

Climate-neutral waste management in The Russian Federation: New approach to sludge treatment on drying beds under climate change

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RECEIVED 02.12.2020

REVIEWED 06.03.2021

ACCEPTED 02.06.2021

Abstract: Identification and ecological diagnostics of the influence of basic load parameters (the cumulative effect of air temperature, the amount of precipitation) is a fundamental aspect of the wastewater sludge treatment at drying beds. The positive dynamics of atmospheric precipitation and the long-term functioning of natural and technical systems for wastewater sludge treatment under the influence of excessive atmospheric moisture does not allow the treatment/drying of precipitation, which provokes soil pollution with subsequent diffusion of pollutants into groundwater, which leads to the degradation of the natural environment components interacting with drying beds. The article is devoted to the adaptation of the process of treatment/drying of wastewater sludge at drying beds. The method includes identification of the dynamics of climatic factors of a long-term chronological series, which makes it possible to predict the effect of atmospheric precipitation on the wastewater sludge drying. The costs for the implementation and subsequent use of the proposed method are absent or insignificant (in the conditions of an increase in usable area during the modernisation of existing drying beds) in comparison with the costs of well-known and widespread methods of deliquescence.

Keywords: climate change, drying beds, precipitations, sludge treatment

INTRODUCTION

Technological problems associated with wastewater treatment and, in particular, the disposal of wastewater sludge at drying beds do not lose their relevance. In the Russian Federation, only a few cities perform wastewater sludge treatment using the incineration method, which is more promising, but at the same time requires significant capital investment and subsequent operating costs.

Almost 90% of all sludge produced in the country and the countries of the post-Soviet space is processed on the drying beds, which indicates the scale of the spread of these structures and their contribution to the environmental management system as techno-natural systems for the wastewater sludge treatment.

The attractiveness of these structures lies in the technological ease of operation and low operating costs. Wastewater

sludge is capable of absorbing and retaining moisture. The amount of moisture is lower than in the thickness in the surface zones of precipitation [EL-GENDY *et al.* 2017; PANDEY, JENSSSEN 2015]. We also can use of ash from the combustion of sewage sludge in building materials. However, in Russia this method is seldom employed, being rather an exception for laboratory installations.

When atmospheric precipitation falls and comes into contact with the wastewater sludge fractions, the specific volumes of the latter increase due to swelling. Therefore, the choice of the method for wastewater sludge treatment at drying beds is no less dependent on the climatic features of the region of change, which are complicated by both spatial heterogeneity and anthropogenic load [CASAJUS *et al.* 2016; DAMERT, BAUMGARTNER 2017; DREGULO, BOBYLEV 2021a, b; DREGULO, VITKOVSKAYA 2018; JAWECKI *et al.* 2017; NIELSEN, STEFANAKIS 2020; ROSER-RENOUF *et al.* 2016].

The observed climate change shows that the average annual growth of air temperature in Russia during 1976–2014 is 0.42°C each ten years, which is 2.5 times higher than the growth of global temperature over the same period [KATSSOV (ed.) 2017]. Significant trends are observed in central Siberia – 3.2% in 10 years. In some areas of the Far Eastern Federal District the growth of precipitation exceeds 5% in 10 years [Rosgidromet 2017].

Overall, the amount of precipitation in Russia grows (2.2% of the normal amount in 10 years), mainly due to the spring precipitation, 6% of the normal amount in 10 years [Rosgidromet 2019]. This is 1% higher than observed a year previously. During the 1960–2012 period, on much of the Russian Federation and a sizable part of Europe one observed both absolute (up to 8% in a decade) and relative (up to 5% in a decade) extremes in the atmospheric precipitation [ZOLINA, BULYGINA 2016].

Changes in climatic factors have a direct impact on both the process of wastewater sludge deliquescence and the operation of techno-natural structures.

Therefore, it is especially important here to note the influence of atmospheric extreme precipitation, both from the point of view of possible flooding of silt detention ponds, and the washout of loaded and lumped sediment on them.

