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Evaluation of the Impact of Sludge Lagoons on the Quality of Water Environment in Surrounding Area

Ocena oddziaływania lagun osadowych na jakość środowiska wodnego w ich otoczeniu

The main goal of this research was to determine the impact of sludge lagoons collecting sewage sludge from the wastewater treatment plant in Almaty (Kazachstan), on groundwater and surface water quality. After geophysical examination of the study area (including Vertical Electroresistivity Survey and Seismic Survey), there were set three sampling points for examination of groundwater quality, and 2 points for sampling water from the river Almatynka Bol'shaya, winding 250÷500 meters from the borders of lagoons. The results obtained from the analysis of collected samples showed high concentrations of Fe, Mn, Zn, PO_4 ions and other compounds in groundwater in the vicinity of sludge lagoons. It was also found that in the river section downstream sludge lagoons there were higher concentrations of heavy metals and other contaminants, than in the river section upstream.

Keywords: **sewage sludge, sludge lagoons, leachate, environmental impact**

Introduction

Current policy goals of the Republic of Kazakhstan are aimed at close integration with world economy. They have also forced many activities in the field of ecology, especially focused on sustainable development [1]. Taking into account the actual state of wastewater treatment and sewage sludge disposal in the Republic there is urgent need for rapid reconstruction and modification of existing facilities.

During wastewater treatment process, liquids and solids are separated and three main constituents are removed from effluent: screenings, grit and sludge, of which sewage sludge is the largest in volume [2]. Although this volume constitutes only 1% of the total effluent from the plant, sludge treatment processes may represent up to 60% of total treatment costs [3]. Also it is well recognised, that increasing efficiency in wastewater treatment, especially considering phosphorus elimination by chemical precipitation, contributes to significant rise in waste sludge production

[4]. For example, implementation of Urban Waste Water Treatment Directive (91/271/EEC) [5] in European Union, which set new standards for effluent quality, led to 50% increase in sludge production by 2005 i.e. 10 million tons annually [6-8].

Sustainable sewage sludge treatment and disposal may be expressed by article 14.1 of the aforementioned Directive [5]: Sludge arising from waste water treatment shall be reused whenever appropriate. Disposal routes shall minimize the adverse effects on the environment. Unfortunately, wastewater treatment facilities in the Republic of Kazakhstan, in its majority, were designed and constructed in 60-80's of XX-th century and as such, do not meet contemporary environmental standards. The main method of sewage sludge disposal form existing municipal treatment plants in Kazakhstan, as in many other former Soviet Union Republics, is storing it on natural or constructed sludge lagoons.

For the economic reasons (low investment and operating costs), sludge lagoons are still popular method of sludge treatment in tropical and sub-tropical regions, where land is inexpensive [9]. Depending on local geophysical and hydrological conditions, the lagoon can be a simple earth basin or concrete reservoir with lining to prevent groundwater contamination [10, 11]. But even properly designed, sludge lagoons present higher risk of negative environmental impact than any other solutions. Possible problems related to operation of sludge lagoons, in most cases refer to high emissions of odours [12] and methane [13], as well as possible contamination of groundwater by leachate [14, 15].

Considering all of above mentioned problems, the need for determination of environmental impact of sludge lagoons and identification of most hazardous substances that threaten water environment in the vicinity of the lagoons, were the main factors inspiring this research. Also sludge quality after different periods of storing on lagoons was examined to verify possible options of further disposal. As the research was conducted at Almaty Wastewater Treatment Plant (Almaty WWTP), obtained results could enhance activities towards modification and reconstruction of the whole sludge treatment and disposal process in the plant, in accordance with sustainable development strategy.

1. Materials and methods

1.1. Description of Almaty WWTP

The wastewater treatment plant of Almaty city, with its average capacity of 390000 m^3/d of treated sewage (640000 m^3/d in maximum), and sludge production of 3500 m^3/d, is the second biggest facility in the Republic of Kazakhstan.

