Optimal location of an intake at a reservoir prone to salt diffusion

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Abstract. There are two main factors which prompt to look for an alternative to traditional approaches to the provision of drinking water. They are climate change and population growth. Climate change and its increasing scale are no longer in doubt. It tends to increase the frequency and intensity of droughts. Changes in average water availability in most Central Asian river basins are estimated to be drastically big for the next 30 years. And, groundwater recharge may also be affected with a reduction in the availability of groundwater for drinking water in some regions. Water use has been increasing worldwide by about 1\% per year since the 1980s, driven by a combination of population growth, socio-economic development and changing consumption patterns. Global water demand is expected to continue increasing at a similar rate until 2050, accounting for an increase of 20 to 30\% above the current level of water use, mainly due to rising demand in the industrial and domestic sectors. These obliging to redefine the strategy for the use of water resources to ensure sustainable drinking water supply forcing the use of all available water resources even those that were not previously taken into account, for example, off stream storage reservoirs. Research, development and innovation play an important role in supporting informed decision-making. Therefore, further scientific and engineering studies are also needed for the development of financially affordable, safe and efficient infrastructure services in the areas of drinking water supply, sanitation and hygiene and its components. The article considers a particular reservoir the bottom of which is composed of saline soils operating in regular filling and emptying and subject to significant wind effects. The research conducted allowed to find a place of water intake location which provides a minimum salt content in the water abstracted.

1. Introduction
The presence of ongoing climate change and their increasing scale have now become apparent. According to the Intergovernmental Panel on Climate Change [1], an increase of greenhouse gases in the atmosphere will probably boost temperatures over most land surfaces, though the exact change will vary regionally. An increase in global temperatures include increased risk of intensity of storms with higher wind speeds. And, there is no end in sight: the records for global mean annual temperature
are being broken again and again. It is clear that the situation is grave and there are massive challenges are ahead for water sector.

Storms, flooding or drought – the number of recorded loss events due to natural catastrophe is very high. According to NCEI [2], there were 14 weather and climate disaster events with losses exceeding $1 billion each across the United States in 2019. These events included 3 flooding events, 8 severe storm events, 2 tropical cyclone events, and 1 wildfire event. Overall, these events resulted in the deaths of 44 people and had significant economic effects on the areas impacted. The 1980–2019 annual average is 6.5 events. The annual average for the most recent 5 years (2015–2019) is 13.8 events.

According to IMF [3], there were more than 8,000 weather related disasters with floods being among the most common between 1990 and 2014. IMF finds that temperature and precipitation are very important predictors of most disasters.

Climate change may not be responsible for the recent skyrocketing cost of natural disasters, but it is very likely that it will impact future catastrophes. Climate models provide a glimpse of the future. Disappointing forecasts pushing to develop models that would allow rapidly develop measures for adapting to unavoidable environmental conditions and to mitigate impacts, including those related to deterioration of water quality in natural water bodies and reservoirs.

2. Methods
One of the main tasks that need to be addressed when studying the possibility of using a water source for a particular purpose is the problem of its qualitative state in the future. And, depending on the eventual use of water and the required accuracy of prediction, different methods of calculation could be used. This paper discusses selected results of studies which are used in environmental practice and practice of designing and constructing of water facilities.

Urbanization of areas adjacent to water sources, contaminated industrial, agricultural and poorly treated municipal domestic sewage is an incomplete list of factors leading to deterioration of water quality which in many cases is the only source of drinking water supply. Most poor water quality is observed in the lower reaches of the Central Asian rivers, where deterioration in water quality are most acute. This is primarily due to a decrease in water flow and discharges into the river of highly mineralized collector-drainage waters containing high concentrations of pesticides, heavy metals, and organic compounds.

In order to meet the demand for potable water it was proposed to use existing reservoir as the source for centralised drinking water supply. One of the main issues that arose in connection with the need to making design decisions, particularly regarding water intake location, was the water quality forecast.

The Kaparas reservoir is a natural depression immediately adjacent to the riverbed. Filling of the reservoir is done through a natural depression blocked by a gated regulator. The bottom of the reservoir is composed of salted loams and sandy loams [8]. The maximum depth of the reservoir at the top of flood-control storage is 30 m. The reservoir is located in the zone with sharp continental climate with sharp daily and seasonal temperature fluctuations. Windy weather prevails in the area. The number of calm days for each month ranges from 3 to 13% throughout the year. The prevailing wind directions are north, northeast, northwest. The average monthly wind speeds vary within 3-4 m / s during the year. The highest wind speeds are confined to the spring and autumn periods and amount to 22 m / s [9].

