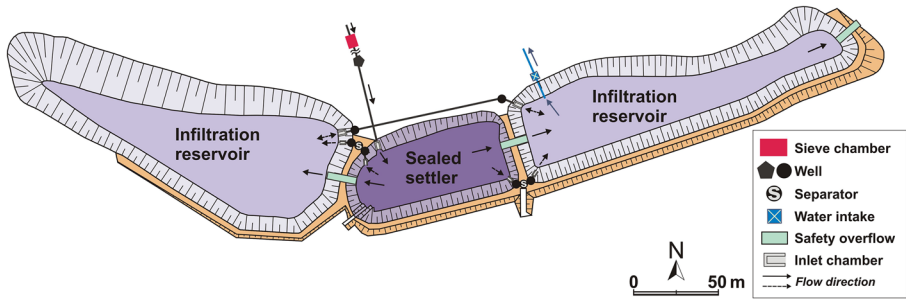
Fig. 3 Rainwater harvesting and treatment system – variant 2 (2014-2020)

The overflow was also made at the end of the eastern reservoir. Following the expansion of RHTS no water flowing over the safety overflows was observed. Rainwater is transferred from the settler to the infiltration reservoirs via pipelines installed in the levees. They are equipped with oil derivatives separators and outlet weirs. Infiltration reservoirs were connected by a pipeline for aligning the water pressure and levels (Fig. 3). Next to the eastern infiltration reservoir a pumping station building was erected to supply the designed artificial rain system in the future (e.g. irrigation of the energy crops plantation).

2.4 Climatic Conditions

Data concerning selected climatic conditions in the study area was retrieved from elaborations prepared by Statistics Poland in Warsaw (CSO 2009, 2010, 2011, 2017; SP 2018, 2019). Special attention was paid to periods during which rainwater runoff quality was analysed. The first of them covers the years 2008-2010 – before the modernisation and expansion of RHTS and the second 2016-2018 – after modernisation and expansion. Analyses of climatic conditions were mainly based on atmospheric precipitation sums and air temperature values responsible for the emergence and volume of rainwater runoffs. Values of those parameters were compared with data pertaining to a multi-annual period (1971-2010).

2.5 Field Observations

During the studies about one thousand photographs of respective units and sections of the RHTS and the adjoining grounds were taken. The longitudinal and transverse profiles measurements of a section of the valley in which the RHTS is located were made. The parameters of the reservoirs were also determined. This was possible based on geodetic measurements and analysis of cartographic materials (topographic maps and orthophotos). A GNSS Topcon HiPer V receiver and a Topcon FC-2600 controller were used. The quantity and quality of erosion changes were recorded and documented. A graphical presentation of the results was prepared using CorelDRAW.

2.6 Water Sampling and Analysis

Analyses of the physico-chemical properties of rainwater accumulated in the reservoirs of RHTS were carried out seasonally (in total 24 measurement dates). Samples were taken

using a bailer in half of the length of the reservoirs during rainless weather. Water was tested at the Water and Wastewater Laboratory of the University of Life Sciences in Lublin. The following devices were used: WTW MPM 2010, WTW Multi 340i, and Slandi LF 205. The following parameters were determined in the samples: electrolytic conductivity (by conductometry), pH (by potentiometry), total suspended solids (by drying and weighing), dissolved oxygen (O_2), BOD_5 (by dilution), COD (by the dichromate method), ammonium ions (NH_4^+), nitrates (NO_3^-), nitrites (NO_2^-), phosphates (PO_4^{3-}), sulphates (SO_4^{2-}), iron (Fe^{3+}), potassium (K^+), and chlorides (Cl^-) (photometric determination). In evaluating the quality of water the extreme and mean values of the analysed indicators were determined for all checkpoints. Statistical variability of the results was based on standard deviation and the coefficient of variation. Non-parametric Wilcoxon and Mann-Whitney tests made it possible to determine the significance of differences in the quality of rainwater in the settler before the modernisation (2008-2010) and after the modernisation of RHTS (2016-2018) and compare the content of pollutants in the settler and the infiltration reservoir in both variants (evaluation of treatment efficiency). The choice of statistical tools depended on the size of the compared sets.