The process of wastewater sludge deliquescence on silt detention ponds is a combination of thermal processes and mass transfer processes [VORONOV, YAKOVLEV 2006].

Organomineral wastewater sludge is a hygroscopic soil-like substance that can absorb and retain moisture. The amount of moisture is lower than in the thickness in the surface zones of wastewater sludges. When atmospheric precipitation falls and comes into contact with the wastewater sludge fractions, the specific volumes of the latter increase due to swelling.

At the same time, the prospects for the use of solar energy and a number of other climatic factors still provide leadership in the choice of a method for treating wastewater sludge beyond the drying beds.

The analysis of deliquescence and compaction of wastewater sludge at drying beds showed that technical solutions are aimed at intensifying the process of sludge deliquescence at already existing structures and do not take into account the dynamics of climatic factors as the fundamental basis of the process of wastewater sludge and cow dung deliquescence at drying beds [DREGULO 2020; DREGULO, RODIONOV 2020]. Therefore, the vast territories of our country require different approaches to the technologies used in the wastewater sludge treatment segment associated with the climatic conditions of the region, which is essentially the goal of this study.

MATERIALS AND METHODS

As you know, regional climatic features are a combination of physical and geographical factors that determine the trend of climate change and the formation of a certain climatic trend, changes in which are complicated by both spatial heterogeneity and anthropogenic load.

A method for calculating a drying bed for areas with a warm climate, in which the drying time is the main parameter [HAANDEN, LUBBE 2007], is used in the foreign practice of operating drying beds.

The mathematical expression for the calculation has the following form:

$$t = \frac{(1 - fi)qi + (1 - fr)qr - qd}{fe \cdot Ew} \quad (1)$$

where: t = drying time of WWS (days); Ew = the rate of evaporation from the free surface of water, mass/area/time/ mm/month; fe = coefficient used to clarify the rate of evaporation from the surface of the sediment; qi = moisture initially present in the mass / zone of sediment; qr = moisture derived from precipitation, mass/area; qd = moisture remaining in the dried sludge, mass/area; fi and fr = share of qi and qr , respectively, which is decanted from the layer. Thus, $(1 - fi)$ and $(1 - fr)$ are the proportion of moisture remaining in the sediment.

The advantage of this method is a mathematical calculation model that allows you to accurately predict the time spent on sludge drying, thereby helping to optimise the economic costs of operating the facilities. The disadvantage of this method is the possibility of its application only in the territories of tropical and subtropical climates with high uniformity of temperature and humidity conditions.

There is a known method for calculating the sludge area taking into account climatic factors, which is the main criterion in the mathematical model of the drying bed area [ALBERTSON *et al.* 1987].

The focus is on the amount of solids in the sludge mixture and the value of volatility. The mathematical expression for the calculation has the following form:

$$A = \frac{0.104S \frac{1-Sd}{Sd(1-Se)/Se} + 100P}{Ke \cdot Ep} \quad (2)$$

where: A = drying bed area (m^2); S = productivity for solid matter (kg); Sd = percentage of dry matter in sediment after decantation (%); Se = percentage of dry solids required for final sludge removal (%); P = annual precipitation; Ke = coefficient of reduction of evaporation from sludge compared to free water surface using 0.6 as a preliminary estimate; Ep = moisture evaporation rate ($cm \cdot y^{-1}$).

The advantages of this method are the optimised coefficient of moisture evaporation from the surface of the sludge mixture. The disadvantages of this method are the empirical vapors used, which are obtained for a specific climatic zone. Along with this, a significant list of empirical indicators, the accounting and dynamics of which is not kept in the practice of operating drying beds, is unlikely to contribute to their normal operation.

Now, in Russian practice, Evilevich's modified method [EVILEVICH 1957] is used. This method [SP 32.13330.2012] has a certain similarity with, namely, borrowing from EVILEVICH [1957] a schematic map to determine the climatic coefficient μ . The load on the drying beds in areas with an average annual air temperature from +3 to +6°C and the amount of precipitation is not more than 500 $mm \cdot y^{-1}$.