Technological process of sewage treatments is accomplished in 2 stages: **mechanical** pre-treatment of raw sewage with screens, sand traps and primary settling tanks, and **biological** - in bioreactors with activated sludge and final clarifiers. Effluent wastewater is discharged via 49 km long ground channel to the storing reservoir Sorbulak (volume of 1.0 mln m^3), from where cleaned wastewater may be withdrawn for irrigation in agriculture. In the case of emergency (mostly due to risk of the overfill of Sorbulak reservoir), there is by-pass channel that after passing the dissinfection station discharges wastewater to Ili river. The quality characteristics of raw and treated wastewater (mean values from 2013/14) are presented in Table 1.

Table 1. **Average parameters of raw (influent) and purified (effluent) wastewater from Almaty WWTP in 2013/14**

Parameters	2013		2014	
	Influent	Effluent	Influent	Effluent
Temperature, °C	18.3	19.4	18.6	19.6
pH	7.6	7.8	7.6	7.8
Total suspended solids, mg/L	477.1	8.5	484.3	8.2
Ammonium nitrogen, mg/L	31.7	5.7	26.18	10.08
Nitrites, mg/L	0.04	0.27	0.04	0.23
Nitrates, mg/L	0.1	1.85	0.16	1.33
BOD_5, mg/L	340.0	4.6	380.4	4.4
COD, mg/L	691.8	11.1	790.38	19.6
Phosphates, mg/L	8.4	3.2	8.7	5.4

It can be concluded, that Almaty WWTP represents typical performance for the facilities designed primary for removal of organic carbon and suspended solids from treated sewage. While the efficiency of BOD_5/COD/TSS removal is on the very high level (98.7%/97.9%/98.2% respectively), the nitrification is only moderate ($N\text{-}NH_4$ removal - 72.2%). The technological layout of the plant doesn't allow the denitrification process and extended accumulation of phosphorus in the biomass.

1.2. Sludge lagoons

The only method of sludge disposal applied in the facility is storage and natural dewatering on sludge lagoons located ca 12 km north of the plant and 27 km away from the city. The lagoons cover total area of 120 ha, from which 80 ha are currently in operation (Fig. 1). Geological structure of this area includes mostly loessy loams with thickness of 5÷20 m. Groundwater table is stabilized 6÷12 m below bottom of lagoons. Climat of the study area may be described as continental, with yearly average temperature 8.5°C and monthly average wind speed 2.8÷4.0 m/s. The nearest river - Almatinka Bol'shaya is located 250÷500 m from the border of lagoons.

The lagoons are constructed on natural soil (without lining, due to low permeability), with dams dividing lagoons into smaller sections and bounding the whole object. Maximum height of the dams is 3.0÷4.4 m. The width of dividing dams is 4.5 m at the top and boundary dams - 6.0 m.