3 Results and Discussion

3.1 Analysis of Climatic Conditions

Special attention was paid to periods during which rainwater runoff quality was analysed (Table 1). In the first period (2008-2010) the mean annual sum of precipitation was 96 mm higher than the multiannual average. In the second period (2016-2018) the mean annual precipitation was close to the mean annual precipitation in 1971-2010. The year 2010 was especially abundant in rainfall as the precipitation sum was 753 mm. Monthly precipitation above 100 mm occurred almost exclusively in the warm season (April-September). In 2008-2010 annual precipitation sums grew successively (from 649 to 753 mm), whereas in 2016-2018 they decreased (from 698 to 481 mm). In 2018 total rainfall was 20% lower than the multiannual rainfall. At that time a hydrological drought occurred. In that year exceptionally high air temperatures were also recorded. The mean annual temperature was 9.3 °C and was higher than the multiannual average by 1.6 °C. In the analysed periods considerable differences were observed between the minimum and maximum monthly precipitation. This could lead to large differences in the rainwater run-off directed to the tested retention reservoirs. Mean annual air temperatures were higher by 0.5 °C (2008-2010) and 1.1 °C (2016-2018) than the multiannual average. In the first period mean annual temperatures successively decreased and in the second period they increased (the situation was the reverse for annual precipitation sums) (CSO 2009, 2010, 2011, 2017; SP 2018, 2019).

3.2 Analysis of the RHTS Operation–variant 1 (1999-2014)

The first problems in the operation of the RHTS were noted five years after its construction. They were mostly connected with errors in the design, operational omissions and harmful activity of third parties. The facility was designed only for collecting rainwater from the area of the market and fuel station. However, during extremely large rainfall the infiltration reservoir was supplied with water flowing on the surface of the northern slope. The average slope inclination is 10%, and its length reaches 60 m. Surface run-offs were the carriers of

Table 1 Monthly and annual precipitation sums and mean air temperature in the study period compared with average climatic conditions in a multiannual period

	Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I-XII
Precipitation (mm)	2008-2010	30	28	52	27	105	81	83	74	78	53	44	38	694
	2016-2018	25	37	42	46	39	49	96	42	51	82	34	54	597
	1971-2010	32	30	37	39	63	69	82	69	63	43	38	33	598
Temperature (°C)	2008-2010	−3.9	−0.8	2.3	9.4	13.1	16.8	19.4	18.6	13.0	7.2	5.2	−2.0	8.2
	2016-2018	−3.4	−0.9	2.8	9.6	14.9	18.1	19.0	19.0	14.7	8.5	3.1	0.5	8.8
	1971-2010	−3.1	−2.0	2.0	8.0	13.5	16.1	18.5	17.7	13.0	7.8	3.0	−1.6	7.7

soil erosion products (Fig. 4A). No levee or surrounding drainage ditch was constructed from the side of the slope. The design assumed that the turf and shrub cover of the slope will provide sufficient protection against uncontrolled surface run-off. Periodic turbidity and sedimentation of loess deposits additionally testify to the incorrect general evaluation of the conditions in pre-design studies. Due to the influx of clay particles to the infiltration reservoir its bottom was probably clogged and water infiltration into the soil base was reduced (Conley et al. 2020). As a result, the degree of filling in the reservoirs started to grow dangerously (Fig. 4C). The safety overflow located between them was increasingly often flooded by stagnating water. In both safety overflows deepening erosion damage was observed (Fig. 4B). Reinforcement of loess levees in the form of geomembrane and concrete slabs was insufficient. In the long run it could lead to building collapse and flooding of adjoining grounds (Danka and Zhang 2015).

The absence of fencing and monitoring resulted in devastation and theft of certain elements of equipment, e.g. a submersible pump and platforms. The use of the rainwater reservoirs for recreational purposes (e.g. for angling) (Fig. 4D) and activities leading to earth loss in levees on the southern side (weakening of structures) were extremely irresponsible.