According to [10] salinity of water in the reservoir in most of the cases is slightly higher than in the river which is the source to fill the reservoir, so when it is filled, stratified flows (density stratification) can occur. Following recommendations [11 - 14], models (1) and (2) were used to forecast water quality in the reservoir.
\[
\begin{align*}
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} + \frac{\partial u_i}{\partial z} + g \left( \frac{\partial z}{\partial x_i} + \frac{1}{\rho} \int z \frac{\partial p}{\partial z} \right) = & \frac{\partial}{\partial z} \nu_T \frac{\partial u_i}{\partial z} + \mu \frac{\partial u_i}{\partial z} \\
\frac{\partial w}{\partial z} = & 0 \\
\frac{\partial S_t}{\partial t} + \frac{\partial S_t u_i}{\partial x_j} + \frac{\partial S_t w}{\partial z} = & \frac{\partial D}{\partial z} \frac{\partial S_t}{\partial z} + q_{sc}
\end{align*}
\]

(1)

here: \(u_i\) - projection of the current velocity vector onto the axis \(x_i\), \(\rho\) - density, \(q_{sc}\) - internal sources of substances, \(\nu\) - kinematic viscosity, \(S_t\) - average concentration is some substance that determines the density (temperature, salinity).

\(D\) - coefficient of vertical diffusion (analogue of \(\nu\)), usually assumed that \(D = \nu\).

\(z' = (z - z_b)/h\) (\(z_b\) - bed level mark); \((x_i)_2 - (x_i)_1 > L; (x_2)_2 - (x_2)_1 > L\).

As is usually done when deriving the Reynolds equations:

\[ u_i = \bar{u}_i + u'_i; \quad w = \bar{w} + w'; \quad \rho = \bar{\rho} + \epsilon; \quad P = \bar{P} + \epsilon, \]

The sigh "$\epsilon$" is volume-averaged, and "$\epsilon'$" deviations from the average

\[ \frac{\partial K}{\partial t} + u_j \frac{\partial K}{\partial x_j} + w \frac{\partial K}{\partial z} = \frac{\partial}{\partial z} \left( \frac{\nu_T}{\sigma_K} \frac{\partial K}{\partial z} - \epsilon \right) - F_e \]

\[ \frac{\partial e}{\partial t} + u_j \frac{\partial e}{\partial x_j} + w \frac{\partial e}{\partial z} = \frac{\partial}{\partial z} \left( \frac{\nu_T}{\sigma_e} \frac{\partial e}{\partial z} - \epsilon \right) - F_e \]

\[ F_e = c_{1e} \frac{e}{K} (P + G)(1 + c_{3e} \text{Ri}_f) - c_{2e} \frac{e^2}{K} \]

\[ \text{Ri}_f = - \frac{G}{\bar{\rho} + G} \]

\[ P = -\nu_T \left[ \left( \frac{\partial u_1}{\partial z} \right)^2 + \left( \frac{\partial u_2}{\partial z} \right)^2 \right] \]

\[ G = -g \frac{\nu_T}{\sigma_i \rho} \frac{\partial \rho}{\partial z}, \]

where: \(K\) - turbulence energy, \(\epsilon\) - turbulence dissipation rate, \(P\) - term of equation characterizing generation of turbulence energy, \(G\) - term of equation characterizing the change in turbulence energy due to Archimedean forces, \(\text{Ri}_f\) - modified Richardson number [9], \(c_{1e}, c_{1i}, c_{2i}, c_{3e}, c_{3i}, c_k, c_i, c_f\) - empirical constants, in shear flows they are as follows [9]:

\[ c_{3e} = 0.09, c_{1i} = 1.44, c_{2i} = 1.92, c_{3e} = 0.8, c_{1i} = 1.0, c_i = 1.3, c_f = 0.9. \]

According to [8], there are salt lenses in the bottom of the reservoir. Therefore, the boundary condition on their surface was:
here $S_e$ - concentration of dissolved salt, $\alpha$ - solvent extraction coefficient (salt leaching rate).

The value of the coefficient $\alpha$ depends on many factors. It is impossible to determine its value a priori. Therefore, field observation identification required. According to [8] the average monthly salt input into the reservoir is about 8 thousand tons. Based on this value, a numerical value of $\alpha$ was determined. It is $2 \times 10^{-6}$ m/s. Our numerical studies showed that the exact value of this coefficient is not significant. The qualitative picture of the distribution of salinity by depth does not change when changing it by one order of magnitude.

In the calculations, the coefficient of wind friction was taken equal $2 \times 10^{-6}$, which corresponds to the range of wind speed $3 - 6$ m/s.

