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Jacobs Journal of Hydrology

Review Article

Groundwater Monitoring in Saint-Petersburg: Past and Present

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Received: *08-19-2015*

Accepted: *08-26-2015*

Published: *10-08-2015*

Abstract

A short history of groundwater monitoring in the second largest Russian city is given. It started in the 19th century and continues till now. In 1960-1980 the total number of monitoring wells was about 250. Based on the long-term monitoring results, several large scale hydrogeological maps have been compiled. They included the map of the groundwater regime, maps of the maximum groundwater table elevations, and geological-hydrogeological maps at the depths of 10, 25, and 50 m, respectively. Various statistical methods were applied for maps' preparation and compilation. These maps are widely used by City's Departments and Services as well as construction companies. As a result, geotechnical investigations at the construction sites could be reduced and focused on solving site specific rather than general problems.

Keywords: Saint-Petersburg; the Groundwater Regime; Maximum Water Table Elevations; Hydraulic Connection between Groundwater and Surface Water

Introduction

Saint-Petersburg is the second largest Russian city with a population of approximately 5.2 million and with a total area of 605.8 km^2. Founded in 1703, it was the Russian capital from 1712 till 1918. The City is located in the delta of the Neva River which flows westward from the Lake Ladozhskoye to the Finnish Gulf of the Baltic Sea.

Numerous Neva's tributaries and natural and dug channels flow through the City that is called «the Northern Venice». The City of Saint-Petersburg is incorporated in the North-West Federal District that includes nine municipal towns and 21 townships. The total population of the District is 5.4 million and the total area is 1,439 km^2.

Early groundwater monitoring

The first systematic studying on the groundwater regime commenced in the 19th century, and the first publication on this subject appeared as early as in 1867. Based on the limited data at the dug wells, Illish [1] made a conclusion that shallow groundwater elevation within the City were defined by water level elevations in the Neva River and its tributaries, instead of depending on precipitation. One year later another article on groundwater was published in the same journal by Pell [2]. The paper was illustrated by a map entitled "A map of soils and groundwaters in Saint-Petersburg". It was based on water table measurements conducted at different times in 107 dug wells, soil excavations and ditches. The depth to the water table was shown by different colors. Each color was dedicated to the specific depth interval (0.0-0.3 m; 0.3-0.6 m; etc., with the maximum depth interval of 3.3-3.6 m). The areas with hydraulic connection between groundwater and surface water have been delineated. Pell [2] also indicated some specific areas where water table fluctuations depended on precipitation rather than the surface water level fluctuations.

Therefore, both researchers focused their attention on the problem of hydraulic connection between groundwater and surface water that was fully understandable. The Neva River experienced frequent and unpredictable, sometimes catastrophic floods caused by strong west-eastern winds from the Finnish Gulf. Each flood resulted in the rapid and damaging groundwater table rise in the areas adjacent to the Neva River and its tributaries.

For further studying of this problem, 16 groundwater moni-

Cite this article: Zaltsberg E. Groundwater Monitoring in Saint-Petersburg: Past and Present. J J Hydrology. 2015, 1(2): 008.

toring wells were installed in the Saint-Petersburg downtown area in 1877 under the supervision of the military engineer A.Tillo. The distance between the wells and the nearest surface water bodies ranged from 32 to 638 m. Water tables, precipitation and air temperature were measured daily from June 1, 1877 to June 1, 1878. The accuracy of groundwater level measurements was 2mm; simultaneously, water level measurements in the Neva River were conducted. All monitoring results obtained were thoroughly analyzed and then published [3].

Comparing groundwater and surface water fluctuations, Tillo [3] came to the conclusion that hydraulic connections between them were observed in the narrow strip along surface water bodies where average annual water table elevations did not exceed 0.5 m above sea level (a.s.l.). In the areas where groundwater level elevations were higher than this mark, hydraulic connections between groundwater and surface water were not observed. Tillo [3] pointed out that his conclusion was based on the one year observations only when there were no significant floods in the Neva River. He also suggested that even during significant floods when water level elevations in the Neva River could rise to 2.0-2.5 m a.s.l., they would not influence groundwater fluctuations in the areas with the average annual water table elevations above 3.0 m a.s.l.