In 2008-2010 rainwater accumulated in the settler featured large differences in quality. High coefficients of variation exceeding 100% were found for conductivity, suspended solids and Cl^- (Table 2). A high value of this parameter was also observed for NO_3^- (91.3%). This phenomenon is connected with the presence of many factors
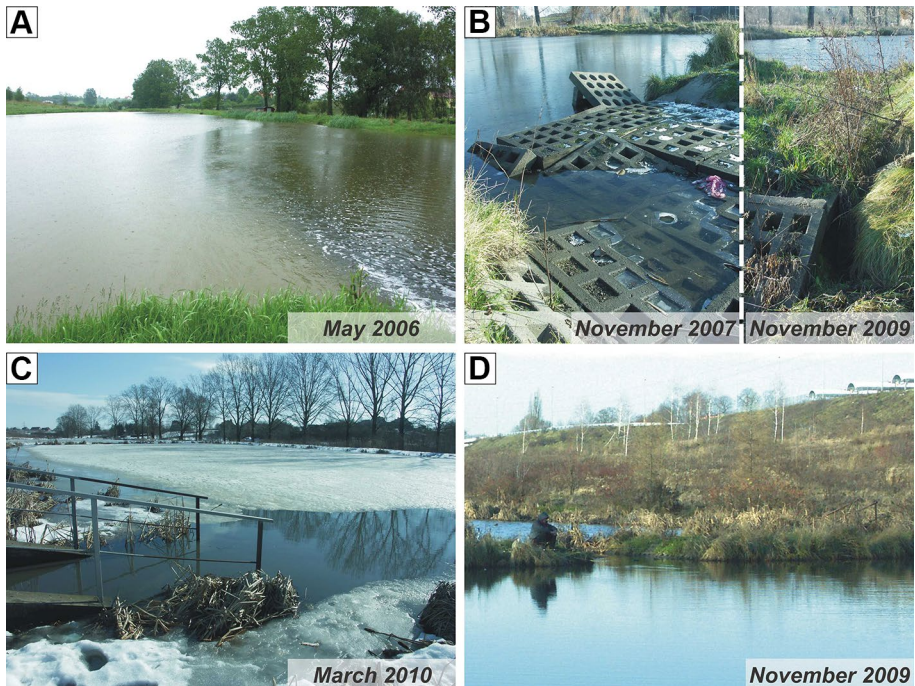

Fig. 4 Examples of operating problems in the RHTS–variant 1 (1999-2014): **A**) uncontrolled influx of the eroded loess material into the infiltration reservoir (increased turbidity near the left bank); **B**) damage of safety overflows due to erosion; **C**) extreme high level of filling of the reservoirs; **D**) illegal use of the rainwater reservoirs (angling)

Table 2 Characteristic values of rainwater quality indicators in settler (control point 1) and infiltration reservoir (control point 2) in 2008-2010 (statistical significance of differences in quality variables was determined for $\alpha = 0.05$ and $\alpha = 0.10$ – Wilcoxon test)

Variables	Control point	Minimal value	Maximum value	Average	Percentage difference	Standard deviation	Variation coefficient	Important difference
Temperature (°C)	1	0.5	25.0	12.2	+0.3	9.3	76.0	–
	2	0.5	25.5	12.3		9.4	76.7	
Conductivity ($\mu S \cdot cm^{-1}$)	1	54	1,730	447.8	−28.1	481.7	107.6	–
	2	67	1,247	322.2		321.7	99.8	
pH	1	5.9	7.7	7.2	+5.1	0.5	7.1	+
	2	5.9	9.3	7.6		0.9	11.6	($\alpha=0.05$)
Suspension ($mg \cdot dm^{-3}$)	1	8.4	144.4	29.0	−43.4	38.1	131.5	+
	2	3.0	61.0	16.4		15.5	94.6	($\alpha=0.05$)
O_2 ($mg \cdot dm^{-3}$)	1	4.0	9.0	6.9	+31.9	1.4	19.6	+
	2	5.1	12.4	9.1		2.1	23.5	($\alpha=0.05$)
BOD_5 ($mg \cdot dm^{-3}$)	1	5.2	7.5	6.1	−23.0	0.7	11.8	+
	2	0.4	8.4	4.7		2.2	47.5	($\alpha=0.10$)
COD_{Cr} ($mg \cdot dm^{-3}$)	1	14	53	30.9	−23.7	11.4	36.9	+
	2	9	40	23.6		10.4	44.3	($\alpha=0.05$)
NH_4^+ ($mg \cdot dm^{-3}$)	1	0.08	1.24	0.42	−46.7	0.3	74.8	+
	2	0.04	0.49	0.22		0.2	73.6	($\alpha=0.05$)
NO_3^- ($mg \cdot dm^{-3}$)	1	0.09	4.38	1.41	−41.0	1.3	91.3	+
	2	0.09	2.12	0.83		0.6	77.5	($\alpha=0.10$)
NO_2^- ($mg \cdot dm^{-3}$)	1	0.03	0.26	0.11	−41.9	0.1	52.6	+
	2	0.03	0.16	0.06		0.04	66.2	($\alpha=0.05$)
PO_4^{3-} ($mg \cdot dm^{-3}$)	1	0.09	1.20	0.50	−17.0	0.3	68.9	–
	2	0.10	0.89	0.41		0.3	74.2	
SO_4^{2-} ($mg \cdot dm^{-3}$)	1	2	18	9.2	−0.9	5.3	57.9	–
	2	3	24	9.1		6.2	67.9	

