REDUCTION OF POLLUTION RISKS OF BANK-FILTERED AQUIFERS BY EFFLUENT OPTIMIZATION OF A PLANNED INDUSTRIAL PLANT

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ABSTRACT. **Reduction of pollution risks of bank-filtered aquifers by effluent optimization of a planned industrial plant**. The optimization of the treated wastewater outlet of a planned vegetable oil manufacturing plant near Foktő, and the reduction of the pollution risk of the River Danube as well as some bank-filtered aquifers were the aims of this study. With a 2D depth averaged hydrodynamic model the flow conditions were calculated for further use in a 2D model for pollutant spreading. A 2D particle mixing model was used to define the optimal outlet location taking all permit limits into consideration. With analytical mixing model the different parameters of the effluent dilution due to longitudinal and transversal dissipation were calculated.

Key-words: pollution risk, effluent, 2D hydrodynamic model, 2D mixing model, analytical mixing model

1. Objectives

Our task was to examine the impact of the treated sewage water – of the planned vegetable oil manufacturing plant in the administrative area of *Foktő* municipality – which should be led into the *Danube*. More precisely:

- **optimization of the outlet location** of the treated wastewater using different mathematical models, by minimization of the contamination caused on the operating and future bank-filtered aquifer,
- **examination of the load capacity of *Danube River*,** investigation of the change of characteristic water quality indicator components caused by the effluent.

The optimal outlet location was set outside the protection area of the two aquifers, near the streamline of the *Danube* cross section 1520 + 706 rkm. The outlet is next to the operating Foktő-Barákai (Kalocsa) (left side) bank-filtered aquifer's hydrogeological protection area of 50 years travel-time. On the right bank the future bank-filtered aquifer's protection area of 50 years travel-time is affected.

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2. Data underlying the investigations

2.1. Characteristics of the design waste water discharge, limit- and background values

According to the regulations, prior to and after the planned treatment, the quality data of the industrial sewage nascent during the production are as follows:

- **Planned daily average effluent discharge:** 1 632 m^3/d, 0,019 m^3/s as a hourly maximum.
- **Planned future daily average effluent discharge**: 2 026 m^3/d, 0,023 m^3/s as a hourly maximum.

Table 1. Characteristics of the industrial sewage, permit limits and background values

Parameter	Unit	Untre-ated	Treated	Limit values	Possible limit values		Danube background values	
					min	max	Paks	Fajsz
Discharge	m^3/s	0,019	0.019	-	-	-	585	585
Future discharge	m^3/s	0,023	0,023	-	-	-	585	585
Water temperature	^oC	30	30	-	-	-	22,70	21,82
COD	mg/l	4 000	99	**150**	50	600	20,57	21,60
BOD_5	mg/l	2 200	25	**50**	15	100	5,38	6,06
ammonia-N	mg/l N	1	20	**20**	2	40	0,22	0,21
nitrate-N	mg/l N	-	11	-	3	28	3,15	3,13
total inorganic-N	mg/l N	10	31	**55**	15	180	3,39	3,35
organic solvent	mg/l	150	10	**10**	2	20		
total suspended solids	mg/l	100	200	**200**	30	200	51,40	48,30
total-P	mg/l P	5	2	**10**	0,7	15	0,18	0,18

The water quality permit limits for operating and future bank-filtered aquifers' 50 years travel time protection area (**Figure 1.**) are listed in **Table 2**. It was examined if the permit limits are met 800 m downstream from the outlet – where the wastewater plume reaches the protection area.

Table 2. Permit limits for aquifers' water quality.

Parameter	**Unit**	**Permit limit**
Nitrate (ground water)	mg/l	50
Nitrate (aquifer's 50 years travel time protection area)	mg/l	**25**
Ammonia	μg/l	**500**
Total suspended solids	*mg/l*	*250*

The above mentioned permit limits for the aquifers are valid for everyday operation, when the treatment operates according to plans. Disasters or similar emergencies are not considered since they are with prevention measurements eliminated.

