Hydrological simulation and assessment of the optimal parameters of the water replenishment of the floodplain lake and old riverbed on the Uzh river

S V Velychko¹ and O V Dupliak¹
¹ Kyiv National University of Construction and Architecture, 31 Povitroflotsky Ave., Kyiv, 03037, Ukraine
E-mail: velychko.sv@knuba.edu.ua, dupliak.ov@knuba.edu.ua

Abstract. One of the tasks in modern approach of the water resources management is improving environment health by the way of the river restoration. On the urban area it is impossible to provide full river restoration, but at the same time it is possible to create the environment close to natural. In our work on the example of the river Uzh located inside the city provides the assessment of the restoring possibility of the part of the floodplain by water replenishment of the old riverbed during the vegetation season. Flood control dyke construction interrupted the connection between old riverbed and river and as a result floodplain lake became muddy, silted up and lost its attractive form. To assess the possibility of the floodplain lake replenishment, the simulation of some scenarios were carried out: natural condition, water replenishment during flood, pumping water, raising water level in the river Uzh near the lake. The connection of the lake and the old riverbed with the river will improve slightly the storage capacity of the lake and allows to provide the depth of up to 1.0 m in the lake during flood, but the water will be absent in the old riverbed during the dry season. Hydraulic calculation showed that replenishment during spring floods and pumping water were not possible due to high hydraulic conductivity of the gravel and pebble soils. The old riverbed replenishment is possible by raising water level in the river Uzh, which will ensure the free water flow into the lake and into the old riverbed during the dry season.

1. Introduction
Water management was aimed to solve flood, social and economic problems of the population, which led to a significant deterioration of riverbeds, the destruction of the floodplains natural state in the XX century. Now, Ukraine implemented the Water Framework Directive, which requires the change in attitudes towards water resources. The river restoration or rehabilitation is one of the priority measures improving the health of the aquatic environment.

In the work [1], river restoration measures are divided into management measures (monitoring of water quality and quantity) and engineering measures aimed at improvement of the river health. The integrated approach is the most modern and includes providing the river with enough room, free movement of sediments, increasing biodiversity, reducing anthropogenic impact [2–4]. The too modified riverbed situated in the city is almost impossible to restore to its natural state due to the significant changes in the environment state and the absence of the free space for natural regime.
Thus, partial measures are often used, which depend on the communities economic capabilities: bank stabilization, clearing of the riverbeds [5], using aquatic plants and animals to clean riverbeds and floodplain lakes from anthropogenic pollution [6], expanding inter-dyke room [7,8], restoration of tortuosity and multi-sleeved channels, connection of the riverbed and the floodplain by hydraulic structures in the dykes or its destruction [9], restoration of natural regime of water and sediments [10]. In addition to economic constraints, according to the work [11] in which restoration projects in different countries were compared, the degree of river restoration is influenced by national specificity, which does not allow to develop a single ideal mechanism for assessing the effectiveness and necessary measures of the river restoration on the urban areas.

If full river restoration in the city is not possible, then what measures of the river restoration to use and with what factors to assess the restoration effectiveness. In the work [12], 110 river rehabilitation projects in rural and urban areas were analysed in France. The most projects in the rural areas were implemented to restore aquatic environments; restoration of longitudinal connection; restoration near natural patterns of river hydromorphology. The dominated projects on the urban areas were aimed to flood protection, to improve the quality of the citizens life, the aesthetics of the river landscape. In Ukraine, most river restoration projects relate only to clearing the riverbed and restoring riffles.

The author [13] proposed the main components of sustainable development of the aquatic environment in the city: clean water, green slopes, flood protection and automated control system. But in addition, the social component is very important in the rural environment, namely the creation of a comfortable environment for recreation [14].

Thus, river restoration is becoming more difficult in the cities due to the flood protection requirement, housing construction and recreation. According to the authors' researches [15–17] biological methods of river restoration, namely the connection of river and floodplain and floodplain water replenishment provide the local species biodiversity increasing and improve water quality. At the same time, it should be noted that the full restoration of the natural regime of river in rural area is not possible, the river requires periodic intervention [15]. Thus, in cities it is possible to create and maintain an urbanized near natural environment, which at the same time provides improve the health of riparian ecosystems, recreational and aesthetic needs of the citizens.

In our work floodplain restoration of the part of the Uzh River inside the Bozdos Park in the centre of Uzhhorod was assessment. The river floodplain replenishment would create the favourable environment for the flora and fauna of the park and the additional recreational area for citizens in the park during the dry season (June-September).

The aim of the work is environmental assessment of the water replenishment possibility of the old riverbed and floodplain in the park and operating volume of the floodplain lake. The following tasks were solved for this aim:
- to analyse the hydrological data of the Uzh river on the study area;
- to determine the floodplain lake volume in modern conditions;
- to simulate the water accumulation in the lake after the connection with the river;
- to calculate the necessary operating volume of the lake for water replenishment of the old riverbed during the dry season.