Table 2 (continued)

Variables	Control point	Minimal value	Maximum value	Average	Percentage difference	Standard deviation	Variation coefficient	Important difference
Fe^{3+} $(mg \cdot dm^{-3})$	1	0.20	0.90	0.46	−45.7	0.2	51.4	+ (α=0.05)
	2	0.08	0.50	0.25		0.1	46.7	
K^+ $(mg \cdot dm^{-3})$	1	1.7	24.0	10.1	−42.5	6.5	63.8	+ (α=0.05)
	2	1.9	10.1	5.8		2.5	42.7	
Cl^- $(mg \cdot dm^{-3})$	1	2.8	210.0	56.0	−34.8	70.9	126.5	−
	2	5.1	140.0	36.5		40.1	109.8	

determining the degree of pollution of rainwater and rainwater run-offs. Significant factors include the variability of weather conditions, method of using the drained area and the rainwater management system. In the analysed rainwater system, for instance, a considerable improvement in the quality of water stored after long-lasting rainfall was observed. After the drained area had been flushed, clear liquid of relatively good quality was supplied to the site and had a diluting effect on rainwater from previous run-offs (Lee et al. 2002; Zubala 2018). On the other hand, the load of pollutants increased during thaw, which was a result of a strong accumulation of pollutants on the snow cover surface (Reinosdotter and Viklander 2005).

On most of the measurement dates rainwater accumulated in the settler was characterised by unsatisfactory quality. Ratios deteriorating the quality of water were primarily BOD_5, COD, and PO_4^{3-} (Table 2). In about 50% of the analysed samples BOD_5 exceeded 6.0 mg·dm^{-3}, and COD 30 mg·dm^{-3}. The results point to a relatively high load of organic pollutants in the settler. Another problem was bottom sediments. Over ten years a 15-centimetre-thick layer of sediments accumulated on the bottom, which given the area of 0.43 ha results in a volume of 645 m^3 (17% of the capacity of the settler). In adverse thermal and oxygen conditions the presence of sediments contributed to secondary contamination of the stored rainwater – e.g. an increase in turbidity due to resuspension or release of phosphorus in biochemical processes (Hu et al. 2019). Analyses of certain chemical and biochemical properties of sediments carried out in 2007 showed significant concentrations of organic carbon (on average 4,540.00 mg·kg^{-1}) and NH_4^+ (on average 83.05 mg·kg^{-1}) in the settler (Zubala et al. 2007). They were several times larger than those found in the sediments in the infiltration reservoir. The content of NO_3^- in the sediments in both reservoirs was comparable and on average amounted to 90.09 mg·kg^{-1}.

The concentration of PO_4^{3-} was two times higher than 1.0 mg·dm^{-3} in rainwater in the settler. According to Yang and Toor (2017), PO_4^{3-} in street runoff likely originates from erosion of soil particles and mineralisation of organic materials. On one of the measurement dates a minimum concentration of dissolved oxygen (4.0 mg·dm^{-3}), maximum content of suspended solids (144.4 mg·dm^{-3}) and elevated temperature of the liquid (19.5 °C) were also noted. Other biogenic indicators (NH_4^+, NO_3^-, NO_2^-) did not reach alarming values. The mean concentrations ranged from 0.11 (NO_2^-) to 1.41 mg·dm^{-3} (NO_3^-) (Table 2). According to some authors, the risk posed by nutrients running off with rainwater from road infrastructure is relatively low (Song et al. 2019).