Such a long-term method of aging without predicting the dynamics of climatic factors leads to a longer process of sludge drying and, as a consequence, the loss of the operational properties of drying beds [DREGULO 2019].

According to the author, the technology described by EVILEVICH [1957] and in SP 32.13330.2012 and used in the Russian

Federation and the post-Soviet countries up to the present time can be optimised by adapting the technological regime for wastewater sludge deliquescence at the drying beds to changing natural and climatic conditions.

The Equation (3) is based on the value of the load, which means the volume of sludge mixture (m^3) per unit area (m^2) per year, including the climatic coefficient μ . Where:

- average annual temperature from +3 to +7°C,
- amount of atmospheric precipitation 500–600 $mm \cdot y^{-1}$,
- relative air humidity 55–70%,
- soil surface temperature from 0 to +6°C.

$$F = \frac{W}{H\mu} \quad (3)$$

where: F = useful area of the drying bed (m^2); W = the annual amount of wastewater sludge entering the drying beds (m^3); H = height of the annual sediment overflow layer (m), according to standards; μ = climatic coefficient.

However, the disadvantages of this method are: 1) the lack of a uniform gradation of climatic coefficients within a certain factor; 2) the need for data interpolation according to the map scheme; 3) an uncertain chronological series of accounting for climatic changes.

The authors admit that the above-mentioned methods of wastewater treatment are more efficient provided that some requirements are met regarding the wastewater sediments. Their inclusion in the article as possible and applicable versions is determined by the need to show that actual practices largely differ from target parameters (in one case this is the drying time, in another the sludge beds' effective area). However, they are essentially different from standards accepted in the Russian Federation. Specifically, they neglect the drying time, solid particles' characteristics, the evaporation rate, etc. The comparison of these methods would be possible if the authors had a large database of the said characteristics. However, the sludge bed operating and designing practice, regulated in Russia by technical standards [SP 32.13330.2012], prevents introduction of other methods unless they are specified in and governed by sectoral documents of the Russian Federation. Unfortunately, this does not allow the authors to make a comparative analysis of their efficiency. For all that, the authors proceed from the assumption that the wastewater sediments treatment technologies used on sludge beds can be optimised in compliance with the Russian Federation's national standards. That is precisely the purpose of this work.

The sludge bed optimisation method which we offer includes the testing of appropriateness and sufficiency of the sludge bed's effective area depending on the mean annual atmospheric precipitation and the mean annual air temperature. We also propose modification of the effective area depending on the impacts it sustains.

The dynamics of the mean annual air temperature and the mean annual amount of atmospheric precipitation has been monitored for 30 years from 1986 to 2015 based on the data supplied by the weather stations and stored at Web Aisori-M HDDL (hydrometeorological data description language) archives of the All-Russian Research Institute of Hydrometeorological

Information, World Data Center (<http://aisori-m.meteo.ru/wai-sori/index0.xhtml>). The temperature and precipitation values for determining the climate dynamics (climate coefficient μ) were graded using a common range in which a single air temperature step was $\pm 4^\circ C$, while a single step for precipitation was ± 100 mm. In a failure to meet the condition $\mu = 1$, which corresponds to the temperature (in $^\circ C$) range of $<3; 6>$ and the precipitation range of 500–600 mm, the coefficient varied increasing or decreasing 0.1 [EVILEVICH 1957].

RESULTS AND DISCUSSION

For the time of the creation of this method, the criteria for the gradation of the climatic coefficient μ reflected the adequate technological parameters of the wastewater sludge treatment.

At present, the cartographic gradation of the coefficient taken in [EVILEVICH 1957; SP 32.13330.2012] is not correct due to the fact that climatic dynamics has changed significantly over the past 60 years [DREGULO 2020]. At the same time, the spatial and temporal dynamics of changes in the amount of precipitation in a particular mesoclimatic zone is not provided for by the climatic coefficient μ , therefore forecasting and identifying the climatic load for dehydration and drying within a certain geographic zone of the Russian Federation according to EVILEVICH [1957] and SP 32.13330.2012 does not allow treatment of sludge due to excess atmospheric moisture due to shortage (insufficiency) of the usable area of the sludge platform, as an aggregate parameter of the process of treatment of sewage sludge, which is in direct proportion to on the amount of sewage sludge entering for processing and, as a result, leads to littering of silt detention ponds, transformation of their areas into a landfill [DREGULO 2019] and further degradation of accumulated environmental harm [DREGULO 2020] in the object.