2. Materials and methods
The Uzh river source is situated in the Carpathian mountains and the lower part of the river reaches the plain. The lower part of the Uzh River located in the Transcarpathian lowlands was studied in the work. The Uzh river crosses the Uzhgorod city. Free meandering of the riverbed in the city was limited by the flood protection dyke construction. In 1954, Bozdos Park was established inside of the river loop and old riverbed and the lake were connected to the river
Uzh by tubular spillways for floodplain water replenishment. Over the last 30 years tubular spillways were blocked by sediments and point bar formed on the left bank of the river Uzh near park. Now the connection between the floodplain in the park and the river is lost, there is no water in the old riverbed. Floodplain lake turned into two small silted lakes (figure 1).

Figure 1. Current state of the floodplain lake: 1 – floodplain lake, 2 - old riverbed, 3 – dyke, 4 – tubular spillways for water replenishment.

The operating volume of the floodplain lake in the ice-free period (March-November) was calculated by the water balance method according to the general equation [18]:

\[ Pf - E_0 f + SI - SO + RI - RO \pm \Delta W = 0, \]  

where \( \Delta W \) – change in storage, \( m^3 \); \( P \) – precipitation, m; \( f \) – lake area, \( m^2 \); \( SI \) – seepage inflow from river, \( m^3 \); \( E_0 \) - evaporation from the water surface in the ice-free period, m; \( SO \) – seepage outflow from the lake, \( m^3 \); \( RI \) – surface river inflow through the intake structures, \( m^3 \); \( RO \) – surface outflow from the lake into the old riverbed, \( m^3 \).

The calculations were carried out for the years of different probability: mean annual flow, low-flow of 75%, 95% probability. Water levels in the years of different probability were calculated using the data from the Uzhhorod hydrologic station, located at a distance of 2.1 km above the park. The water levels fluctuation in the river near the lake is 107.6-108.5 m during the dry season (figure 2). The temperature, wind speed, precipitation data were taken from the Uzhhorod climate station. Evaporation from the water surface during the ice-free period was calculated by the method described in the work [19].

The seepage inflow from river and the seepage outflow from the lake to the downstream calculated by the equation [20]:

\[ SI(SO) = K \frac{L}{2d}(H_1^2 - H_2^2), \]  

where \( K \) – hydraulic conductivity, m/s; \( L \) – seepage length, m; \( d \) – distance between river and lake, m; \( H_1, H_2 \) – water levels in the river and lake, m.

The top layer is silty loam with the pebbles and gravel inclusion of 15 to 25%, its hydraulic conductivity is 0.2-1 m/day. The gravel-pebble soil with loamy and clay aggregate is located below silty loam. Its hydraulic conductivity is 30-50 m/day. Hydraulic conductivity of the floodplain soils were obtained based on the results of field research conducted in 1988.

The replenishment of the floodplain is carried out by the tubular spillway. The discharge of tubular spillway under gravity flow is determined by the equation [21]:

\[ Q = \varphi w_c \sqrt{2g(H_1 - H_2)}, \]
Figure 2. Water levels fluctuation in the Uzh river for mean annual flow 50%, low-flow of 75% and 95% probability.

where $Q$ – discharge, $m^3/s$; $\varphi$ – velocity coefficient; $w_c$ – pipe area, $m^2$; $H_1$, $H_2$ – water head before and after tubular spillway, m.

The tubular spillway supplies water from the river to the lake during the dry season. Since the river has low water levels during the dry season, it is not possible to supply water directly from the river into the old riverbed. Therefore, water replenishment of the old riverbed is carried out through the lake using its operating volume.

The operating volume was calculated for the following scenarios:
- current conditions (dyke separates floodplain from river);
- restoration of the connection between the floodplain and the river.

During the period of extreme floods in the river, the tubular spillway is closed with the gate to prevent turbid water and debris from river entering the lake. The outflow from the lake to the river was not taken into account, because the gate will be closed during this period, and water will flow into the old riverbed for its replenishment.

3. Results and discussion
The study of the current state of the relationship between river and floodplain showed (figure 2) that the water levels in the river cannot provide the constant flow into the old riverbed, as evidenced by visual observations of the lakes and old riverbed. Thus, it is necessary to consider the possibility of water replenishing using operating volume of the lake.