Despite increasing problems related to operation and design, a positive effect of the RHTS on the quality of rainwater runoff was observed in 2008-2010. Many significant differences were found in the level of contamination of rainwater accumulated in the settler and infiltration reservoir. The average concentrations of suspended solids, NH_4^+, NO_3^-, NO_2^-, Fe^{3+} and K^+ in the infiltration reservoir were 41.0-46.7% lower than in the settler (Table 2). NO_3^- and NO_2^- were eliminated to a greater degree than in the rainwater reservoir studied by Ivanovsky et al. (2018). The opposite trend was observed for NH_4^+. Despite a relatively high average reduction in BOD_5 (23.0%) and COD (23.7%), those indicators reached alarming values in the infiltration reservoir (BOD_5 mostly in cold seasons, and COD in warm seasons). This phenomenon could be a result of the presence of an internal source of organic contaminants such as decaying dead aquatic plants. On the other hand, positive concentrations of oxygen were observed for water accumulated in the infiltration reservoir. In comparison to the settler they were 31.9% higher (average saturation 9.1 mg·dm^{-3}). Oxygen is one of the most important components conditioning self-purification processes in the aquatic environment (Li et al. 2013). The pH values of the analysed water

ranged between 5.9-9.3. Periodic alkalinization of rainwater run-offs was probably a result of the presence of alkaline silt, salinity and processes occurring in the bottom sediments (Degtjarenko 2016).

3.3 Analysis of the RHTS Operation–variant 2 (2014-2020)

During the modernisation and expansion of the RHTS the northern edges of the reservoirs were not secured by levees and drainage ditches (Fig. 5A). A large risk of outwashing the products of erosion from the uncovered slope existed in the first months after the modernisation (lack of permanent plant cover). In addition, the steep slopes of the infiltration reservoirs were not initially secured. Rill and surface erosion occurred very quickly (Fig. 5B) and resulted in the accumulation of sediments at the foot of the slopes (shallowing of the reservoirs). The phenomena were particularly visible on the northern side after intensive rainfall. Surface erosion processes had been observed to slow down since 2015 due to the fact that the analysed area became overgrown with grass. Afterwards, another dangerous erosion phenomenon occurred, posing a risk to adjoining grounds. In the bottom of the western infiltration reservoir a piping well started to form (Fig. 5C). This process may result in land subsidence near the rainwater reservoirs, for instance, on farms with single-family buildings or a busy national road (Fig. 1) (Bernatek-Jakiel and Poesen 2018). The presented data indicates that it is a big mistake not to sufficiently take into account the specific features of land at risk of water erosion in investment processes and treating popular technical and design solutions as reliable in any conditions. Measures that must be taken in

Fig. 5 Examples of operating problems in the RHTS–variant 2 (2014-2020): **A**) the risk of influx of the products of erosion from the steep northern slope; **B**) rill and surface erosion on the escarpments of the reservoirs; **C**) piping in the bottom of the western infiltration reservoir; **D**) too high elevation of the intake of water after treatment

the analysed grounds include preventing the concentration of uncontrolled run-off of rainwater by applying adequate technical and biotechnical solutions and biological stabilisation (Zhang et al. 2014b). Increasing the capacity of infiltration reservoirs minimised the risk of overloading the RHTS with rainwater and damaging the safety overflows due to erosion. After several years of hydrological drought the infiltration reservoirs were filled with water at a minimum level. Throughout the whole term of the observation the water intake was located above the level of the stored water (Fig. 5D). In such conditions the functioning of the artificial rain system will not be possible.

In 2016-2018 rainwater accumulated in the settler was characterised by larger differences in quality than in 2008-2010. A high coefficient of variation, close to 100%, was found for conductivity, COD, NH_4^+, NO_3^-, PO_4^{3-}, K^+ and Cl^- (Table 3).