3. Results and Discussion

The purpose of the calculations was to identify the characteristics of water mixing and its impact on the water quality at four type of water outlets: surface and bottom one at the vicinity of the outlet to the reservoir and surface and bottom one at the distance of 3.5 km to the southwest from the water works.

The following calculations were carried out. A uniform distribution of salinity in the reservoir was taken as initial conditions $S_0$. Then the wind action was turned on.

Field surveys conducted [8] observed that the salinity distribution over the depth of the reservoir is almost uniform with the exception of places confined to salt lenses, i.e. leachable salt is being distributed throughout the whole reservoir.

The following numerical experiment was performed to demonstrate that a medium-intensity wind destroys stratified currents. Initial conditions: the upper layer of water 6.7 m thick had salinity $S_1$, and the bottom layer had $S_2$, and, $S_1 < S_2 < 1$ g/l. According to [8] the distribution of $\tilde{S} = (S - S_e)/S_2$ by depth at various points in the reservoir at the 5th day of wind blow does not change. Numerical modelling of the salinity distribution with the winds impacts specific of this region [9] brought the similar results, i.e. the water in the reservoir is mixed by depth so that there is no stratification. There is an almost uniform distribution of the density of water by depth, with the exception of small deep layers confined to salt lenses. Mixing time with winds of $3 - 6$ m/s is 5 - 6 days. Therefore, it can be accepted that there is no density stratification before filling in the reservoir.

In the calm period, when the reservoir is filled with less salty or, what is the same, less dense water, sharply pronounced stratification occurs. Calculations were performed for the representative difference in salinity between the supplied and reservoir water $\Delta S = 0.4$ g/l and both for a calm period and for winds with different direction and the speed of $W = 4$ m/s.

Results of numerical simulations showed that in a calm period the salt propagates in the surface layer, i.e. pronounced stratification occurs. Stratification is observed up to a distance of 3.5 km from the inlet when the reservoir is exposed to wind.

The changes of salt concentration at the designed water withdrawal intake which is proposed to be located at the immediate vicinity of the outlet to the reservoir at $\Delta S = 0.4$ g/l are on Fig. 1.
Figure 1. Salt concentration on the surface near the intake.
Legend: 1 – W = 0 (no wind); 2 – North wind, W = 4.0 m/sec; 3 – South wind, W = 4.0 m/sec.
At a surface water intake, concentration reaches 0.75% of its maximum value in a calm period with the southerly wind and it is several times lower with a northerly wind. Ceteris paribus, near the deep-water intake the salt concentration in the calm period will be 30 times and with wind is approximately 2 times lower (figure.2).

Figure 2. Salt concentration on the bottom near the intake.
Legend: 1 – W = 0 (no wind); 2 – North wind, W = 4.0 m/sec; 3 – South wind, W = 4.0 m/sec.
The results of the simulations of the salt concentration for the withdrawal intake located approximately 3.5 km from the outlet to the reservoir at the remote surface intake are on Fig. 3.

Figure 3. Salt concentration at the remote surface intake.

Legend: $W = 0$ (no wind). There is no the curve with $W \geq 4$ m/s on Fig. 3 because it practically coincides with the similar curve on Fig. 4.

The results of the simulations of the salt concentration for the withdrawal intake located approximately 3.5 km from the outlet to the reservoir at the remote surface intake are on Fig. 3.
Figure 4. Salt concentration at the remote submerged intake.

Legend: 1 – W = 0 (no wind); 2 – North wind, W = 4.0 m/sec.

As can be seen from the figures, in all cases the best water quality is ensured at a remote water withdrawal intake compared with the intake located at the immediate vicinity of the outlet to the reservoir. Therefore, it is advisable to locate the water withdrawal intake at a distance of 3-3.5 km to the southwest from the intended location.

4. Conclusions

Numerical simulations of the distribution of substances in the reservoir allowed to conclude that studies of substances distribution over a long period $T_{c} \leq T_e \leq 3$ days, ($T_e$ - calm period of 50% exceedance probability) can be carried out with two-dimensional modes i.e. allowing full mixing. Numerical simulations by the model used showed that complete mixing with the existing characteristics of the wind effecting this reservoir occurs within 10-15 days.

Numerical simulations allowed to make a detailed forecast of changes in water quality in the reservoir. It was also allowed to come to the conclusion that the reservoir could be used as a water source for drinking water supply.

It was recommended to locate the water withdrawal intake at a distance of 3-3.5 km to the southwest from the outlet to the reservoir and construct a submerged one.
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