Now the floodplain lake consists of two separate lakes, which are fed by rainwater and groundwater from the Uzh river. If the water level rises in the river, the water level rises too in the lakes, and thus the operating volume of the lakes is increased. At the same time, the gravel-pebble soil around the lakes has high hydraulic conductivity, which leads to significant seepage losses into the river downstream. The simulation of lakes operation in modern conditions
and the water balance calculation showed that water levels do not exceed 108.0 m during the vegetation season (March – October) even in the mean year (50% probability), so water from the lakes can flow into the old riverbed only during spring flood. Water levels fluctuation in the lakes is shown on the figure 3. The average total month volume of the lake’s ranges from 11.6 to 16.0 thousand $m^3$ during the vegetation season.

![Figure 3. Lakes water levels in current condition.](image)

The second simulation scenario is water replenishment of the floodplain by connecting the lake with the river by tubular spillway. It allows to fill the lake up to the water level in the river. The results of water level simulation in the lake is shown on the figure 4. We can see that the water level in the lake is kept above the bottom level (108.0m) of the old riverbed during the mean year, and therefore it is possible to supply water into it. It is possible to keep the water depth of 20cm in the old riverbed by creating the backwater at the end of the old riverbed. It is not possible to supply water into the old riverbed during the dry season in the low-flow years of the 75% and 95% probability. The average total month volume of the lake that can be created by water replenishment is 16.5-23.8 thousand $m^3$.

It is possible to increase the water depth and the operating volume in the lake to 69.8 thousand $m^3$ by clearing the lake bottom and deepening it to the level of 107.0 m. Clearing will improve the ecological condition of the lake, but it will not change the flow amount into the old riverbed.

To ensure five times the water exchange in the lake and old riverbed, it is necessary to supply the water with flow rate of 0.01 $m^3/s$ during the dry season. The water depth will range from 1.0 to 0.7m in the low-flow years and from 1.8m to 1.2 m in mean year in the lake. The water depth will be 0.2m in the old riverbed during the dry season in mean year.

From the point of view of the components of the water balance after the connection of the lake with the river, the loss part of the water balance is compensated by taking water from the river to the lake (table 1). But to supply water into the old riverbed in the low-flow year it is necessary to raise the water level in the lake up to 109.8 m. Which will create the water level of 1.8 m in the old riverbed.

It is possible to raise the water level up to 109.8m in the lake by pumping water into the lake from the river. The results of water level simulation in the lake is shown on the figure 5.
Figure 4. Lake water levels after restoration.

Table 1. Components of floodplain lake water balance, thousand m$^3$.

| Year | Inflow  | Precipitation | Evaporation | Seepage losses | Outflow | Change in storage |
|------|---------|---------------|-------------|----------------|---------|-------------------|
|      |         |               |             |                |         |                   |
|      | Current condition |             |             |                |         |                   |
| 95%  | 32.9    | 14.3          | 17.6        | 31.4           | 0       | 1.8               |
| 75%  | 19.1    | 17.6          | 15.9        | 15.7           | 0       | -5.6              |
| 50%  | 20.5    | 23.3          | 16.9        | 15.9           | 0       | -10.9             |
|      |         |               |             |                |         |                   |
| After restoration |             |             |             |                |         |                   |
| 95%  | 125.1   | 17.4          | 21.1        | 71.1           | 48.6    | -1.7              |
| 75%  | 142.5   | 20.1          | 17.7        | 66.3           | 61.7    | -16.9             |
| 50%  | 229.2   | 27.4          | 19.3        | 102.1          | 109.4   | -25.7             |
|      |         |               |             |                |         |                   |
| The water level raise by raising the water level in the Uzh river near the park |             |             |             |                |         |                   |
| 95%  | 215.1   | 26.7          | 45.1        | 85.0           | 93.2    | -18.5             |
| 75%  | 222.5   | 30.5          | 39.9        | 85.9           | 122.7   | -4.5              |
| 50%  | 172.0   | 29.1          | 36.7        | 84.1           | 141.0   | -12.7             |
|      |         |               |             |                |         |                   |
| The water level raise by pumping water into the lake |             |             |             |                |         |                   |
| 95%  | 617.3   | 23.7          | 39.6        | 437.9          | 117.4   | -46.1             |
| 75%  | 466.0   | 22.7          | 29.9        | 308.1          | 139.8   | -10.9             |
| 50%  | 429.3   | 22.5          | 28.9        | 329.2          | 131.5   | 37.7              |

The pumping will lead to slightly increasing the water losses due to evaporation because of the water surface increasing, and due to seepage losses because of increased seepage pressure. The seepage loss will not lead to water loss by the ecosystem, because the lake is located between
the upstream and downstream of the Uzh river inside the loop. But evaporation and seepage losses with average amount of 65%, are converted into operational losses, and pumping is not acceptable from an economic point of view, a similar situation and conclusions were made by the authors [11] during field research of the pumping water replenishment of floodplain lake. Other way to increase the water level in the lake is to raise the water level in the Uzh river near the park during the dry season. Raising river water levels during the dry season and connecting the river with the lake will ensure high lake levels and outflow into old riverbed even during the minimal water flow in the river. The comparing of the economic and social components of the water level raising by pumping water or raising water level in the river Uzh requires further research and calculations.