2.2. Characteristics of the affected Danube section

For the **model of mixing** the following low water level and discharge data of the *Danube* are considered as design values.

Gauge at Dombori (1506,8 rkm), on the basis of daily water level and discharge values between the years 1936 and 2009:

- lowest navigable water level (DB2004) discharge of 93,4% probability: 1 180 m^3/s,
- lowest discharge (Q_{min}): 585 m^3/s.

At the planned river streamline location (1520+706 rkm), with the help of **2D hydrodynamic model** the water depth and the depth averaged velocity components were calculated:

- in case of lowest navigable water level:
  - water level, $Z = 84{,}32$ m above Baltic sea level (maB),
  - water depth, $h = 3{,}51$ m,
  - depth averaged velocity, $v = 1{,}14$ m/s,
- in case of lowest discharge:
  - water level, $Z = 83{,}65$ m above Baltic sea level,
  - water depth, $h = 2{,}64$ m,
  - depth averaged velocity, $v = 0{,}75$ m/s.

In the introduced case full mixing occurred on a short distance (approximately on a distance of 5 times water depth) in vertical sense, because of turbulence and bottom friction. So a 2D depth averaged approximation could be used.

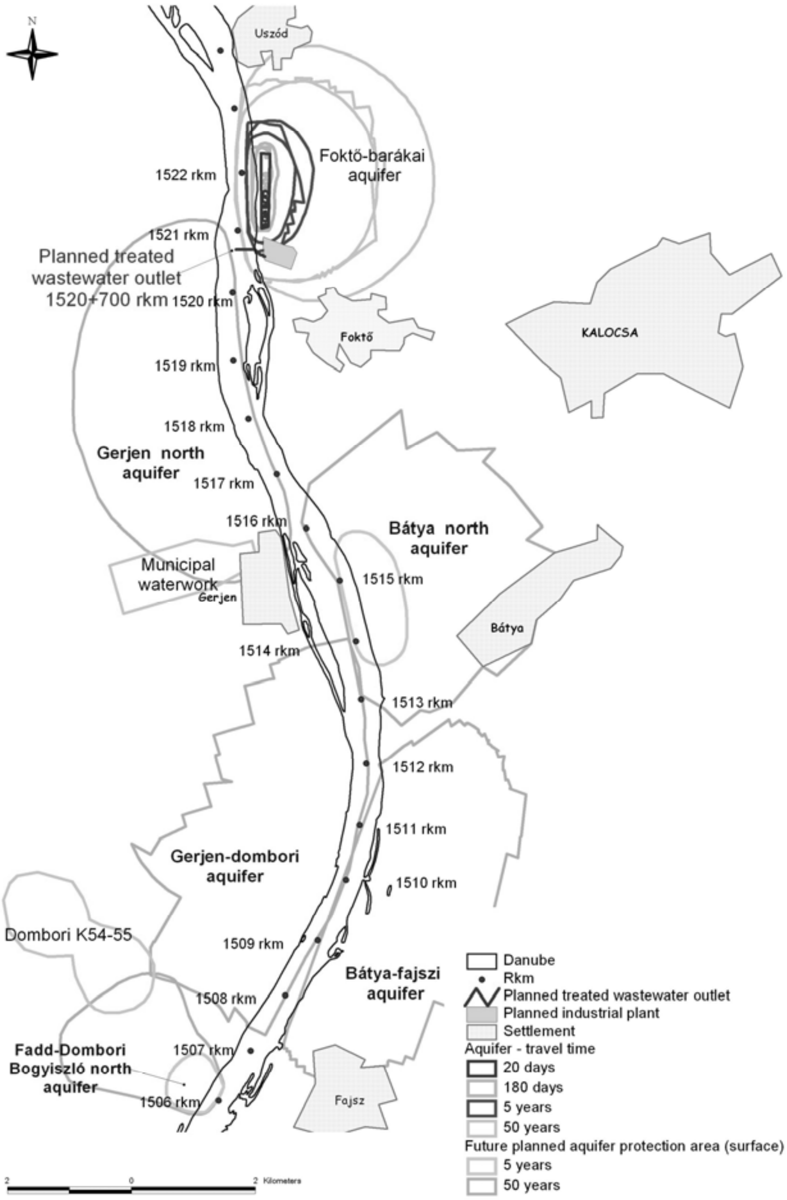

Figure 1. Environment of the planed wastewater outlet and hydrogeologic protection areas of aquifers with different travel time.

3. Mixing and loadability study

3.1. Model for calculating the hydrodynamic parameters and results

For analyzing the impact of the effluent as well as for defining the optimal outlet location and for analyzing the mixing, spatial distribution of some hydrodynamic characteristics (water depth, magnitude and angle of velocity) has to be known. With a **2D depth averaged hydrodynamic calculation the flow conditions were calculated** for 2D modelling of pollutant spreading. The results of the 2D hydrodynamic model are water depth, and depth averaged velocity in x and y direction calculated on a dense grid (5 m grid), provide basic data for further studies. The software called ***River2D***, used for the calculation is a two-dimensional, depth averaged, finite element model implemented by the University of Alberta.