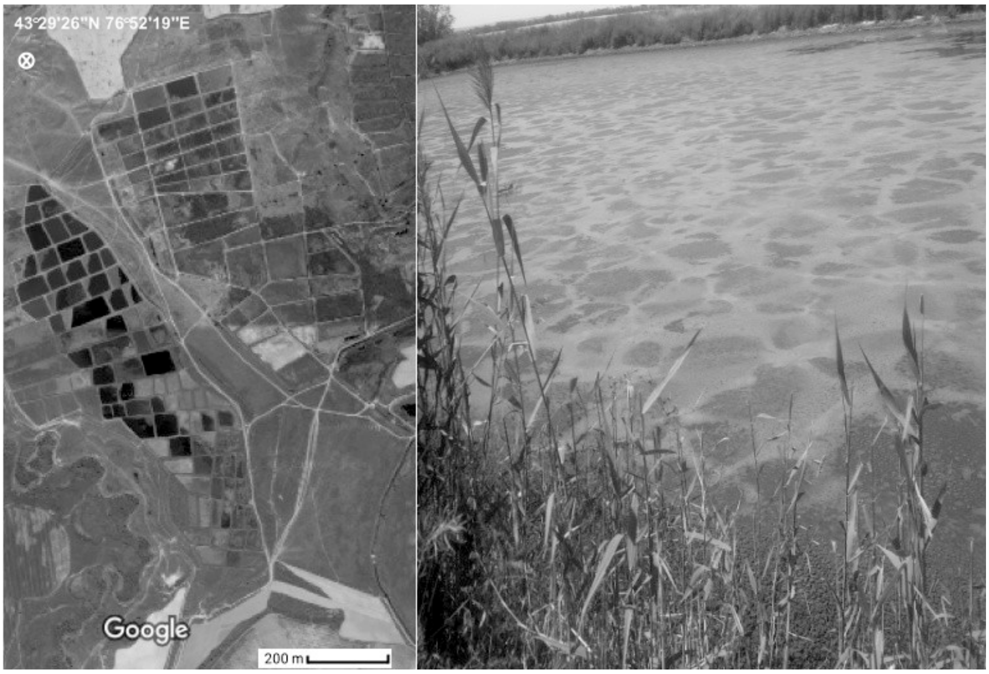

Fig. 1. Map and photo of sludge lagoons of Almaty WWTP
Source: Google Maps; Authors archive

Sludge lagoons receive both raw sludge from primary settling tanks and waste activated sludge from bioreactors. Raw sludge from settling tanks with its average water content of 97%, constitutes gelatinous suspension of grey to light-brown colour. Due to high content of easily biodegradable organic matter it tends to decay rapidly, changing colour to dark-grey and black and emitting unpleasant sour odour. Waste activated sludge is a suspension comprising amorphous flocks of aerobic bacteria and protozoa, with small fraction of solids adsorbed from wastewater and water content of 99.7%. It is also decaying easily due to lack of stabilization process in Almaty WWTP.

Sludge may be delivered to lagoons separately: raw and activated or mixture of both, by means of 2 pressure mains. The primary role of the lagoons is storing and dewatering of sewage sludge from treatment facilities, but there are also selected fields serving as reserve storage for emergency discharge (in case of emptying treatment plant objects for conservation, repairs, etc.). Screening and grit removed from wastewater during mechanical pre-treatment are collected in the lagoons. Those residues are transported by trolleys and unloaded to empty sections. Then, waste material is covered by thin layer of soil (to protect from dispelling with the wind) and finally - lagoon is filled with sludge.

1.3. Geophysical surveys

The geological survey of the study area was prepared using combined methods of vertical resistivity sampling (VES) and seismic reflection sampling (SRS). There were chosen 6 points for VES with 100-250 m spacing and 4 profiles for SRS with 140÷520 m spacing, which covered the distance of 1070 m along the west-east diagonal of the lagoons area.

SRS was conducted with 24-channel digital seismic station ISN-01-24 which is suitable for seismic surveys of low depth profiles. The device initiates elastic waves by 8 kg sludge hammer blows, thus generating waves with frequency not less than 50÷60 Hz. Reflected waves were collected by geophones located on the ground with 2 m spacing. For each profile 4-5 points of seismic vibration were established along 100 m long section (2 points at the boundaries, 1 point in the middle and remaining points at coordinates 40÷80 m). The whole survey was conducted according to standard methodology [16].

VES was used as additional source of information on geophysical properties of the study area, especially - for determination of groundwater table. For this research, specialized station VP-F with 4 symmetric electrodes (probes) arranged in pairs: 2 current electrodes + 2 potential electrodes. From the current (I) and voltage (V) values it is possible to calculate apparent resistivity using simple formula $P_a = k \cdot V/I$ [17], where k - geometric factor which depends on arrangement of four electrodes.

Results from the measurements of apparent resistivity were plotted versus electrode distances and layer depths (in logarithmic scale) thus creating geo-electrical profile of examined area. On this profile it was possible to determine maximum gradients of apparent resistivity, which indicated the groundwater level (GWL) [18].