Statistical analyses showed significant differences between the quality of rainwater in the settler in the years 2008-2010 and 2016-2018. In the second period an improvement was observed in the quality of the liquid, which was evidenced by decreased concentrations of NH_4^+, PO_4^{3-}, K^+ ($\alpha=0.05$) and suspended solids ($\alpha=0.10$). Differences in the mean values of these variables amounted to 57.1, 54.5, 22.8 and 64.9% respectively. In addition, an increase of 31.6% in the mean concentration of dissolved oxygen was noted. The reason behind the positive changes was the removal of sediments from the bottom of the settler (Hernández-Crespo et al. 2019). The simultaneous decrease in the content of suspended solids and nutrients may testify to a strong relationship between those components, and this thesis was supported by the studies of other authors (Wakida et al. 2014).

Similar to 2008-2010, water in the settler was characterised by high oxygen demand (Table 3). In subsequent years, the level of oxygen saturation of water decreased from 10.1 mg·dm^{-3} (2016) to 7.2 mg·dm^{-3} (2018). This phenomenon was connected with an increase in mean annual air temperatures, decrease in atmospheric precipitation (Table 1) and increased heating of water in the reservoir. Elevated temperatures did not foster the natural solubility of oxygen in water (Li et al. 2013).

In 2016-2018 as much as 70% of the analysed water quality indicators showed lower average values in the infiltration reservoirs than in the settler. However, the results of the statistical test corroborated the existence of significant differences only for conductivity, suspended solids, NO_3^-, NO_2^- (decrease in value by 25.6-33.6%) and pH (increase in value by 5.5%) (Table 3). To compare, in 2008-2010 a different distribution was found for twice as many variables of water quality. A relatively lower treatment efficiency in 2016-2018 noted for some indicators was connected with their decreased concentration in the settler in that period (lower initial concentrations) and small differences in the degree of contamination of rainwater in infiltration reservoirs in both variants of the RHTS. Statistical test showed that the infiltration reservoirs in variant 2 were less loaded with suspended solids (difference 53.8%), NH_4^+ (49.3%), PO_4^{3-} (80.8%) and K^+ (51.4%) than the infiltration reservoir in variant 1 (Tables 2 and 3). In 2016-2018 in the infiltration reservoirs a considerable increase in the concentration of Fe^{3+} was noted in comparison to the infiltration reservoir in 2008-2010 (difference 144.5%). During the modernisation of the RHTS a layer of subsoil rich in iron compounds reduced and activated due to long-lasting contact with water could be uncovered (Kabata-Pendias and Mukherjee 2007). In turn, an increased content of iron resulted in a considerable decrease in the concentration of PO_4^{3-} in the water after treatment, which should be deemed positive. Reactions of iron with phosphate ions are commonly used in the processes of chemical treatment of wastewater (Wilfert et al. 2015). In the infiltration reservoirs elevated BOD_5 and COD continued to be observed. The average value of COD in 2016-2018 was 55.9 mg·dm^{-3} (Table 3).

Table 3 Characteristic values of rainwater quality indicators in settler (control point 1) and infiltration reservoirs (control point 2) in 2016-2018 (statistical significance of differences in quality variables was determined for $\alpha = 0.05$ and $\alpha = 0.10$ – Wilcoxon test)