This is primarily due to the fact that when interpolating the data and obtaining the value of the zonal μ , the range of precipitation (± 100 mm) can vary from 1–2 mm to 98–99 mm (for example, 601 mm and 699 mm, respectively), which significantly increases the uncertainty in determining the optimal load on silt detention ponds and, as a consequence, its excessiveness.

This problem can be solved by preliminary identification of the climatic load, where it is additionally necessary to consider changes in cyclical fluctuations in atmospheric precipitation and determine the degree of deviation of the high-water phase to the low-water phase (K_f). After that, it is necessary to determine the useful (optimised) area of sludge maps (F_n) to prevent excessive watering of wastewater disposal. This is shown schematically in Figure 1.

For an objective assessment, it is necessary to additionally consider the degree of deviation (K_{nc}) from the trend in the amount of atmospheric precipitation to ensure the controllability of the natural-technical systems of silt detention ponds in a certain mesoclimatic zone of their location.

During construction and operation, this problem is due to insufficient usable area of drying beds (F) (a process parameter that is directly dependent on atmospheric precipitation), the amount of waste received for processing (W_p) and heights layer of waste sludge filling (H).

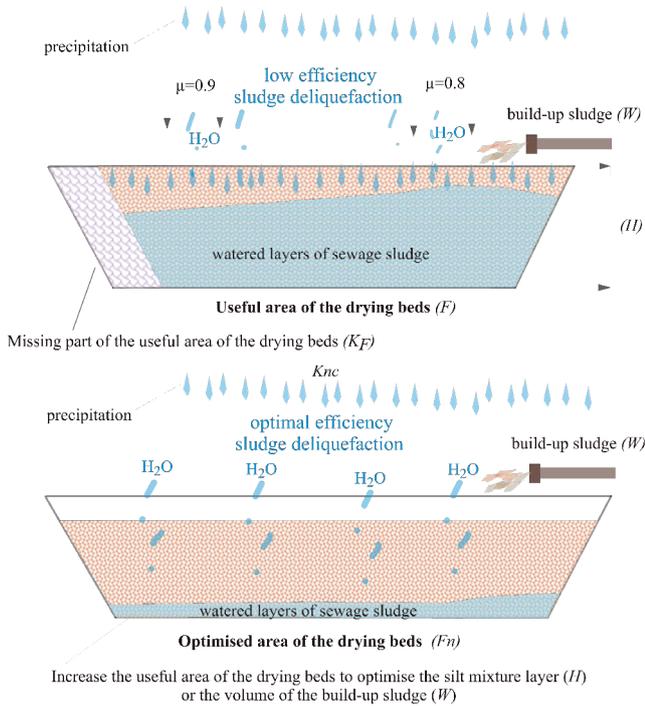


Fig. 1. Diagram of activated sludge pilot plant and photobioreactor of microalgae cultivation; source: own elaboration

To optimise the operation of sludge beds we have drawn up a map of the climate coefficient's territorial zoning in the Russian Federation based on results of a combined (multi-parametric) spatial interpolation of the mean annual temperature and the mean annual amount of atmospheric precipitation.

Map-scheme (Fig. 2) of spatial visualisation is built, the climatic coefficient μ unifying the results from values of temperature and precipitation (built on the basis of data from 516 stations in period 1985–2015) where different hatch patterns in Figure 2 indicating the value (0.7; 0.8; 0.9; 1.0; 1.1; 1.2; 1.3; 1.4), the boundaries corresponding to a specific (calculated) climatic coefficient μ are specified [DREGULO 2019].