Groundwater temperature measurements conducted by Tillo [3] indicated the groundwater “warming” effect associated with City’s buildings. Groundwater temperature in 12 wells installed in backyards ranged from 3.7 to 7.5 ^{o}C while the temperature in 4 wells installed in basements ranged from 9.9 to 16.9 ^{o}C.

The next round of groundwater monitoring was initiated by Professor Luboslavsky and conducted in 1892-1925 in the park of the Forestry Academy located at the northern suburb of the City at a distance of several kilometers from the Neva River. The water table was measured daily in several monitoring wells installed in shallow Quaternary deposits. One well was equipped with the recorder. In addition, precipitation, air temperature and soil temperature in the unsaturated zone were measured on the daily basis. Unfortunately, almost all measurements were lost during the Second World War. Only some of them along with conclusions have been published in a short article [4]. Analyzing water table fluctuations and precipitation, Voronina [4] indicated that “the influence of precipitation on water table fluctuations is evident especially considering their annual values”.

Considering daily water table fluctuations and precipitation, Voronina [4] indicated that the water table rise depended on the water content in the unsaturated zone immediately prior to precipitation. She also pointed out the influence of atmospheric pressure on water table fluctuations during winter seasons and the dependence between the spring water table rise and the snow cover thickness at the end of the winter season.

Groundwater monitoring after 1945

The most extensive groundwater monitoring and associated investigations commenced after the Second World War. By 1980 the monitoring network in the City consisted of approximately 250 wells completed in various Quaternary and underlying deep Cambrian deposits. Quaternary water bearing formations included technogenic (urban) deposits, sands, loams, lacustrine clays, upper fractured till and sandy layers in massive till. They are encountered at the ground surface and have the total thickness of up to 140-160 m.

Groundwater monitoring was conducted within the upper segment of these deposits and the depth of the monitoring wells usually ranged from 2-5 to 15-20 m.

Groundwater monitoring was also conducted within the artesian Cambrian (Gdovsky) aquifer. It consists of sands and sandstones; its top is located at a depth of 140-160 m from the ground surface.

Shallow groundwaters within the City are responsible for basement flooding, water inflows into construction excavations and ditches and existing underground structures. In order to avoid unpredictable groundwater flooding, knowledge of the shallow groundwater regime is of paramount interest to construction companies and various City’s Departments responsible for safe and efficient maintenance of underground structures and systems.

For many years comprehensive groundwater monitoring and studying of groundwater regime and balance in the City of Saint-Petersburg and its vicinity were conducted by the North-West Hydrogeological Station under the direction of prominent Russian hydrogeologists B.Archangelsky, P.Gass and N.Shvedchikova.Based on the long term monitoring results, several generalized hydrogeological maps for the territory of the City have been compiled. They included the following:

1. The 1967 map of the shallow groundwater regime (scale 1: 50,000)

   The following areas were shown on the map:

- The areas with the natural groundwater regime which usually coincide with City’s suburbs and big parks. The water table regime is defined by precipitation and air temperature. Depending on lithology of shallow water bearing formations, seasonal and long term water table fluctuations range from 1-2 to 4-5 m;

- The areas with the partially disturbed groundwater regime that is caused by the medium density housing development and the presence of underground systems. The seasonal and long term groundwater fluctuations range from 0.5-1.0 to 1.5-2.0 m and depend on both the meteorological and urban factors; and

- The areas with the disturbed groundwater regime which are located in the historical City’s downtown. Seasonal and long term water table fluctuations are flattened and usually in the order of 0.1-0.5 m. This regime is caused by dense urban development, the presence of numerous underground systems and structures, the asphalt and concrete cover and impermeable embankments.