Variables	Control point	Minimal value	Maximum value	Average	Percentage difference	Standard deviation	Variation coefficient	Important difference
Temperature (°C)	1	1.5	26.0	13.1	+2.2	8.7	66.4	–
	2[a]	2.3	26.8	13.4		8.7	65.0	
Conductivity ($\mu S \cdot cm^{-1}$)	1	121	2,360	670.3	–26.7	619.9	92.5	+ ($\alpha=0.05$)
	2	106	1,967	491.2		681.4	138.7	
pH	1	6.5	9.6	7.5	+5.5	0.9	11.8	+ ($\alpha=0.10$)
	2	6.7	8.6	7.9		0.6	7.4	
Suspension ($mg \cdot dm^{-3}$)	1	4.0	18.2	10.2	–25.6	5.4	53.2	+ ($\alpha=0.10$)
	2	2.5	16.7	7.6		3.6	48.2	
O_2 ($mg \cdot dm^{-3}$)	1	3.9	12.9	9.1	+7.6	2.7	29.7	–
	2	6.1	12.4	9.8		1.8	18.9	
BOD_5 ($mg \cdot dm^{-3}$)	1	2.4	8.4	5.6	+1.4	1.9	34.4	–
	2	3.4	8.5	5.7		1.9	34.2	
COD_{Cr} ($mg \cdot dm^{-3}$)	1	18	165	52.7	+6.2	50.0	95.0	–
	2	8	162	55.9		50.5	90.4	
NH_4^+ ($mg \cdot dm^{-3}$)	1	0.04	0.63	0.18	–37.0	0.2	115.0	–
	2	0.05	0.35	0.11		0.1	79.2	
NO_3^- ($mg \cdot dm^{-3}$)	1	0.10	1.81	0.67	–33.6	0.6	89.7	+ ($\alpha=0.05$)
	2	0.09	1.73	0.44		0.5	119.6	
NO_2^- ($mg \cdot dm^{-3}$)	1	0.03	0.26	0.09	–29.9	0.1	72.4	+ ($\alpha=0.10$)
	2	0.01	0.28	0.06		0.1	114.6	
PO_4^{3-} ($mg \cdot dm^{-3}$)	1	0.02	1.22	0.23	–65.0	0.4	163.6	–
	2	0.02	0.18	0.08		0.1	76.8	
SO_4^{2-} ($mg \cdot dm^{-3}$)	1	1	20	7.8	–13.8	5.9	75.4	–
	2	1	16	6.8		5.1	76.2	

Table 3 (continued)

Variables	Control point	Minimal value	Maximum value	Average	Percentage difference	Standard deviation	Variation coefficient	Important difference
Fe^{3+} ($mg \cdot dm^{-3}$)	1	0.21	1.16	0.66	−7.8	0.4	54.5	–
	2	0.20	1.06	0.61		0.3	48.9	
K^{+} ($mg \cdot dm^{-3}$)	1	1.3	44.8	7.8	−63.8	12.7	162.6	–
	2	1.4	6.3	2.8		1.9	65.8	
Cl^{-} ($mg \cdot dm^{-3}$)	1	3.9	82.4	31.1	−19.9	29.7	95.3	–
	2	3.9	79.5	24.9		24.3	97.4	

[a]Mean value of quality variable for stormwater in infiltration reservoirs

Due to the relatively good quality of the water after treatment, it can be used for commercial purposes within the wholesale market. The condition is the rearrangement of the water intake in the infiltration reservoir (lower drainage elevation). Water can be used for irrigating energy crops growing on the surface of the northern slope (about 3 ha) adjoining the rainwater reservoirs. The project would provide the ultimate management of rainwater runoff, production of energy biomass and protection of the slope surface against erosion. Some authors have demonstrated that integrated management of rainwater is associated with big economic and environmental benefits (Mitchell et al. 2007).

4 Conclusions

The condition for stable and efficient operation of large RHTSs in loess areas at risk of erosion, is their adequate design, construction and use. Failing to take specific features of erosion-affected areas into account in the life cycles of systems based on earthen reservoirs can result in defects and, as a consequence, pose a risk to adjoining grounds. Particular attention must be paid to effective protection of steep slopes, escarpments and elements through which water often flows. Excessive transfer of rainwater between respective facilities in the gravity treatment systems can be prevented by designing sufficiently large active capacities of respective reservoirs, reducing clogging of the bottoms of the infiltrating basins and increasing the use of water after treatment for commercial purposes.

Despite design and operational faults being found, the analysed RHTS had a beneficial effect on the quality of water. The values were considerably decreased for: conductivity, suspended solids, mineral forms of nitrogen, iron and potassium. At all stages of treatment, the concentration of dissolved oxygen maintained a satisfactory level. In the first variant of the RHTS (capacity 9500 m^3) a considerable hydraulic load and higher contamination of water in the settler was observed in comparison to the second variant (20700 m^3). Due to a worse initial quality of water in the first variant of the RHTS (settler) and insignificant differences in the level of contamination of water in the infiltration reservoirs in both variants, the water treatment efficiency was normally higher before the modernisation.

Declarations

Financial Interests The author has no relevant financial or non-financial interests to disclose.

Conflicts of Interest/Competing Interests The author declares that he has no conflict of interest.

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