Fig. 2. In situ parameters of wastewater; TDS = total dissolved solids; source: own study

Next, the average annual data sets of the amount of atmospheric precipitation K_i for the selected cities are analysed by the method of [DROZDOV 1954] of integral-difference curves (IDC) according to the Equation (4):

$$K_i = \frac{M_i}{M_n} \tag{4}$$

where: M_i = the value of this factor (average annual precipitation), M_n = the average value of the series by analogy for the selected cities.

After that, their deviations from the average value are determined acc. to Equation (5):

$$K = K_i - 1 \tag{5}$$

Next, an integral curve is plotted by sequentially summing these deviations according to expression (6):

$$\sum_1^N (K_i - 1) = f(N) \tag{6}$$

where: N = number of years (period).

After that, according to the obtained values.

The transition from the ordinates to the ordinates of the chronological series is carried out through the expression (7):

$$K(nc) = \frac{K_n - K_k}{N} + 1 \tag{7}$$

where: the ordinates of the integral-difference curve (K_n low-water phase and K_k high-water phase) for a certain phase, in the interval of N years (Fig. 3).

Next, the K_{nc} coefficient is determined, which characterises the degrown deviation of K_n to K_k (Eq. 8):

$$K_{nc} = K_n - K_k \tag{8}$$

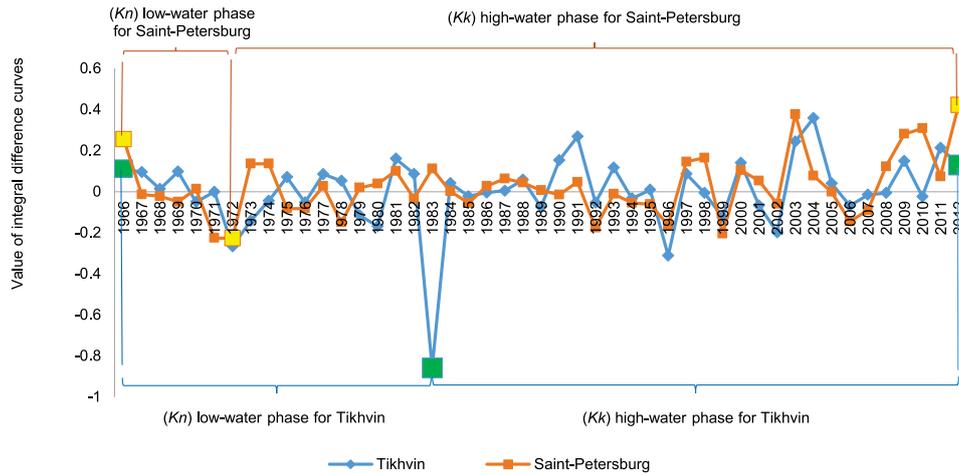


Fig. 3. Average flow rate (Q) per month; source: own study

Next, according to the Equation (3), the approximate useful area of the drying bed is calculated. Then the coefficient is calculated according to the Equation (9):

$$K_F = F \cdot K_{nc} \quad (9)$$

where: K_F showing how much it is necessary to change the useful area of the drying bed depending on the degree of atmospheric precipitation.

Then the useful area of the drying bed F_n considering the coefficient K_F is calculated according to the Equation (10):

$$F_n = F + K_F \quad (10)$$

Thus, the set of distinctive features characterising the proposed invention provides an increase in the efficiency of using the sludge platform by intensifying the process of sludge deliquescence, which expands the technological capabilities of the drying beds, allows you to optimise the costs of treating/drying wastewater sludge.

CONCLUSIONS

Thus, the wastewater sediments treatment quality on sludge beds in the Russian Federation can be improved in compliance with specifics of the nationally accepted regulations through a prior establishment of climate factors, i.e., air temperature and amount of atmospheric precipitation that determine the climate coefficient μ , and influence the spatial and temporal dynamics of the amount of atmospheric precipitation in a concrete mesoclimatic zone for obtaining values of a sludge bed's effective area.