There is a detailed literature regarding the mathematical principle and numerical solution. The basic equations are derived by depth averaging the three dimensional *Reynolds-equations* valid for time averaged turbulent flow in a viscous, incompressible fluid. The derivation of the *Reynolds-equation* from the *Navier-Stokes-equation* are known for university lecture notes, (for example: *Németh 1963, Liggett 1975, Rátky 1986, Abbott-Basco 1989*).

The so called shallow water 2D basic equations are the mass and momentum equations for depth averaged, open channel, two-dimensional, single layer, unsteady flow, derived from the *Reynolds-equations*.

For the numerical solution the continuous domain was discretized with a Δx_i, Δy_i, and Δt grid. The unknown were calculated on the intersection of the triangular grid. The numerical calculations are based on a finite element method. As a result of the calculation the model provides the following functions on discrete points:

$$h = h(x,y,t), \quad u = u(x,y,t), \quad v = v(x,y,t)$$

The studied river section was the *Danube* between 1505 and 1523 rkm.

Assuming constant hydrological and hydraulic conditions a steady flow was modelled. The **upstream boundary condition** was a constant discharge coming into the studied section while the **downstream boundary condition** was the relevant water level.

The morphological boundary conditions of the model were the **digital terrain model (DTM)** of the studied riverbed. The ca. 18 km long digital terrain model mapped the main training works of the river such as groynes and longitudinal training works. For the simulation the most recent data of the *Danube* river bed (*VITUKI Nonprofit Kft.*) as well as aerophotos provided by *ADU-KÖVIZIG* were used.

The parameter used for calibrating the model was the **roughness height** (k_s, m). The calibration was done for the lowest navigable water of year 2004 (DB2004)

1180 m^3/s. Since the design case for modelling pollutant mixing and propagation is also the low water state, the calibration was also providing hydrodynamic boundary conditions for the further modelling. The maximal difference of the calibrated water level from the low navigable water (DB2004) was:

$$dZ = Z_{calculated} - Z_{DB2004} = [-4{,}4\ \text{cm}; +2{,}9\ \text{cm}].$$

Figure 2. shows the velocity distribution calculated by the calibration with the digital terrain model and the DB2004 water levels.