Specific geophysical surveys were supported by geodetic measurements in order to estimate topography of examined area of sludge lagoons.

1.4. Analytical methods

Samples of the groundwater, water from the river Almatynka Bol'shaya and sewage sludge were collected manually and transported to the laboratories of Kazakh National Technical University and Almaty WWTP. Chemical analysis were performed according to the national standards, among them: NDP 30.1:2:3.9-08 (organic carbon and total nitrogen), PND F 14.1:2:4.143-98 (aluminium, barium, etc.), PND F 14.1.175-00 (anions …), PND F 14.1:2:4.254-09 (suspended solids …), PND F 14.1:2:4.178-02 (sulfides …) [19-23], using specialized equipment and analytical methods (carbon analyzer - combustion infrared detection, nitrogen chemiluminescence detector, inductively coupled plasma mass spectrometry, ion chromatography, photometry with Griess reagent, solvent extraction and other).

2. Results and discussion

The first stage of investigation was analysis of the data obtained from geophysical surveys. As the result - the geological profile of sludge lagoons was created (Fig. 2).

The profile represents hydrogeological structure of the lagoons across their central part, along 1160 m line from west (Almatynka river valley) to the east (100 m out of lagoons boundary dam). The sampling points for VES survey are located in 0, 160, 500, 600, 800, 1050 meters, while SRS points in 0, 160, 500 and 1030 m. As shown in Figure 2, maximum surface elevation of the study area is in sampling point on 1050 m (SP-1050) - 18 m above water level in the Almatynka river (RL = 0). On the other hand, maximum groundwater level was estimated for SP-800: 8.5 m above RL. It can be also observed that groundwater table has general slope towards river valley (from +5.5 m above RL in SP-1050 to 0). However, between SP-500 and and SP-1050 there is a deviation from this pattern, caused by hydro-dome. This phenomenon may be explained by presence of leachate from the sludge lagoons, which affects groundwater hydrodynamics resulting in local bulge of water table.

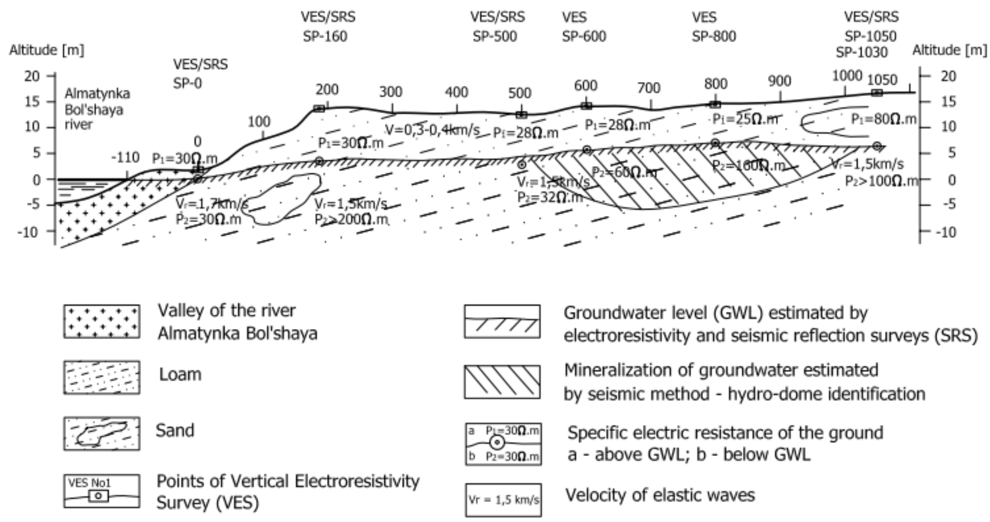

Fig. 2. Geological profile of sludge lagoons based on the resistivity and seismic surveys