The advantages of the proposed method are:

- 1) increasing the load on the drying beds or reducing the usable area considering the dynamics of climatic factors;
- 2) simplicity of processing the initial information for using the proposed algorithm for optimising the operational properties of the engineering model of the drying bed;
- 3) the ability to adapt the technology to any drying beds;

- 4) combination of technology with all known mechanical and physicochemical methods of intensifying the sludge treatment process;
- 5) reduction of operating costs for the use of flocculants and other mechanical and physicochemical methods of sludge dehydrogenation.

REFERENCES

- ALBERTSON O., BURRIS B., REED S., SEMON J., SMITH J. JR., WALLACE A. 1987. Design manual: dewatering municipal wastewater sludges [online]. EPA/625/1-87/014 (NTIS PB95186417). [Access 15.10.2021]. Available at: https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NRMRL&dirEntryID=46573
- CASAJUS N., PÉRIÉ C., LOGAN T., LAMBERT M.C., DE BLOIS S., BERTEAUX D. 2016. An objective approach to select climate scenarios when projecting species distribution under climate change. PLoS One. Vol. 11(3). DOI 10.1371/journal.pone.0152495e0152495.
- DAMERT M., BAUMGARTNER R.J. 2017. Intra-sectoral differences in climate change strategies: evidence from the global automotive industry. Business Strategy and Environment. Vol. 27(3) p. 265–281. DOI 10.1002/bse.1968.
- DREGULO A.M. 2019. Identifikatsiya i prognozirovaniye klimaticheskoy nagruzki dlya proyektirovaniya i ekspluatatsii ilovykh kart (ploshchadok) [Identification and prediction of climatic loads for design and operation of drying beds]. Voda i ekologiya: problemy i resheniya. No. 1(77) p. 35–43. DOI 10.23968/2305-3488.2019.24.1.35-43.
- DREGULO A.M. 2020. Vliyaniye klimaticheskikh faktorov na ekspluatatsiyu prirodno-tekhnicheskikh sistem obrabotki otkhodov vodootvedeniya [Influence of climatic factors on the operation of natural and technical systems for waste treatment of wastewater disposal]. Vestnik Moskovskogo Unviersiteta. Seriya Geografiya. No. 6 p. 32–40.
- DREGULO A.M., BOBYLEV N.G. 2021a. Integrated assessment of groundwater pollution from the landfill of sewage sludge. Journal of Ecological Engineering. Vol. 22(1) p. 68–75. DOI 10.12911/22998993/128872.
- DREGULO A., BOBYLEV N. 2021b. Heavy metals and arsenic soil contamination resulting from wastewater sludge urban landfill