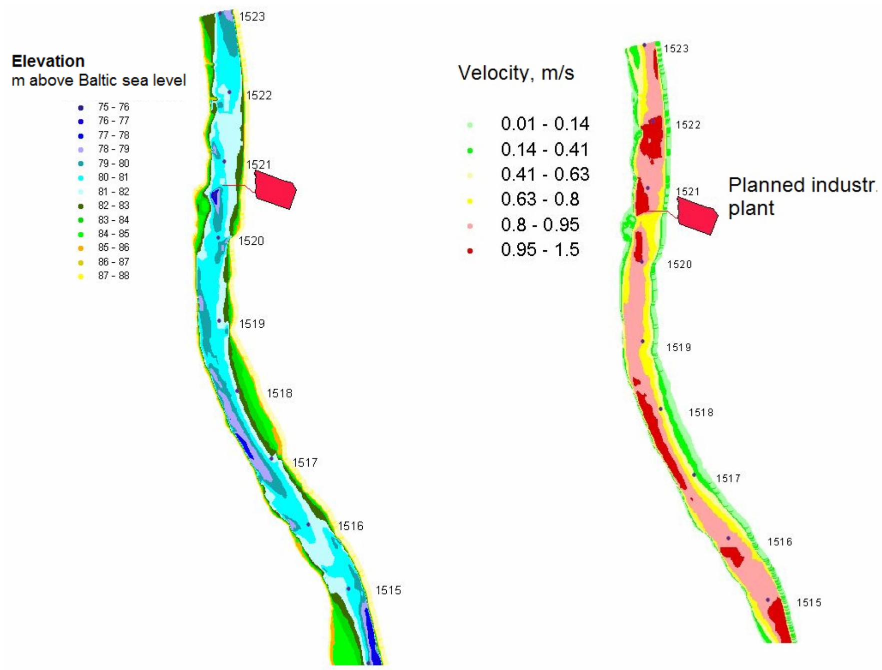

Figure 2. DTM and velocity distribution

3.2. Particle mixing model and results

The theoretical background of *Lagrangian* particle tracking in the used two-dimensional (depth averaged) shallow water flow, or the calculation of the random movement (Brownian motion) can be found in the following articles (as an example: *Józsa-Kontur 1988, Józsa 1989, Szél-Józsa 1990, Józsa-Szél-Kontur 1992, Szél 1996*).

In two-dimensional shallow water flows the transport of conservative solutes or in other words advective dispersion can be characterised with the following equation (written in a conservative form):

$$\frac{\partial(hC)}{\partial t} + \frac{\partial(h\boldsymbol{U}_i C)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(h\boldsymbol{D}_{ij}\frac{\partial C}{\partial x_i}\right)$$

with x_i – local coordinates (x, y); h – water depth, (h(x,y,t)); $\boldsymbol{U}(u,v)$ – *Reynolds* time and depth averaged, two-dimensional velocity vector; C – *Reynolds* time and depth averaged scalar quantity, concentration or temperature; $\boldsymbol{D}_{ij}$ – dispersions tensor.

From the advective-diffusive equation, using the similarity with the *Fokker-Plack equation* the stochastic changing coordinates (x,y) of a particle can be derived. (*Józsa 1991*).

Elder's longitudinal and transversal dispersion coefficients were used (*Elder 1959, Holly 1985*):

$$D_L := e_L \cdot v_* \cdot h, \qquad D_T := e_T \cdot v_* \cdot h.$$

with: e_L –longitudinal dispersion coefficient, ($\kappa/6 + 0.404/\kappa^3 = 5.93$), e_T – transversal dispersion coefficient, ($\kappa/6 + 0.16 = 0.23$), v_*- shear velocity, κ - *Kármán constant* ($\kappa \cong 0.4$).

Of course a particle can be at any location of the flow filed. The results(u,v,h) of the River2D hydrodynamic finite element model were withdrawn on a Cartesian coordinate system (on a $\Delta x = \Delta y = 5$ m grid). From the known flow characteristics (u,v,h) with interpolation were the flow characteristics defined at the particle's position.

Defining the optimal outlet location.