The other information provide data on apparent resistivity and elastic wave velocity estimated in sampling points. For example loams above GWL have apparent resistivity Pa = 25÷30 Ω·m, and Pb = 32÷160 Ω·m when located below GWL. In the central part of sludge lagoons (SP-500 and SP-600), resistivity of loams below GWL remains on relatively lower level than in other sampling points (Pb = = 32÷60 Ω·m). This possibly indicates much higher contamination of groundwater in that area, as the water rich in electrolytes has much smaller electric resistance than pure water. This phenomenon was used by other researchers to study for example the extension of the leachate contamination plume area [24]. VES survey also indicated the presence of clay lens in SP-1050 (area with very low resistivity Pa = 8 Ω·m). As for the velocity of elastic waves estimated from SRS survey, it is noteworthy that limiting velocity characteristic for GWL is similar for all sampling points (1.5÷1.7 km/s), which indicates uniform waves velocity distribution in the study area.

In the next stage of the study, the focus was on groundwater quality in the vicinity of sludge lagoons and water quality in the river Almatynka Bol'shaya. Taking into account existing hydro-geological conditions evaluated by VES and SRS surveys, 3 sampling points in the river valley (between sludge lagoons and the river) and 2 sampling points on the Almatynka river. The location of sampling points is shown in the Figure 3.

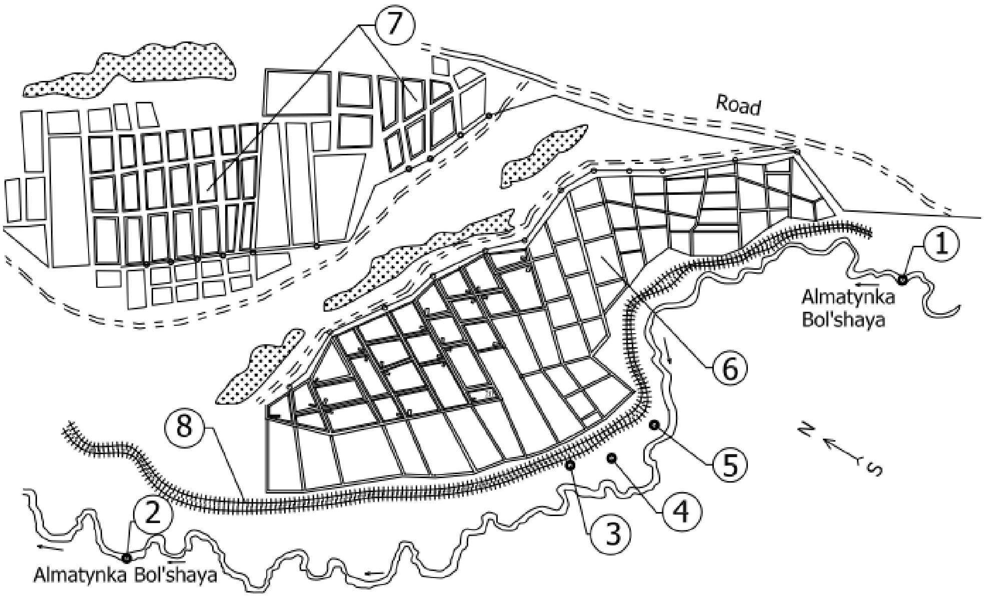

Fig. 3. Location of sampling points for river water and groundwater examination (1, 2 - sampling of river water; 3-5 - sampling of groundwater; 6 - sludge lagoons; 7 - filtering beds and reserve lagoons; 8 - boundary, protective dam)

Samples from points No 1 and 2 were taken directly from the river Almatynka Bol'shaya (river sections upstream and downstream of sludge lagoons respectively). Point No 3 was located 180 m from lagoons and 130 m from the river and then sample was taken from depth of 7 m, No 4 - 200 m/125 m and depth 9 m, No 5 - 245 m/20 m and depth 6 m.

The results of chemical analysis of collected samples are presented in the Table 2.