- disposal. Polish Journal of Environmental Studies. Vol. 30(1) p. 81–89. DOI 10.15244/pjoes/121989.
- DREGULO A.M., RODIONOV V.Z. 2020. «Goryachiye tochki» KHELKOM: zhivotnovodcheskiy kompleks «Pashskiy» kak ob"yekt nakoplenogo vreda okruzhayushchey srede [HELKOM "hot spots": cattle-breeding complex "Pashskiy" as the object of accumulated environmental damage]. Theoretical and Applied Ecology. No. 4 p. 49–54. DOI 10.25750/1995-4301-2020-4-049-054.
- DREGULO A.M., VITKOVSKAYA R.F. 2018. Microbiological evaluation of soils of sites with accumulated ecological damage (sewage dumps). Fiber Chemistry. Vol. 50(3) p. 243–247. DOI 10.1007/s10692-018-9969-0.
- DREGULO A.M., VITKOVSKAYA R.F. 2020. Analysis of foreign and domestic practice of operating sludge platforms to minimize negative environmental impact. IOP Conference Series: Earth and Environmental Science. Vol. 613, 012026. DOI 10.1088/1755-1315/613/1/012026.
- DROZDOV O.A. 1954. O svoystvakh integral'no-raznostnykh krivyykh [On the properties of integral-difference curves]. Trudy Gosudarstvennoy geofizicheskoy observatorii. Vyp. 162. Leningrad p. 3–6.
- EL-GENDY A.S., EL-KASSAS H.I., RAZEK T.M.A., ABDEL-LATIF H. 2017. Phyto-dewatering of sewage sludge using *Panicum repens* L. Water Science and Technology. Vol. 75(7) p. 1667–1674. DOI 10.2166/wst.2017.039.
- EVILEVICH A.Z. 1957. K raschetu ilovykh ploshchadok [To the calculation of sludge-drying beds]. Vodostabzheniye i sanitarnaya tekhnika. No. 10 p. 30–32.
- HAANDEN A., LUBBE J. 2007. Biological waste water treatment – Design and optimisation of activated sludge system. Leidschendam. Quist Publishing. ISBN 9781780407753 pp. 360.
- JAWECKI B., PAWĘSKA K., SOBOTA M. 2017. Operating household wastewater treatment plants in the light of binding quality standards for wastewater discharged to water bodies or to soil. Journal of Water and Land Development. No. 32 (I–III) p. 31–39. DOI 10.1515/jwld-2017-0004.
- KATTSOV V.M. (ed.) 2017. Doklad o klimaticheskikh riskakh na territorii Rossiyskoy Federatsii [Report on climate risks in the Russian Federation]. Saint-Petersburg. Glavnaya geofizicheskaya observatoriya im. A. I. Voyeykova. ISBN 978-9500833-1-5 pp. 105.
- NIELSEN S., STEFANAKIS A.I. 2020. Sustainable dewatering of industrial sludges in sludge treatment reed beds: Experiences from pilot and full-scale studies under different climates. Applied Sciences. Vol. 10(21), 7446. DOI 10.3390/app10217446.
- PANDEY M.K., JENSSEN P.D. 2015. Reed beds for sludge dewatering and stabilization. Journal of Environmental Protection. Vol. 06(04) p. 341–350. DOI 10.4236/jep.2015.64034.
- Rosgidromet 2016. Doklad ob osobennostyakh klimata na territorii Rossiyskoy Federatsii za 2018 god [A report on climate features on the territory of The Russian Federation in 2018]. Moskva. Federal'naya sluzhba po gidrometeorologii i monitoringu okruzhayushchey srede. ISBN 978-5-906099-58-7 pp. 70 [online]. [Access 10.10.2020]. Available at: http://www.meteor.ru/upload/pdf_download/%D0%94%D0%BE%D0%BA%D0%BB%D0%B0%D0%B42016.pdf
- Rosgidromet 2019. Doklad ob osobennostyakh klimata na territorii Rossiyskoy Federatsii za 2018 god [A report on climate features on the territory of The Russian Federation in 2018]. Moskva. Federal'naya sluzhba po gidrometeorologii i monitoringu okruzhayushchey srede. ISBN 978-5-906099-58-7 pp. 79.
- ROSER-RENOUF C., MAIBACH E.W., LI J. 2016. Adapting to the changing climate: An assessment of local health department preparations for climate change-related health threats 2008–2012. PloS ONE. Vol. 11(3). DOI 10.1371/journal.pone.0151558.
- SP 32.13330.2012. Kanalizatsiya. Naruzhnyye seti i sooruzheniya. Aktualizirovannaya redaktsiya SNiP 2.04.03-85 [Sewerage. Outdoor networks and structures. Updated version of SNiP 2.04.03-85] [online]. [Access 10.10.2020]. Available at: <http://docs.cntd.ru/document/1200094155>
- VORONOV Y.V., YAKOVLEV S.V. 2006. Vodootvedeniye i ochistka stochnykh vod. Uchebnoye izdaniye [Water disposal and wastewater treatment. Textbook for universities]. Moskva. Izdatel'stvo ASV. ISBN 5-93093-119-4 pp. 677.
- ZOLINA O.G., BULYGINA O.N. 2016. Sovremennaya klimaticheskaya izmenchivost' kharakteristik ekstremal'nykh osadkov v Rossii [Current climatic variability of extreme precipitation in Russia]. Fundamental'naya i prikladnaya klimatologiya. No. 1 p. 84–103. DOI 10.21513/2410-8758-2016-1-84-103.