Using two-dimensional hydrodynamic model a single particle was in the flow added at different locations, in the cross-section of the planned outlet (*Danube 1520+706 rkm*). The particle tracks (single particle streams) present the concentration maximum and its location compared to the river bank. At 5 different outlet location near the river streamline were the particle tracking made for the *Danube* section between 1520 and 1505 rkm.

As a refinement of the calculations for finding the optimal outlet location, at each alternative spot (5 spots) 1000 – 1000 particles were added in the flow. Studying different outlet

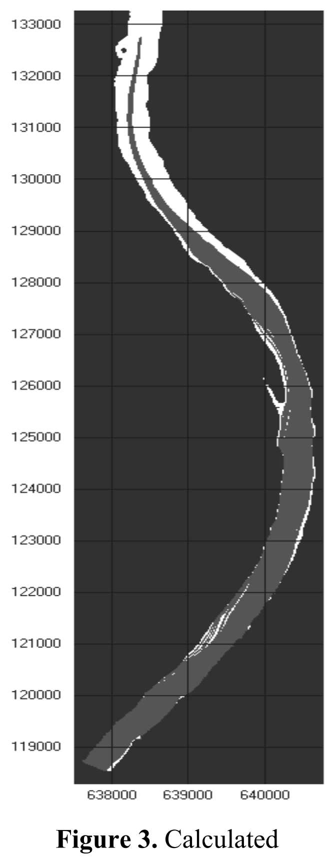

Figure 3. Calculated pollutant cloud

locations the particles reaching the riverbank (and staying for a longer time) were between 0 and 103 on the *Danube* section between 1520 – 1505 rkm. The optimal outlet location is near the deepest point of the cross section, in this case only few particles were reaching the left and right river bank. In that case less than 1% of the 1000 added particles reached either the left or right riverbank.

After finding the optimal location for the treated wastewater outlet, the movement of the pollutant cloud was studied. Result of the calculations with continuous particle outlet can be seen on **Figure 3**.

Introducing the applied analytical mixing model

After defining the optimal outlet location regarding mixing, the different parameters of the effluent dilution due to longitudinal and transversal dissipation were calculated. The dissolved or suspended – depth averaged – ollutant concentration, or temperature can be defined with the following equation (*MI-10-298-85*):

$$C_{m,h} = \frac{M}{2 \cdot h(\pi \cdot D_{y,1} \cdot v_x \cdot x)^{1/2}} \left\{ \exp\left(-\frac{v_x}{4D_{y,1} \cdot x} \cdot (y - y_0)^2 \right) + \exp\left(-\frac{v_x}{4D_{y,1} \cdot x} \cdot (y + y_0)^2 \right) \right\}$$

with: x, y – local coordinate system at the outlet: y, stands for transversal distance from the outlet, whereas x, stands for the longitudinal distance; $C_{m,h}$ – transversal distribution of a scalar quantity (depth averaged concentration or temperature); v_x – depth averaged longitudinal velocity; $D_{y,1}$ – transversal dispersion; M – mass flow rate (load) ($M = CQ$); Q – flow rate of the waste water and h – relevant water depth.

The calculated pollutant concentration should be considered as an increment of the recipient water bodies concentration (background concentration). In our case the recipient water body's, the *Danube*'s pollutant concentration – as a background concentration constant is space and time – was the design concentration with 90% probability form the long-time database of the National Water Quality Network (**Table 1.**).

The transversal dispersion coefficient was defined considering measurements by **VITUKI** (*Muszkalay*) and *Technical Guidelines (MI-10-298-85)* and set a low value of $D_{y,1} = 0,025$ m^2/s.

The vertical mixing length of a point source is about five times the water depth, which is about 20-25 m at low water conditions of the *Danube*.