Within the areas with the natural and partially disturbed regimes two subareas were delineated:

a) the subarea with the groundwater regime defining by meteorological factors and the absence of hydraulic connection between groundwater and surface water; and

b) the subarea with hydraulic connection between groundwater and surface water. This subarea is stretched along the Finnish Gulf, the Neva River and its tributaries. The width of this subarea depends on its lithological setting and ranges from 100 to 300 m. The annual average water table elevations within the subarea do not exceed 2 m a.s.l. Therefore, the previous conclusions regarding the size of this subarea made by Illish [1], Pell [2] and Tillo [3], were further clarified.

2. The 1975 map of maximum water table elevations (scale1:50,000).

- Maximum water table elevations in shallow Quaternary deposits were shown on this map. The water table measurements at approximately 300 shallow monitoring wells (both existing and abundant) have been utilized for the map's compilation. The observation period in each well ranged from a few months to 25-27 years. Short observation periods at some wells have been extended by means of correlation with measurements at corresponding long term observation wells; and
- In addition, single measurements at several thousand shallow exploration geotechnical wells installed during the high water table periods (springs and falls) were incorporated into a map.

Since 1975 the map of maximum groundwater levels has been further verified and updated. In 1989 the map of maximum groundwater levels (scale 1:25,000) with probability of 5% was compiled by the Northwest Geological Survey. 20 years later this map was revisited again and the latest monitoring data were incorporated into it.

3. The 1970s geological-hydrogeological maps at the depth of 10, 25, and 50m from the ground surface (scale 1: 50, 000).

- They were based mainly on the bore whole log data from more than 100,000 exploration geotechnical wells drilled at various time within the City's territory. At each specific depth the main aquifers and aquitards have been delineated; and
- Piezometric heads typical for main water bearing formations at each specific depth were indicated at each of three maps.

For areas with natural and partially disturbed regimes representative wells with observation periods not less than 20--25 years were selected. Using the multiple correlation method, the equation for predicting the winter minimum and spring maximum water tables were calculated for each well [5].

For predicting the winter minimum level, the following predictors have been utilized: the maximum level in the previous fall and the average winter air temperature in December--February. For predicting the spring maximum groundwater level two other predictors have been used namely the minimum previous winter level and winter precipitation in December-- February or December-March. Using these equations, seasonal forecasts of the extreme groundwater levels were calculated, mapped and distributed among various Municipal and City Departments and construction companies which utilized them in planning their upcoming operations.

The results of long term groundwater level monitoring have been used for calculating groundwater balance components such as groundwater inflow and outflow, groundwater infiltration and evapotranspiration. Such calculations have been conducted for numerous experimental sites within the City with various geological settings and types of the groundwater regimes [6].

General information on hydraulic properties of shallow Quaternary deposits that is necessary for these calculations was derived from pumping and water inflow tests conducted at the shallow monitoring wells. In addition, about 500 express tests were performed in shallow dug test pits. Each test consisted of water inflow into the pit and the following water level decline measurements. All results were statistically processed, and the average hydraulic conductivity value and its standard deviation for each water bearing deposit have been calculated and mapped.

Close correlation was established between the density of housing development and the long term and seasonal groundwater fluctuations within various Quaternary water bearing deposits. These equations were used for forecasting shallow groundwater levels in the areas of the proposed housing development.

Of special interest is hydraulic head monitoring within the deep Cambrian (Gdovsky) artesian aquifer. First water supply wells were installed in this aquifer in the 1860s under the supervision of Professor A. Inostrantsev. At that time the piezometric head was above ground surface at elevation of 4 m a.s.l. In the following decades especially after 1945, water from this aquifer was widely used for cooling industrial equipments. In 1965 the water withdrawal from the aquifer reached its maximum of 36,000 m^3/day, in 1975 the withdrawal rate was 32,000 m^3/day [7]. In the 1970s hydraulic head elevations of the Cambrian (Gdovsky) aquifer in the central part of the City were 65-70 m below sea level (b.s.l.) and the total area of the cone of depression was about 20,000 km^2.

Starting from the 1980s, the Soviet economy began to decline, the industrial production in Saint-Petersburg was significantly shrunk and groundwater extraction from the Cambrian aquifer was reduced accordingly.