Table 2. **Concentration of selected chemical compounds in the samples from the study area**

Parameter	Concentration in the samples, mg/L				
	Almatynka Bol'shaya		Groundwater		
	No. 1	No. 2	No. 3	No. 4	No. 5
Suspended solids	5.0	7.0	50.0	80.0	40.0
BOD_5	3.0	5.0	2.7	2.4	2.7
COD	4.0	26.0	30.0	30.0	14.5
Nitrite	0.11	0.36	0.04	0.112	0.168
Nitrates	24.5	43.6	8.5	20.0	10.0
Calcium	24.0	34.0	96.0	56.0	56.1
Magnesium	1.2	7.3	77.0	81.5	81.5
Phosphates	0.8	1.7	8.5	8.2	6.8
Petroleum products	0.06	0.08	0.6	0.8	0.6
Chlorides	10.6	11.5	24.0	28.0	18.0
Sulfates	28.8	37.0	120.0	427.0	103.0
Hydrocarbonate	109.8	134.2	274.5	750.0	463.6
Copper	0.06	0.06	0.46	0.39	0.09
Iron	0.3	0.42	0.31	4.2	0.5
Zinc	0.06	0.09	0.46	0.39	0.9
Bromine	0.08	0.12	0.21	0.29	0.07
Strontium	0.44	0.54	5.85	6.95	1.02

From the results of laboratory analysis of samples collected nearby sludge lagoon it can be observed that groundwater nearby sludge lagoons (samples No 3, 4, 5) is highly contaminated with chemicals, particularly heavy metals, nitrites and nitrates, phosphates, sulphates and hydrocarbons. As for the water quality in the Almatynka river, comparison of the results for samples No 1 and 2 shows significant increase in concentrations of several compounds in the river downstream the lagoons. Such indicators like magnesium, COD, nitrates in sample No 2 are “multiplied” by factors 9.1; 6.5 and 1.8 respectively.

The last stage of presented research was related to determination of sewage sludge quality in different periods of its storage on lagoons, with regard to possible utilization in agriculture or land applications. Analysis were accomplished for 2 sources of stored sludge: lagoon after one and three years of operation. The results are presented in Tables 3 and 4.

Significant amount of organic matter in dry mass of stored sludge allows to apply it for the improvement of physical characteristic of the soil [25]. On the other hand, high content of nutrients like nitrogen, phosphorus and potassium, which are necessary for plants growth, indicates possible implementation as fertilizer. This property of sewage sludge seems to be the most important factor determining final utilization of the sludge [26].

Table 3. **Organic and nutrient compounds in dry mass of the sewage sludge stored in lagoons of Almaty WWTP**

Parameter	Fats mg/kg	Proteins mg/kg	Total nitrogen mg/kg	Total phosphorus mg/kg
Sludge age = 1 year	12.1	5316.0	1220.0	617.0
Sludge age = 3 year	26.75	6013.0	1380.0	529.1

Table 4. **Heavy metals in dry mass of sewage sludge stored in lagoons of Almaty WWTP**

Parameter	Heavy metals, mg/kg						
	Cd	Cu	Mn	Ni	Pb	Cr	Zn
Sludge age = 1 year	5.01	19.01	202.0	45.57	57.63	214.0	916.0
Sludge age = 3 years	4.56	17.72	256.0	37.7	57.00	887.0	876.0
Limit value for land applications [27]	< 15	< 750	–	< 200	< 250	< 500	< 1750
Limit value for agriculture [28]	20÷40	1000÷1750	–	300÷400	750÷1200	–	2500÷4000

Other important factors deciding about utilization of sewage sludge for land applications are: heavy metals content and sanitary safety. As seen from Table 4, almost all of the parameters (except chromium in a 3-year-old sludge) meet state requirements for heavy metals [27] as well as provisions of EU directive 86/278/EEC [28]. But bacteriological analysis of sewage sludge from lagoons, showed very high content of fecal bacteria - coli index was higher than 2380 and coli titre - less than 0.4. Such a result should not be surprising, if one consider lack of stabilization process in sludge disposal system af Almaty WWTP. For this reason, further utilization of sewage sludge from lagoons of Alamty WWTP is still impossible.