Results of the impact analysis of loadability

When defining the maximal loadability the following aspects should be considered:

- The worst state of the **recipient**, highest background concentrations:
  - the worst state concerning water quantity in the recipient: in our case low water,

  - the worst state concerning water quality: in our case pollutant concentration with 90% probability.
- The worst state of the **treated waste water**, with highest waste load:
  - the worst state concerning water quantity of the treated waste water: in our case the peak discharge of the planned vegetable oil manufacturing plant,
  - the worst state concerning water quality of the treated waste water: in our case the permit limit concentrations.

The worst state regarding the recipient's water quantity can be characterised with the lowest discharge measured at the water gauge *Dombori*: 585 m^3/s (based on the daily discharge data between 1936 and 2009). The design background values are stated in **Table 1**. as well as the quality parameters of the treated waste water.

The change of the *Danube* water quality was studied, as an effect of the planned effluent, for **COD, BOD_5, ammonia-N, nitrate-N, total inorganic-N, organic solvent, total suspended solids** and for **total-P** load, as well as for the future planned discharge rates for **nitrate, ammonium** and **total inorganic-N** concentration. Our study covered if permit limits for the future planned bank-filtered aquifer's protection area of 50 years travel-time can be met. Concerning the total suspended solids the path distance of the lowest effluent limit of 30 mg/l set by the *Environmental, Nature and Water Inspectorate* was examined.

Regarding the **water temperature** we examined after which distance will the effluent's water temperature of 30°C cool down to $T_{background}$ +1°C

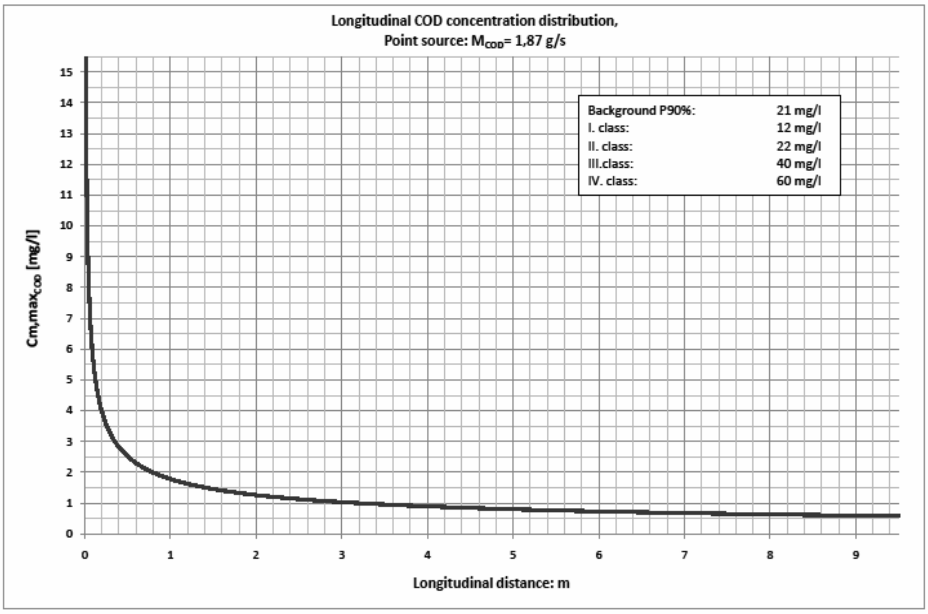

Figure 4. The longitudinal distribution of maximal **COD** concentration

As an example on the next figures the impact of **COD** load will be shown. The longitudinal distribution of maximal concentration increment as result of the effluent load can be seen on **Figure 4**. On **Figure 5.** the transversal distribution of the **COD** concentration - 4 m, 10 m, 50 m, 100 m and 200 m from the outlet.

It can be stated that the *Danube* water quality – in respect of **COD** concentration – is II. class (good) (according to the Hungarian Standard MSZ 12749:1983: ***Water quality of open channel flows, quality parameters and classification***). Changes of the water quality is only at an immediate vicinity of the outlet: after 10 m in longitudinal and after 3 m in transversal direction the increment of the **COD** concentration is less than 1 mg/l. The background concentration of the *Danube* is 21,6 mg/l, so the permit limit set by the *Environmental, Nature and Water Inspectorate* for **COD** concentration (50 mg/l), and a change in water quality class occurs only at an immediate vicinity of the outlet.