4. Conclusions

1. It is almost impossible to provide the river with enough room to restore its natural state in urban conditions, because flood protection is the integral part of the safe existence of the population. So, we cannot destroy the dykes to restore the Uzh river but as the simulation showed it is possible to restore the connection between the floodplain and the river by water replenishment and supplying water to the old riverbed.

2. In current conditions, when the lake is cut off from the river, climatic conditions significantly affect the water accumulation in the lake, the maximum operating volume is 16.0 thousand $m^3$ in the lake in the summer – autumn period. Low water levels in the river do not allow to supply water into the old riverbed.

3. The river restoration by connecting the lake with the river allows to replenish the lake with surface water, which leads to the rapid water levels increase in the lake. Operating volume of the cleared lake up to the 69.8 thousand $m^3$ will be enough to replenish the old riverbed for one month. So, only floods accumulation during the high-water period (spring and summer floods) are not enough for supply water into the old riverbed during the dry season.
4. It is possible to store enough water in the lake for water supply into the old riverbed only during the high-flow years with frequent floods in the summer-autumn period.

5. Existing water levels in the Uzh river are not enough to create the necessary ecological conditions: the depth in the pond higher than 1.5 m and water outflow into the old riverbed in the summer-autumn period of the dry year. The required level of the lake for water replenishment of the floodplain in the park is 109.80 m, it is equal to the volume of 142-164 thousand m$^3$.

6. According to the research of many authors, an integral part of the river restoration is the rainwater and domestic wastewater treatment and control of its outlet.

**ORCID iDs**

S V Velychko https://orcid.org/0000-0001-8848-289X
O V Dupliak https://orcid.org/0000-0002-3500-5106

**References**

[1] Zhang X, Zhang X, Zhang Z, Zhang J and Fan P 2020 Measures, methods and cases of river ecological restoration IOP Conference Series: Earth and Environmental Science vol 601 (IOP Publishing) p 012025

[2] Johnson M F, Thorne C R, Castro J M, Kondolf G M, Mazzacano C S, Rood S B and Westbrook C 2020 *River Research and Applications* 36 3–12

[3] Nardini A G C and Conte G 2021 *Water* 13 1336

[4] Peilin G, Meng C, Lichao Z, Yuejun S, Minghao M and Lingyun W 2019 Study on water ecological restoration technology of river IOP Conference Series: Earth and Environmental Science vol 371 (IOP Publishing) p 032025

[5] Chia B, Wang Y and Chen Y 2020 *Journal of Management in Engineering* 36 05020009

[6] Cao Y 2020 Water pollution control and ecological restoration of urban lake landscape IOP Conference Series: Earth and Environmental Science vol 525 (IOP Publishing) p 012064

[7] Habersack H and Piégay H 2007 *Developments in earth surface processes* 11 703–735

[8] Bauer M, Harzer R, Strobl K and Kollmann J 2018 *River research and applications* 34 451–460

[9] Clilverd H, Thompson J, Heppell C, Sayer C and Axmacher J 2016 *River research and applications* 32 1927–1948

[10] Korpak J and Lenar-Matyas A 2019 *Environmental Earth Sciences* 78 1–13

[11] Zingraf-Hamed A, Greulich S, Wantzen K M and Pauleit S 2017 *Water* 9 206

[12] Zingraf-Hamed A, Greulich S, Pauleit S and Wantzen K M 2017 *Restoration Ecology* 25 994–1004

[13] Wang Y, Liu X and Hu W 2021 *European Journal of Remote Sensing* 54 200–210

[14] De Bell S, Graham H and White P C 2020 *Sustainability* 12 695

[15] Stoffers T, Collas F, Buijse A, Geerling G, Jans L, Van Kessel N, Verreth J and Nagelkerke L 2021 *Science of the Total Environment* 755 142931

[16] Weigelhofer G, Hein T, Kucera-Hirzinger V, Zornig H and Schiemer F 2011 *Ecological Engineering* 37 1507–1514

[17] Funk A, Martínez-López J, Borgwardt F, Trauner D, Bagstad K J, Balbi S, Magrach A, Villa F and Hein T 2019 *Science of the Total Environment* 654 763–777

[18] Dawidek J and Ferencz B 2014 *Hydrology and Earth System Sciences* 18 1457–1465

[19] Velychko S and Dupliak O 2021 *Journal of Ecological Engineering* 22

[20] Jamel A 2016 *Diyala Journal of Engineering Sciences* 9 38–49

[21] Smolders S, João Teles M, Leroy A, Maximova T, Meire P and Temmerman S 2020 *Journal of Marine Science and Engineering* 8 27