As a result, piezometric heads started to recover at a rate of approximately 0.5-1.5 m/year. In 2005 piezometric heads were observed at elevations 22.6-25.2 m b.s.l. The relatively slow recovery rate is due to the fact that the water withdrawal from the aquifer is still continuous for the municipal water supply beyond the City's boundaries.

Cyclicity of groundwater level fluctuations

Long term groundwater level monitoring allowed identification of the cyclic (harmonic) components in water table fluctuations using the classical Fourier analysis [5]. Some results of this analysis are given in **Table 1.**

Table 1. The results of Fourier analysis by Zaltsberg [5].

Long term series analyzed	Duration of harmonics in years										
1. The City of Saint-Petersburg The average annual groundwater level in Quaternary deposits											
Well 160* (1946-1980)	3		5		9				26		
Well 170* (1933-1980)	3		5		10				26		
Well 860* (1946- 1980)	3		5		9				27		
2. The North-West Federal District The average annual groundwater level in Ordovician limestones											
Well 1002* (1933-1980)		4				11	16		27		
Well 1009* (1933-1980)			5		8		16		25		
3. The average annual water level in Lakes											
Ladozhskoye (1882-1980)				6		13			27	29	
Onezhskoye (1891-1980)				6		11		22	25		
4. The average annual flow in the											
Neva River (1860-1980)				6		11				29	
The meteorological station											
Saint-Petersburg											
Annual precipitation (1900-1980)			5	6		11					33
Average annual air temperature											
(1871-1980)						12					
					8				24		
Average air temperature in the											
winter season (1950-1980)						11					
	3									28	

Notes: * Measurements are partially reconstructed.

The following cycles (harmonics) were found in the long-term groundwater level fluctuations: 23-27, 16-17, 8-11, 4-5, and 3 years. The similar harmonics were observed in the long series of the hydrological data (the average annual water level in the nearby lakes, the annual flow in the Neva River). Harmonics of similar durations were found also in series of meteorological data. Such similarities should be expected because both groundwater level and surface water level fluctuations are defined mainly by meteorological conditions.

Fourier analysis allows defining several harmonics and the random component in the measurement series. Each harmonic is characterized by the amplitude, duration and the initial phase. Using these parameters, each harmonic specified and their sum could be extended beyond the observation period and, therefore, some prediction on the future annual average groundwater level with the lead time of 1-2 years could be made. Such forecasts have been calculated for the monitoring wells mentioned in Table 1, and their accuracy was satisfactory.

Conclusion

The maximum amount of groundwater monitoring works was conducted in Saint-Petersburg in the 1960s and 1970s. In the 1990s the state governed Soviet economy was transformed into the market economy. As a result, government's funding for groundwater monitoring was significantly reduced. By 2005, the monitoring network in the North- West Federal District consisted of about 70 shallow and deep monitoring wells [7].

It is interesting to compare the groundwater monitoring network in Saint-Petersburg and in some other cities. In the Russian capital Moscow the number of monitoring wells was as follows: 369 in 1995, 280 in 2000, and 154 in 2008. In the biggest Canadian City of Toronto there were 2 monitoring wells in 2010, while in the New York City there was only one monitoring well in the same year. Due to lack of the long-term monitoring data, there are no detailed hydrogeological maps for either Toronto or New York demonstrating the peculiarities of the groundwater regime within their territories. Such a deficiency has practical implication. For example, prior to commencing any construction project in Toronto, the significant amount of exploration work needs to be conducted for characterizing general geological/hydrogeological conditions at the construction site. In Saint-Petersburg this information could be easily obtained from the previously compiled large scale hydrogeological maps based on the long-term groundwater monitoring results. During exploration work at the construction site in Saint-Petersburg the main efforts are focused on solving site specific hydrotechnical problems rather than on gathering general hydrogeological information that is already available. As a result, a total cost of the construction work is significantly reduced and expenditures associated with map compilations have been returned in a relatively short period of time.

Using the huge previously collected groundwater monitoring data base, even the reduced groundwater monitoring network in Saint-Petersburg still satisfies the needs of various City's services and construction and transportation companies, as well as provides valuable and timely information on the groundwater regime, balance and resources.

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