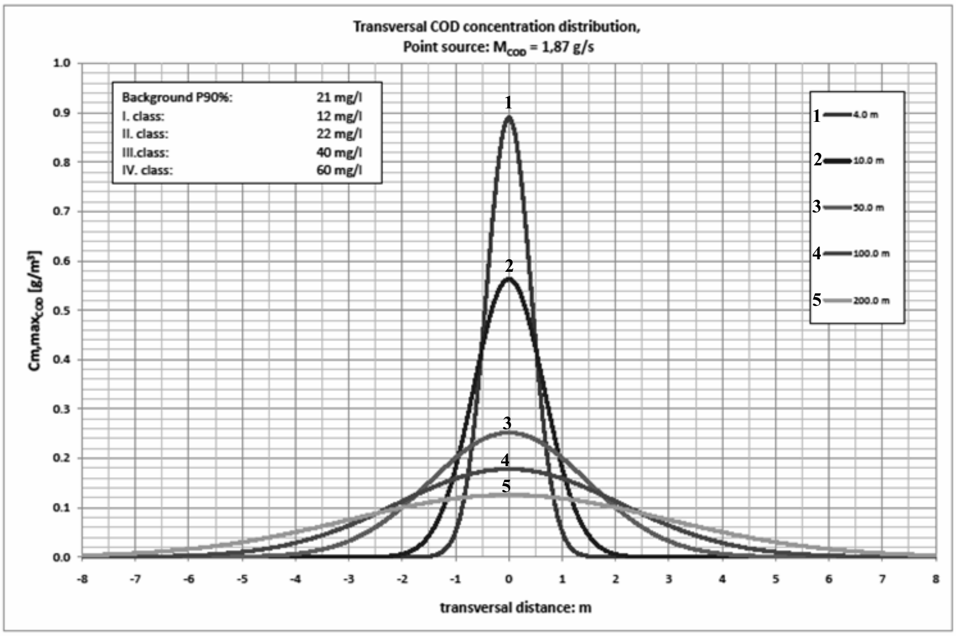

Figure 5.: Transversal distribution of the **COD** concentration

Final summary

Calculations of water quality changing of the *Danube* – as an open channel water body According to our calculations at low-water discharge conditions the mixing of the planned wastewater effluent (for operational and future conditions) is conform to the following regulations: *28/2004. (XII. 25.)*. The concentration maximum (of **COD**, **BOD_5, ammonia-N, nitrate-N, total inorganic-N, organic solvent, total suspended solids**) decrease under the permit limit set by the

Environmental, Nature and Water Inspectorate. Compared to the *Danube* as a background within 5 m mixing length the decrement of the water temperature is less than 1^{o}C; the increment of the total suspended solids is less than 3 mg/l whereas the increment of the organic solvent is less than 1 mg/l.

Concerning loadability of *Danube* water it can be stated that the planned vegetable oil manufacturing plant's effluent has a negligible effect on the water quality, since a change in the water quality class is only local (according to the Hungarian Standard MSZ 12749:1983: ***Water quality of open channel flows, quality parameters and classification***).

Calculations of water quality changing of the *Danube* – as part of the aquifer protection area

In 5 m distance from the planned outlet under operational and future effluent discharge conditions the concentration of **nitrate** and **total-N** reduces; after 20 m **ammonium** concentration reduces under the permit limits set for aquifers (*6/2009. (IV. 14.) KvVM Regulation* (Ministry of Rural Development). The future planned bank-filtered aquifer's (Gerjen North) protection area of 50 years travel-time is 800 m downstream from the outlet, so the regulations are fully completed, in case of minimum discharge conditions.

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