It should be emphasized, that our research did not cover all substances that pose a risk related with sewage sludge landfilling. Recent studies [29-32] show that there should be paid special attention to the presence of organic compounds - among them carcinogens, such as absorbable organic halogen (AOX), polycyclic aromatic hydrocarbons (PHAs), polychlorinated biphenyls (PCBs) and other, both in the stored sludge and the leachate. Although several risk assessments conducted on the presence of organic compounds (OCs) in sewage sludge concluded that exposure to those from the agricultural use of sludge is no greater than background levels, many countries have established limits for different groups of OCs in sludge (for example: PCBs and and polychlorinated dibenzodioxins and furans - PCDD/Fs in Germany, PCBs and PHAs in France). For that reason, it is likely that during consultation on the revised Sludge Directive 86/278/EEC, the agreement on regulation of OCs will be one of key points of interest [33].

Conclusions

Results of carried out research show clearly that current state of sludge disposal system in Almaty WWTP, consisting only of sludge lagoons, is highly deficient and can be harmful to the environment, especially for surface waters and groundwater.

Geological surveys of the study area, accomplished by means of electro-resistivity and seismic sampling, indicated that insulation layer of low permeable soil between the bottom of sludge lagoons and groundwater table is not sufficient barrier to stop the leachate from lagoons, thus the quality of the groundwater is endangered, and natural balance of underground water is disturbed, causing local uplifts of water table (hydro-dome).

Due to natural inclination of groundwater table towards Almatynka Bol'shaya river, in the river valley artificial swamp was formed, from where the samples of groundwater were analyzed. The results of laboratory analysis demonstrated increased concentrations of nitrates, nitrites, phosphates, sulphates, ions of metals, and many other compounds. Also, the analysis of the samples taken from Almatinka river proved that leachate from sludge lagoons may significantly change the water quality, as most of the parameters in the sample taken downstream the lagoons were higher than in the sample taken in the river section upstream.

Bacteriological analysis of sewage sludge stored in the lagoons demonstrated high sanitary risk related to the presence of coliform bacteria, and possibly - pathogens. This fact should be carefully considered by authorities, and zones of limited agricultural use of land in vicinity of sludge lagoons should be created. This is a particular adverse effect, because the sewage sludge containing significant fractions of organic matter and nutrients, could be useful and valuable resource in many economic applications. It should be also emphasized that solution for this problem requires complex studies aimed at selecting best available technologies in specific circumstances of the Republic of Kazakhstan, that will lead to efficient and sustainable sewage sludge disposal.

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Streszczenie

Głównym celem przeprowadzonych badań było określenie wpływu lagun osadowych na jakość wód powierzchniowych i podziemnych na przykładzie obiektu gromadzącego osady ściekowe z oczyszczalni ścieków w Ałmaty (Kazachstan). Na podstawie badań geofizycznych terenu, przeprowadzonych z wykorzystaniem m.in. sondowania sejsmicznego oraz elektrooporowego, ustalono 3 punkty pomiarowe do badania jakości wód gruntowych oraz 2 punkty poboru wody z rzeki Almatynka Bol'shaya, przepływającej ok. 300 m od granic lagun. Uzyskane rezultaty wykazały wysoką zawartość jonów Fe, Mn, Zn, PO_4 i in. w wodach gruntowych w sąsiedztwie badanych lagun. Stwierdzono również, że w dolnym przekroju badawczym rzeki (poniżej lagun osadowych) stężenia metali ciężkich oraz szeregu innych zanieczyszczeń były znacznie wyższe niż w przekroju górnym (powyżej lagun).

Słowa kluczowe: **osady ściekowe, laguny osadowe, odcieki, oddziaływanie na środowisko**